CAN BRIDGE DESIGNERS BENEFIT FROM PERFORMING SITE-SPECIFIC GROUND MOTION RESPONSE ANALYSIS (SSGMRA)?
SPATIAL ANALYSIS OF BENEFITS OF SSGMRA
(RESEARCH PROJECT NO. TRC1901)

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Motivation

- Site-Specific Ground Motion Response Analysis (SSGMRA) may reduce seismic demands in parts of Arkansas which will result in cost saving.

Objectives of TRC1901

- OBJECTIVE 1: OBTAINING SITE SPECIFIC SHEAR-WAVE VELCITY PROFILES
- OBJECTIVE 2: COLLECT SOIL BORING LOGS
- OBJECTIVE 3: PERFORMING SITE-SPECIFC ANALYSIS
- OBJECTIVE 4: GROUND SURFACE CONTOUR MAPS
- OBJECTIVE 5: DEVELOPING DOCUMENTATIONS AND SPECIFICATIONS FOR SITES THAT NEED SITE-SPECIFC STUDIES

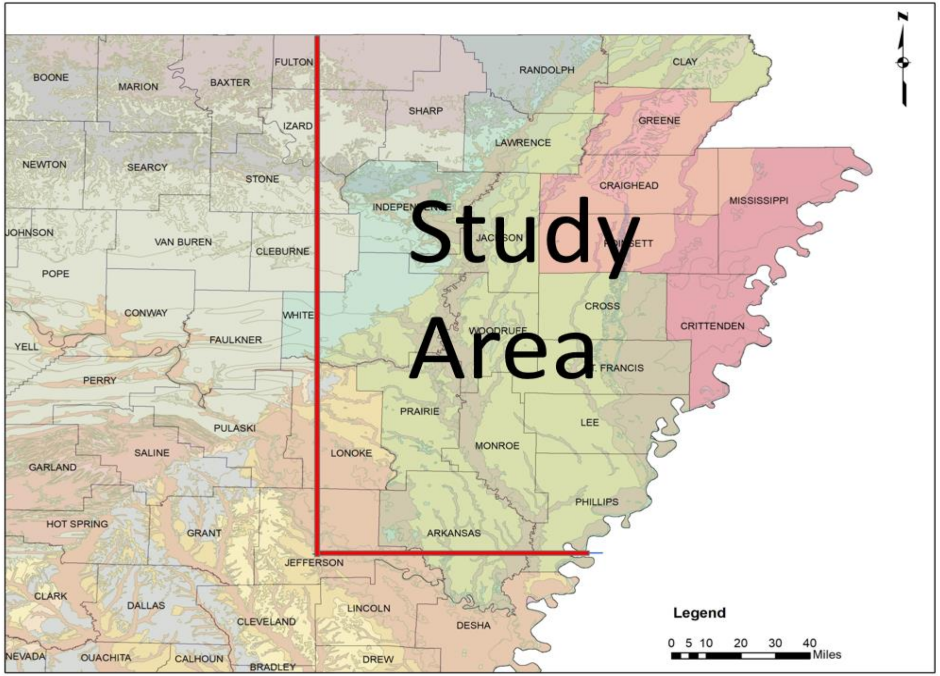
OBTAINING SITE SPECIFIC SHEAR-WAVE VELCITY PROFILES

- Planning and meeting with ARDOT to select 20 sites.
- ReMi and MASW measurements at the selected sites.
- Processing of the collected data.
- Determination of shear-wave velocity profile.

Objectives of TRC1901

- OBJECTIVE 1: OBTAINING SITE SPECIFIC SHEAR-WAVE VELCITY PROFILES

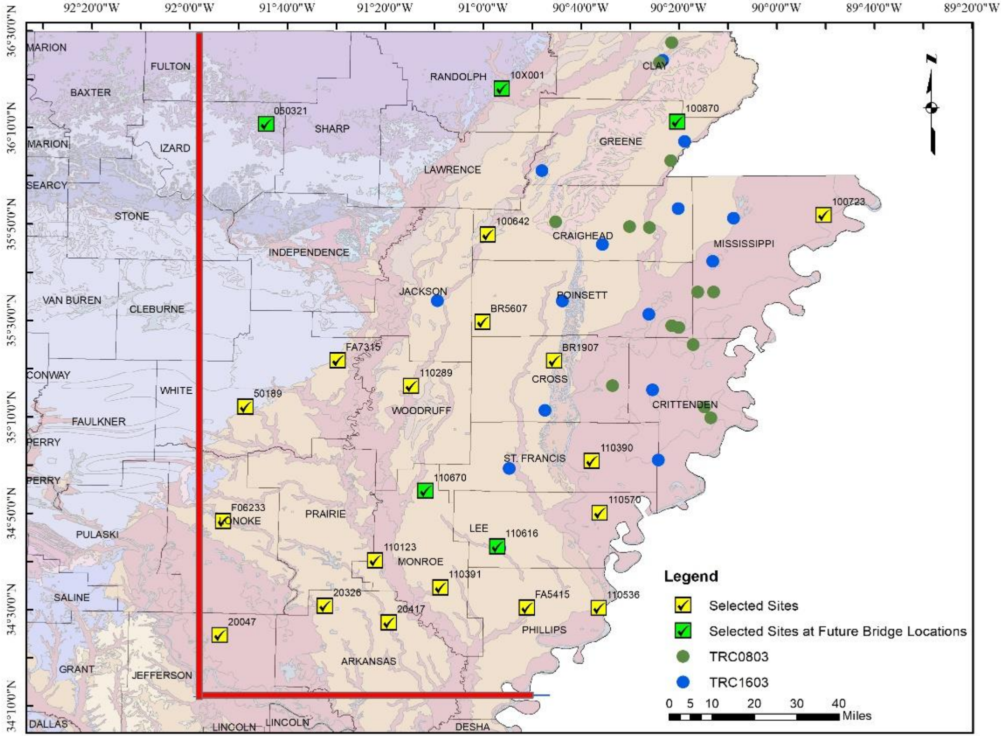
Study Area

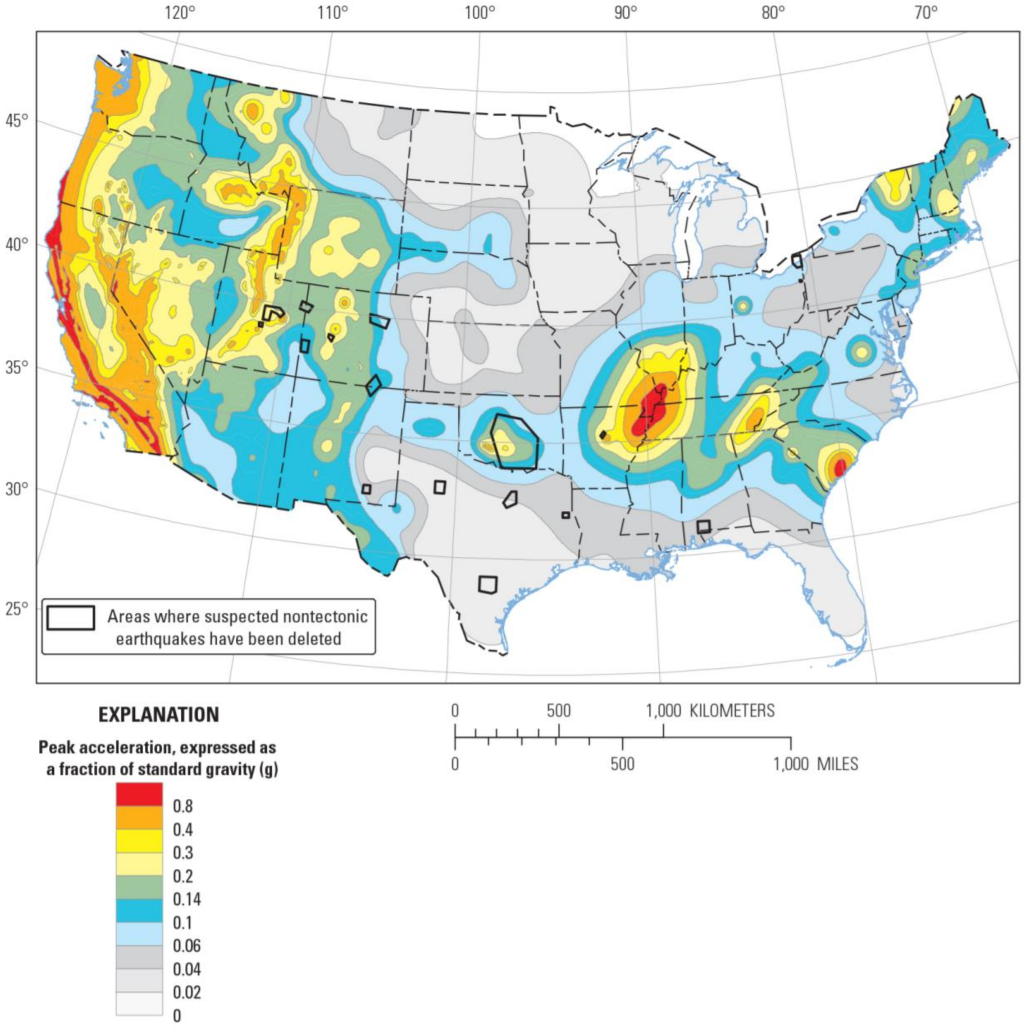

Study Area
BOONE
MARION
BAXTER
FULTON
RANDOLPH
CLAY
SHARP
IZARD
GREENE
LAWRENCE
NEWTON
SEARCY
STONE
CRAIGHEAD
MISSISSIPPI
JOHNSON
VAN BUREN
CLEBURNE
POPE
CONWAY
WHITE
CROSS
CRITTENDEN
YELL
FAULKNER
PERRY
PRAIRIE
LEE
PULASKI
SALINE
MONROE
GARLAND
LONOKE
PHILLIPS
HOT SPRING
GRANT
ARKANSAS
JEFFERSON
CLARK
DALLAS
LINCOLN
CLEVELAND
DESHA
NEVADA
OUACHITA
CALHOUN
BRADLEY
DREW
Legend
0 5 10 20 30 40
Miles

Site selection

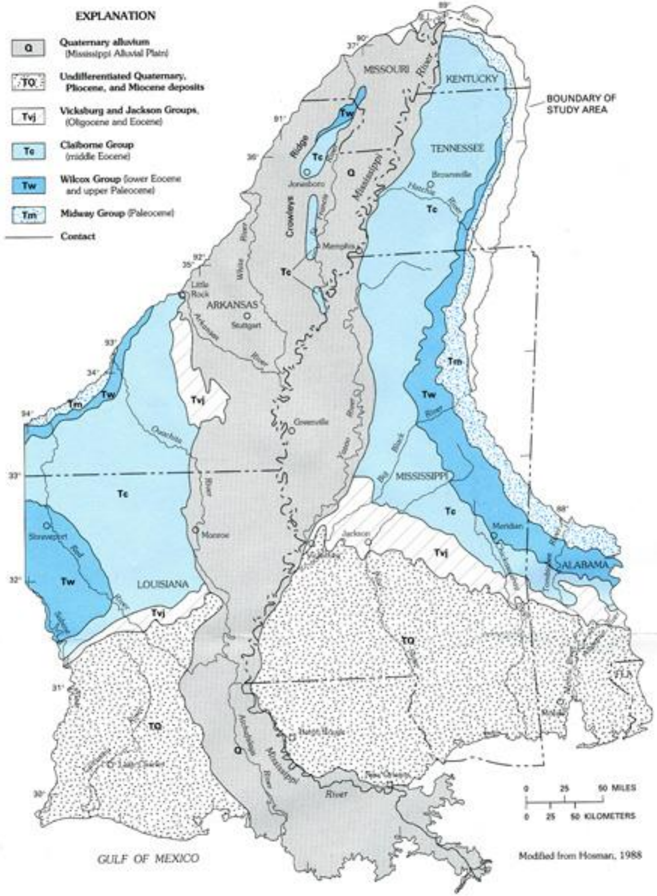
- Geological considerations
- Area coverage
- Boring log information availability

Locations of Proposed Sites and Sites Investigated by TRC1603 and TRC0803 Projects





Map showing peak ground acceleration for 2-percent probability of exceedance in 50 years and V_{S30} site condition of 760 meters per second, 2014 version. (USGS Open-File Report, 2014)



OUTCROPPING GEOLOGIC UNITS

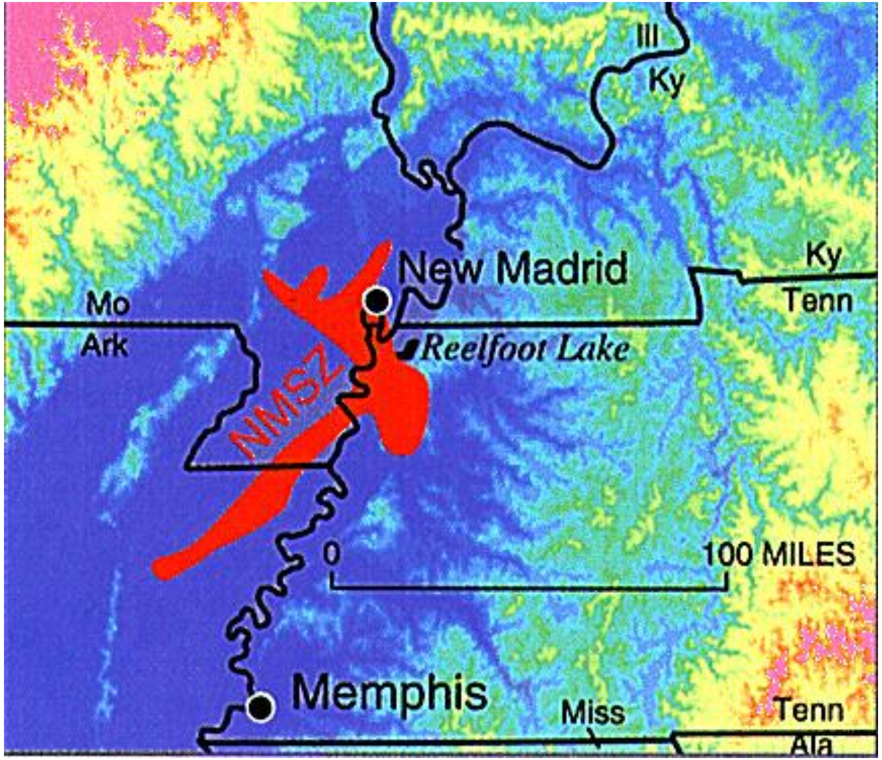
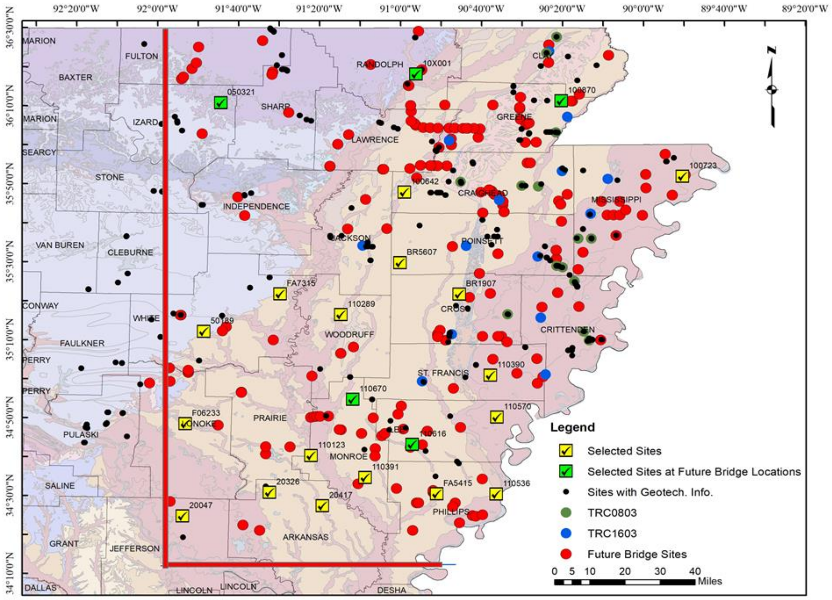


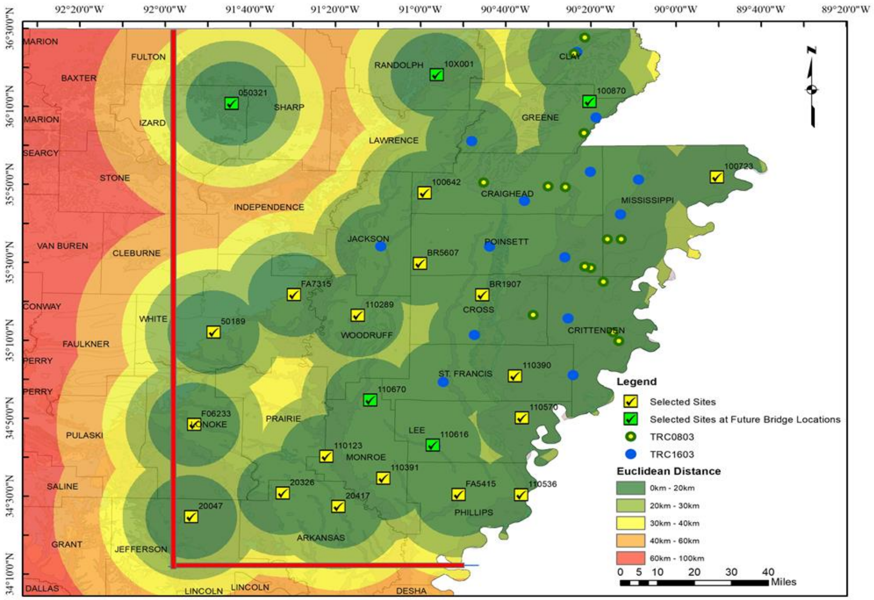
Image adapted from [New Madrid Fault Topography]

Arthur and Taylor (1998).

Area Coverage



Selected Sites, TRC0803, TRC 1603, Future Bridge Sites and available ARDOT Boring logs



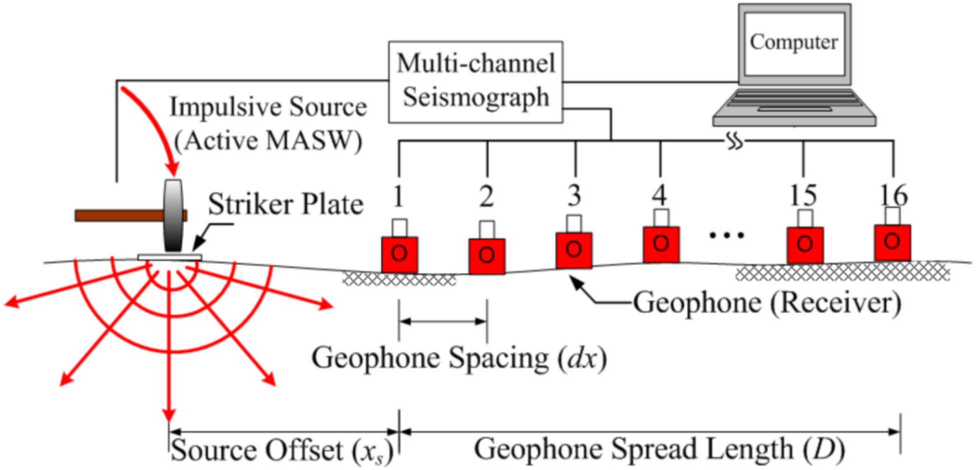
Site Selection based on Boring log locations and area coverage.
Contours show the Euclidian distance between sites

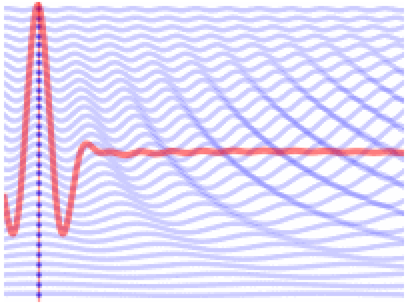
MASW and ReMi

- Shear wave velocity can be obtained using invasive or non-invasive techniques.
- Non-invasive techniques include active and passive surface seismic methods such as
  - Multi-channel Analysis of Surface Waves (MASW),
  - Refraction Microtremor (ReMi)
- Vertical variation of mechanical properties of the medium are estimated from spectral variation of phase velocities through the inversion of dispersion curves.

MASW

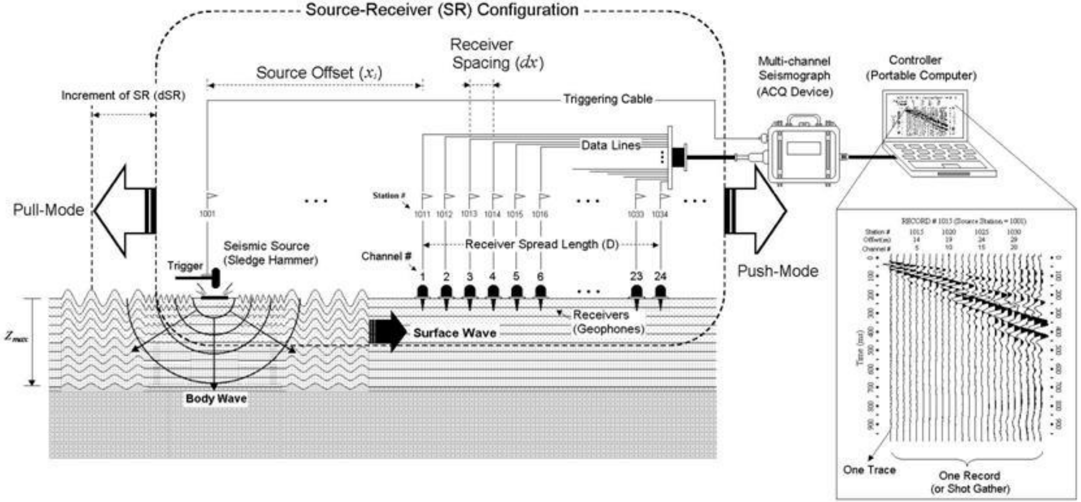
- Wave generation of a principal vertical ground motion using either an impulsive (hammer) or a continuous (shaker) sources;
- Data recording;
- Spectral analysis of the recorded time series data to produce dispersion curves (variation of phase velocity (Raleigh wave velocity) with frequency (or wavelength);
- Inversion of dispersion curves to estimate the shear-wave velocity-depth profiles.





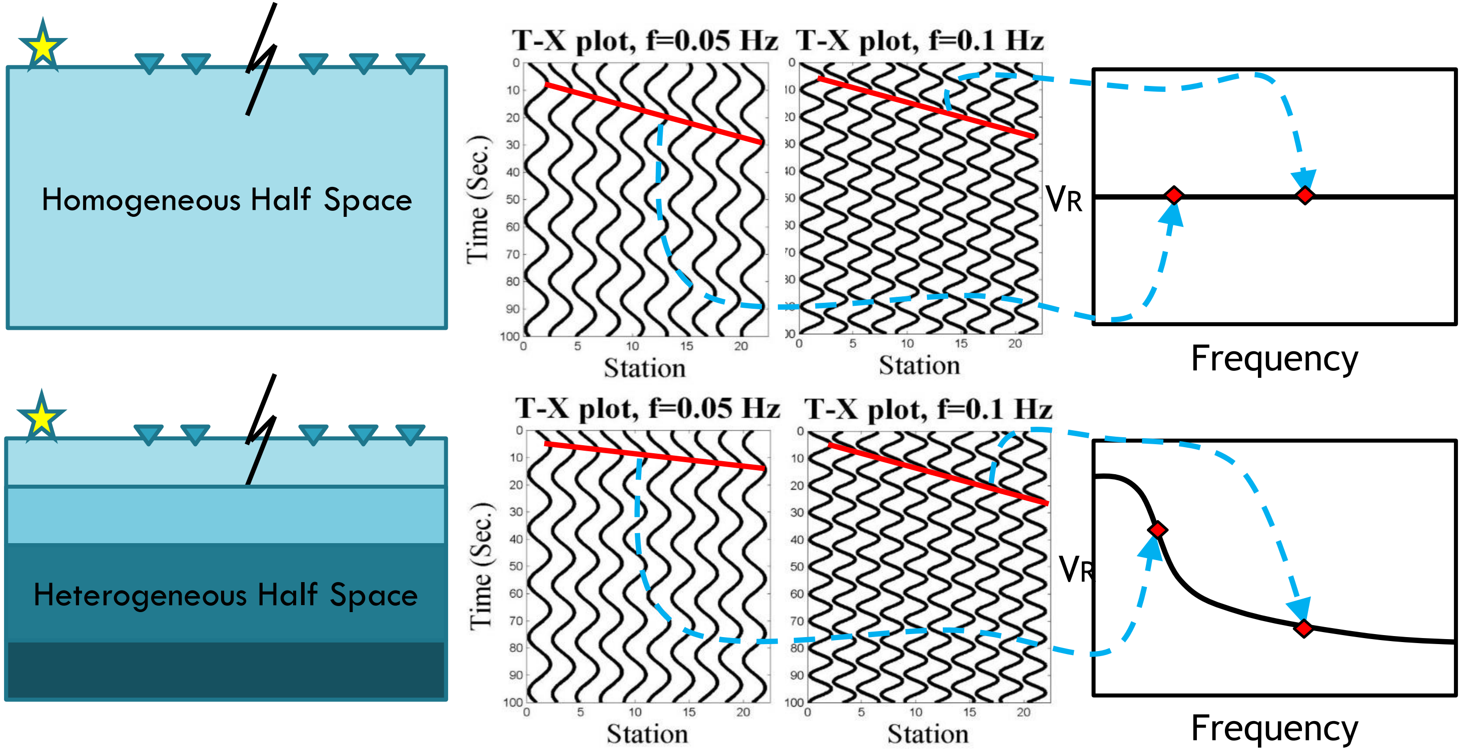
Equipment for Testing Procedure for MASW

- MASW (Multi-channel Analysis of Surface Waves)
  - Vertical Geophones (4.5 Hz)
  - Uniform 2 meter Spacing
  - Sledgehammer
  - Geodes (Data acquisition devices)



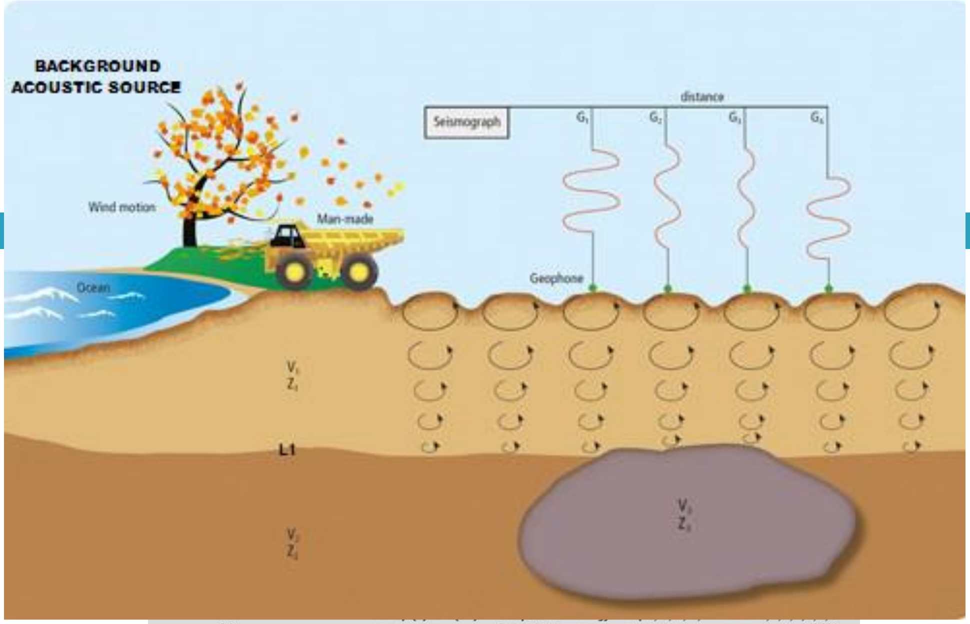
MASW field work

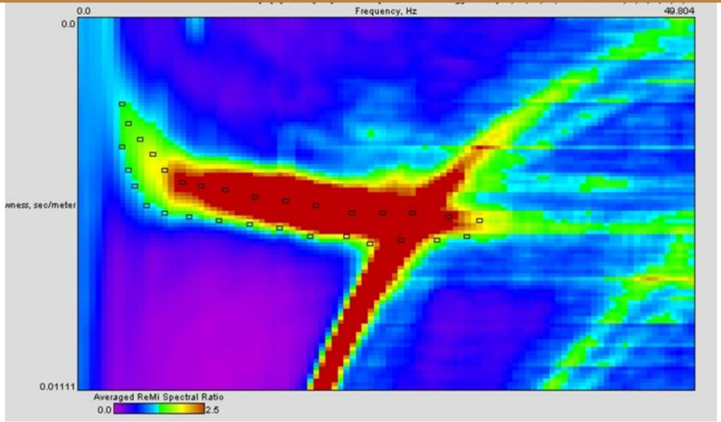
Dispersion Curve!
Heterogeneity : Source for Dispersion



ReMi

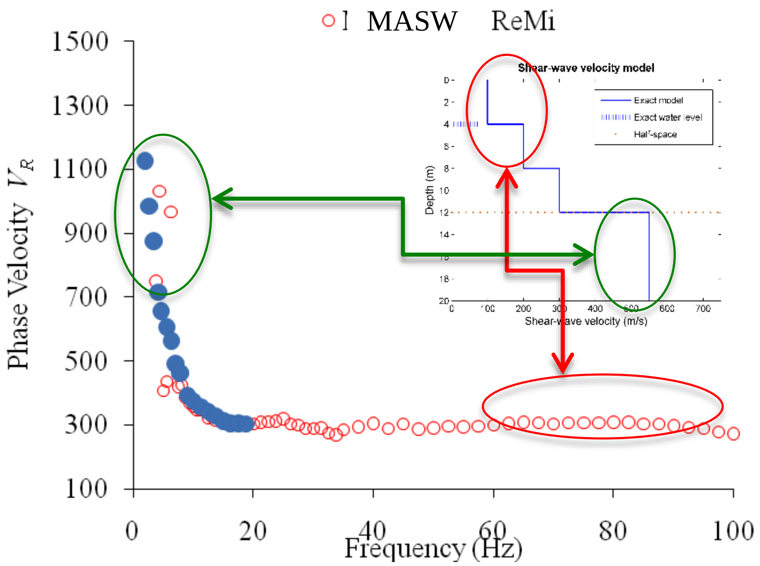
- To improve the accuracy of the experimental dispersion curve in low frequencies, we use the refraction microtremor (ReMi) passive method.
- ReMi uses ambient noise to determine the experimental dispersion curve in the low frequency range.



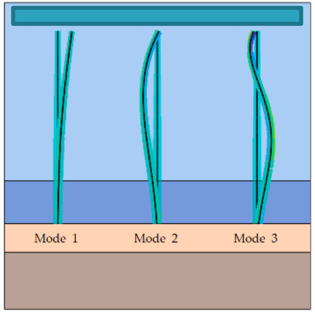


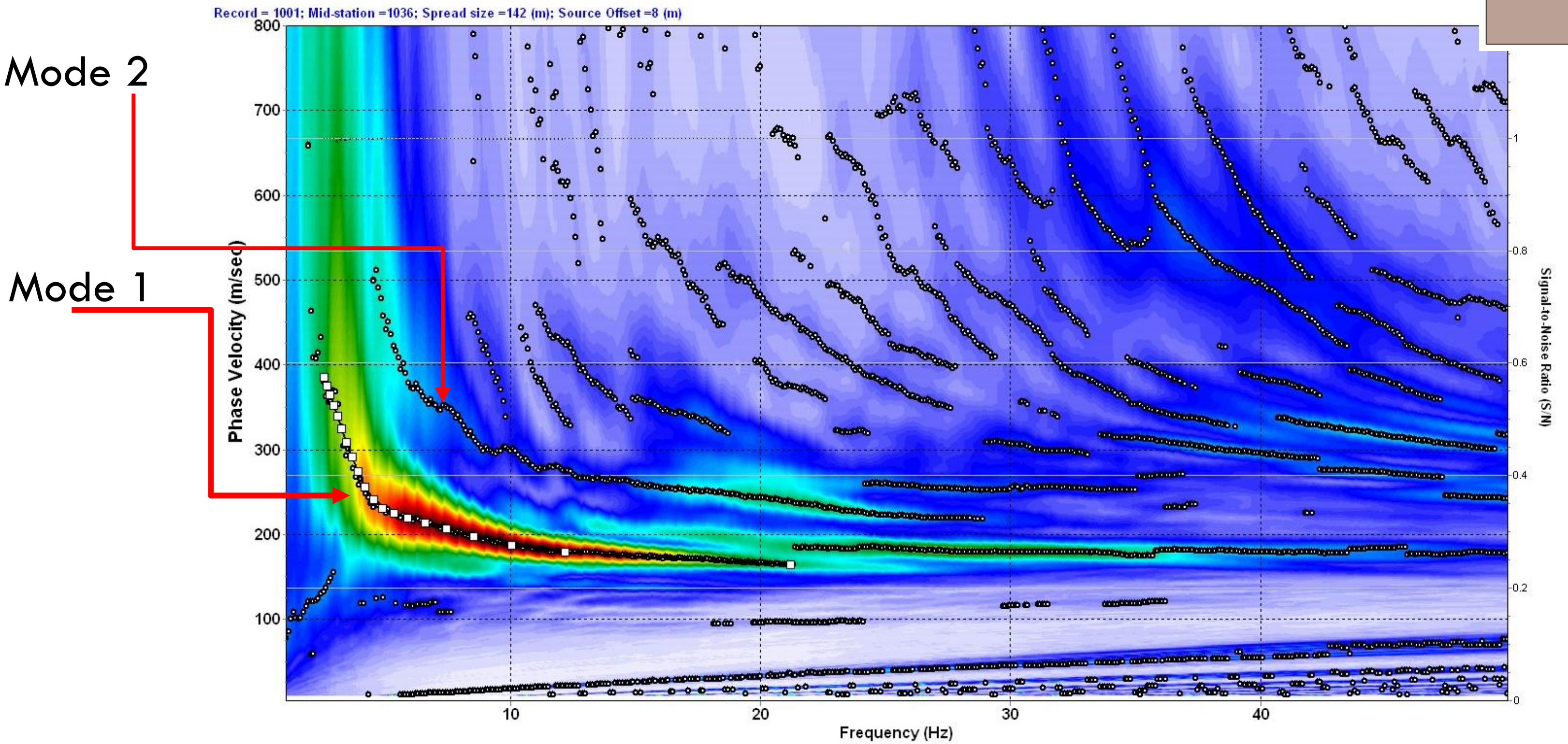
Composite Dispersion Curve

- High frequency waves at shallow depths and low frequency waves at deeper depths.
- ReMi alone does not provide good resolution for shallow depths which have more influence on the site response analysis.



Example of Dispersion Curve

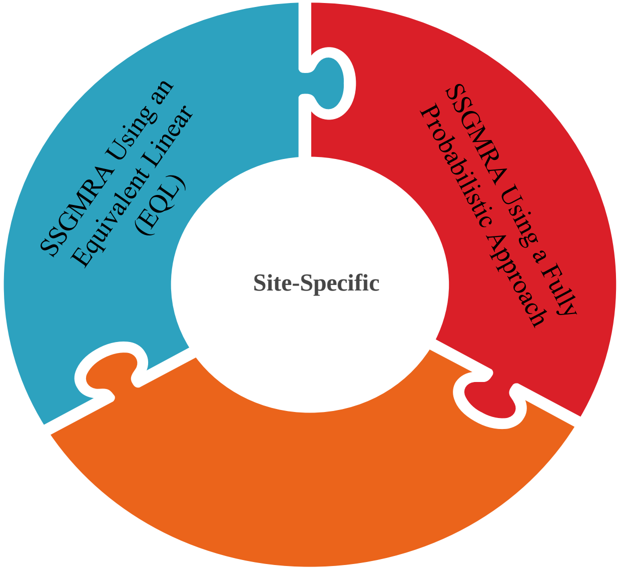




Objectives of TRC1901

- OBJECTIVE 3: PERFORMING SITE-SPECIFC ANALYSES

- Two Approaches are used:
  - SSGMRA Using a Fully Probabilistic Approach (Method 1)
  - SSGMRA Using an Equivalent Linear (EQL) Approach (Method 2)



Site Class Definition

Table 3.10.3.1-1—Site Class Definitions

Site Class	Soil Type and Profile
A	Hard rock with measured shear wave velocity, $\bar{v}_s > 5{,}000$ ft/s
B	Rock with 2,500 ft/sec < $\bar{v}_s$ < 5,000 ft/s
C	Very dense soil and soil rock with 1,200 ft/sec < $\bar{v}_s$ < 2,500 ft/s, or with either $\bar{N}$ > 50 blows/ft, or $\bar{s}_u$ > 2.0 ksf
D	Stiff soil with 600 ft/s < $\bar{v}_s$ < 1,200 ft/s, or with either 15 < $\bar{N}$ < 50 blows/ft, or 1.0 < $\bar{s}_u$ < 2.0 ksf
E	Soil profile with $\bar{v}_s$ < 600 ft/s or with either $\bar{N}$ < 15 blows/ft or $\bar{s}_u$ < 1.0 ksf, or any profile with more than 10.0 ft of soft clay defined as soil with $PI > 20$, $w > 40$ percent and $\bar{s}_u$ < 0.5 ksf
F	Soils requiring site-specific evaluations, such as: • Peats or highly organic clays (H > 10.0 ft of peat or highly organic clay where H = thickness of soil) • Very high plasticity clays (H > 25.0 ft with PI > 75) • Very thick soft/medium stiff clays (H >120 ft)

Exceptions: Where the soil properties are not known in sufficient detail to determine the site class, a site investigation shall be undertaken sufficient to determine the site class. Site classes E or F should not be assumed unless the authority having jurisdiction determines that site classes E or F could be present at the site or in the event that site classes E or F are established by geotechnical data.

Site Factors

Table 3.10.3.2-1—Values of Site Factor, F_{pga}, at Zero-Period on Acceleration Spectrum

Site Class	Peak Ground Acceleration Coefficient (PGA)[1]				
	PGA < 0.10	PGA = 0.20	PGA = 0.30	PGA = 0.40	PGA > 0.50
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	2.5	1.7	1.2	0.9	0.9
F[2]	*	*	*	*	*

Notes:

[1]Use straight-line interpolation for intermediate values of PGA.

[2]Site-specific geotechnical investigation and dynamic site response analysis should be performed for all sites in Site Class F.

Table 3.10.3.2-2—Values of Site Factor, F_a, for Short-Period Range of Acceleration Spectrum

Site Class	Spectral Acceleration Coefficient at Period 0.2 sec (S_S)[1]				
	S_S < 0.25	S_S = 0.50	S_S = 0.75	S_S = 1.00	S_S > 1.25
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	2.5	1.7	1.2	0.9	0.9
F[2]	*	*	*	*	*

Notes:

[1]Use straight-line interpolation for intermediate values of S_s.

[2]Site-specific geotechnical investigation and dynamic site response analysis should be performed for all sites in Site Class F.

Table 3.10.3.2-3—Values of Site Factor, F_v, for Long-Period Range of Acceleration Spectrum

Site Class	Spectral Acceleration Coefficient at Period 1.0 sec (S_1)[1]				
	S_1 < 0.1	S_1 = 0.2	S_1 = 0.3	S_1 = 0.4	S_1 > 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	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F[2]	*	*	*	*	*

Notes:

[1]Use straight-line interpolation for intermediate values of S_1.

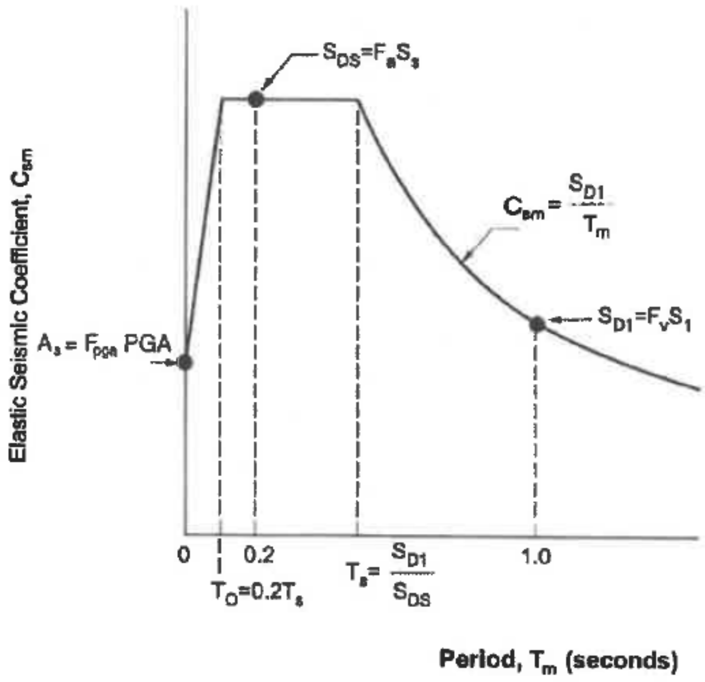
[2]Site-specific geotechnical investigation and dynamic site response analysis should be performed for all sites in Site Class F.

Code Procedure - Site Coefficients, F_a and F_v

$$A_S = \boxed{F_{pga}}\, PGA \qquad S_{DS} = \boxed{F_a}\, S_S \qquad S_{D1} = \boxed{F_v}\, S_1$$

Soil Profile Type

AASHTO Design Response Spectrum



Development of Base-Case Shear-Wave Velocity Profiles

- To perform SSGMRA studies, we need shear wave velocity profiles deeper than 30 m (100 ft.).
- To extend the shallower portion of the velocity profile to the deeper portion, the 3D velocity model developed for Central United States (CUS) was used.
- The CUS 3D velocity model has been developed by Ramirez-Guzman et al. (2012) and is a result of several efforts in previous years including Allen and Wald (2007), Chung and Rogers (2010), Cramer et al. (2004), Ginzburg et al. (1983), Gomberg et al. (2003), Bradley (2003), Mooney et al. (1983), Prodehl et al. (1984), and Stewart (1968).

Development of the Base-Case Soil Profile

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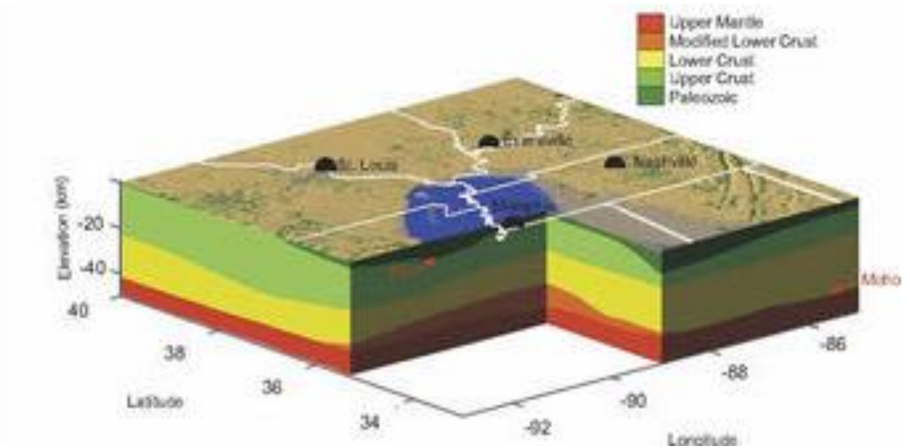
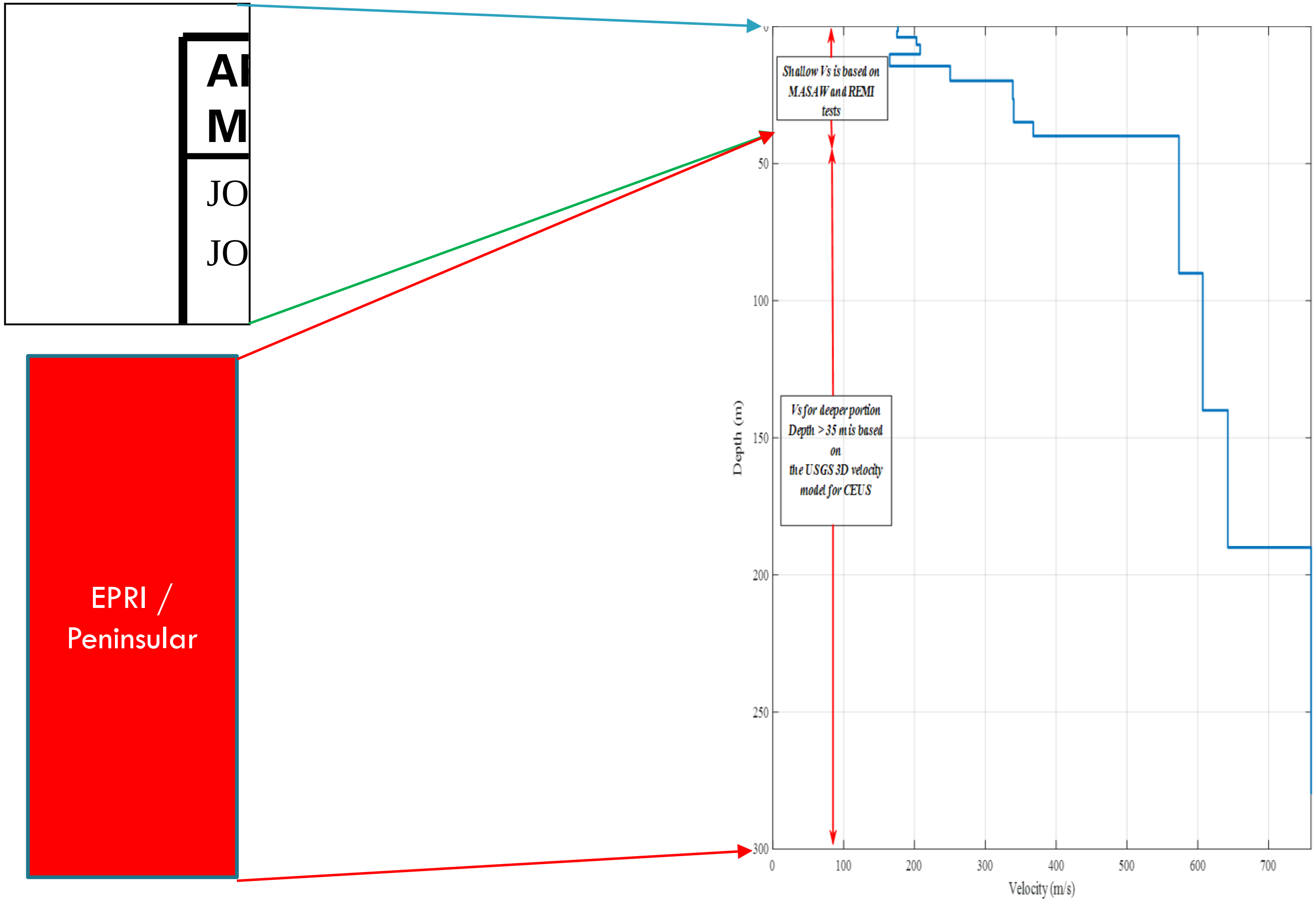
Search

Earthquake Hazards

Central U.S. Seismic Velocity Model



How Velocity Profiles are Constructed



Deaggregation

Return period: 1000 yrs
Exceedance rate: 0.001 yr^{-1}
PGA ground motion: 0.520475 g

Mode (largest m-r bin)

Return period: 1005.4933 yrs
Exceedance rate: 0.00099453666 yr^{-1}

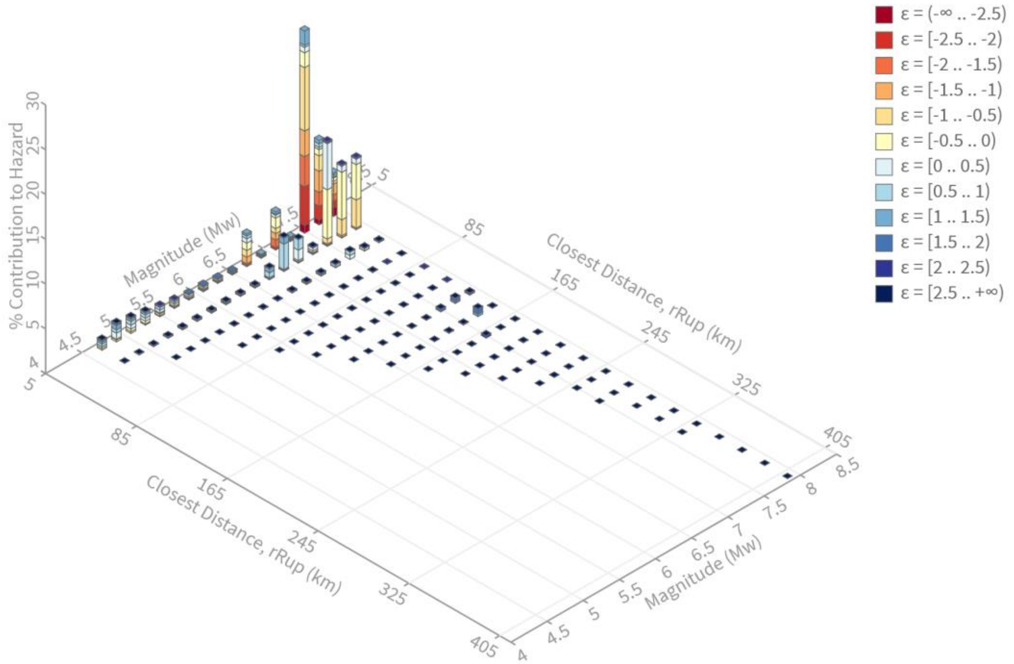
Mode (largest m-r-ε_0 bin)

Binned: 100 %
Residual: 0 %
Trace: 0.55 %

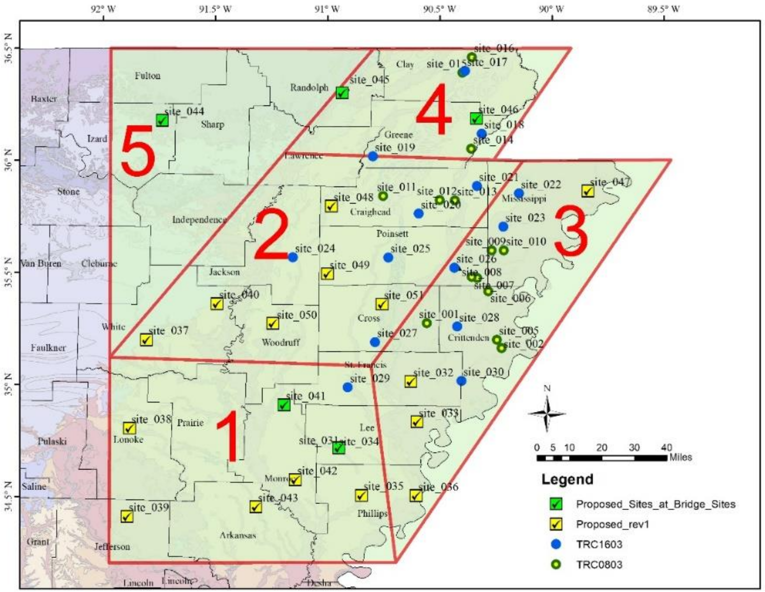
Discretization

m: 7.26
r: 28.2 km
ε_0: -0.35 σ

Epsilon keys



Selecting Acceleration Time Series



Mean Moment Magnitude and Mean Distance for Each of the Five Zones

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Mean M	7.50	7.51	7.51	7.51	7.50
Mean R	154.50	82.40	62.50	64.95	162.19

Acceleration Time Series for Zone 3

30

Horizontal Component 1 | Horizontal Component 2

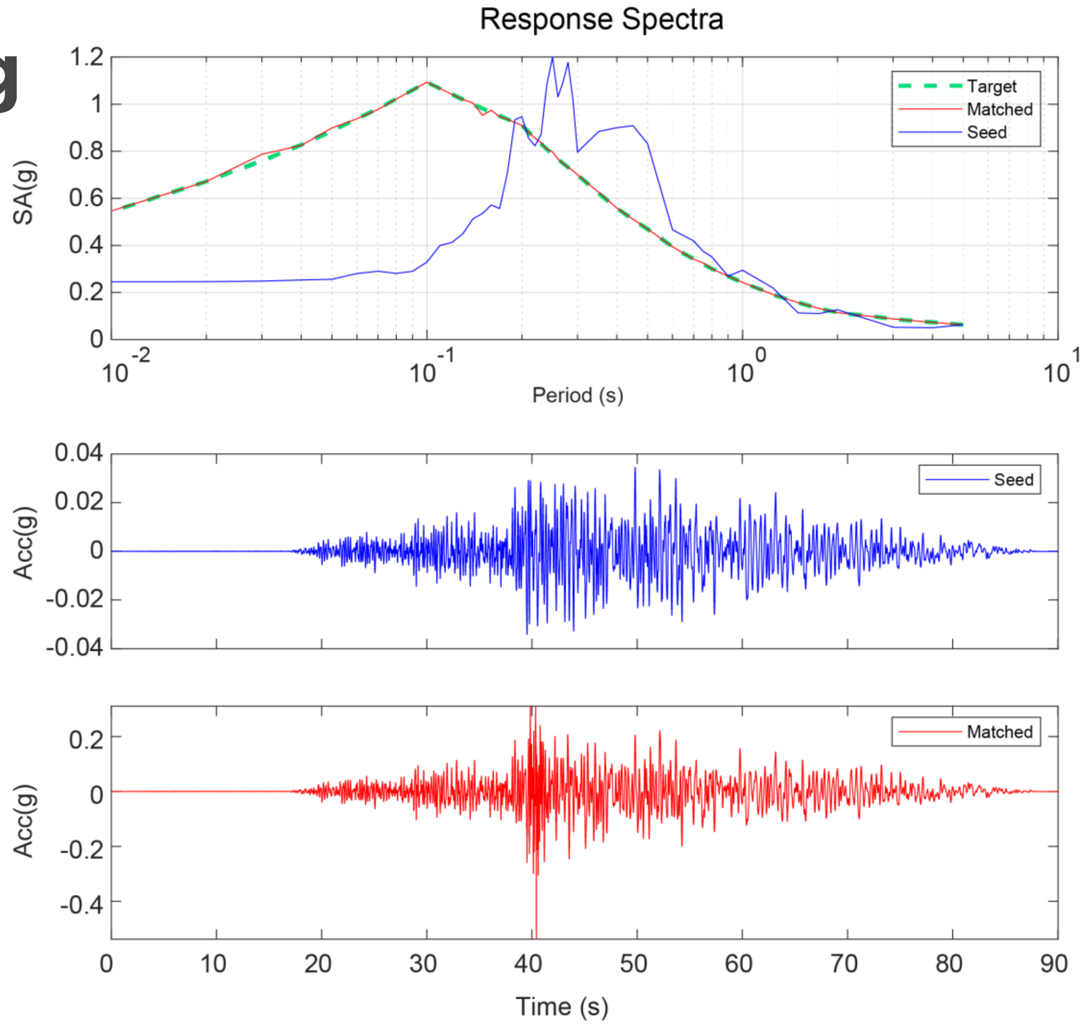
No.	First Component	Second Component
1	RSN1577_CHICHI_TTN025-E	RSN1577_CHICHI_TTN025-N
2	RSN1161_KOCAELI_GBZ000	RSN1161_KOCAELI_GBZ270
3	RSN1245_CHICHI_CHY102-E	RSN1245_CHICHI_CHY102-N
4	RSN1256_CHICHI_HWA002-N	RSN1256_CHICHI_HWA002-W
5	RSN1485_CHICHI_TCU045-E	RSN1485_CHICHI_TCU045-N
6	RSN1582_CHICHI_TTN032-E	RSN1582_CHICHI_TTN032-N
7	RSN1585_CHICHI_TTN040-N	RSN1585_CHICHI_TTN040-W
8	RSN1587_CHICHI_TTN042-N	RSN1587_CHICHI_TTN042-W
9	RSN1613_DUZCE_1060-N	RSN1613_DUZCE_1060-E
10	RSN1787_HECTOR_HEC000	RSN1787_HECTOR_HEC090
11	RSN1633_MANJIL_ABBAR—L	RSN1633_MANJIL_ABBAR--T

Spectral Matching

RSPmatch (Abrahamson 1993)

- **Matching Seed Acceleration to the Site's UHS**

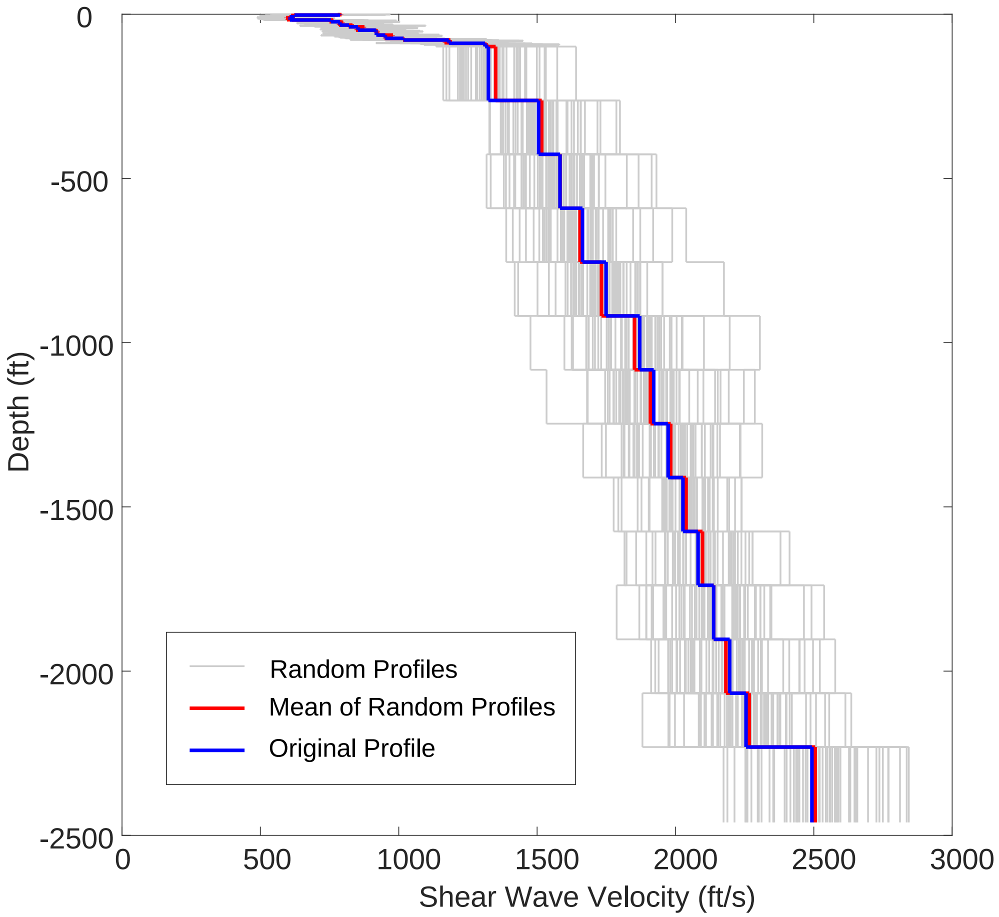
RSN1577_CHICHI_TTN025-E



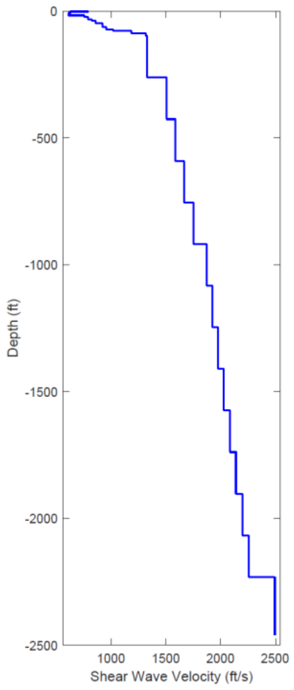
Soil Profile Randomization

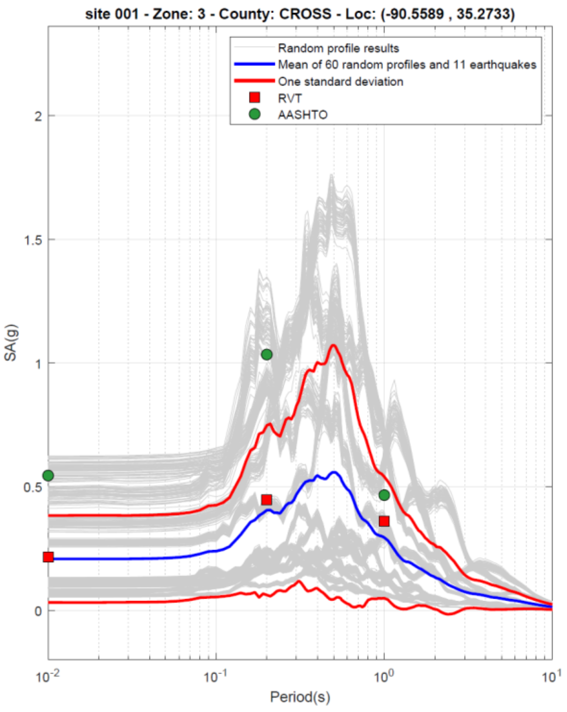
Random Parameter (Toro 1993)

- Generating random soil profile



Final Results for Site 1





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Analyses

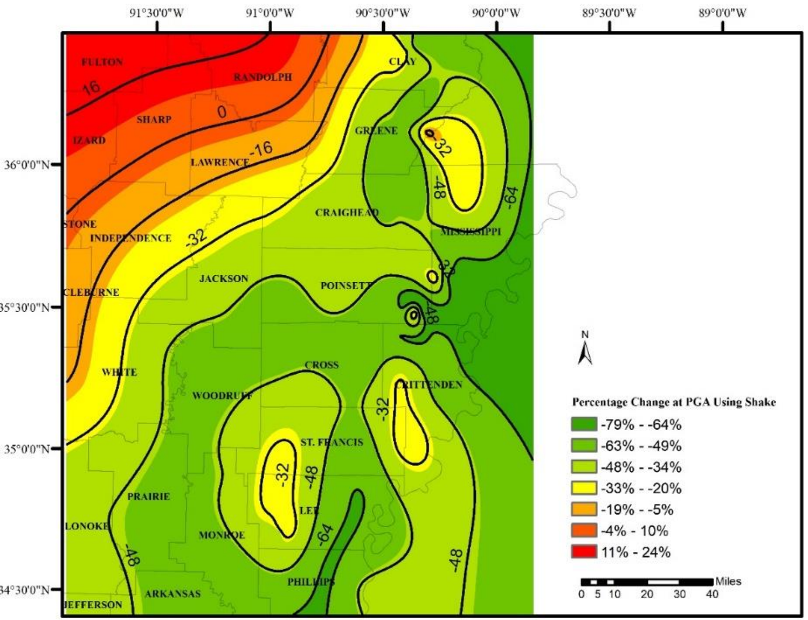
Final Products

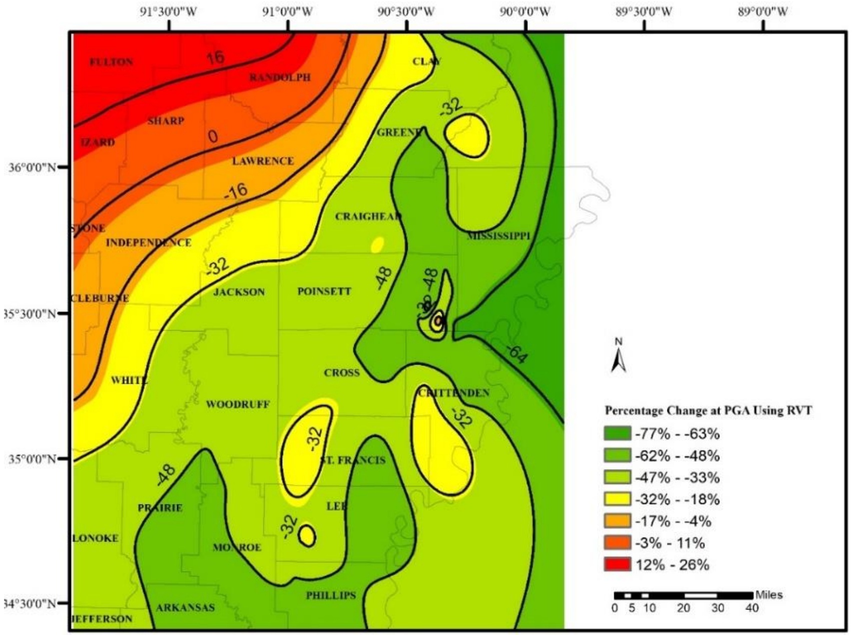
a) PGA, 0.2 s, and 1.0 s contour maps based on site-specific ground motion response analysis (SSGMRA),
b) Contour map of PGA, 0.2 s, and 1.0 s based on AASHTO,
c) Contour map of the difference between SSGMRA and the code-based PGA values at the ground surface, and
d) An estimate of cost saving or increase in the cost if SSGMRA is performed based on item “a” above and the information provided in literature.

Ground Surface Contour Maps

- The 51 sites or the sample data points are used to cover the entire study region.
- Using ESRI ArcGIS (http://www.arcgis.com), one can apply predictive spatial analysis techniques to interpolate between available data points and create contour maps.
- A variety of interpolation approaches are available in ArcGIS, and they will almost always generate different outputs.

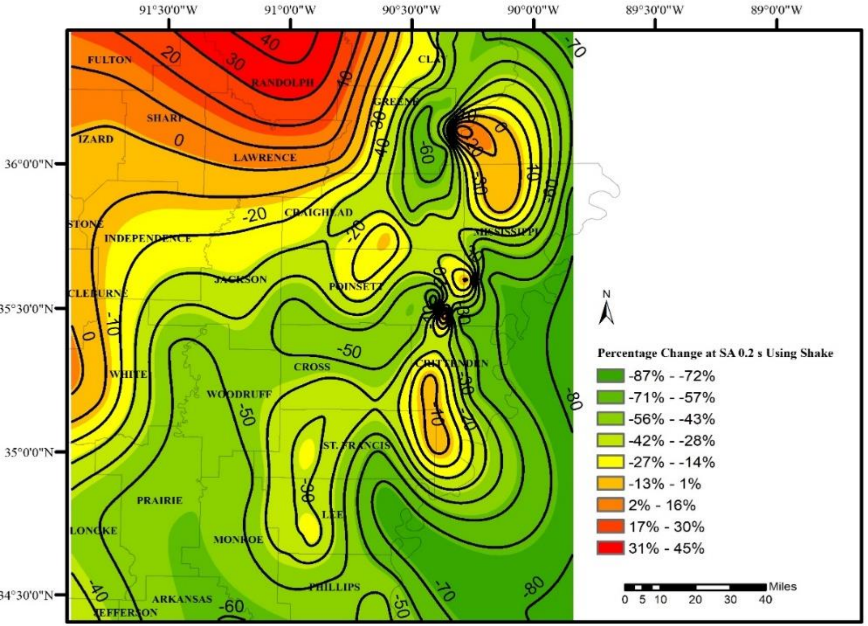
Sample Contour Map

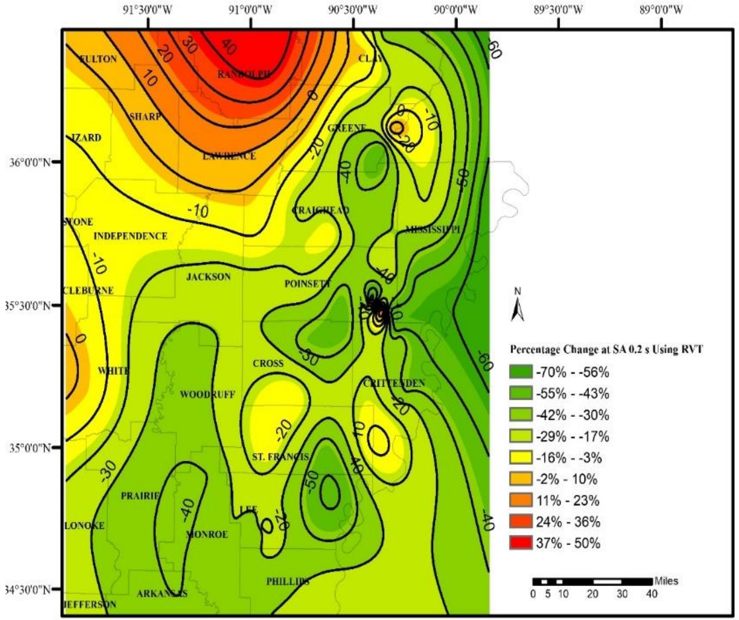




Percentage Change (from AASHTO) of PGA (As) Based on Method 1 (right) & Method 2 (left)

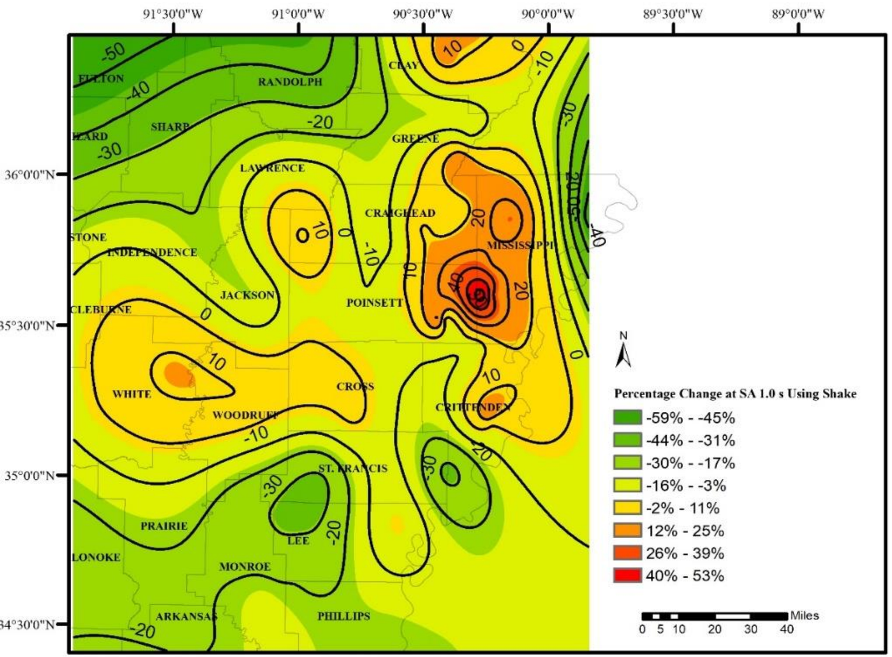
Sample Contour Map

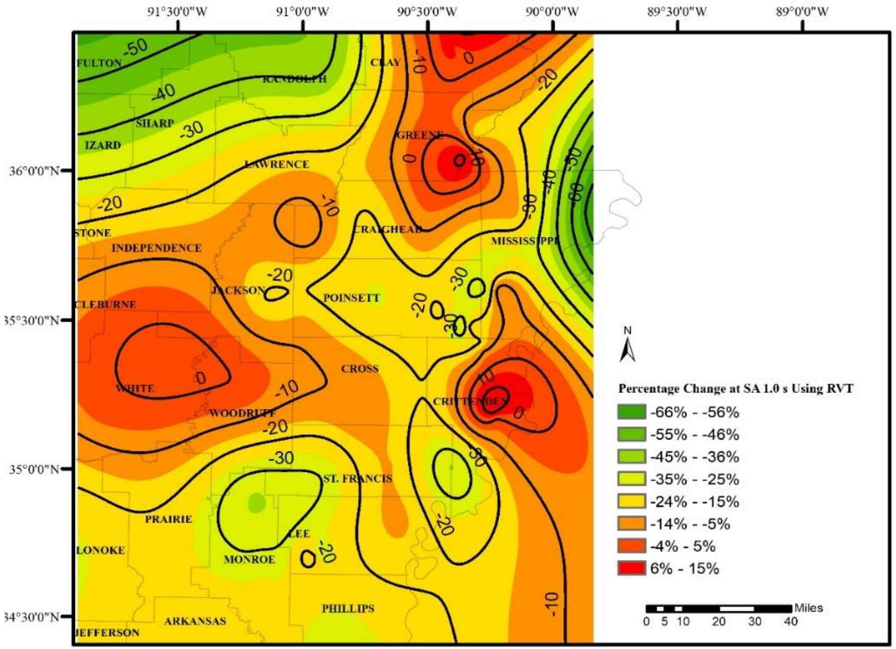




Percentage Change of
S_S Based on Method 1 (right) & Method 2 (left)

Sample Contour Map





Percentage Change of

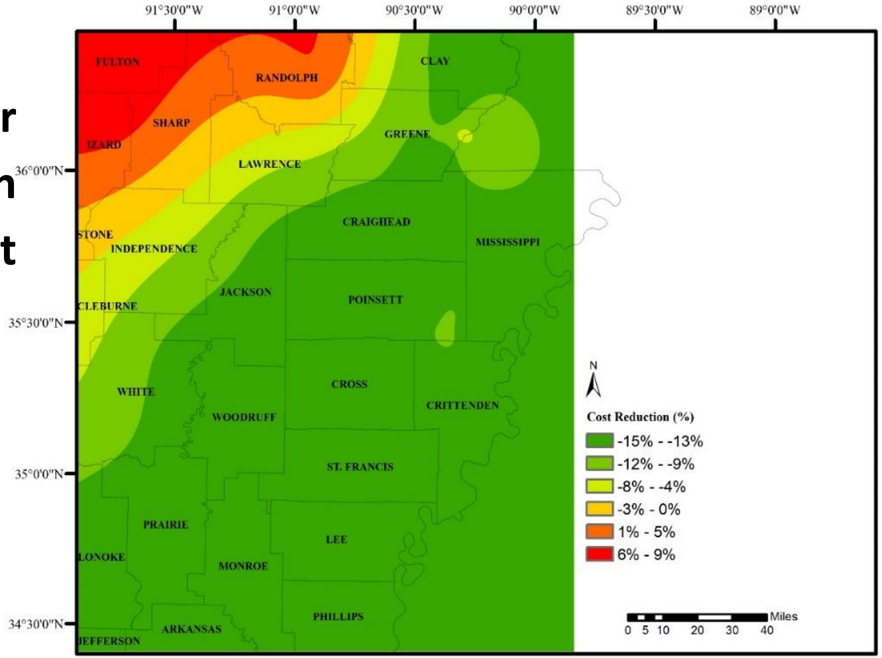
S_1 Based on Method 1 (right) & Method 2 (left)

Potential Cost Saving

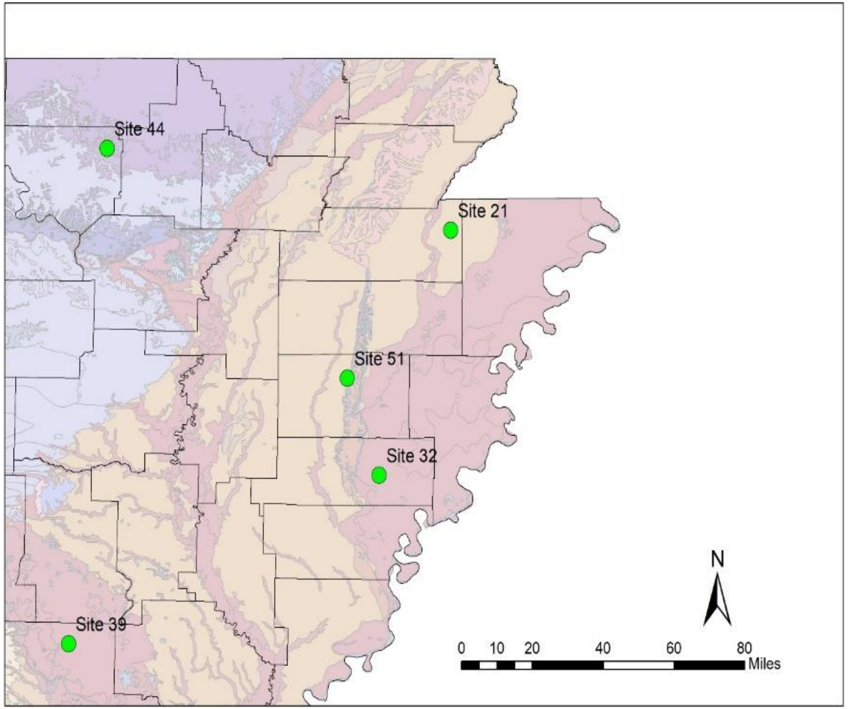
- As part of this project, potential savings are estimated based on the Ketchum et al. (2004) recommendations.
- Ketchum et al. (2004) recommendations are not directly applicable to steel bridges in Northeast Arkansas due to the bridge types included in their study.
- However, based on what was included in the TRC1603 report, there were similarities in the cost savings estimated using the Ketchum et al. (2004) method with the cost savings calculated as part of the TRC1603 for a steel girder bridge in Northeast Arkansas; thus, **it is used in this study**.
- Detailed cost savings of steel bridges was not part of the scope of this project.
- Ketchum et al. (2004) conclude that: "For the most commonly used low-overhead concrete bridges, construction cost escalates about 5 percent per 10 percent increase in PGA above a baseline cost at 0.3 g to 0.4 g. For tall concrete box girder bridges, construction cost escalates about 10 to 12 percent per 10 percent increase in PGA above a baseline cost at 0.6 g to 0.7 g."

Sample Contour Map

Percentage of the Cost That Can be Reduced for Low-Overhead Concrete Bridges Based on Method 2. Negative Values Indicate Cost Reduction



Example of Five Sites



Example of Five Sites

Five Selected Sites, Project Number Associated with the Selected Sites, AASHTO, and Site-Specific Acceleration Coefficients Obtained USING GIS Provided Contour Maps

Site Number	TRC Project Site ID No.	AASHTO Hazard Values (Map Values)			Site-Specific Hazard Values (Map Values)		
		PGA	SA0.2s	SA1.0s	PGA	SA0.2s	SA1.0s
21	TRC1603_5	0.682	1.202	0.544	0.313	0.611	0.579
32	TRC1901_1	0.372	0.749	0.348	0.158	0.313	0.317
39	TRC1901_8	0.180	0.360	0.199	0.108	0.239	0.157
44	TRC1901_13	0.213	0.409	0.180	0.240	0.419	0.108
51	TRC1901_20	0.498	0.960	0.429	0.225	0.432	0.424

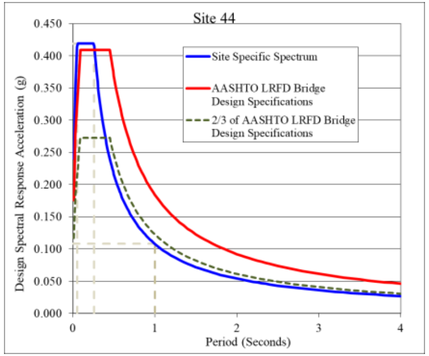
Example of Five Sites

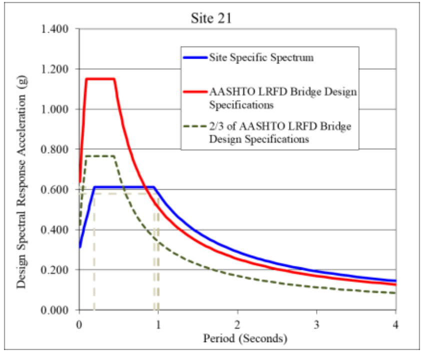
Cost Saving at the Five Selected Sites

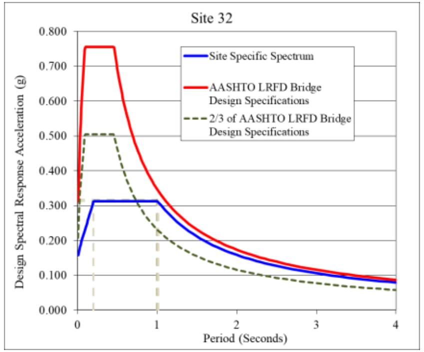
Project	Low-overhead Concrete Bridges cost reduction (M1) Map
TRC1603_5	-15%
TRC1901_1	-15%
TRC1901_8	-15%
TRC1901_13	+6.68%
TRC1901_20	-15%

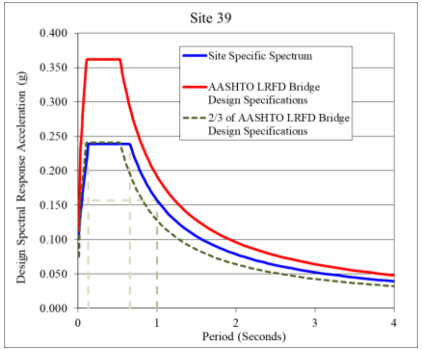
Example of Five Sites

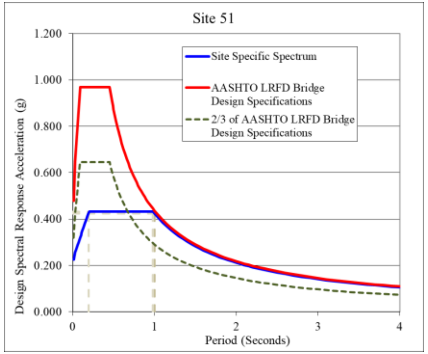
Response Spectra Based AASHTO LRFD Design Specifications and Site-Specific Results Based on Method 2 for Site 51











Can We Really Save Money?

- ARDOT authorized a SSGMRA study for Project CA0613 (3 bridges over US-67).
- Task Order Value: $26,800.
- According to ARDOT, the results allowed the design consultant to reduce the Seismic Zone, hence a more economical design.
- Initial Estimated Cost Saving: ~$180,000.

Objective 5

- OBJECTIVE 5: DEVELOPING DOCUMENTATIONS AND SPECIFICATIONS FOR SITES THAT NEED SSGMRA STUDIES

Literature Search

- Twelve states that are impacted by seismic zones
- Main questions:
  - Do you have Geotechnical Manual?
  - Does your manual have provisions for performing SSGMRA studies?
  - Do you have prequalification procedure for consultants who perform them?

Results

- All twelve states have geotechnical manuals
- A few has Geotechnical Seismic Design provisions
- SC Manual include detailed provisions for performing SSGMRA studies
  - SC GDM stands out as the best
- None had procedures for consultant prequalification for performing SSGMRA

Shear Wave Velocity Profiling

- No universal agreement or consensus regarding the best method for obtaining V_s profiles
- PI Recommendations:
  - ReMi should not be used as a stand-alone V_s profiling method; it can be combined with MASW.
  - MASW is superior to SASW.
  - Invasive techniques such as Crosshole, downhole and seismic CPT are all suitable for V_s profiling in the study area. Seismic CPT has the advantage of providing geotechnical subsurface information due to its ability to penetrate to a great depth in Northeast Arkansas.

Shear Wave Velocity Profiling cont.

- For small new bridges (single to 4-span) or bridge replacement projects, a single profile using downhole, seismic CPT, or a surface method should be considered sufficient.
- For longer, multiple, long-span (more than 4) bridges and where the soil conditions are considered erratic, consideration should be given to generating more than a single V_s profile.

Shear Wave Velocity Profiling cont.

- For essential or critical bridges, or bridges deemed by ARDOT to be relatively more important than what was previously described, multiple V_s profiles should be determined. If such a bridge crosses a waterway, multiple profiles should be determined on both sides of the channel.

Analysis Type

- SSGMRA can be performed using one, two, or three dimensions, either equivalent-linear or nonlinear domain
- Several computer programs are available to perform these studies. Software examples are SHAKE, DEEPSOIL, and STRATA
- Results from equivalent-linear and nonlinear analyses can be substantially different
- Contrary to popular belief, nonlinear analyses may not produce realistic results at high shear strains; which is expected in Northeast Arkansas (Griffiths et al.)

Analysis Type - PI Recommendations

- For small new bridges (single to four spans) or bridge replacement projects, a single one-dimensional, equivalent-linear analysis should be considered sufficient.
- For longer, multiple-span (more than four) bridges, a single one-dimensional, equivalent-linear analysis plus a single one-dimensional nonlinear analysis should be considered sufficient.
- For bridges deemed by ARDOT to be relatively more important than the ones described above, multiple equivalent-linear and nonlinear analyses should be performed.

PI Recommendations cont.

- For essential or critical bridges, we recommend that ARDOT retain a “third party” firm or person with a well-established, nationally recognized reputation to serve as the “Owner Representative” and establish guidelines for how SSGMRA studies should be performed. This firm/person should also serve as a “Peer Reviewer” of the results and recommendations on ARDOT’s behalf.
- Care should be exercised upon establishing a “combined envelope” response spectra when both equivalent-linear and nonlinear analyses are performed; the results of the two analyses can be substantially different.

Consultant Selection

- PI recommendation: ARDOT prequalifies consultants who wish to perform SSGMRA studies and establishes a list (similar to on-call contract)
- When a study is needed, either ARDOT or the bridge design consultant can choose a subconsultant choose from the list

Consultant Prequalifications

- Firm / individuals who perform the study should demonstrate the ability to perform SSGMRA studies by means of individual training, course work, and experience
  - A minimum of 10 years of experience in geotechnical seismic design
  - A minimum of 7 site-specific response analyses (3 if three nonlinear site response analyses) in the last five years
  - The consulting firm must possess the equipment and experience to perform shear-wave velocity profiling using both non-invasive and invasive techniques
  - The consulting firm must own the computer programs needed for performing ground motion analyses

Documents to be Provided by ARDOT

- Plans showing bridge locations, including bents and abutments
- Drawings showing approach profiles and cross-sections
- Reports of any geotechnical exploration performed at the site
- Any limitation an ARDOT bridge designer would have on the design response spectra (for example, SCDOT will not allow the site-specific design response spectra to be less than 70 percent of the 3-point, or code-based, method)

Request for Proposal (RFP)

- Cost-based selection is prohibited, should be solely Qualification-Based Selection (QBS)
- ARDOT can advertise a Request for Qualification (RFQ)
- Once a qualified firm is selected, then ARDOT can evaluate the cost estimate

Questions?