Nonlinear Site Response Analysis Using SASW Data in the New Madrid Seismic Zone (USA): Case Study

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Abstract

New Madrid seismic zone (NMSZ) in the United States, is one of the most active and dangerous seismic zones, where NS and EW highways are crossing. According to the satellite data in this zone, during the strongest earthquakes of 1811-1812, a lot of liquefaction phenomena were observed in the Mississippi embankment. Based on historical and intensity data, the moment magnitude of the strongest shock of 12/16/1811 at 02h15m a.m. earthquake, is proposed to be $M_w = 7.0-7.5$. As there is a lack of strong motion data, for the study of nonlinear site response analysis of two sites under bridge construction, synthetic accelerograms were used. For determination of soil profiles, SASW technique was used and compared with other in-situ techniques. This paper focuses on the engineering significance of the geophysical methods used for the purpose ground response analysis.

Introduction

The New Madrid Seismic Zone (NMSZ) represents the most hazardous seismic zone in the central and eastern US. The sites under investigations are located in the NMSZ on the Mississippi embayment, characterized by very thick sediments (730-780m) overlying the Paleozoic rock [1-3].

The great earthquakes of 1811-1812 caused extensive ground failures (especially liquefaction), and evidence of this phenomena can be seen even today on satellite images.

The great thickness of the soil sediments has been the focus to study the amplification or de-amplification given input strong ground motions with PGA > 0.4g due to degradation of shear moduli and increase of strains in depth.
The upper part of these deep sediments (80m) consists of very poor Quaternary deposits, studied by SASW and cross-hole techniques [1-3].

As there are no strong motion records in this area, therefore synthetic ground motions were used.

This paper focuses on the engineering significance of the geophysical method used for the purpose ground response analysis assuming that the resolution and quality of SASW data would be sufficient for the purpose of ground response analysis in shallow and deep soil deposits such as the ones present in the NMSZ.

Author of this paper participated in FHWA project for bridges in NMSZ with a research team of Missouri S&T, in Rolla

Seismic Activity of New Madrid Zone (NMSZ)

Maximum expected magnitude according to statistical data

Generally it’s known that the size of small earthquakes (M < 6.5) is better measured by body wave magnitudes (mb), (saturated at the value about 6.5).

Based on the earthquake catalogue for the period 1795-1995 for New Madrid Zone [3], all the magnitudes are given as body wave magnitudes (mb).

| Mb  | 4.0 | 4.4 | 4.7 | 5.1 | 5.5 | 7.5 |
|-----|-----|-----|-----|-----|-----|-----|
| Mn  | 1.9 | 2.6 | 3.3 | 4.0 | 4.7 | 8.2 |
| n   | 89  | 42  | 21  | 6   | 5   | 1   |
| N   | 164 | 75  | 33  | 12  | 6   | 1   |

\[ \log n(M_b) = a - b M_b \]
\[ \log n(M_s) = a - b M_s \]
\[ \log N(M_b) = a - b M_b \]
\[ \log N(M_s) = a - b M_s \]

Table 1: Conversion of mb to Ms values according to the relationship \( mb = 0.56 Ms + 2.9 \) [5].

Conversion of mb magnitudes to Ms magnitudes

For NMS all mb magnitudes were transformed to Ms magnitudes according to the relationship [5]: \( mb = 0.56 Ms + 2.9 \).

It can be seen that cumulative relationships: \( \log N(mb) \) and \( \log N(Ms) \) are more reliable (greater coefficients of correlation (0.963 & 0.969) and b-values are very small (b = 0.30-0.35) which confirms very high tectonic activity of NMSZ.

According to non cumulative graph \( \log n(Ms) \) relationship it can be observed that:

- The minimum magnitude to be considered should be \( mb = 4.4 \) (Ms = 2.8)

- Non-cumulative \( \log n(M_s) = a - b M_s \) graph show \( M_{max} = 6.3 \)
- Non-cumulative \( \log n(m_b) = a - b m_b \) graph show \( m_{max} = 6.0 \)

According to cumulative graph \( \log N(Ms) \) the minimum magnitude to be considered should be \( mb = 4.4 \) (Ms = 2.8)

- Cumulative \( \log N(M_s) = a - b M_s \) graph show \( M_{max} = 7.0 \)
- Cumulative \( \log N(m_b) = a - b m_b \) graph show \( m_{max} = 6.8 \)

The expected maximum earthquake following the linear extrapolation of cumulative plots for NMSZ should be ~ Ms = 7.0.

Figure 2: Non-cumulative plots \( \log n(Ms) \) & \( \log n(mb) \).
Maximum expected magnitude according to seismic intensity data for the New Madrid earthquakes of 1811-1812

As can be seen from the log n(Ms) graph there is a lack of data for magnitudes mb = 5.5 - 7.5 or Ms = 4.7 - 8.2.

As at the time when New Madrid earthquake occurred were no instruments, the most reliable data are those on seismic intensities felt during this earthquake, which was felt widely in CEUS.

There are a lot of publications concern this problem, but we took into consideration two of them [7,8].

The generalized isoseismal map of NMSZ earthquakes

The isoseismal map of the shock of December 16,1811, is characterized by an unusually large felt area, with intensities of V as far away as the southeast Atlantic coastal area.

Assessment of the magnitude of New Madrid earthquakes from seismic intensities

The size of large ones (M > 6.5) is better measured by Ms especially for those in the range 6.5 - 8.0, but saturates above that value.

The assessed expected maximum earthquake following the linear extrapolation of cumulative plots should be about:

\[ Ms = 7.0 - 7.5 \]
which coincides with the seismic intensity $\text{MM} = \text{VIII}$ according to the isoseismal map, but there are differences from 8-11 degrees.

For very large earthquakes was proposed "moment magnitude "Mw" [9].

$$M_w = M_s = \left( \frac{2}{3} \right) \log_{10} M_o - 10.7$$

where: $M_s$ is seismic moment

Then expected maximum earthquake for NMSZ should be at least

$$M_w = 7.0 - 7.5$$

**Near-Fault Earthquake Effects for Highway Bridge sites in NMSZ**

**Synthetic ground motions used as input - Point source model**

**Geotectonic model**

The Bridges sites under investigation are situated on the top of thick sediments overlying the Reelfoot Rift in New Madrid Zone.

The bridges are part of the located alongl-55 highway in the southeast corner of the state of Missouri near the cities of Hayti and Steele.

**Depth to bedrock**

For the determination of the depth to Paleozoic bedrocks the data from MoDNR [1] were used (Table 2).

|    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| L  | 80 | 25 | 55 | 55 | 25 | 55 | 725 | -700 | 780 | 5350 | -6000 | 6080 | 20 |
| A  | 80 | 25 | 55 | 55 | 25 | 55 | 675 | -650 | 730 | 5350 | -6000 | 6080 | 20 |

|    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1. | Ground surface approximate elevation (m) | 2. | Base of Unconsolidated Alluvium Approximate Elevation (m) | 3. | Approximate Depth to Base of Unconsolidated Alluvium (m) | 4. | Approximate Thickness of Unconsolidated Alluvium (m) | 5. | Top of Unconsolidated Tertiary& Cretaceous Sediments (m) | 6. | Approximate Depth to Top of Unconsolidated Tertiary& Cretaceous Sediments. | 7. | Approximate Thickness of Unconsolidated Tertiary & Cretaceous Sediments (m) | 8. | Top of Paleozoic Bedrock. Approximate Elevation (m) | 9. | Approximate Depth to Top of Paleozoic Bedrock (m) | 10. | Approximate Thickness of Paleozoic Bedrock (m) | 11. | Top of Precambrian Basement (m) | 12. | Approximate Depth to Top of Precambrian Basement (m) | 13. | Approximate Bottom of Seismogenic Crust (km) |

**Modification of strong ground motions generated by the Reelfoot Rift by geological conditions**

The thickness of soil layer on the top of hard Paleozoic rocks was derived from the data supplied by MoDNR (Table 2):

1. Top of Paleozoic bedrock at depths: $h = -700$ m (L site) and $h = -650$ m (A site) behaving linearly
2. Thickness of consolidated sediments: $H =$ 700 m (L site), $H =$ 650 m (A site)
3. Approximate thickness of unconsolidated alluvium and Tertiary sediments: $H =$ 55 + 25 = 80 m (L site), $H =$ 55 + 25 = 80 m (A site) studied by SASW and CH techniques behaving nonlinearly. That may cause the amplification or de-amplification for $\text{PGA} > 0.4g$ due to degradation of shear moduli and increase of strains in depth.
4. The great earthquakes of 1811-1812 caused extensive ground failures (especially liquefaction). Evidence on satellite images.

5. As there are no strong motion records in this area, the synthetics as input motions were generated at the top of consolidated sediments overlying the Paleozoic bedrock.

Results of a study using the Point-Source Model

Shear wave velocity (V_s) models

For the generation of synthetic ground motions the velocity models for Mid-America & NMSZ according to the inversion of teleseismic data were used [10], so named Soil USGS96 source model (M5). The preliminary sediment thickness for the model was 1000m thick for New Madrid Seismic Zone.

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Synthetics for H = 0m

Correspond to generation of synthetics on free surface of rocks.

Synthetics for H = 650m

Synthetics were generated for the thickness h = 730 - 80 = 650m.

Acceleration time histories and velocity time histories were computed for 5 random values (seeds) (123, 1234, 2345, 345, 78).

For each of three combinations of distances and magnitudes

\[ D = 10\text{km} \quad \text{&} \quad M_w = 7.1 \]
\[ D = 16\text{km} \quad \text{&} \quad M_w = 7.8 \]
\[ D = 20\text{km} \quad \text{&} \quad M_w = 8.1 \]

Computer Codes

For generating synthetic motions, Boore's SMSIM package [11] is used in which: using input data were \( M_w \), D(km), h(m), number of simulations, and seed number, were computed acceleration time history, peak motions (PGA, PGV, PGD), and response spectra for a given damping (5%).

Acceleration time histories (Synthetics) [12]

Synthetics used as input motions were generated for different thickness of sediments (H) on the top of consolidated sediments overlying the Paleozoic bedrock.

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#### Strong Motion Parameters according to Seismic Hazard Maps

According to the USGS seismic hazard maps for PE = 2% in T = 50yrs, by entering a latitude and longitude for A, and L bridge sites at the USGS-National Seismic Hazard Mapping Project the strong motion parameters listed in Table 4 can be deduced.

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#### Table 3: Prototype Model [10].

| Layer | Material     | Thickness (m) | Vp (m/sec) | Vs (m/sec) | Density gm/cc | Q_p | Q_s |
|-------|--------------|---------------|------------|------------|---------------|-----|-----|
| 1     | Soil         | 0-2000        | 1800       | 250h^{3/2} | 0.8 log Vs-0.1 | 6 h^{3/4} | 6 h^{3/4} |
| 2     | Upper Paleozoic | 500          | 4500       | 2500       | 2.5           | 500 | 500 |
| 3     | Lower Paleozoic  | 500         | 5000       | 3000       | 2.6           | 500 | 500 |
| 4     | Precambrian   | -            | 6000       | 3500       | 2.7           | 500 | 500 |

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#### Table 4: Seismic Hazard Parameters at Bridge Sites.

| Parameter | Bridge Site A | Bridge Site L |
|-----------|---------------|---------------|
| PGA (g)   | 1.510068      | 1.475792      |
| 0.2sec Sa (g) | 3.105915  | 3.001929      |
| 0.3sec Sa (g) | 2.526520  | 2.465689      |
| 1.0sec Sa (g) | 0.982504  | 0.969057      |

Table 4: Seismic Hazard Parameters at Bridge Sites.

The distances and magnitudes used to calculate these hazard values were found according to the USGS special tables for PGA, 0.2 sec \( S_a \), 0.3 sec \( S_a \) and 1.0 sec \( S_a \), as functions of log (km) and moment magnitude (Mw). The synthetics for both bridge sites were generated for three combinations of parameters were chosen, as

\[ D = 10\text{km} \quad \text{&} \quad M_w = 7.1 \]
\[ D = 16\text{km} \quad \text{&} \quad M_w = 7.8 \]
\[ D = 20\text{km} \quad \text{&} \quad M_w = 8.1 \]

#### Computer Codes

For generating synthetic motions, Boore's SMSIM package [11] is used in which: using input data were \( M_w \), D(km), h(m), number of simulations, and seed number, were computed acceleration time history, peak motions (PGA, PGV, PGD), and response spectra for a given damping (5%).

#### Acceleration time histories (Synthetics) [12]

Synthetics used as input motions were generated for different thickness of sediments (H) on the top of consolidated sediments overlying the Paleozoic bedrock.

#### Synthetics for H = 0m

Correspond to generation of synthetics on free surface of rocks.

#### Synthetics for H = 650m

Synthetics were generated for the thickness h = 730 - 80 = 650m.

Acceleration time histories and velocity time histories were computed for 5 random values (seeds) (123, 1234, 2345, 345, 78).

For each of three combinations of distances and magnitudes

\[ D = 10\text{km} \quad \text{&} \quad M_w = 7.1 \]
\[ D = 16\text{km} \quad \text{&} \quad M_w = 7.8 \]
\[ D = 20\text{km} \quad \text{&} \quad M_w = 8.1 \]

### Table 5: Synthetics on hard rocks for A Bridge Site.

| Synthetics | M   | D (km) | Seed | PGA (g) |
|------------|-----|--------|------|---------|
| 1D         | 7.1 | 10     | 123  | 1.6799  |
| 6D         | 7.8 | 16     | 123  | 2.1274  |
| 11D        | 8.1 | 20     | 123  | 1.9572  |

Table 5: Synthetics on hard rocks for A Bridge Site.

PGA values for the thickness of H=650m

PGA & PGV values for 15 synthetics for each bridge site are close to each other.
Figure 6: Acceleration Time Histories at A Bridge Site for different combinations of M and D (the same seed number 123).

Figure 7: PGA values (g) in different depths for synthetics (Model M5 for M=7.1, D=10 km, S=123).
Figure 8: PGA (a) and PGV (b) values for 15 synthetics.

Figure 9: Sa spectra (D=0.05) in different depths for synthetics (model M5 for M=7.1, D=10 km, S=123).

Figure 10: Comparison of average Sa spectra for 3 combinations of Mw and D (km) for M5 model (bridge site A).
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Figure 11: Sa spectra for 15 synthetics M5 model (bridge site A).

Figure 12: Comparison of average Sa spectra (D=0.05) for Point Source Model (M=7.1, D=10km, H=650m, average of 5 seeds) with average values (100 simulations) for Composite Model (Mw=7.0) for A Bridge Site [12].

Figure 13: Comparison of average Sa spectra for 3 combinations of Mw and D (km) for M5 model (bridge site A).
Sa spectra

Synthetic Sa spectra for different thickness H of sediments on the top of Paleozoic rocks

The maxims of Sa spectra of synthetics are displaced to the longer periods and decreasing as values with the increasing of thickness of sediments (H).

Sa spectra for 5 random values for different combination of Mw and D (km)

Average values of Sa spectra for 5 random values for different combination of Mw and D (km) are close to each other with the lowest values for Mw = 7.1, D = 10km and the highest ones for Mw = 7.8, D = 20km.

Comparison of Sa spectra for synthetics with H=0m & H=650m

Sa spectra for H = 0m (blue lines) are characterized by the highest response values versus smaller periods (0.04-0.16sec).

Sa spectra for H = 650m (red lines) have the lower peak values versus medium periods (0.25-0.55sec).

Comparison of Sa spectra for synthetics with H = 650m for point source model with those for composite model

From figure 12 it can be seen that the average Sa spectra (D = 0.05) for both Point Source (H = 650m) (red line) and Composite Model (blue lines) are very close to each other concerning the shape, but they differ concerning the amplitudes.

Strong Motion Parameters According to NEHRP Maps

The USGS 1996 seismic hazard maps for PE = 2% in T = 50yrs by entering a latitude and longitude for two bridge sites at the website of National Seismic Hazard Mapping Project [10] were used to find the corresponding seismic hazard parameters (Table 6).

| Parameters | Bridge Site A | Bridge Site L |
|------------|---------------|---------------|
| PGA(g)     | 1.510068      | 1.475792      |
| 0.2sec Sat(g) | 3.105915      | 3.001929      |
| 0.3sec Sat(g) | 2.526520      | 2.465689      |
| 1.0sec Sat(g) | 0.982504      | 0.960957      |

Table 6: Seismic hazard parameters for bridge sites.

The distances and magnitudes used to calculate these hazard values were found according to the USGS special tables for PGA, 0.2sec Sa, 0.3 sec Sa and 1.0 sec Sa, as functions of log (km) and moment magnitude (Mw). To generate synthetics for both bridge sites three combinations of parameters were chosen, as shown below:

D = 10km & Mw = 7.1
D = 16km & Mw = 7.8
D = 20km & Mw = 8.1

Sa spectra of synthetics for 3 combinations of Mw and D(km)

The average values of Sa spectra for 5 random values for different combination of Mw and D (km) are close to each other with the lowest values for Mw = 7.1, D = 10km and the highest one for Mw = 7.8, D = 20km.

Non-linear soil response analysis of the upper part of soil profiles

Based on above mentioned synthetics it can concluded that

1. Closer to near field records are those of M = 7.1 and D = 10km with PGAav = 1.01g for A bridge site and PGAav = 0.98g for L bridge site.
2. At the level of input motion (top of Paleozoic rock at ~ 650-700m) the input PGA was determined as 1.0g (for A site and L site).
The upper part with a thickness of 80m is characterized by the nonlinear response of sediments. At depths below the response is elastic one.

3. The increase of the thickness of sediments on the top of Paleozoic rocks by 50 meters (L site) has a very small influence on the mean PGA average value (only 0.01g less).

Soil profiles based on shear wave velocity data

The soil profiles of the bridge sites were compiled using geologic-lithological data and shear wave velocity data from two sources: CH and SASW data.

For L site (Figure 16a) the SASW testing was performed nearby the location where a seismic cone penetrometer (SCPT) was previously advanced.

For A site (Figure 16b) both SASW and cross-hole data were acquired in addition to the SCPT data at that site.

Results of Nonlinear Response Analysis for RW and CH Models

Soil Response Profiles

Sa spectra for the shallow soil profile (h~60m) show small differences in the ground response analysis (at periods $T = 0.5 - 1.5$).

Most of the differences are seen in periods $T < 0.5$ sec., which tend to be of little significance for bridges and possibly an artificial product of the synthetic motions.

$S_a$ spectra for deep profile

For a deep soil profile the differences in Sa spectra are even less pronounced and comparisons between the SASW and CH data are difficult to identify.
Conclusions

For soil profiles modeled using geophysical techniques in NMSZ:

1. Equivalent non-linear response analysis for shallow soil model (h~60m) is most pronounced for CH model compared with SASW model and show small differences in the range T = 0.5 - 1.5sec.

   The most differences are seen in the range T < 0.5 sec., which tend to be of little significance for bridges.

2. For deep soil profiles (compiled by SASW and CH data), using the point source model, to generate the synthetics, those differences are even less pronounced and comparisons between the SASW and CH data are difficult to identify.

3. Therefore advantages of using high quality CH data for use in ground response are not justified.

4. SASW surface geophysics results tend to satisfy the engineering requirements for ground response analysis.

5. For shallower deposits and more intrinsic soil-structure interaction analysis the CH geophysical characterization may be justified.

Based on this analysis the main problem in NMSZ is not the high level of amplitudes of strong ground motions, but possible ground failure phenomena to be developed during future strong earthquakes, to be taken into account for the bridges in this area by increasing bearing capacity of the soils and foundations.

Figure 17: Sa spectra for Shallow (hypothetical) Soil Profile ~60m for the SASW (pink line) and CH (blue line) models using M=7.1 input synthetic motion (black line).

Figure 18: Sa spectra (5% damping) for Deep Soil profile, SASW (pink line) and CH (blue) models using M=7.1 input synthetic motion (black line).
Competing Interests

The author declare no competing interests.

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