GEOTECHNICAL SITE CHARACTERIZATION

Neil Anderson, Ph.D.
Professor of Geology and Geophysics
Richard W. Stephenson, P.E., Ph.D.
Professor of Civil, Architectural and Environmental Engineering
University of Missouri-Rolla (UMR)

Geotechnical and Bridge Seismic Design Workshop
New Madrid Seismic Zone Experience

October 28-29, 2004, Cape Girardeau, Missouri

Outline

- Objectives of exploration program
- Exploration Program
  - Drilling and sampling
  - Geophysical testing
- Results of exploration program
  - Subsurface stratigraphy
  - Soil properties
  - Shear wave velocity profiles
- Site Classification
- Strain-dependent shear modulus and damping functions
- Final Comments

OBJECTIVES

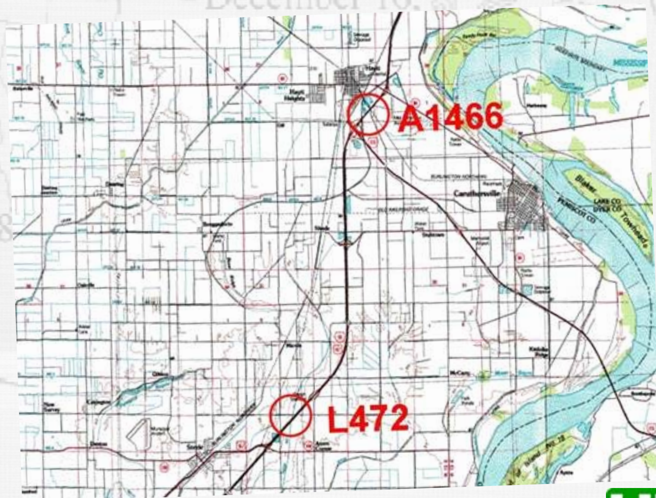
- Determine strain-dependent shear modulus and damping characteristics of subsoil
- Identify soil strata prone to liquefaction

Major Issues

- Deep unconsolidated soils
- High ground water levels
- High levels of ground motion

GEOTECHNICAL EXPLORATION PROGRAM

- Site



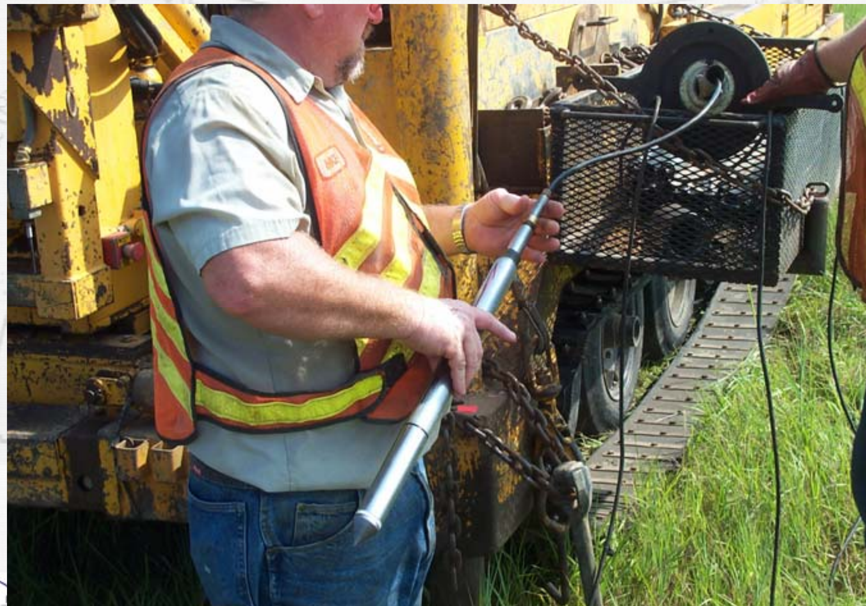
Field Exploration Program

Drilling – Failing 1500
- Rotary with mud
- Truck mounted
- Normal capacity
  - -1500 ft deep and 2-in to 13-in diameters
  - - 4.5 in for this project

- Hollow Stem Auger
  - 80 to 200 feet deep
- SPT Tests
  - Automatic safety hammer
- Sampling
  - Every 5 feet for first 25 feet
  - Every 10 feet below 25 foot depth
  - Cohesionless soils
    - Standard and oversize split spoon samples
  - Cohesive Soils
    - Seamless steel tubes (Shelby Tubes)

- Cone Penetration Testing
  - Continuous log of :
    - Tip Resistance
    - Side Sleeve Friction
    - Pore Water Pressures
- CPT & SCPT
  - Manufacturer: Hogentogler Co.
    - Electronic Subtraction Cone
      - Tip resistance
      - Local resistance
      - Pore pressure
      - Inclination
      - Downhole seismic velocity
      - Temperature

- Pushing Rigs - CME 850
- Cone tip saturated in vacuum with glycerin
  Push speed – 20 cm/s

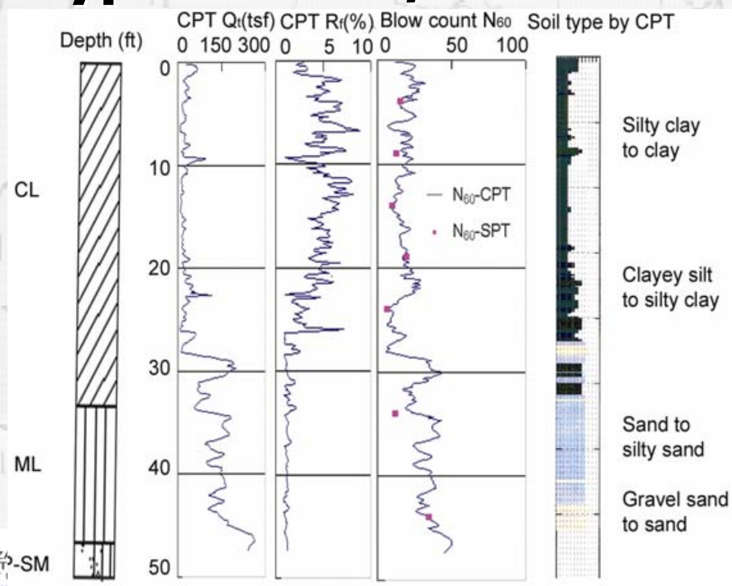


Site Charact. - 11

CPT subtraction probe
(Hogentogler & Co.)

Site Charact. - 12

Typical Cone/SPT Data

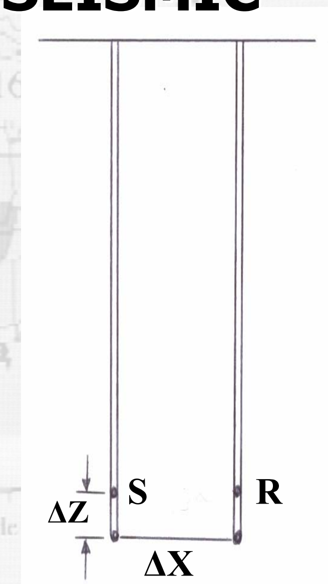


GEOPHYSICAL TESTING

- Seismic Cone Penetration
- Cross-Hole Seismic Velocity
- Spectral Analysis of Surface Waves (SASW)

CROSS-HOLE SEISMIC

Technique employs twinned (or tripled) boreholes completed at the base of the zone of interest and separated by surface distances on the order of 3 to 4 m. (Subsurface separ-ations are determined using a borehole inclinometer.)



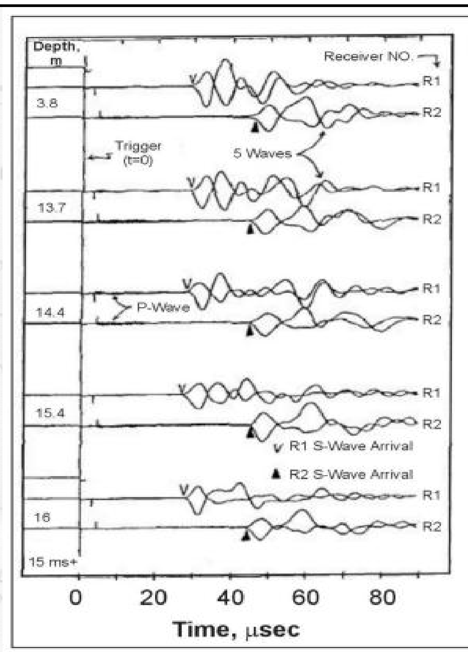
NATURAL HAZARDS MITIGATION INSTITUTE

UMR UNIVERSITY OF MISSOURI-ROLLA

CH SEISMIC

Shear-wave source lowered to base of one borehole; triaxial geophone lowered to same depth in adjacent borehole.

Hammer source is discharged twice - with opposite directional impacts - thereby generating two opposite-polarity shear-wave records.



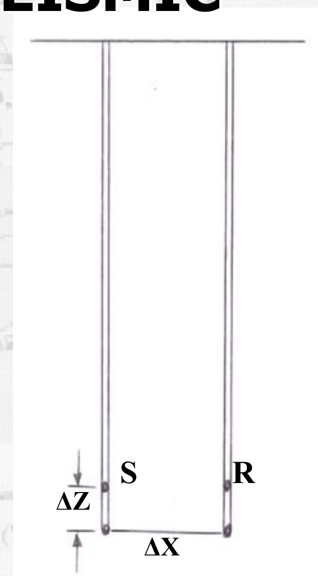
NATURAL HAZARDS MITIGATION INSTITUTE

UMR UNIVERSITY OF MISSOURI-ROLLA

CROSS-HOLE SEISMIC

Source and geophone are raised (at regular intervals) to top of borehole. Interval shear-wave velocities (V_{int}) calculated for each layer tested on the basis of borehole separation (x) and shear-wave travel time (Δt).

$Vint = \Delta x/\Delta t$



NATURAL HAZARDS MITIGATION INSTITUTE

UMR UNIVERSITY OF MISSOURI-ROLLA

CROSS-HOLE SEISMIC

Strengths: Cross-borehole tool is “theoretically” capable of providing more accurate in-situ, shear-wave interval velocities than either the SCPT or MASW techniques.

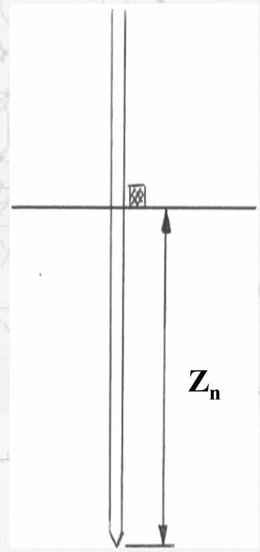
Weaknesses: Related to cost and site accessibility, as twinned boreholes are required.

NATURAL HAZARDS MITIGATION INSTITUTE

UMR UNIVERSITY OF MISSOURI-ROLLA

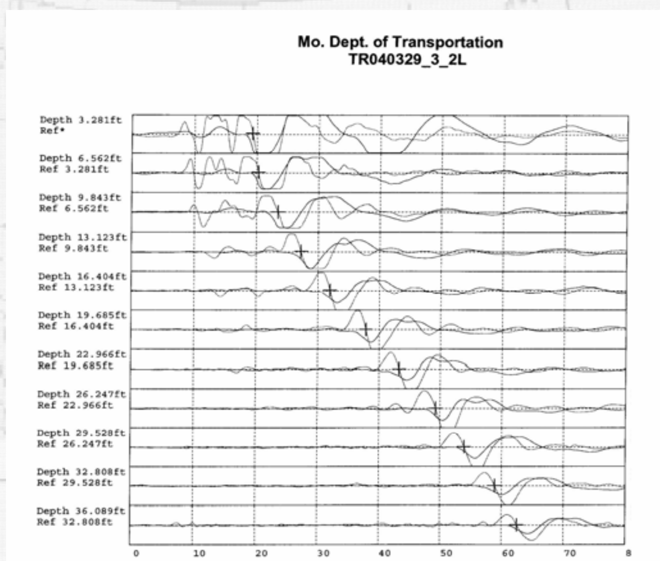
SEISMIC CONE PENETROMETER

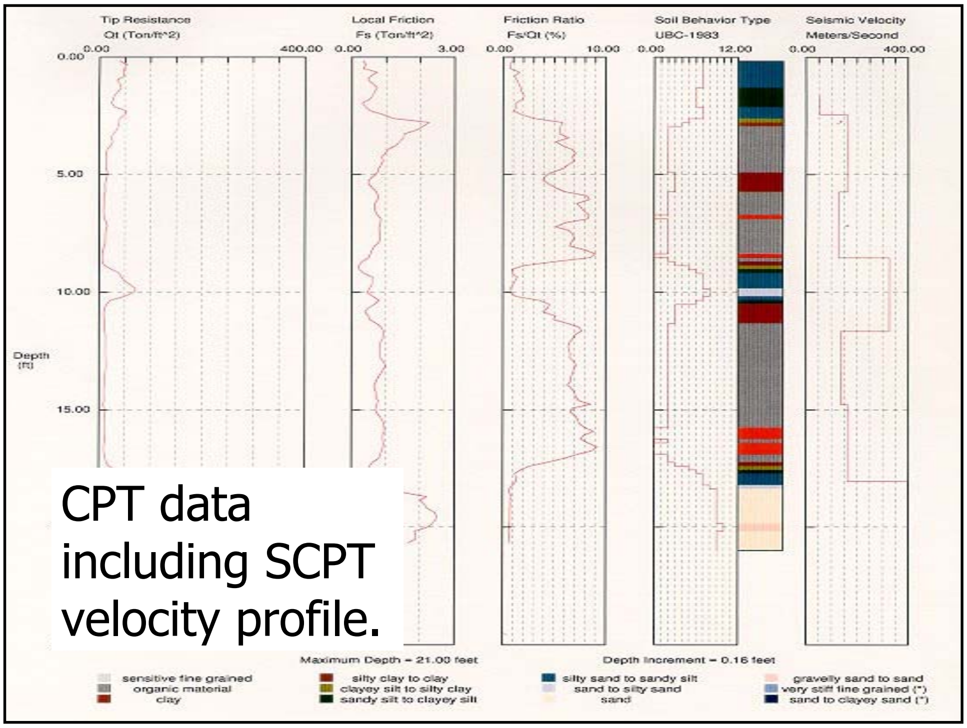
Employs a down-hole geophone and surface source. As SCPT cone is pressed into the soil, it is halted at predetermined depths and surface shear-wave source is discharged. The travel time of the shear-wave energy (ΔT_n) is measured for each SCPT test depth (Z_n).



SEISMIC CONE PENETROMETER

An interval velocity is then calculated for each depth interval.





CPT data including SCPT velocity profile.

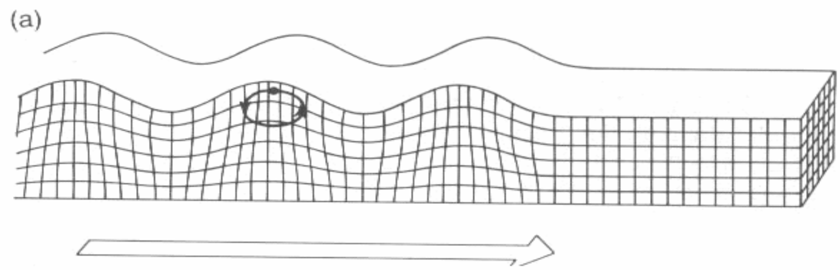
SEISMIC CONE PENETROMETER

Strengths: If all travel times are measured accurately, the SCPT tool is capable of providing accurate interval velocities for layers with thicknesses on the order of 1 m.

Weaknesses: If all travel times are not accurately measured, the output interval velocities will be inaccurate.

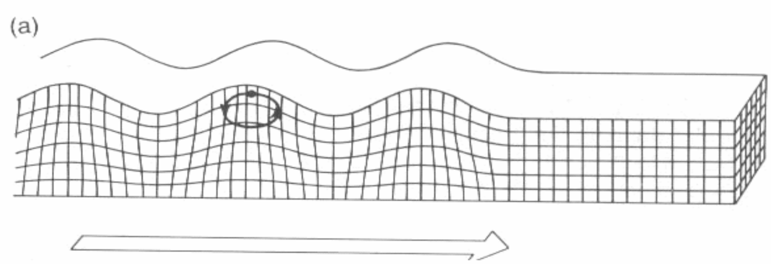
SASW TECHNIQUE

Rayleigh waves are generated using active and/or passive sources. In a heterogeneous earth, shear-wave and compressional-wave velocities vary with depth. Hence, the different component frequencies of Rayleigh waves exhibit different phase velocities.



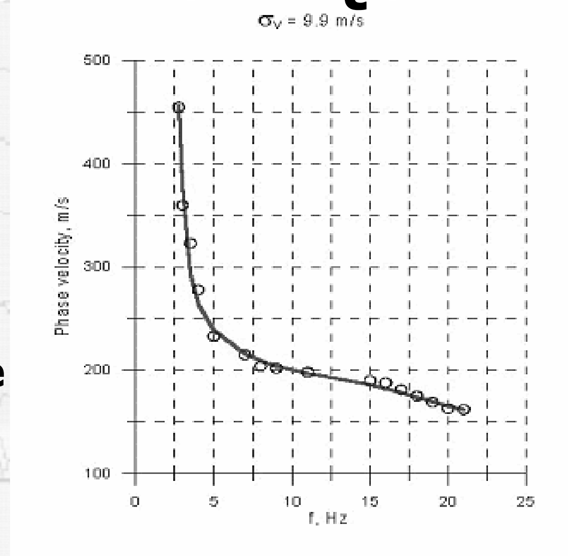
SASW TECHNIQUE

The phase velocity of each component frequency is a function of the variable body wave velocities over the vertical depth range of particle motion associated with that specific wavelength.



SASW TECHNIQUE

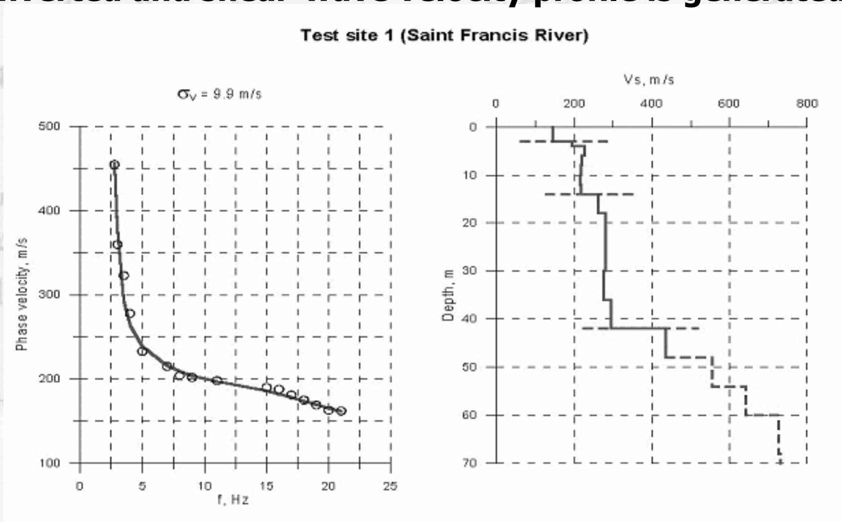
During processing, phase velocities are calculated for each component frequency of the recorded Rayleigh waves.



NATURAL HAZARDS MITIGATION INSTITUTE

UMR UNIVERSITY OF MISSOURI-ROLLA

Dispersion curve (phase velocity vs. frequency) is inverted and shear-wave velocity profile is generated.



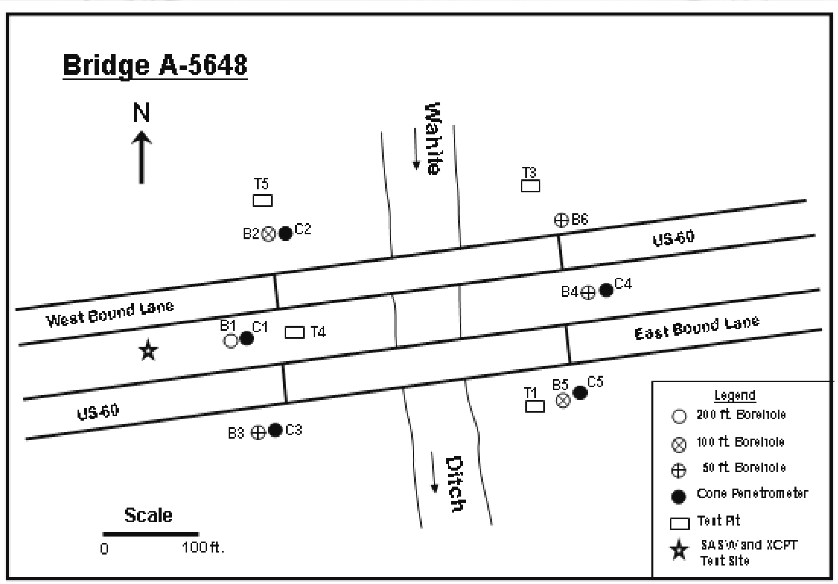
NATURAL HAZARDS MITIGATION INSTITUTE

UMR UNIVERSITY OF MISSOURI-ROLLA

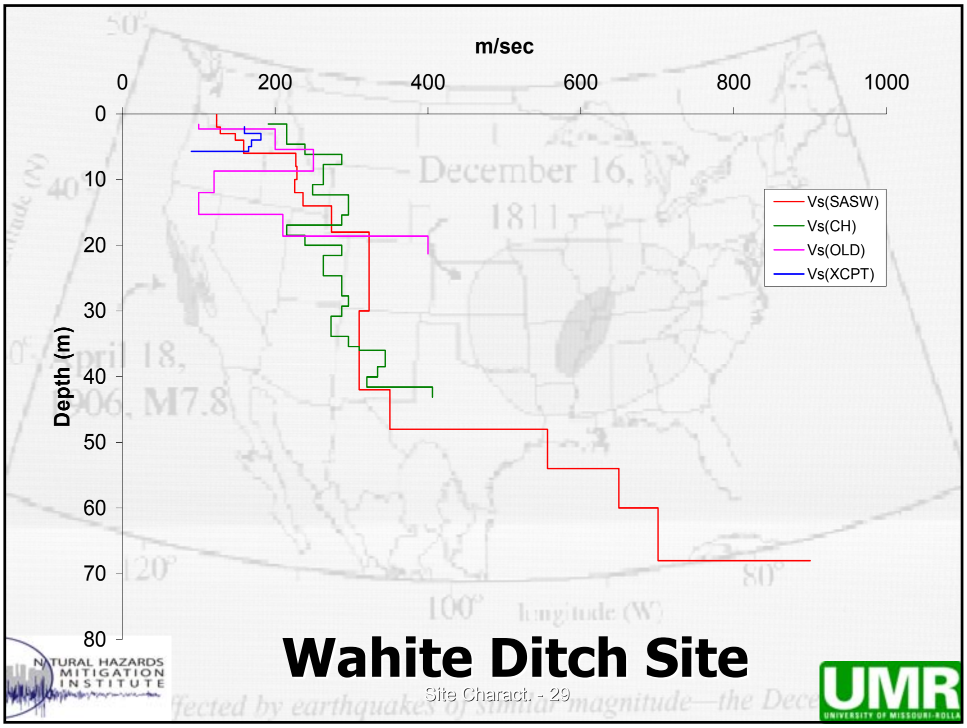
SASW TECHNIQUE

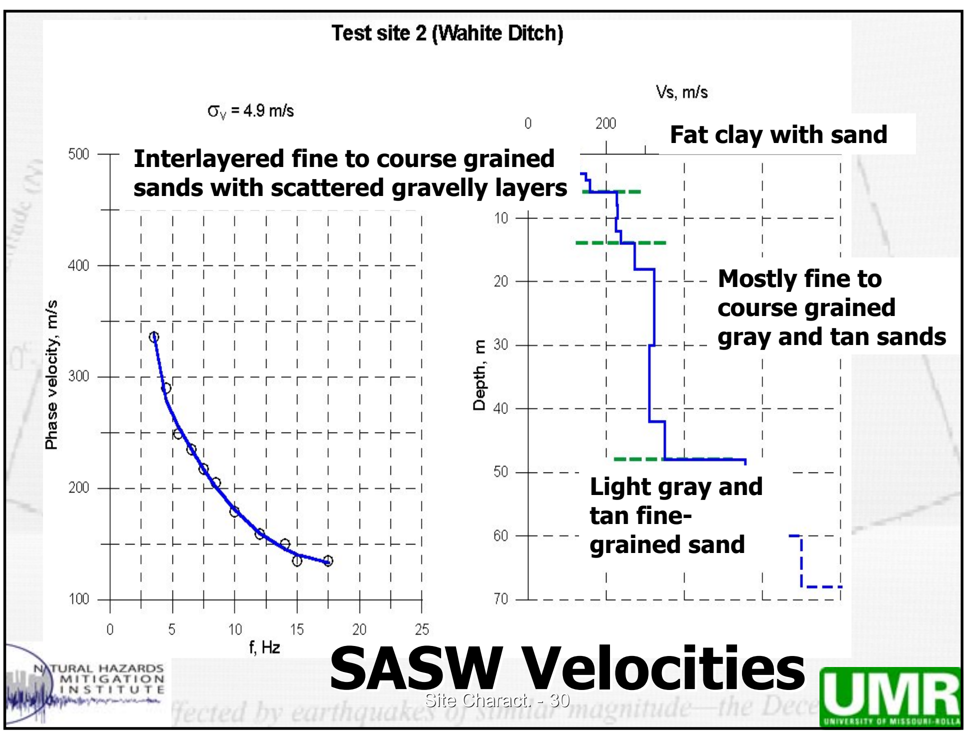
Strength: The technique can be used in areas where the SCPT cannot be employed. SASW data are relatively inexpensive to acquire.

Weakness: Depth of investigation is limited by source. Vs/Vp ratios must be estimated during inversion.



Wahite Ditch Site


m/sec
0
200
400
600
800
1000
Depth (m)
0
10
20
30
40
50
60
70
80
Vs(SASW)
Vs(CH)
Vs(OLD)
Vs(XCPT)
December 16, 1811
April 18, 1906, M7.8
longitude (W)
NATURAL HAZARDS MITIGATION INSTITUTE
Wahite Ditch Site
Site Charact. - 29
UMR
UNIVERSITY OF MISSOURI-ROLLA


Test site 2 (Wahite Ditch)
σV = 4.9 m/s
Interlayered fine to course grained
sands with scattered gravelly layers
Phase velocity, m/s
100
200
300
400
500
f, Hz
0
5
10
15
20
25
Vs, m/s
0
200
Fat clay with sand
Depth, m
10
20
30
40
50
60
70
Mostly fine to
course grained
gray and tan sands
Light gray and
tan fine-
grained sand
NATURAL HAZARDS MITIGATION INSTITUTE
SASW Velocities
Site Charact. - 30
UMR
UNIVERSITY OF MISSOURI-ROLLA

CH Velocities

CH velocities correlate well with SASW data. SASW velocities increase step-wise from ~130 m/s to ~350 m/s. Same interval on the BH profile is characterized by shear-wave velocities that increase gradually from about ~150 to ~380 m/s.

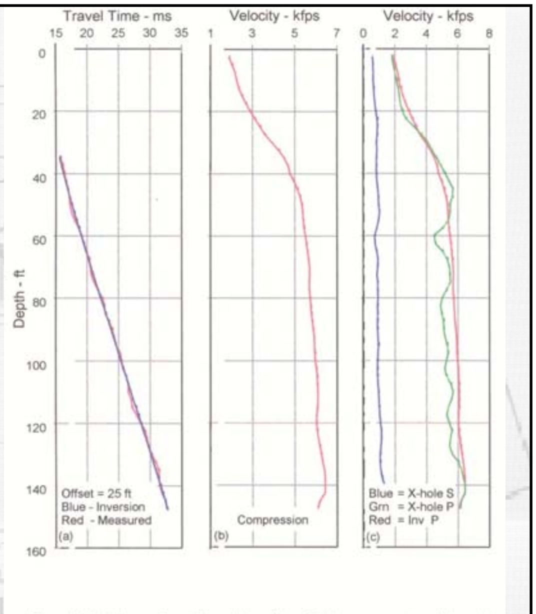
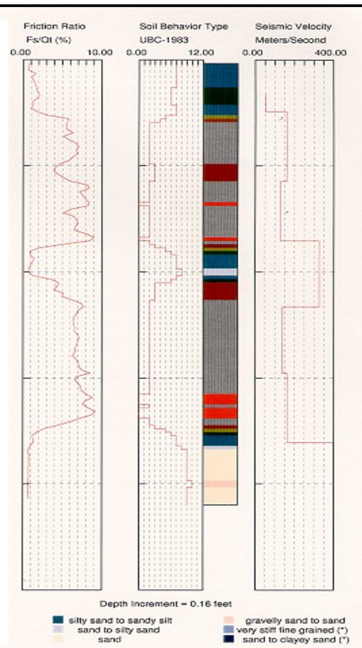


Figure 10. (a). Comparison of travel times from field measurements and inversion model. (b). Corresponding inversion velocity. (c). Comparison of inversion velocity with tomographic velocities.

SCPT Velocities

Near-surface (<6 m) clays characterized by SCPT shear-wave velocities ranging from ~100-240 m/s. Highest velocities are observed at depths of ~3 m. Underlying sands are characterized by velocities on the order of 400 m/s. Values are significantly higher than SASW and cross-borehole velocities over same lithology/ same depth intervals.



Conclusions

- SASW-derived shear-wave velocity profiles correlate well with subsurface lithologic logs & available cross-borehole shear-wave velocity control.
- Clays, silts and sands exhibit relatively characteristic SASW-derived shear-wave velocities, which increase step-wise with depth of burial.
- The SASW and BH shear-wave velocity profiles and borehole lithologic data do not correlate particularly well with the SCPT shear-wave velocity profiles – particularly at shallow depths.

Testing Program

Bridge A1466

Test type	CPT	SCPT	Borehole		
Number	4	3	2	1	2
Depth (ft)	23~65	40~66	80	100	200
Note	An observation well was installed at one 80’ borehole. Two 200’ boreholes were used for cross-hole geophysical test.				

NATURAL HAZARDS MITIGATION INSTITUTE

Site Charact. - 35

UMR UNIVERSITY OF MISSOURI-ROLLA

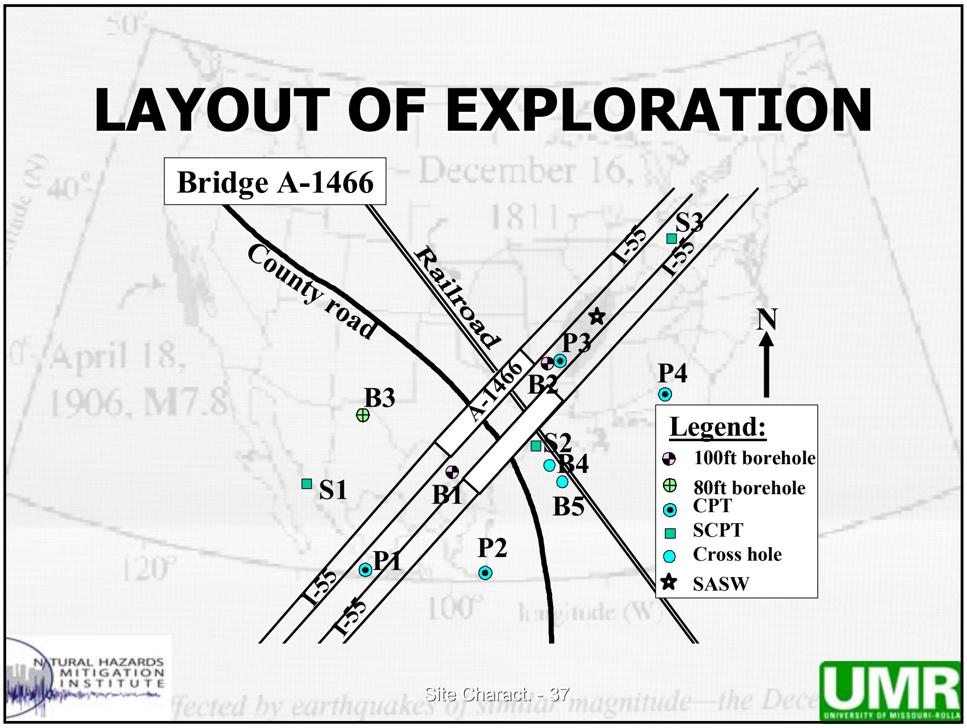
Bridge L472

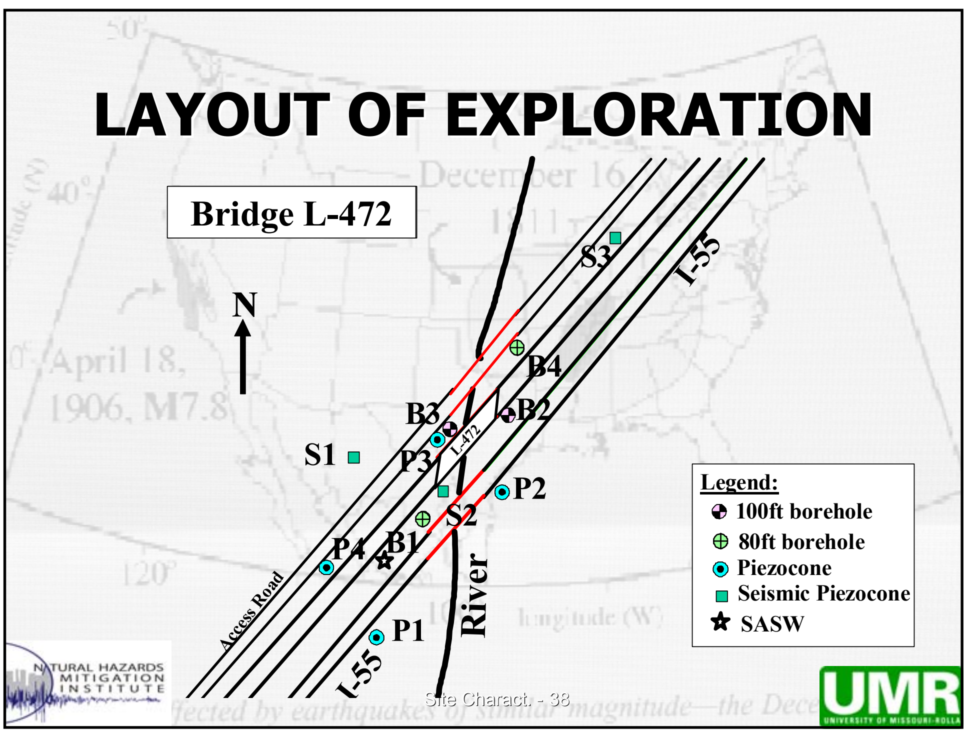
Test type	CPT	SCPT	Borehole	
Number	4	3	2	2
Depth (ft)	41~54	36~41	80	100
Note	P1 and P2 were moved from the bottom to the top of slope due to the soft soil after raining			

NATURAL HAZARDS MITIGATION INSTITUTE

Site Charact. - 36

UMR UNIVERSITY OF MISSOURI-ROLLA

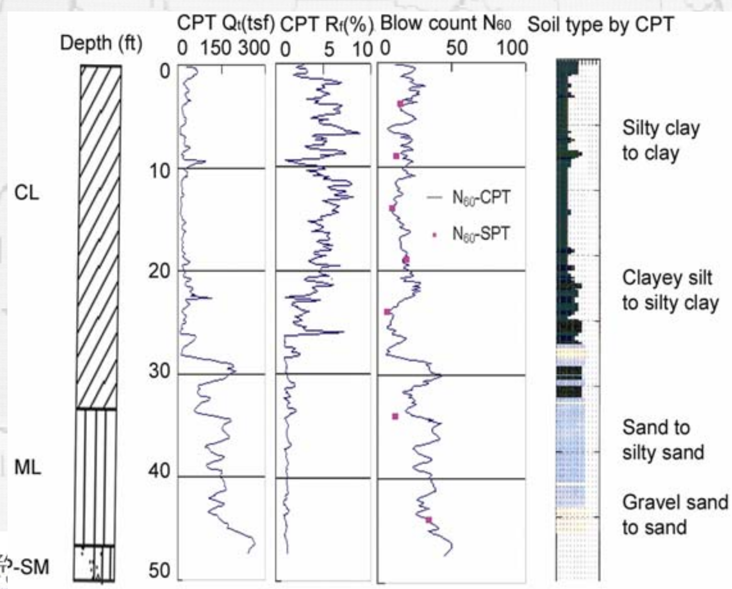

LAYOUT OF EXPLORATION
Bridge A-1466
County road
Railroad
I-55
I-55
I-55
I-55
A-1466
S3
P3
B2
P4
N
B3
S2
B4
S1
B1
B5
P2
P1
Legend:
100ft borehole
80ft borehole
CPT
SCPT
Cross hole
SASW
NATURAL HAZARDS MITIGATION INSTITUTE
Site Charact. - 37
UMR
UNIVERSITY OF MISSOURI-ROLLA


LAYOUT OF EXPLORATION
Bridge L-472
N
S3
I-55
B4
B3
B2
L-472
S1
P3
P2
S2
P4
B1
Access Road
River
P1
I-55
Legend:
100ft borehole
80ft borehole
Piezocone
Seismic Piezocone
SASW
NATURAL HAZARDS MITIGATION INSTITUTE
Site Charact. - 38
UMR
UNIVERSITY OF MISSOURI-ROLLA

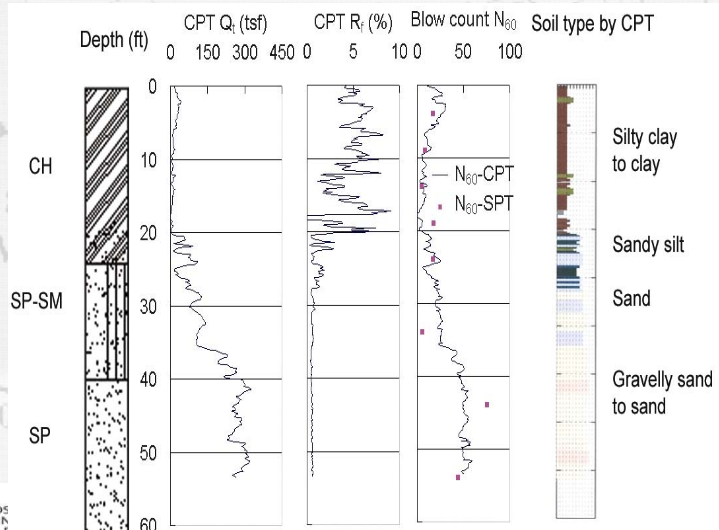
CPT CLASSIFICATION

- Based on UBC83
  - Tip resistance
  - Friction ratio
  - Laboratory classification tests

A1466



L472



DEEP SOIL PROPERTIES

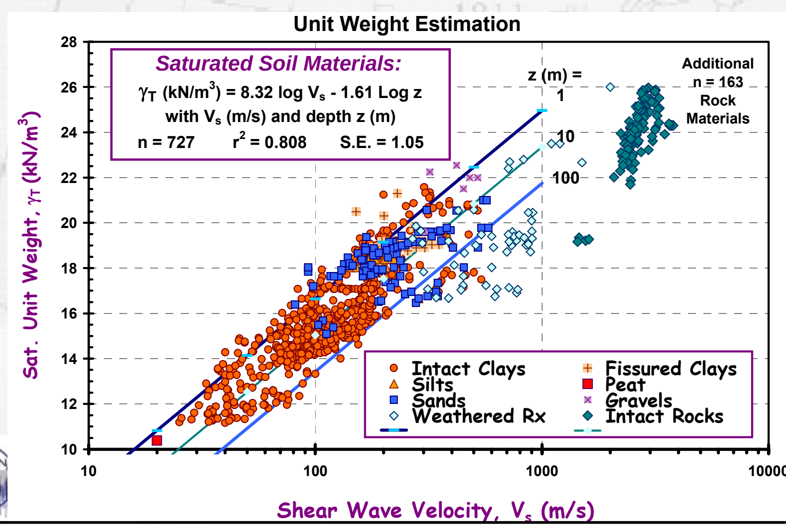
- CPT maximum depth ~ 20 m (60 ft)
- SPT maximum depth ~ 60 m (200 ft)
- Depth of soil profile:
  - 650 to 720 m (2100-2400 ft)
- Must determine necessary soil properties from available correlations

- Soils at depth were classified from water well log descriptions
  - Well No. 2 was drilled in 1949 at Steele.
    - 720 m deep.
  - Well No. 4 was drilled in 1947 at Hayti
    - 650 m deep

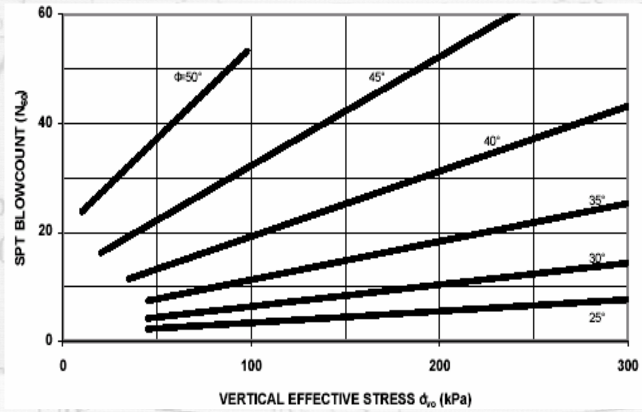
Site Charact. - 43

CORRELATIONS

- Unit Weight (Mayne, 2001)

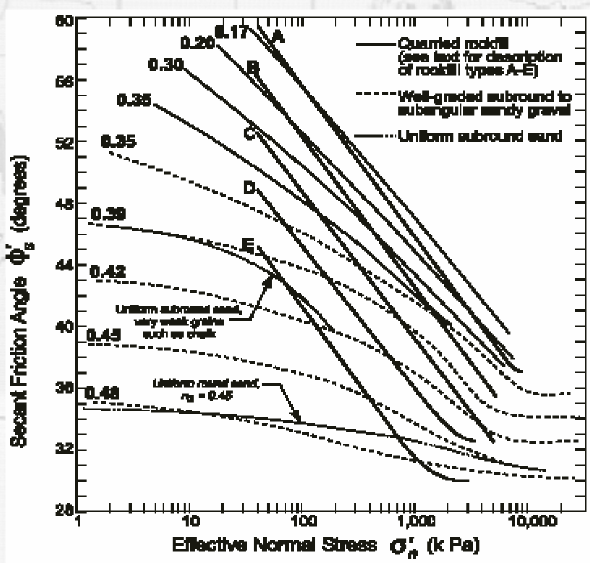


- Internal friction angle, Φ
  - Schmertmann, 1975)

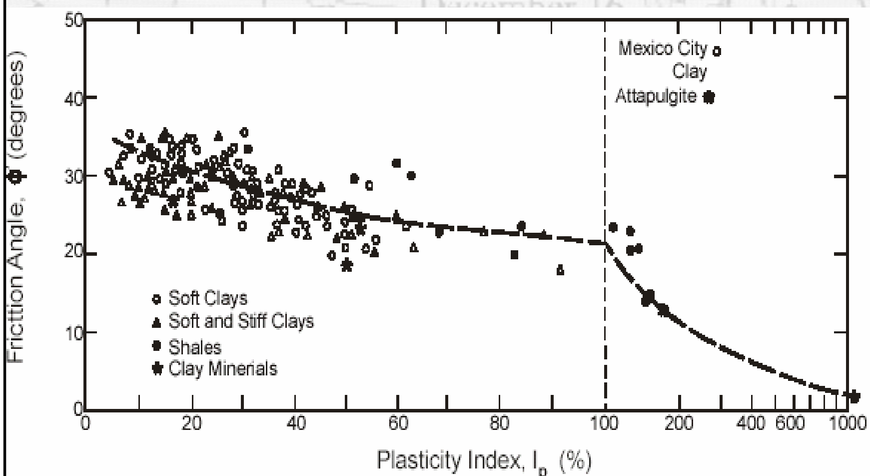


$$\phi' \approx \tan^{-1}\left[N_{60}/12.2 + 20.3\sigma'_{v0}/P_a\right]^{0.34}$$

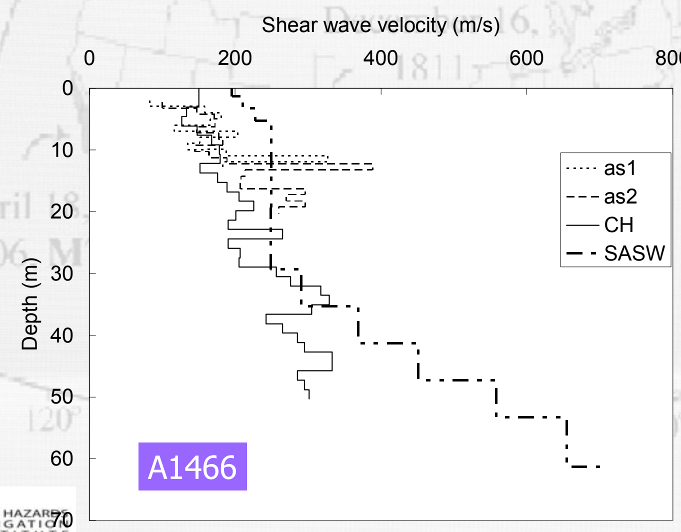
- Deep soils without SPT N values:
  - Terzaghi, et al., 1996

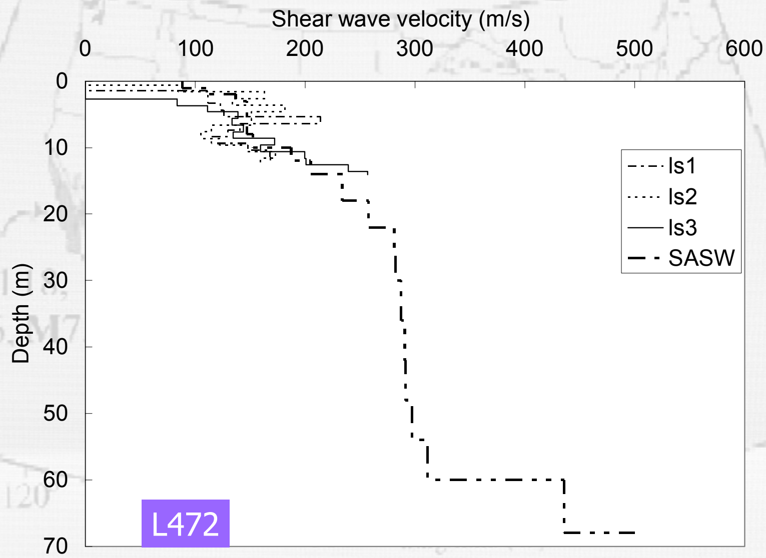


- Cohesive Soils
  - Mesri, 1993



SHEAR WAVE VELOCITIES





- Maximum Shear Modulus

$$G_{max} = \rho v_s^2$$

ρ- mass density
v_s-shear wave velocity

$$G_{max} = 1230 OCR^k \frac{(2.973 - e)^2}{1 + e} (\sigma'_0)^{0.5}$$

OCR-overconsolidation ratio
e-void ratio
σ'_0-mean principal effective stress
k-function of PI

Comparison of (Gmax)field/(Gmax)correlation at B3 of A1466

Ratio of G_{max}	SCPT/Hardin	SASW/Hardin	Cross-hole/Hardin
CL (0~5.5 m)	0.87	3.13	0.95
ML (5.5~9.1 m)	0.87	3.18	0.81
SM (9.1~13.2 m)	1.57	1.50	0.82
SP (13.2~21.3 m)	-	0.74	0.45
SP-SM (21.3~25.6 m)	-	0.70	0.66
Overall	1.06	1.30	0.68

NATURAL HAZARDS MITIGATION INSTITUTE

UMR UNIVERSITY OF MISSOURI-ROLLA

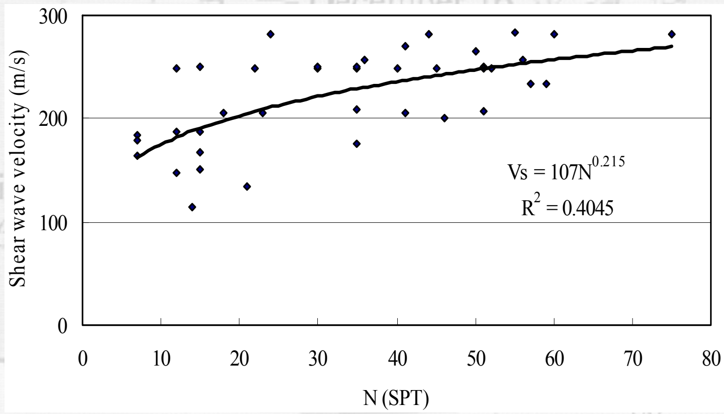
Comparison of (Gmax)field/(Gmax)correlation at B1 of L472

Ratio of G_{max}	SCPT/Hardin	SASW/Hardin
CL (0~3.7 m)	0.58	0.56
OH (3.7~5.2 m)	1.41	1.18
CL (5.2~6.4 m)	0.70	0.71
CH (6.4~8.5 m)	0.35	0.67
SM (8.5~11.6 m)	0.37	0.47
SP-SM(11.6~25.6 m)	-	0.87
Overall	0.60	0.79

NATURAL HAZARDS MITIGATION INSTITUTE

UMR UNIVERSITY OF MISSOURI-ROLLA

SHEAR WAVE VELOCITY FROM SPT TESTING

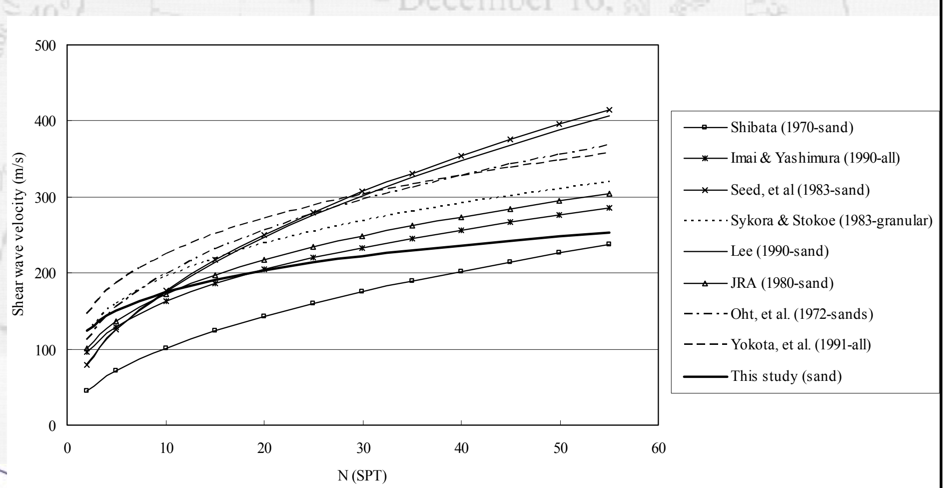


$$V_s = 107\,N^{0.215}$$

NATURAL HAZARDS MITIGATION INSTITUTE

UMR UNIVERSITY OF MISSOURI-ROLLA

COMPARISON TO PUBLISHED VALUES

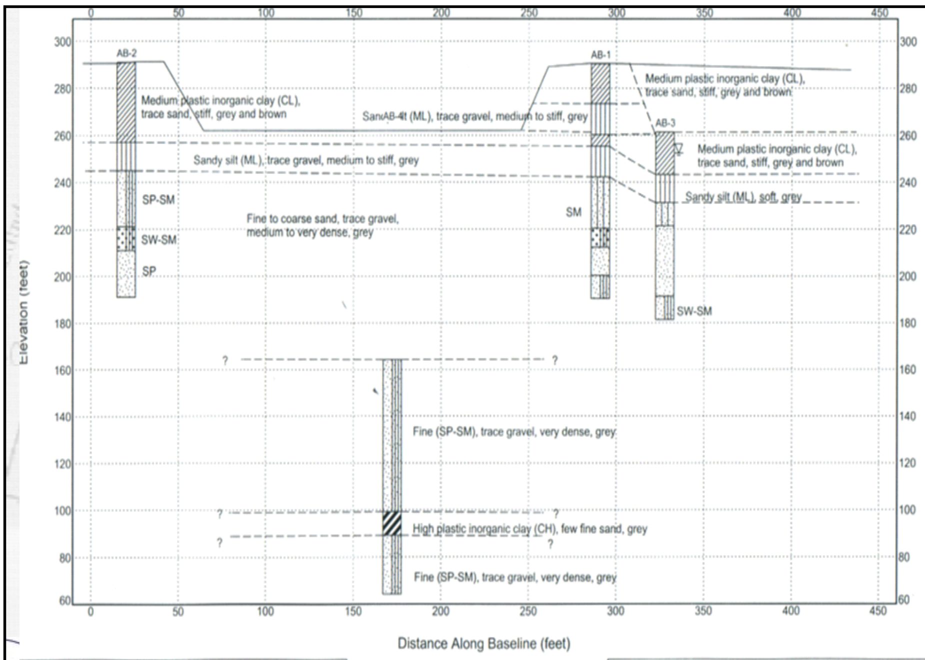


MITIGATION INSTITUTE

UMR UNIVERSITY OF MISSOURI-ROLLA

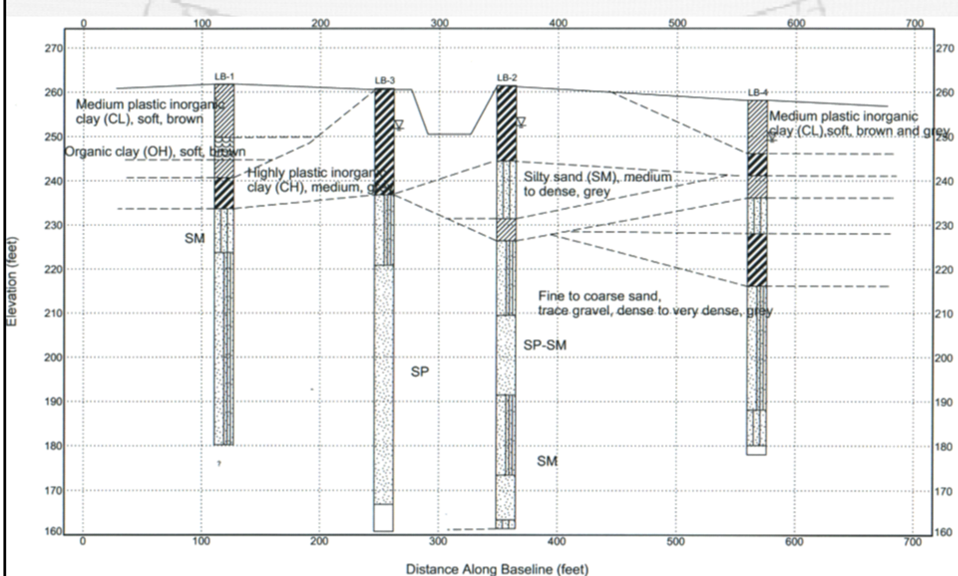
SOIL PROFILE AT BRIDGE SITE A1466

Site Charact. - 55



Site Charact. - 56

SOIL PROFILE AT BRIDGE SITE L472



SITE CLASSIFICATION

- Based on National Earthquake Hazards Reduction Program (NEHRP).

NATURAL HAZARDS MITIGATION INSTITUTE

Site Charact. - 59

UMR UNIVERSITY OF MISSOURI-ROLLA

Site Class	Description
A	Hard rock with $\bar{v}_s$ > 1500 m/s
B	Rock 760 m/s < $\bar{v}_s \le$ 1500 m/s
C	Very dense soil and soft rock with 360 m/s< $\bar{v}_s \le$ 760 m/s
D	Stiff soil with $\bar{v}_s$< 180 m/s or with 15≤N'≤50 or 50 kPa≤ $\bar{s}_u$ 180 m/s ≤ 100 kPa
E	A soil profile with $\bar{v}_s$ < 180 m/s or with either N' ≤15, s_u<50 kPa or any profile with ore than 10 ft (3 m) of soft clay defined as soil with PI>20, w≥40 %, and s_u< 25 kPa
F	Soils requiring site-specific evaluations: 1. Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, and collapsible weakly cemented soils. 3. Peats and/or highly organic clays (*H* > 3 m of peat and/or highly organic clay where *H* = thickness of soil) 3. Very high plasticity clays (*H* > 8 m with PI > 75) 4. Very thick soft/medium stiff clays (*H* > 36 m)

Site Class	Maximum Considered Earthquake Spectral Response Acceleration at Short Periods				
	$S_s \leq 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \geq 0.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	3.5	1.7	1.2	0.9	0.9
F	*a*	*a*	*a*	*a*	*A*

Site Class	Maximum Considered Earthquake Spectral Response Acceleration at long Periods				
	$S_l \leq 0.1$	$S_l = 0.2$	$S_l = 0.3$	$S_l = 0.4$	$S_l \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	3.4	3.0	1.8	1.6	1.5
E	3.5	3.2	3.8	3.4	3.4
F	*a*	*a*	*a*	*a*	*A*

BRIDGE SITE A1466

Geophysical tests	S1	S2	S3	Cross-hole	SASW
Depth (m)	13.92	20.23	6.55	30.50	29.28
V_S (m/s)	135.96	171.53	220.01	178.06	241.78
Borings	B1	B2		B3	
Depth (m)	21.65	23.56		25.6	
$\overline{N}$	22	20		8.56	

Site Class E-Based on average shear wave velocity from cross-hole test

Site Class D-Based on average shear wave velocity from SASW test

BRIDGE SITE L472

Geophysical tests	S1	S2	S3	SASW
Depth (m)	11.90	13.50	14.07	30
v_s(m/s)	133.02	130.45	128.54	193.10
Borings	B1	B2	B3	B4
Depth (m)	25.6	31.1	31.1	25.6
$\overline{N}$	11.54	17.63	13.88	8.59

Site Class D-Based on average shear wave velocity from SASW test

INCONSISTENCIES

- Maybe classified as:
  - D based on average shear wave velocity
  - E based on average SPT values
- Classification based on Western United States conditions
  - New Madrid zone is much different
  - Little data on deep soil properties

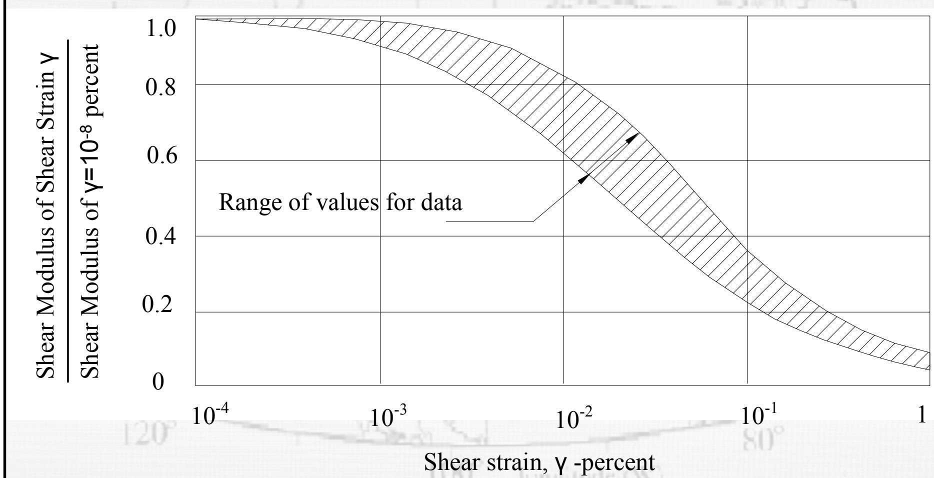
DYNAMIC SOIL PROPERTIES

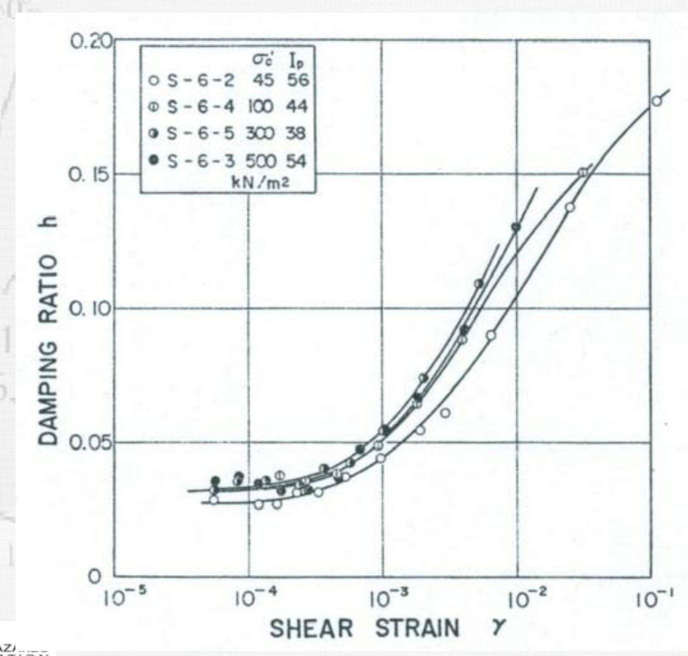
SHEAR MODULUS AND DAMPING RATIO AT LOW STRAIN LEVELS

- Measured from:
  - Shear wave velocity measurements
    - Field (geophysical testing)
    - Laboratory
      - Resonant column
      - Ultrasonic velocity

Influencing parameters

- Soil type
- Density (void ratio)
- Overconsolidation ratio (OCR)
- Effective confining stresses


Shear Modulus of Shear Strain γ
Shear Modulus of γ=10-8 percent
1.0
0.8
0.6
0.4
0.2
0
Range of values for data
10-4
10-3
10-2
10-1
1
Shear strain, γ -percent


σc' Ip
S-6-2 45 56
S-6-4 100 44
S-6-5 300 38
S-6-3 500 54
kN/m2
0.20
0.15
0.10
0.05
0
DAMPING RATIO h
10-5
10-4
10-3
10-2
10-1
SHEAR STRAIN γ

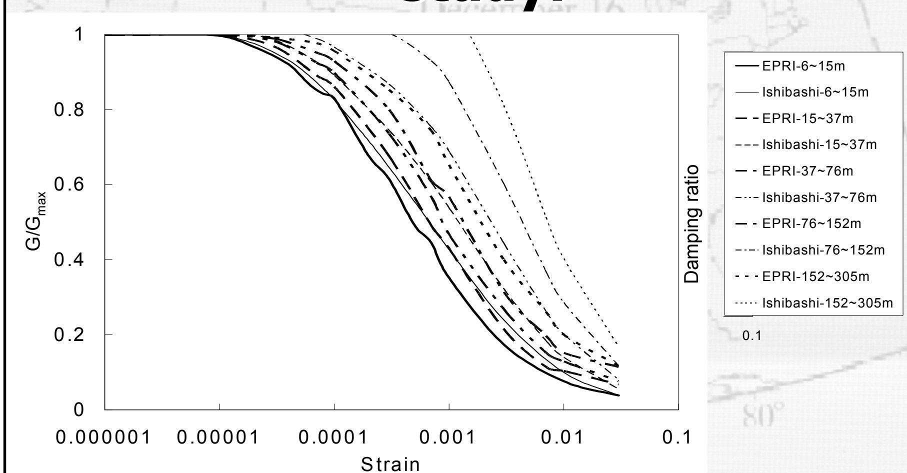
We found more than two dozen published correlation equations for strain-dependent shear modulus and damping.

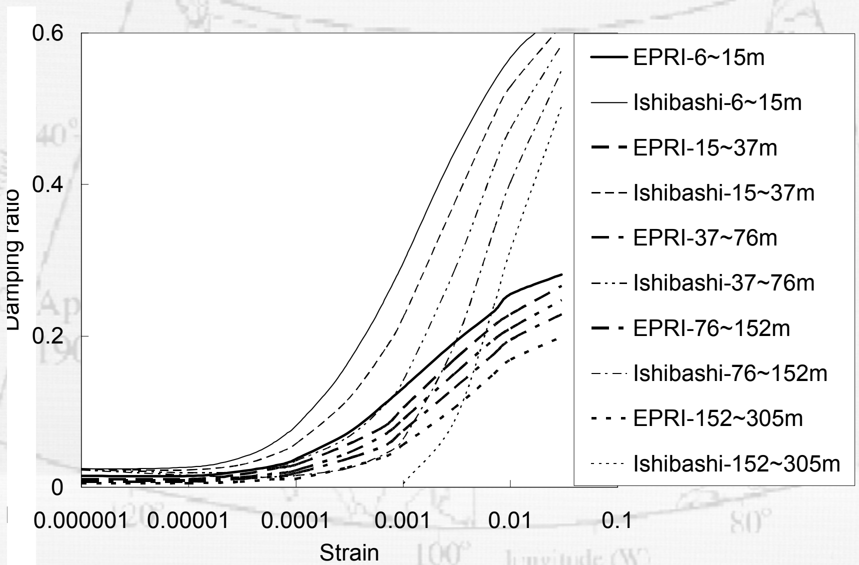
Conclusions

- Gmax increases with PI and time increasing for cohesive soil. Gmax is not sensitive to confining duration time for sandy soil.
- Gmax increases and damping ratio at small strain decreases with confining pressure increasing and Gmax is independent of loading frequency.
- Grain size, grain shape, gradation, degree of saturation, and frequency of vibration introduce insignificant effects on shear modulus of sands.
- G/Gmax and D are not sensitive to confining pressure and OCR but highly dependent on PI for cohesive soils. It increases with PI decreasing.

- The effect of loading frequency on G/Gmax reduction curves can be negligible.
- G/Gmax increases and D decreases with confining pressure increasing for sand.
- G/G_0' and D is relatively confining pressure independent for clayey sands.

Relationships used for this study:



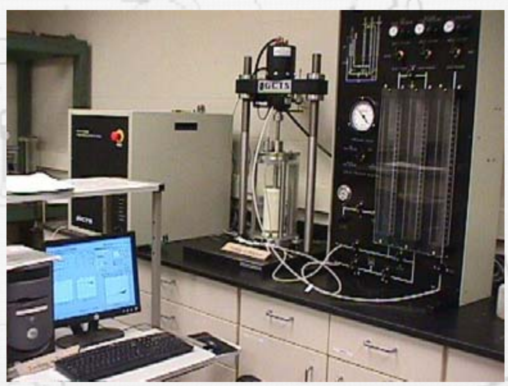


Final Comments

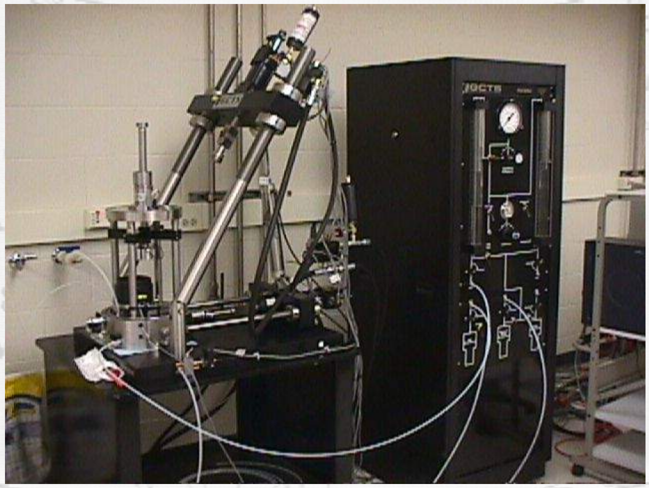
- Hampered by lack of deep exploration boreholes in the NMSZ
- Lack of information on the effect of high confining pressures on soil properties
- Lack of information on the behavior of silty soils, i.e., ML,SM, etc.

Future Work

- Comprehensive Laboratory Study of silts, silty clays



Stress path Triaxial



Cyclic Simple Shear

Ultrasonic Velocity

Resonant Column

Site Charact. - 41