Analysis of TVA's Watts Bar Nuclear Power Plant Strong-Motion Records of the M 4.4 December 12, 2018 Decatur Tennessee Earthquake

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Watts Bar Nuclear Power Plant Strong-Motion Records of the 12 December 2018 M 4.4 Decatur, Tennessee, Earthquake

Vladimir Graizer*[1], Dogan Seber[1], and Scott Stovall[1]

SRL Seismological Research Letters

Abstract

The moment magnitude M 4.4 on 12 December 2018 Decatur, Tennessee, earthquake occurred in the eastern Tennessee seismic zone. Although the causative fault is not known, the earthquake had a predominantly strike-slip mechanism with an estimated hypocentral depth of about 8 km. It was felt over a distance of 500 km stretching from Southern Kentucky to Georgia. Strong shaking, capable of causing slight damage, was reported near the epicenter. The Watts Bar nuclear power plant (NPP) is only 4.9 km from the epicenter of the earthquake and experienced only slight shaking. The earthquake was recorded by the plant's seismic strong-motion instrumentation installed at four different locations. Near-real-time calculations by the plant operators indicated that the operating basis earthquake (OBE) ground motion was not exceeded during the earthquake. We obtained and processed the recorded motions to calculate corrected accelerations, velocities, and displacements. In addition, we computed the Fourier and 5% damped response spectra to compare them with the plant's OBE. Comparisons of the ground-motion prediction models with the digital recordings at the plant site indicated that recorded ground motions were significantly below the predicted results calculated using the ground-motion prediction models approved for regulatory use. Availability of high-quality, digital recordings in this case helped make a quick decision about the ground motions not exceeding the OBE and hence prevented unnecessary shutdown of the NPP. Availability of earthquake recordings from the four locations in the NPP also presented an opportunity to analyze the linear response of plant structures.

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Earthquake Information from the USGS

https://earthquake.usgs.gov/earthquakes/eventpage/se60247871/executive

Tectonic Summary

The December, 12, 2018 9:14 (UTC) earthquake occurred in the Eastern Tennessee Seismic Zone (ETSZ). The ETSZ extends across eastern Tennessee and northwestern Georgia into northeastern Alabama. It is one of the most active earthquake areas in the Southeast. Although the zone is not known to have had a large earthquake, a few earthquakes in the zone have caused slight damage.

Earthquakes in the central and eastern U.S., although less frequent than in the western U.S., are typically felt over a much broader region. The **December, 12, 2018 M4.4 Decatur, Tennessee earthquake** was felt over 310 miles from Southern Kentucky to Fort Benning, Georgia. Strong shaking capable of causing slight damage have been reported near the epicenter.

The Eastern Tennessee seismic zone is laced with known faults, but numerous smaller or deeply buried faults remain undetected. Even the known faults are poorly located at earthquake depths. Accordingly, few, if any, earthquakes in the ETSZ can be linked to named faults.

Watts Bar Nuclear Plant

- The Watts Bar nuclear plant is operated by the Tennessee Valley Authority (TVA). The plant is located in Rhea County, Tennessee, near Spring City, between the cities of Chattanooga and Knoxville. The plant has two Westinghouse pressurized water reactor (PWR) units: unit 1 was completed in 1996, and unit 2 was completed in 2015. Both units are the newest operating civilian reactors to come online in the United States, and unit 2 is the first and only new reactor to enter service in the twenty-first century.

- Hypocenter of the December 12, 2018 moment magnitude (**M)** 4.4 Decatur, Tennessee, earthquake was located at a depth of 7.9 km. The epicentral distance to the plant was 4.9 km. The earthquake occurred on an unknown fault and has a predominantly strike-slip mechanism.

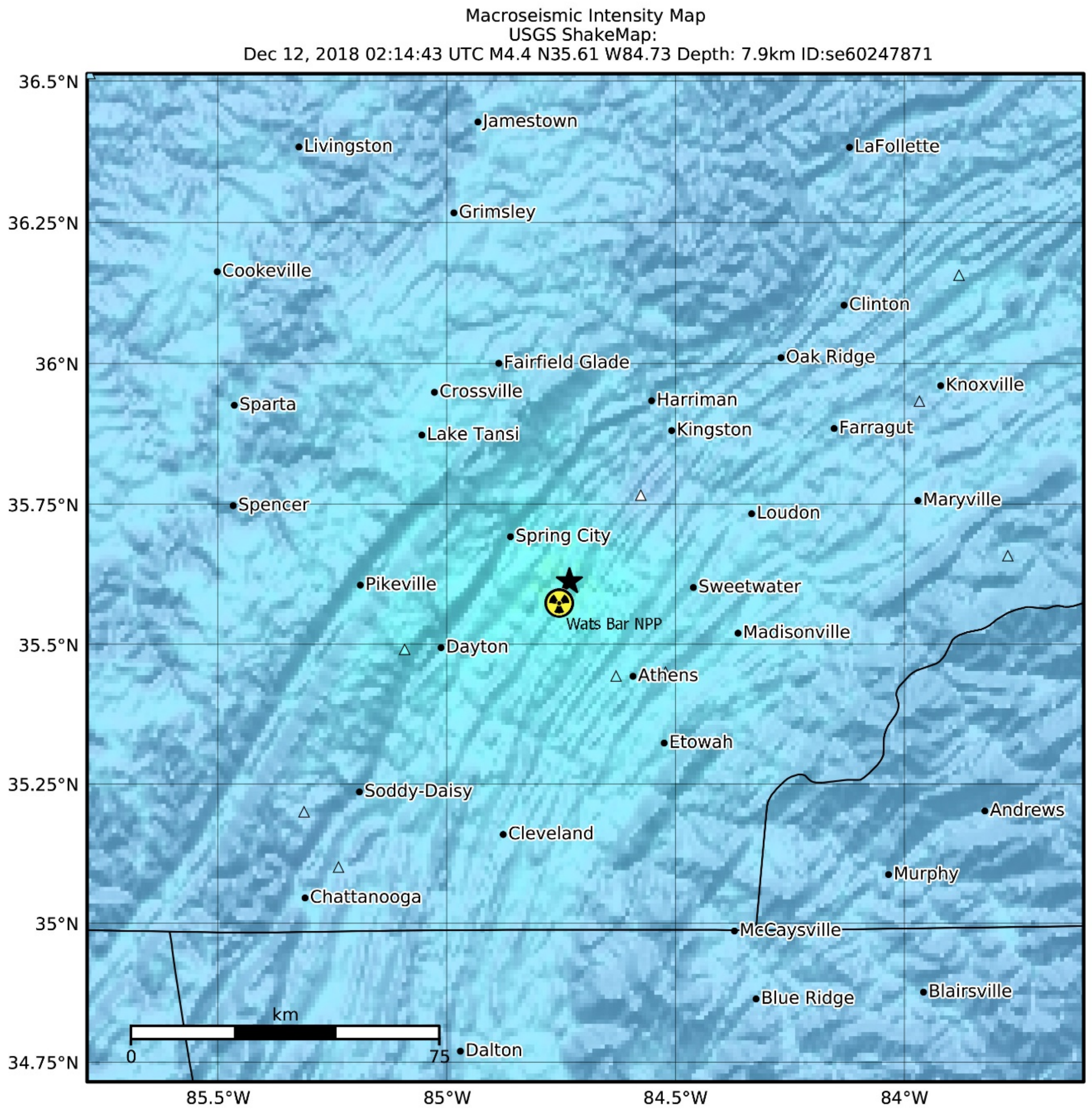
M4.4 Decatur earthquake ShakeMap and Watts Bar NPP location

Location: 35.612° N and 84.732° W

Hypocenter depth 7.9 km

Epicentral distance to NPP 4.9 km

The earthquake fault mechanism was predominantly strike slip



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.01	0.08	0.95	4.99	8.76	15.4	27	47.4	>83.2
PGV(cm/s)	<0	0.04	0.52	3.03	6.48	13.9	29.6	63.4	>136
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Atkinson and Kaka (2007) Version 2: Processed 2018-12-19T15:45:38Z

△ Seismic Instrument ○ Macroseismic Observation ★ Epicenter

Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE)

U. S. Code of Federal Regulations (CFR) requires designing nuclear power plant structures, systems, and components important to safety to withstand the effects of natural phenomena, such as earthquakes, without loss of capability to perform their safety functions. Specific requirements include the establishment of Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE) ground motions which are used to assess the integrity of the plants' structures, systems, and components as well as shutdown and restart procedures following an earthquake. Both SSE and OBE ground motions are characterized by response spectra.

The US regulations define the SSE as the vibratory ground motions for which certain structures, systems, and components must be designed to remain functional. The OBE ground motions are associated with plant shutdowns and inspections. Watts Bar NPP Unit 1 operating license was issued in February 1996. In plants licensed before January 10, 1997 OBE is usually set up as one-half or less of the SSE (earthquake engineering criteria in appendix A to 10 CFR part 100). If vibratory ground motions at a NPP site exceed the OBE spectra, a plant shutdown and specific inspections are required as described in Regulatory Guide (RG) 1.166 (1997). To assess whether earthquake ground motions have exceeded the OBE or SSE, it is important that a reliable seismic instrumentation system be in place.

NPPs licensed before 1997 are not required to have a free field instrument. The free-field requirement first appeared in RG 1.12 Rev. 2 published in March 1997. However, the most recent regulatory guide, RG 1.12 Rev. 3 (2017), suggest new NPPs to have more extensive seismic instrumentation including a free-field accelerograph to allow direct comparisons with the current ground motion models and calculation of the cumulative absolute velocity (CAV), and a borehole instrument for the direct comparison to the plant's design SSE and OBE ground motions.

Seismic Instruments and Recordings at Watts Bar NPP

The existing seismic instrumentation system at the NPP unit 1 was installed in September 1999 and consists of the Kinematrics CONDOR digital recorder connected to three triaxial accelerometers and an ETNA triaxial strong motion accelerograph.

The earthquake was recorded in Unit 1 by the CONDOR recording system at three locations:

1. Elevation 702.78 ft. in Unit 1 Reactor Bldg. on the base (75A)
2. Elevation 756.63 ft. in Unit 1 Reactor Bldg. on the floor slab (75B)
3. Elevation 742 ft. in Diesel Generator Bldg. on the base slab (75D)

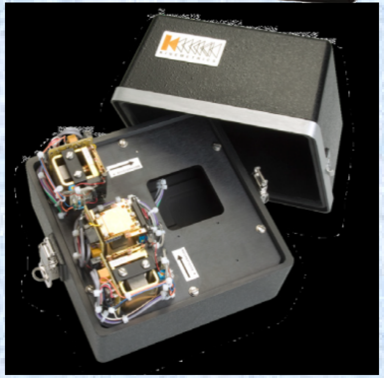
   And an independent accelerograph ETNA at the

4. Auxiliary Bldg. at elevation 757 ft. (BA)

The CONDOR recording system is located in the Control Building. First three transducers are interconnected and have full scale range of 0 to 1.0 g with a bandwidth of 0 to 50 Hz, and 3-sec pre-event and 10-sec post-event memory. ETNA accelerograph at the Auxiliary Building have a range of 0 to 2.0 g and 20-sec of pre-event and 10-sec post-event memory.

An internal seismic trigger actuates the recording systems when a threshold acceleration level is sensed. The trigger threshold is set to initiate recording when the acceleration at the containment foundation exceeds **0.01g.** Sampling rate is 200 samples per second.

CONDOR Seismic Monitoring System for NPPs



SPECIFICATIONS

Recorder	
General	
Model:	Obsidian 24X
Quantity:	(1) One
Number of Channels:	24 channels
Data Acquisition	
Type:	Individual 24-bit Delta Sigma converter per channel
Anti-alias filter:	Double Precision FIR Filter Causal/Acausal; >140 dB attenuation at output Nyquist
Dynamic Range:	200 sps ~127 dB (RMS noise to RMS clip - Typical) 100 sps ~130 dB (RMS noise to RMS clip - Typical)
Frequency response:	DC to 80 Hz @ 200 sps
Sampling rate:	1, 10, 20, 50, 100, 200, 250, 500, 1000, 2000, 5000 sps, selectable
Channel skew:	None – simultaneous sampling of all channels
Output data:	24 bit signed (3 bytes) in user selectable format. Kinemetrics' EVT standard
Trigger	
Type:	IIR bandpass filter (three types available)
Channel Triggering:	Independently selected for each channel
Threshold Trigger:	Selectable from 0.01% to 100% of full scale
Threshold De-trigger:	Selectable from 0.01% to 100% of full scale
Trigger voting:	Internal, external and network trigger votes with arithmetic combination
Additional trigger:	STA/LTA, Time Window
Pre-event recording time:	Limited just by the storage capacity, selectable
Post-event recording time:	Limited just by the storage capacity, selectable
Timing	
Type:	Oscillator digitally locked to GPS or PTP. Integrates completely with system, providing timing, internal oscillator correction, and position information.
Accuracy:	<1 microseconds of UTC with GPS or PTP
Storage	
Data:	Internal SDHC Card Slot, standard 32 GB
System:	Internal SDHC Card Slot, 4 GB
Recording capacity:	Approximately 42 kB per channel per minute on Memory Card of 24-bit data @ 200 sps
Communications	
Ethernet interface:	Standard TCP/IP
FSoftware	
Type:	Multi-tasking operating system supports simultaneous acquisition and interrogation; allows remote and automatic firmware upgrades
Security:	Supports SSH and SSL
System control:	Configure sample rate, filter type, trigger type and voting, maintains communications and event storage
File formats:	Standard Kinemetrics EVT. Other available
Intelligent alerting:	Initiate communications when an event is detected or if an auto-diagnostic failure occurs
Auto-diagnostics:	Continuously check system voltages, temperature, humidity, and timing system integrity
Rapid setup:	Can be configured from a parameter file
System timing:	Supports PTP Slave and PTP Master timing (Using Internal GPS as Master clock), NTP and External 1PPS
I/O and Display Power input:	Mil-style connector for DC power input, external battery connection, Power over Ethernet (Option)
Interface:	10/100 BaseT Ethernet
EMI/RFI protection:	All I/O lines EMI/RFI and transient protected
LED:	System, power and event status, Ethernet Link & Data
Recorder Power Supply	
Type:	Internal high efficiency switched power supply and battery charger system with extensive SOH outputs
DC input:	9-28 VDC (>15.5VDC for Battery Charger Operation)
External AC/DC:	Universal Input 100-250 VAC 50/60 Hz
Power module:	Output 15.5 VDC
Internal battery charger:	Digitally temperature compensated output for external Valve Regulated Lead Acid (VRLA) batteries with reverse protection and deep discharge recovery
Fuses:	None. Uses resettable Polyswitch protection
Current drain:	605mA @12V (without sensors)
External power supply:	110 VAC 60Hz
Operating temperature:	-20C to 70C
Humidity:	0 to 100 % RH
Enclosure rating:	IP67 Equivalent
Model Number:	114170-24-PL
System Power Supply	
Type:	Rack-mountable Uninterrupted Power Supply
Power autonomy:	More than 48 hours. (For a standard system configuration with six FBA-3 sensors and 1500 VA UPS with two battery packs)

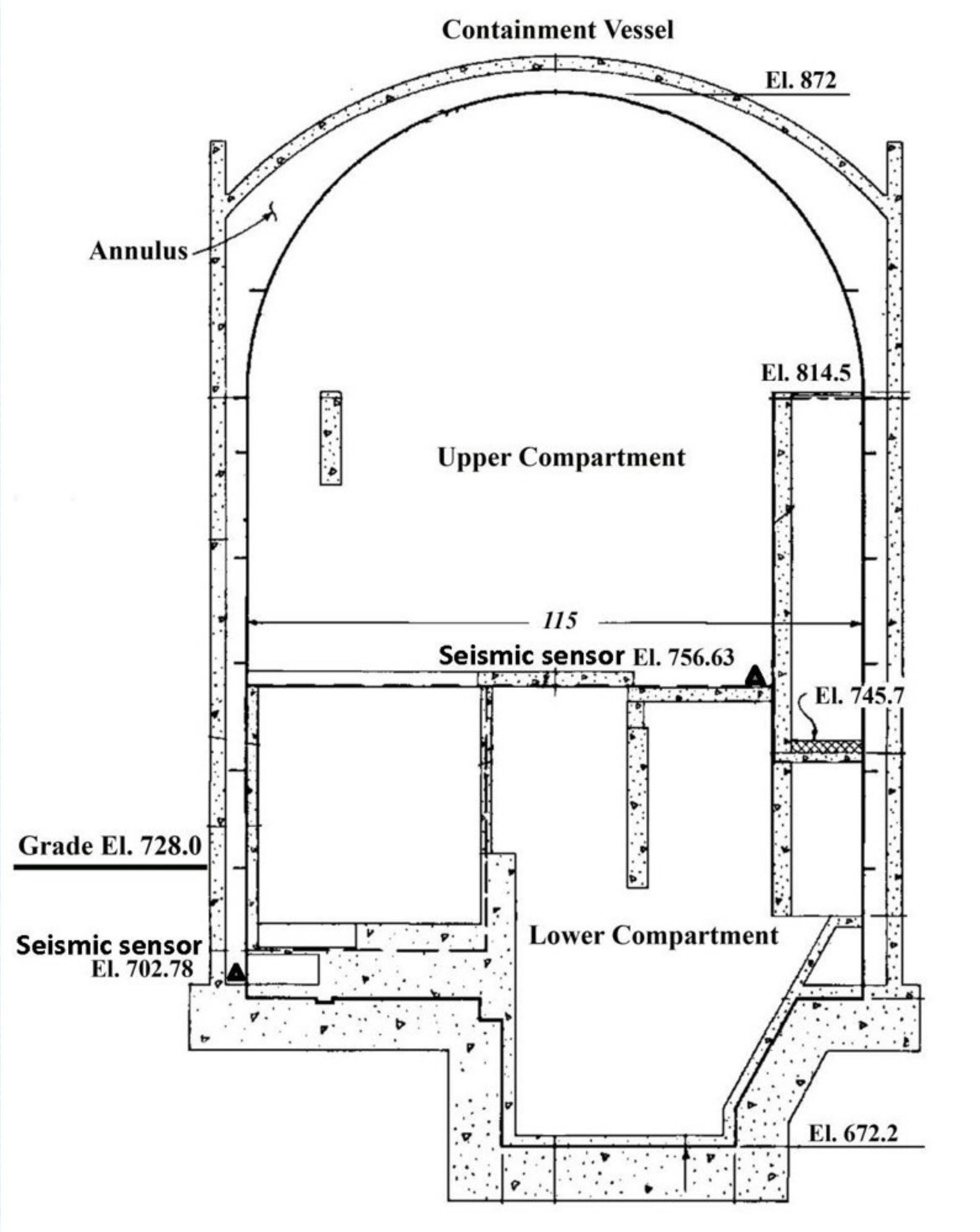
SPECIFICATIONS

Sensor	
Model:	FBA-3
Quantity:	(6) Six
Type:	Triaxial Force Balance
Full scale range:	+/- 1G
Natural frequency:	50 Hz
Bandwidth:	DC to 50Hz
Damping:	Nominal 70% critical (measured values furnished with each Sensor)
Operating temperature:	-20C to 70C
Sensitivity:	2.5 V/G
Zero offset:	25 mV
Cross-axis sensitivity:	0.03g/g
Linearity:	<1% of Full scale
Noise (0 to 50 Hz):	25 µV
Noise (0 to 10,000 Hz):	2.5 µV
Dynamic Range (0 to 50 Hz):	100dB
Humidity:	0 to 100 % RH
Calibration:	Electrical commands can be applied to produce damping and natural frequency outputs
Enclosure:	Watertight
Model Number:	102450-PL (aluminum casing) 102450-K1-PL (stainless steel casing)
Alarm & Interconnect	Housed in a rack panel, this provides a relay, general-purpose Input/Output, and LEDs for Recorder Alarms, Event, OBE, AC Loss and DC Loss.
Uninterrupted Power Supply (UPS)	This UPS provides up to one half hour of operation for the Central Controller Com puter and Alarm Panel.
Printer	Printer in a rackmount panel.
System Cabinet	Seismically qualified.
Environment	Recorder and Sensor
Operating Temp:	-20°C to 70°C
Humidity:	0% to 100% RH
All other equipment	
Operating Temp:	5°C to 40°C
Humidity:	50% to 80% RH

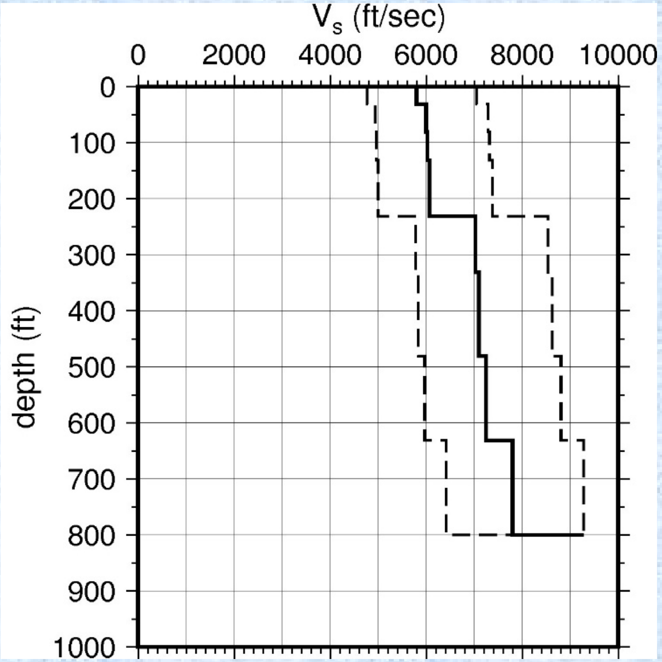
(Note: All other equipment is installed in the system cabinet)

Downloaded from Kinemetrics archives.

Triaxial Accelerometers in Unit 1 Containment



Shear wave velocity profile at control point 64 ft below plant grade

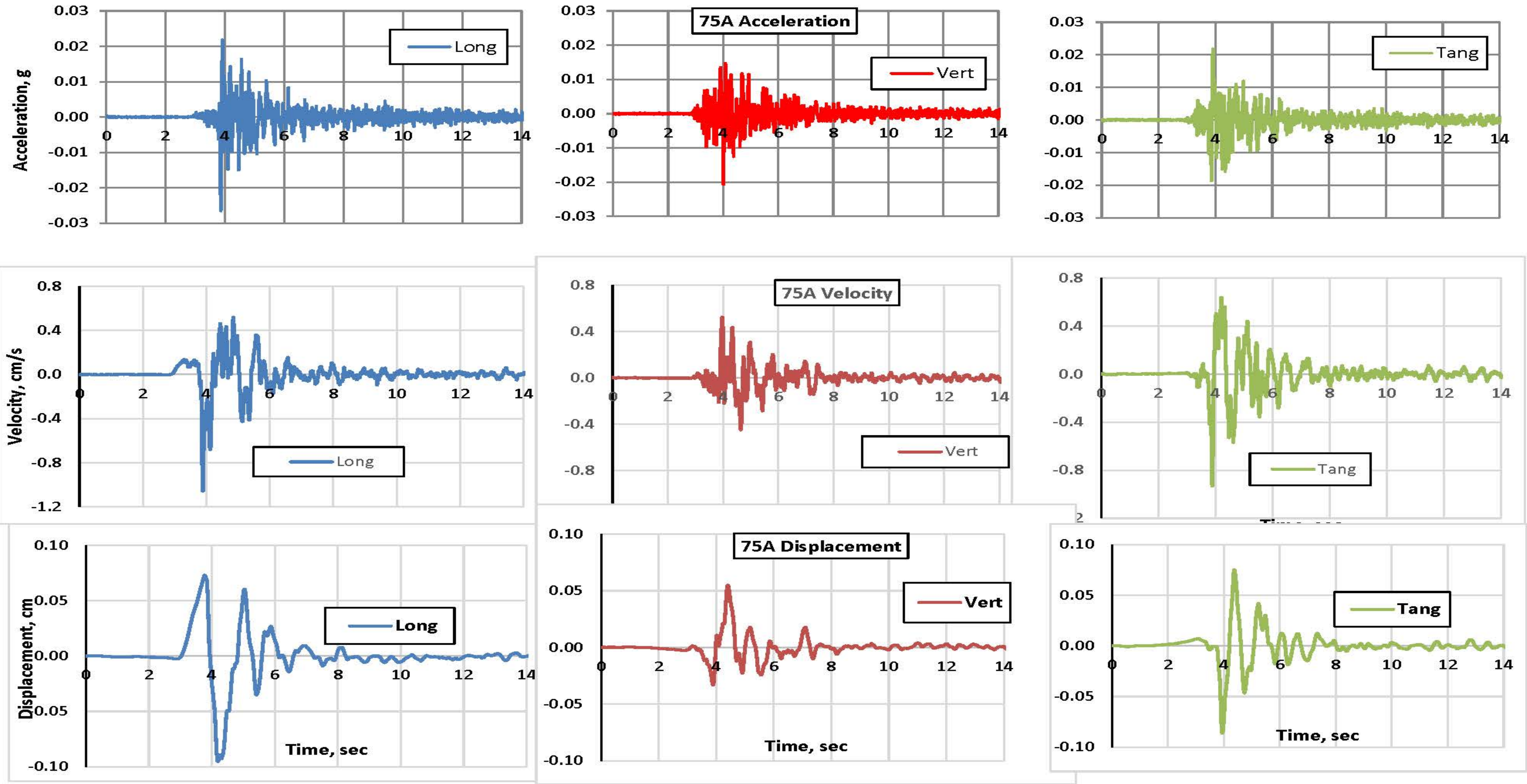


Reactor Building, Elevation 703 ft.

Accelerations

Velocities

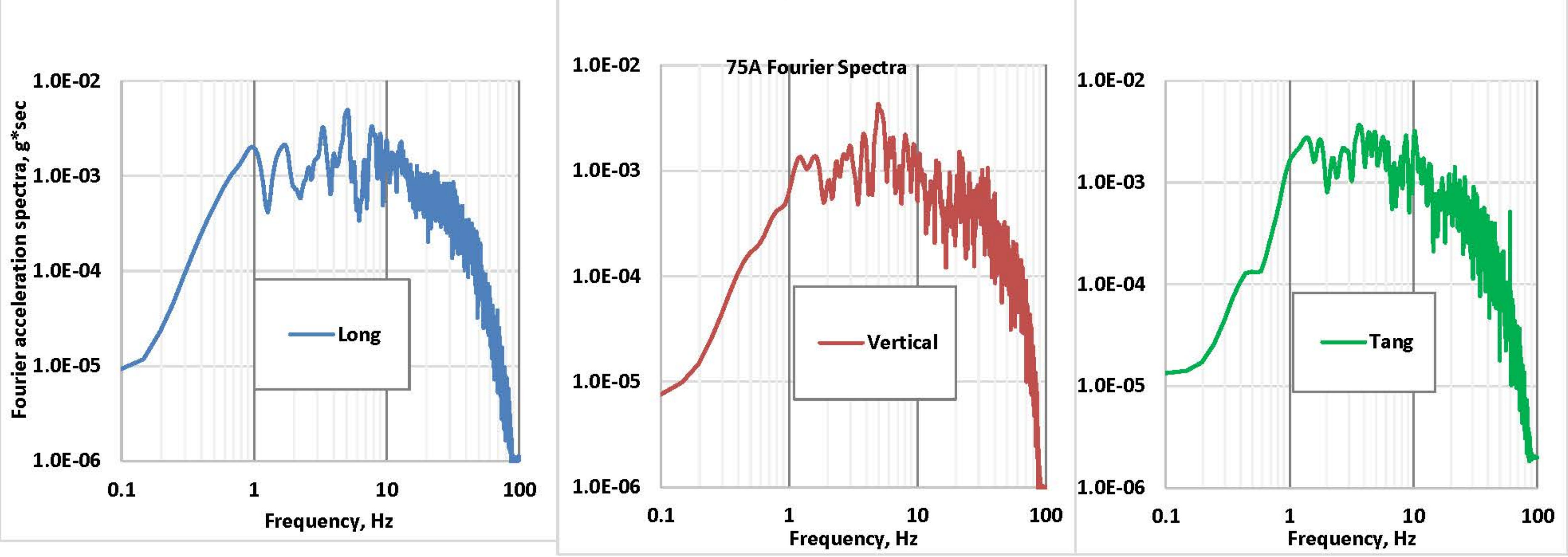
Displacements



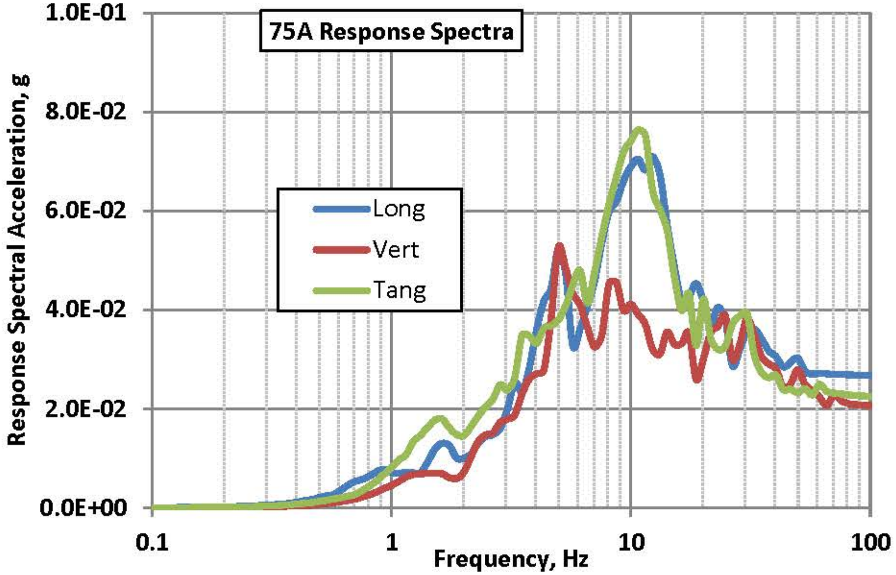
We read the Kinemetrics EVT files using their software to get uncorrected acceleration files, and reprocessed the files to get corrected accelerations, velocities, displacements and Fourier and 5% damped response spectra.
Processed data have a bandwidth of 0.65 to 53 Hz.

Reactor Building, Elevation 703 ft.

Fourier Spectra



5% damped
Response Spectra

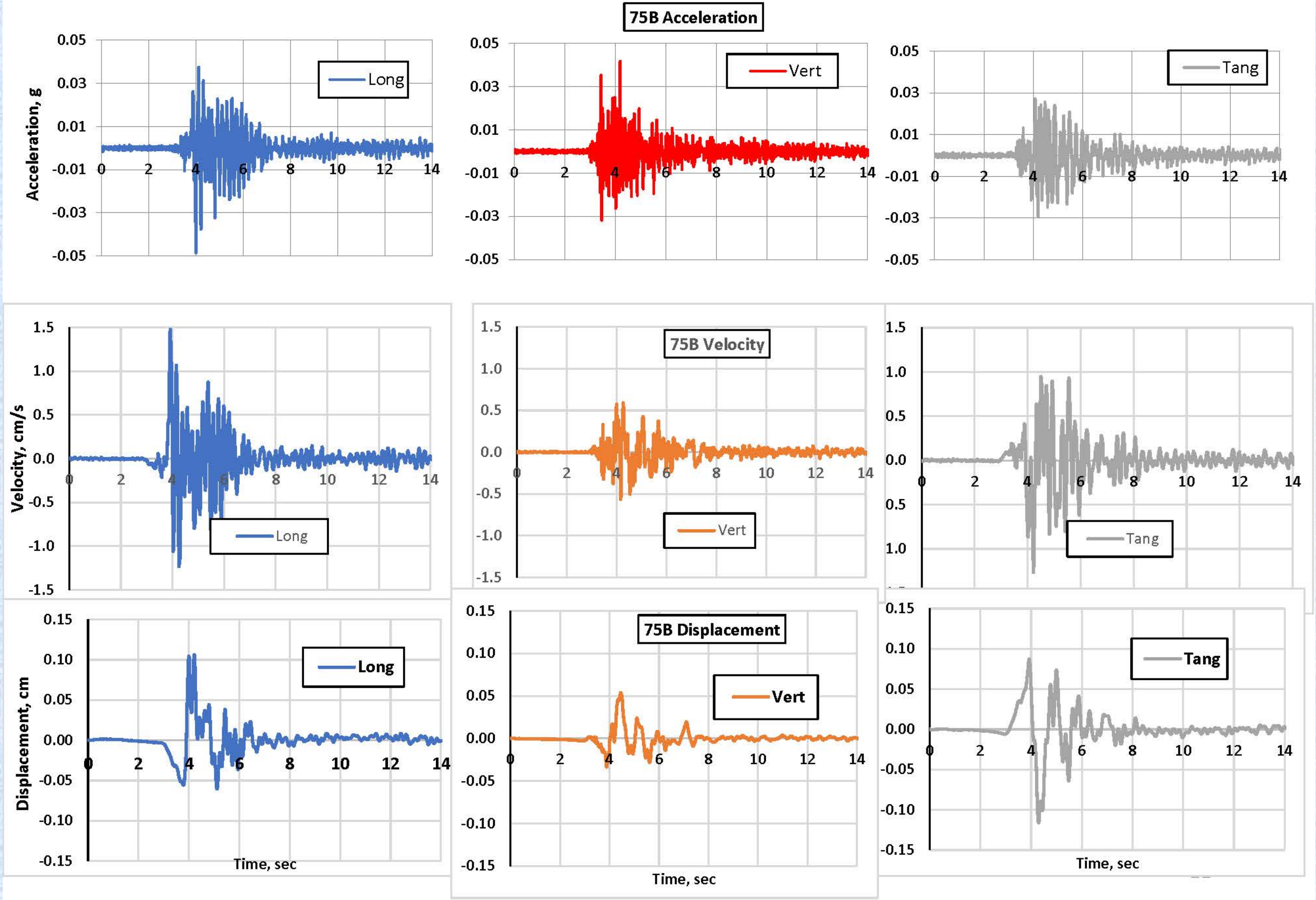


Accelerations, Velocities and Displacements at Reactor Building, Elevation 757 ft.

Accelerations

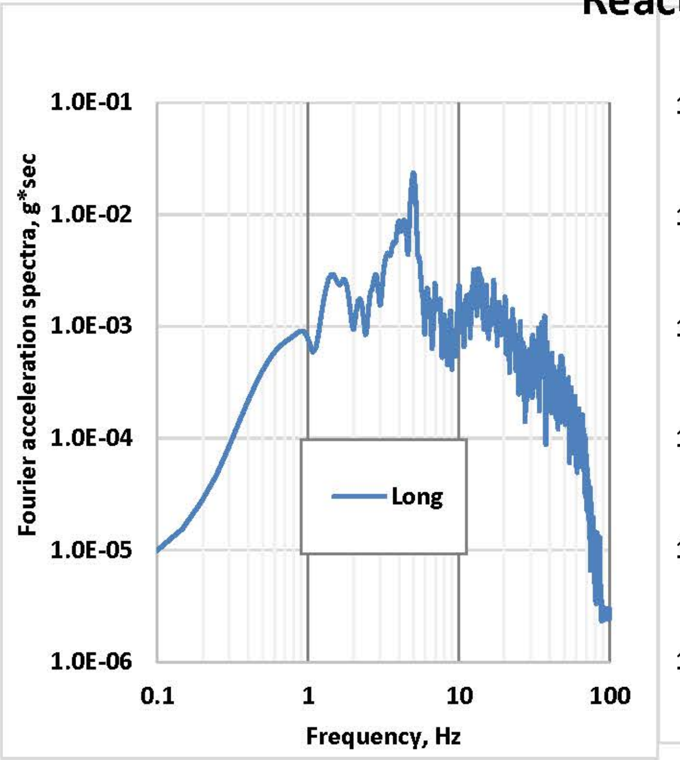
Velocities

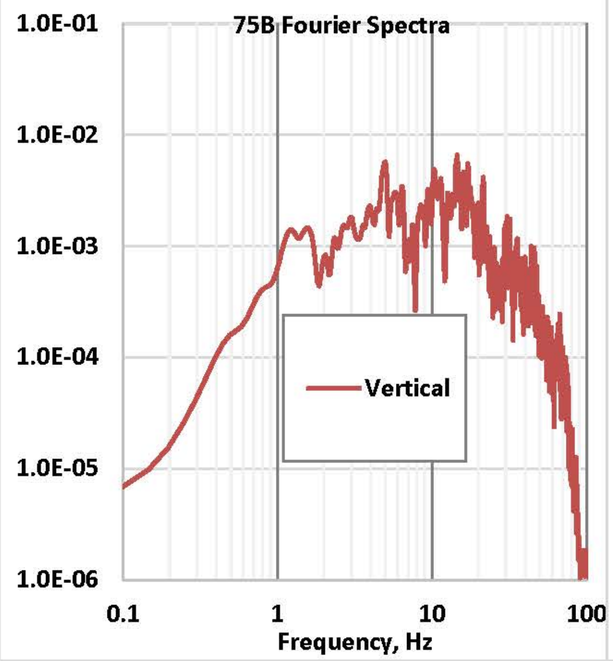
Displacements

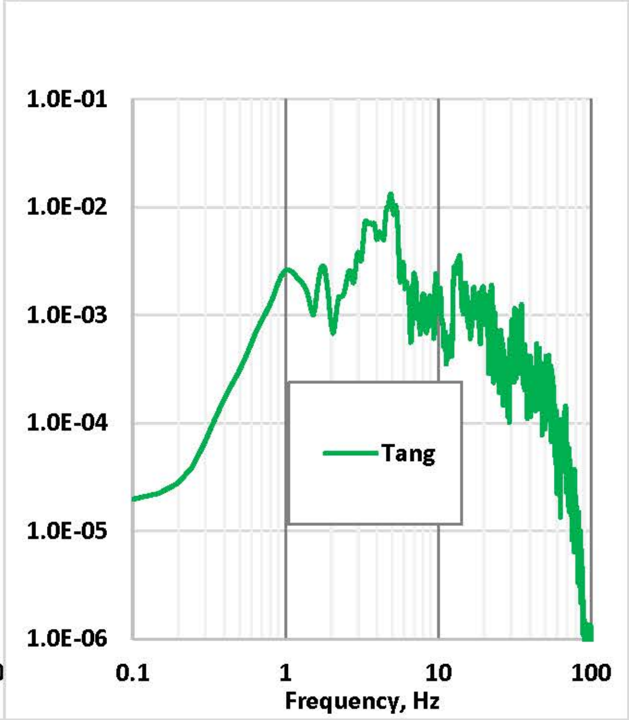


Reactor Building, Elevation 757 ft.

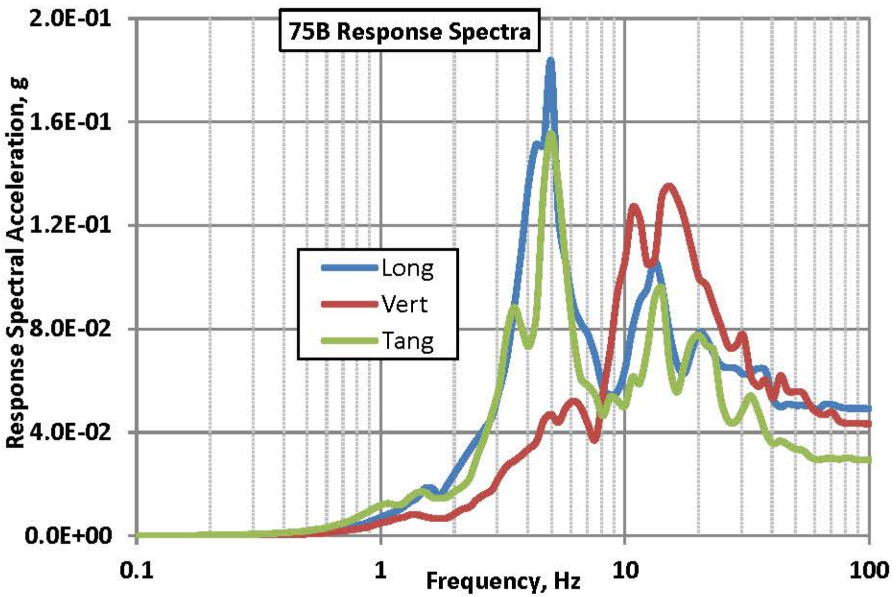
Fourier Spectra







5% damped Response Spectra

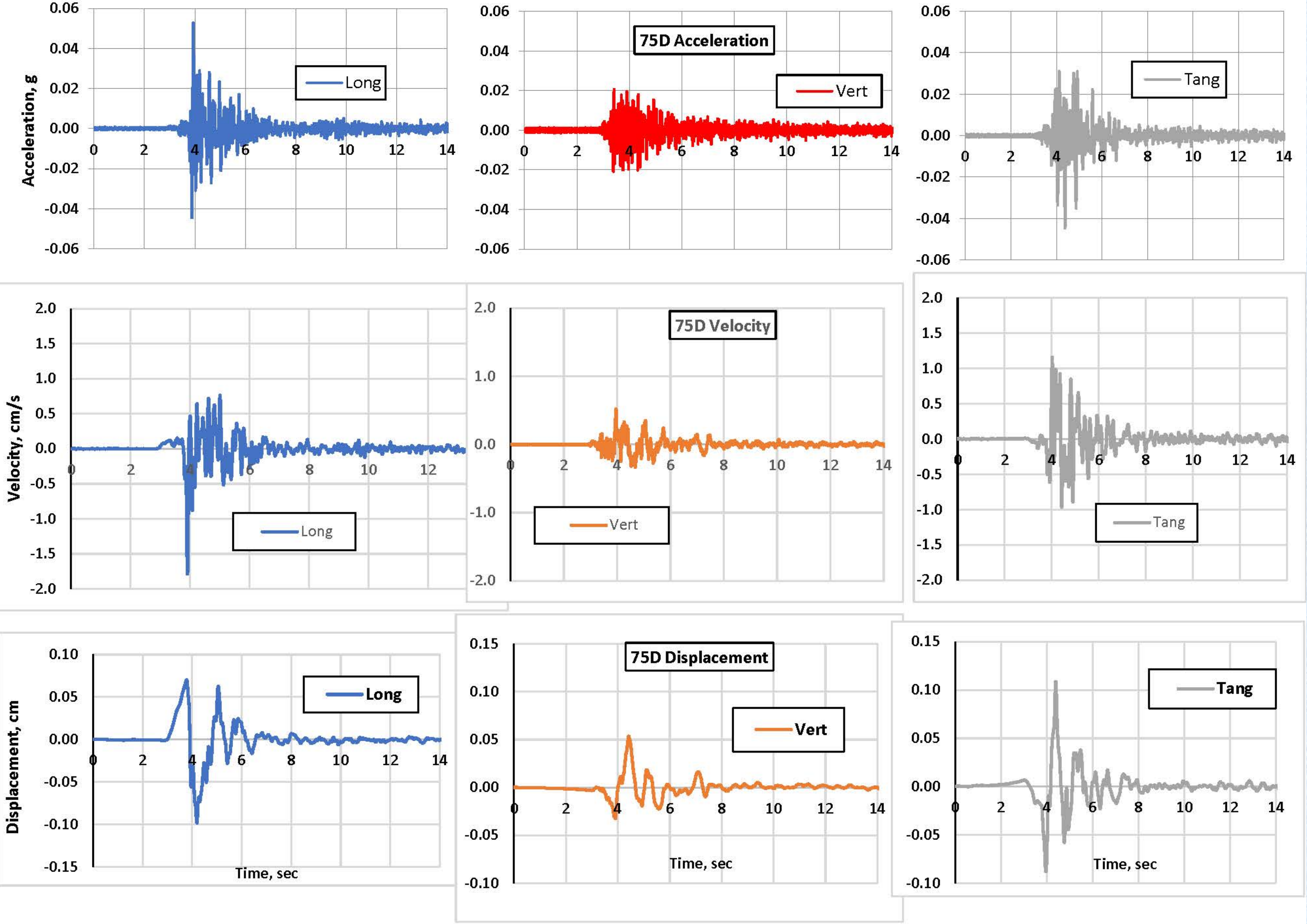


Accelerations, Velocities and Displacements at Diesel Generator Bldg, Elevation 742 ft.

Accelerations

Velocities

Displacements



Accelerations, Velocities and Displacements at Auxiliary Building, Elevation 757 ft.

Accelerations

Velocities

Displacements

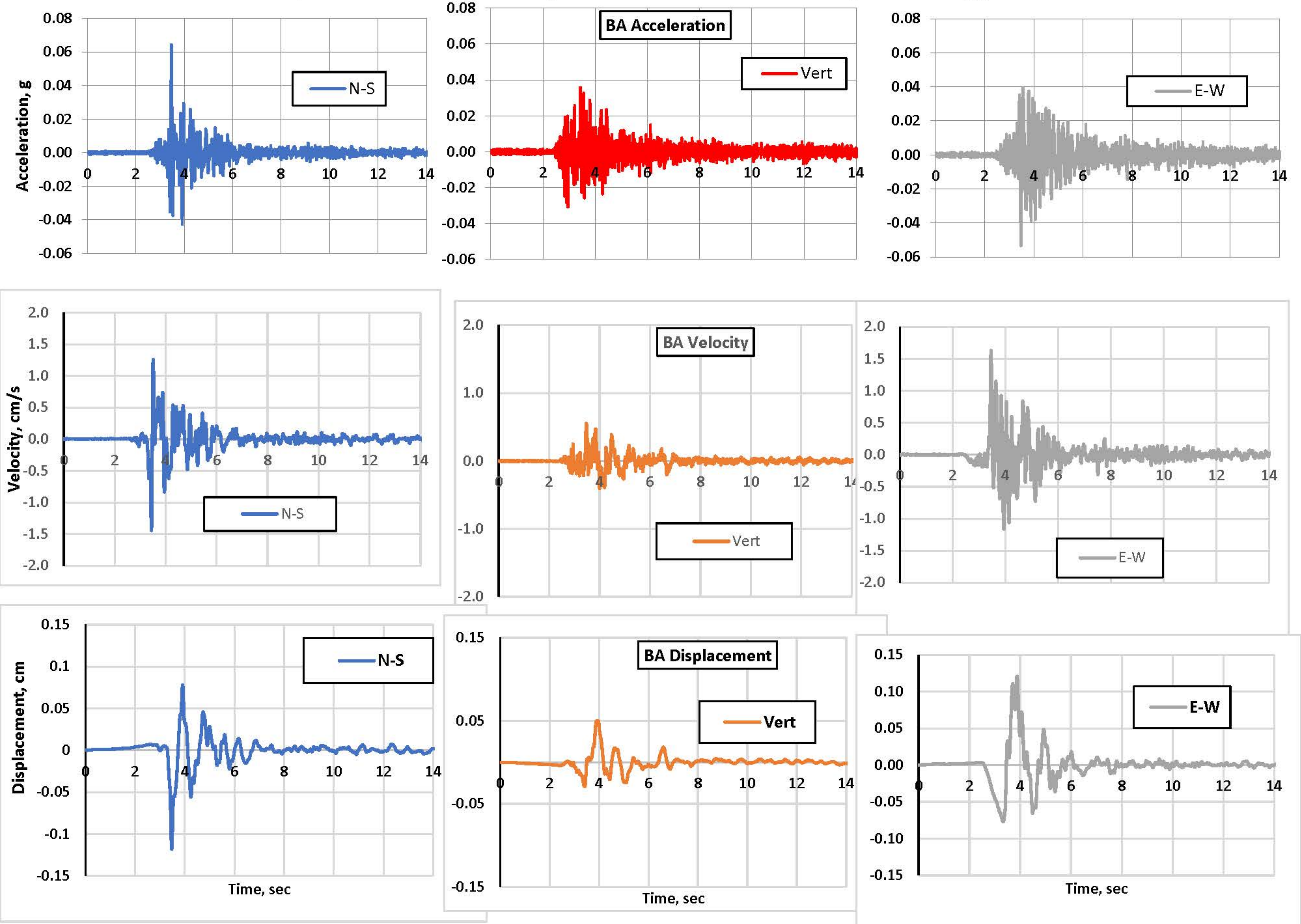
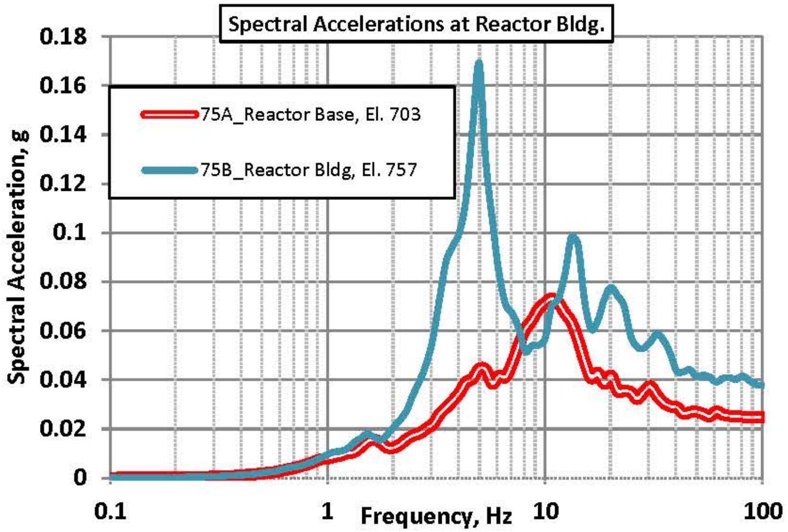


Table 1. Peak amplitudes of acceleration, velocity and displacement recorded by seismic sensors in Unit 1.

Location/Channel	Acceleration, g	Velocity, cm/sec	Displacement, cm
Reactor, El.703 ft, Long	0.0264	1.011	0.0853
Reactor, El.703 ft., Vert	0.0206	0.508	0.0493
Reactor, El.703 ft, Tang	0.0216	0.925	0.0802
Reactor, El.757 ft, Long	0.0482	1.434	0.0993
Reactor, El.757 ft., Vert	0.0417	0.578	0.0480
Reactor, El.757 ft, Tang	0.0290	1.229	0.1097
Diesel Gen., El.742 ft, Long	0.0527	1.741	0.0879
Diesel Gen., El.742 ft, Vert	0.0206	0.502	0.0487
Diesel Gen., El.742 ft, Tang	0.0443	1.135	0.1034
Auxiliary, El.757 ft, N-S	0.0642	1.435	0.110
Auxiliary, El.757 ft, Vert	0.0354	0.5367	0.0455
Auxiliary, El.757 ft, E-W	0.0529	1.579	0.108

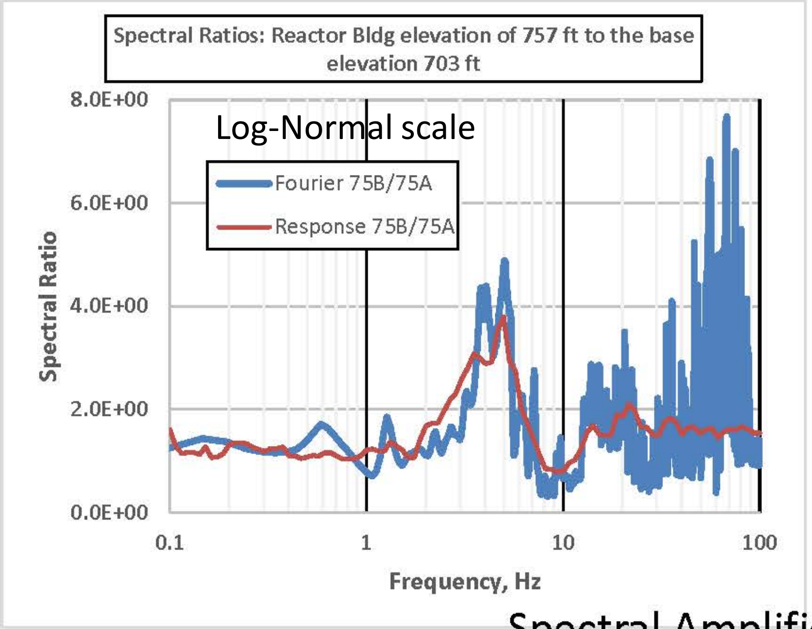
Spectral Ratios of Fourier and Response Spectra in Reactor Bldg at the Base (El. 703 ft) and on the Higher Level (El. 757 ft).

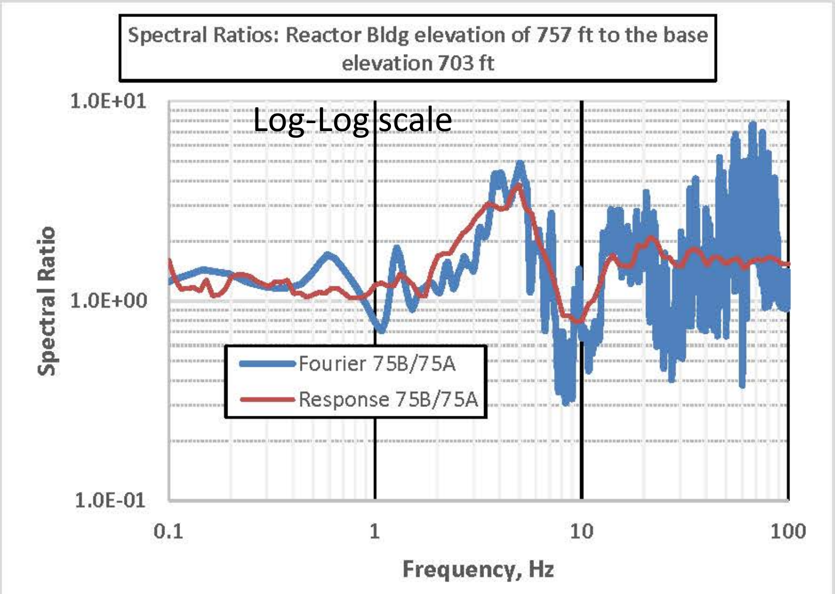
Average Horizontal Spectral Accelerations



Instractural response resonance frequencies at about 5, 13-14, 20 and 33 Hz.
5 Hz resonance is also visible at Reactor base.

Fourier and Response Spectral Ratios





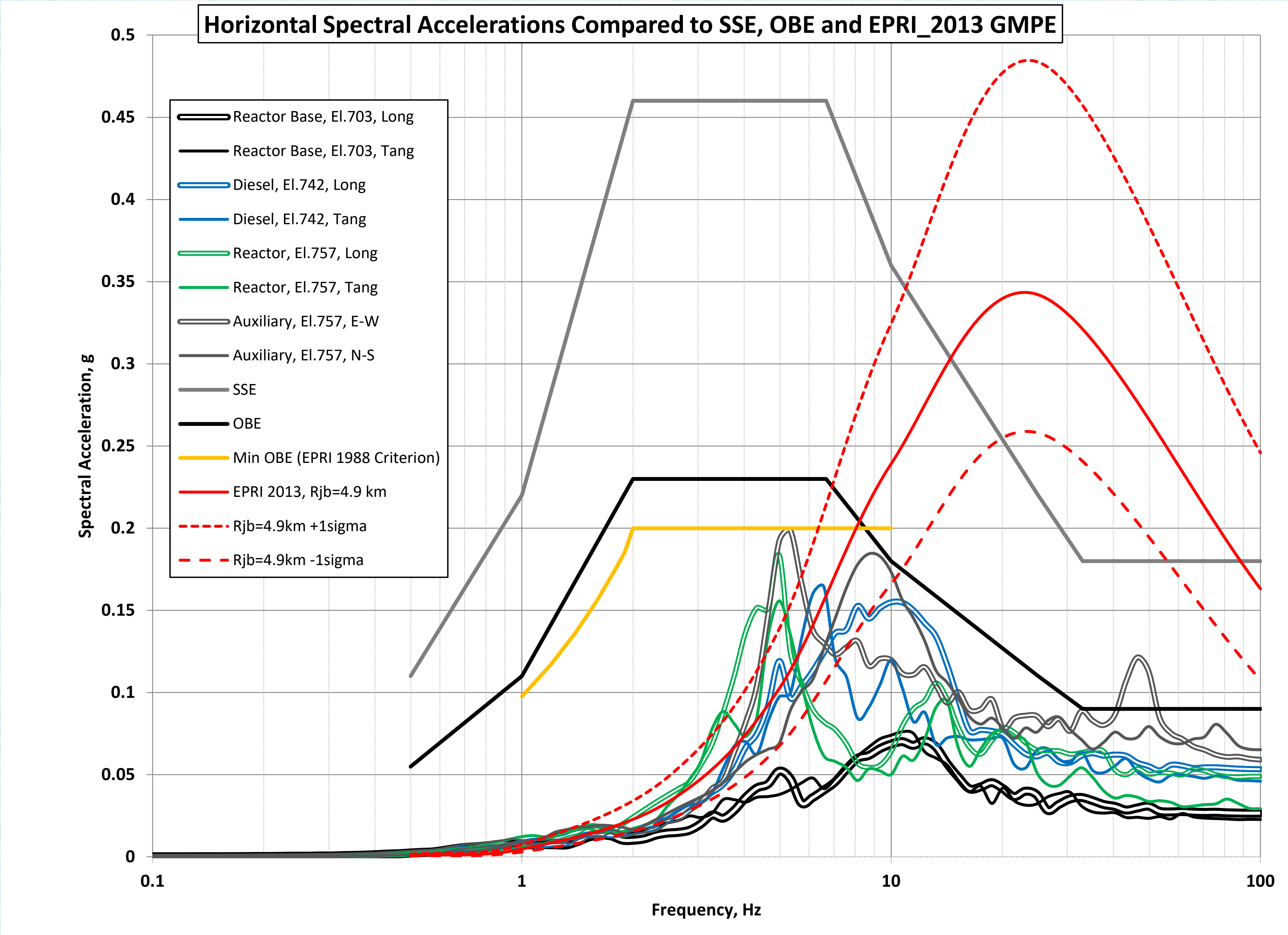
Spectral Amplification at 3.5 – 5.0 Hz and 14.2 – 21 Hz.

Structural Resonances in PWR Containment

- Structural resonance frequencies depend upon a number of factors including the elevation of seismic instrument, its proximity to the specific structural component and the depth of the Reactor building embedment. Multiple finite element model calculations of the seismic response of PWR result in a variety of resonance frequencies depending upon the specifics of the plant.

- ~5 and ~14 Hz structural resonances are consistent with modeling results shown in the papers of Kang and Lee (14WCEE, Beijing, China, 2008) and Lee et al. (15 WCEE, Lisbon, Portugal, 2012) for the PWR NPP.

Comparisons with Horizontal OBE and SSE

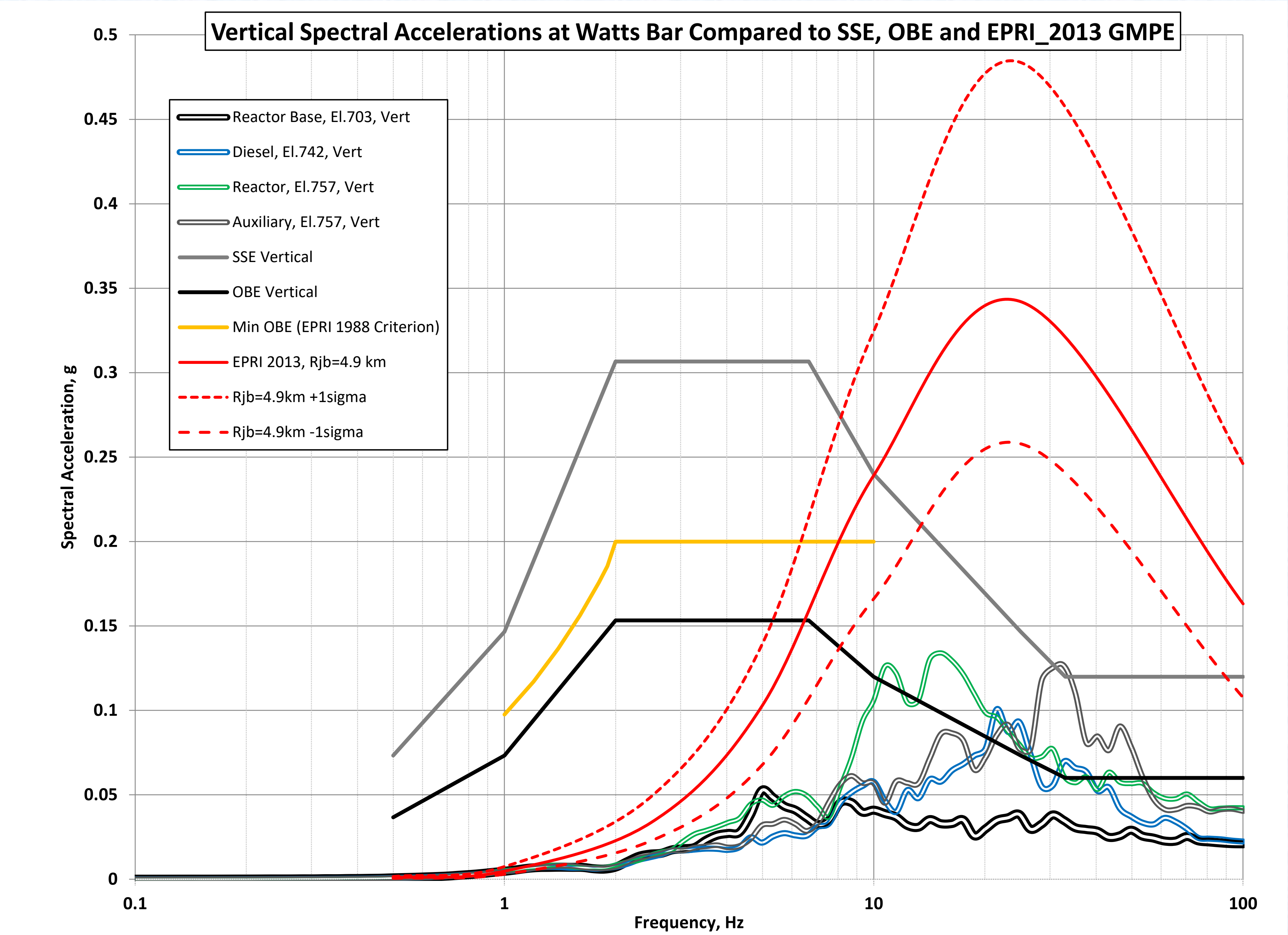


Horizontal OBE = 0.09g
SSE = 0.18g

5% damped response spectral accelerations recorded at 4 locations are below the OBE. Small exceedance at Auxiliary bldg at one horizontal component at frequencies of 45-50 Hz is beyond the limits of consideration.

Availability of records helped making quick decision of ground motions non-exceeding OBE and no need of plant shutdown.

Comparisons with Vertical OBE and SSE



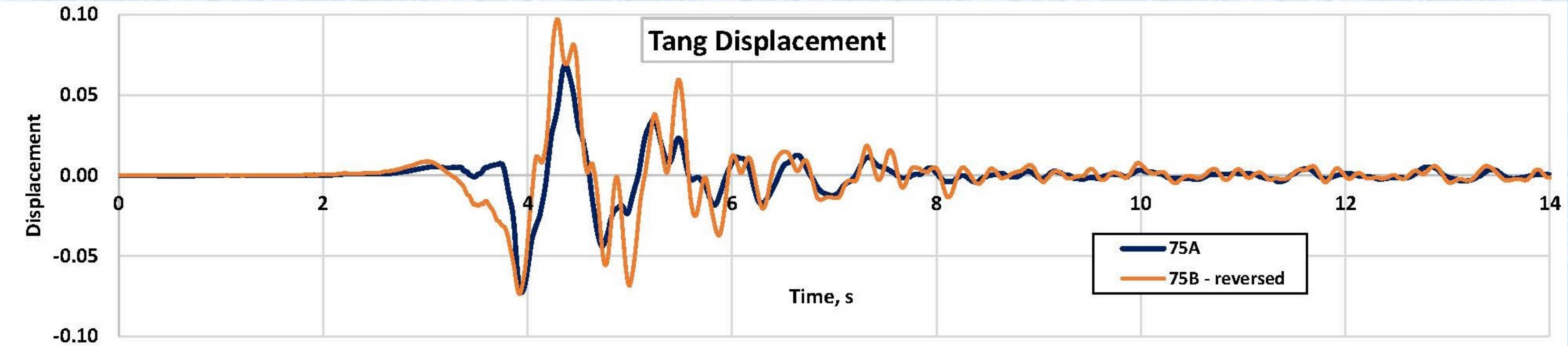
Vertical OBE=0.06g
SSE=0.12g

5% damped response spectral accelerations recorded at 4 locations are below the OBE at frequencies < 10 Hz.

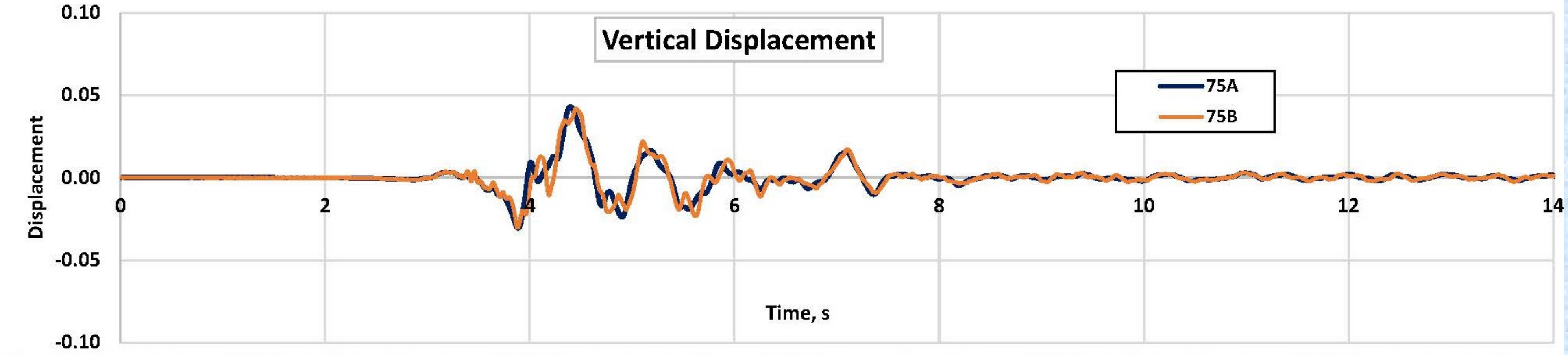
Availability of records helped making quick decision of ground motions non-exceeding OBE and no need of plant shutdown.

Comparing Displacements in Containment at Base at El. 703 ft and El. 757 ft

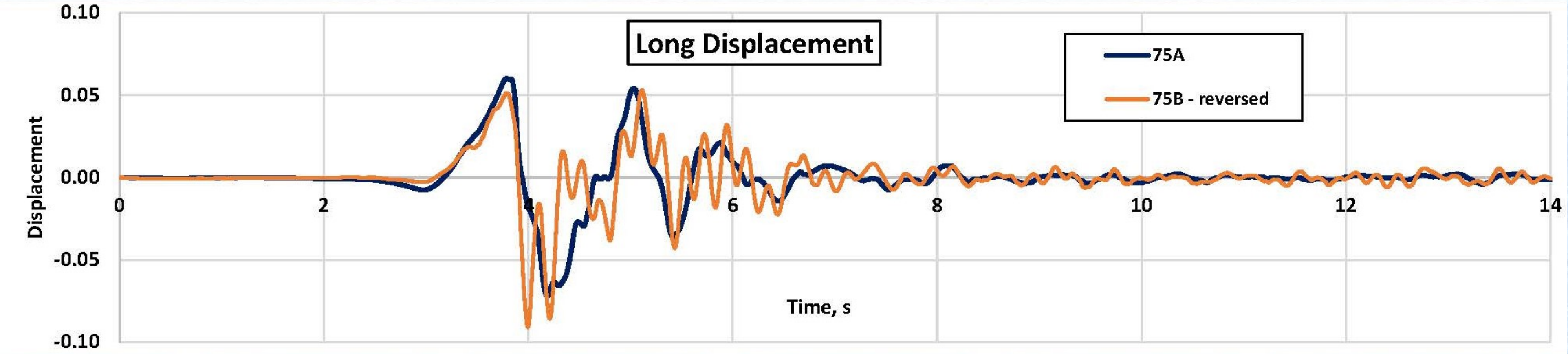
Tangential



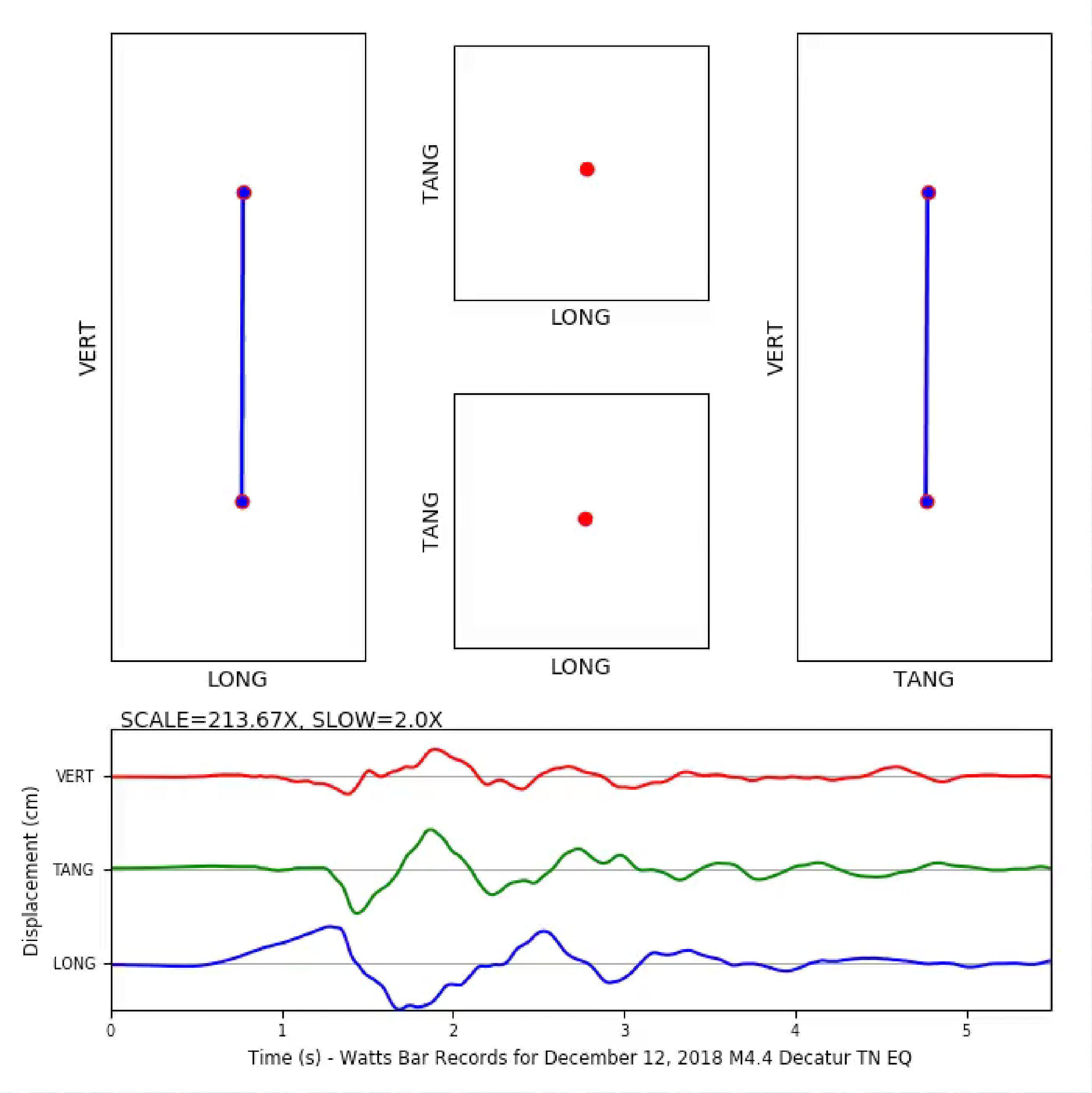
Vertical



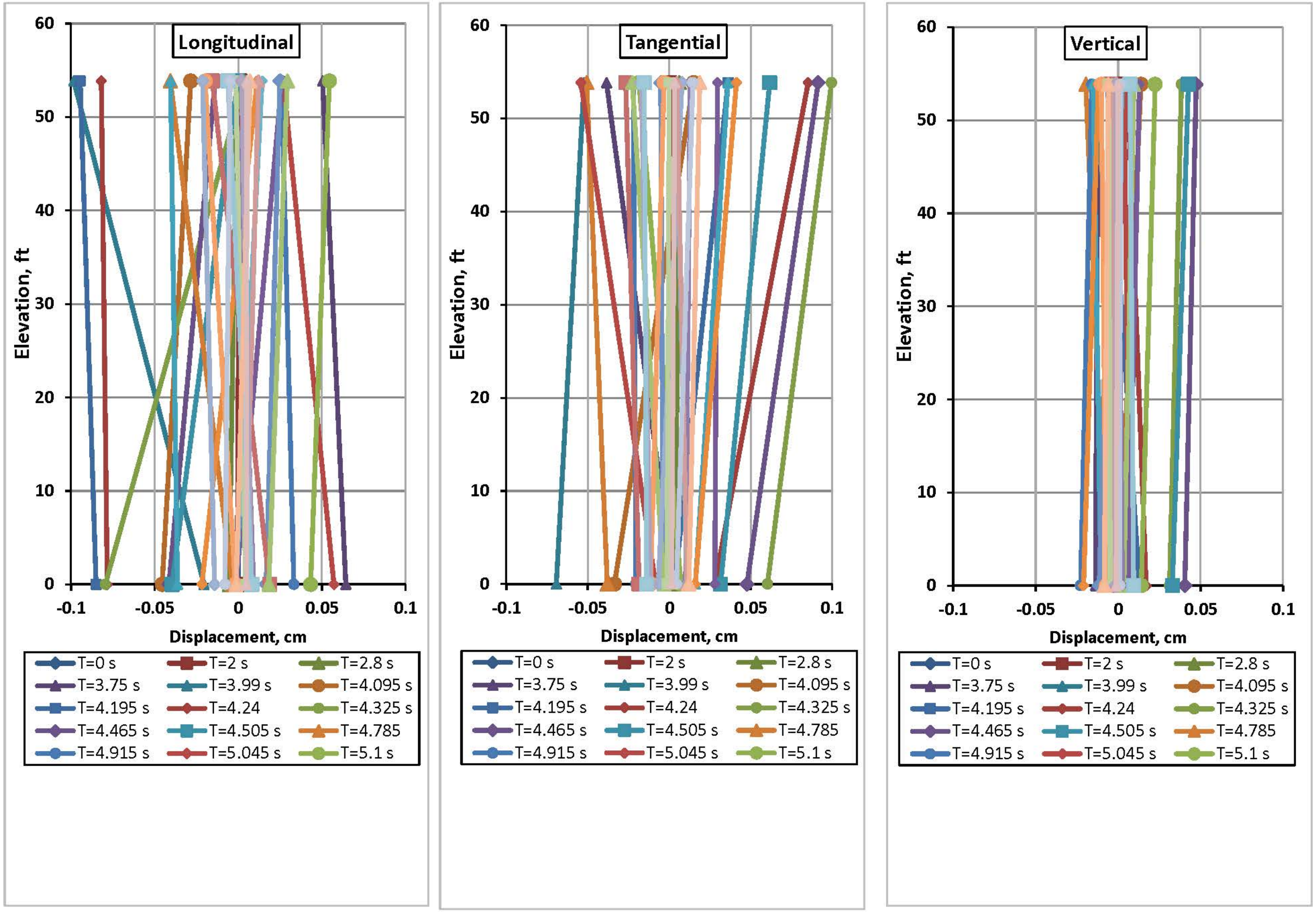
Longitudinal



Animation of Absolute Motion of Containment



Absolute Displacements at Base (El. 703 ft) and Floor (757 ft) in Containment

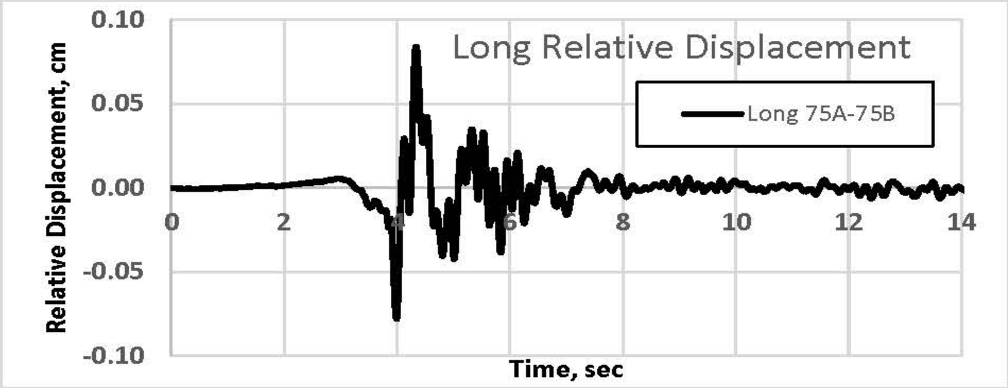


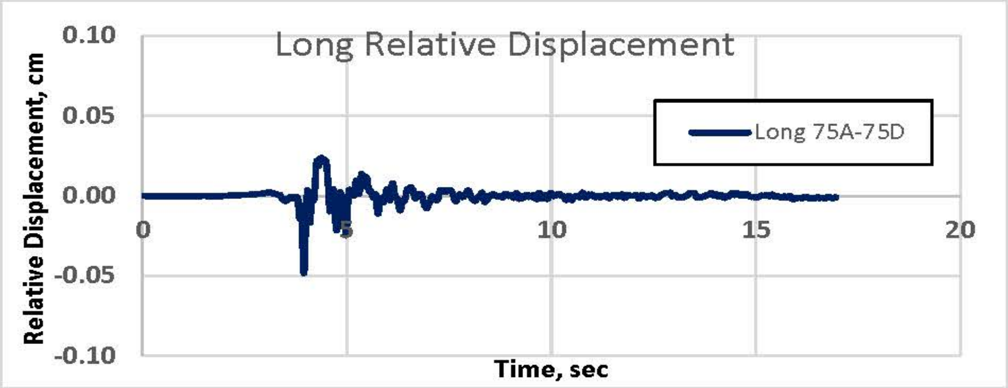
Relative Displacements

Base (El. 703 ft) and Floor (757 ft) in Containment

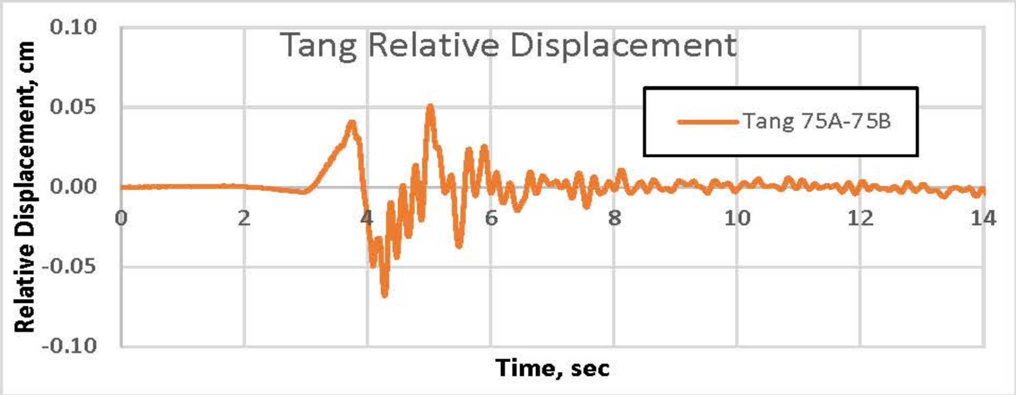
Base of Containment (El. 703 ft) and Diesel Generator (El. 742 ft)

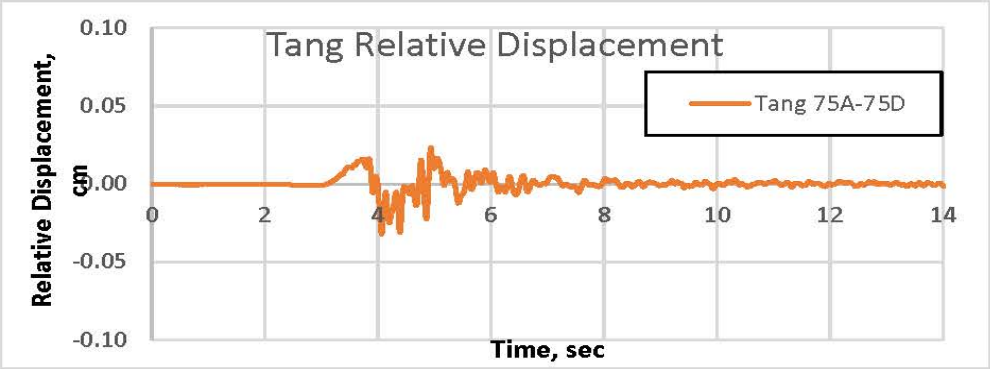
Longitudinal



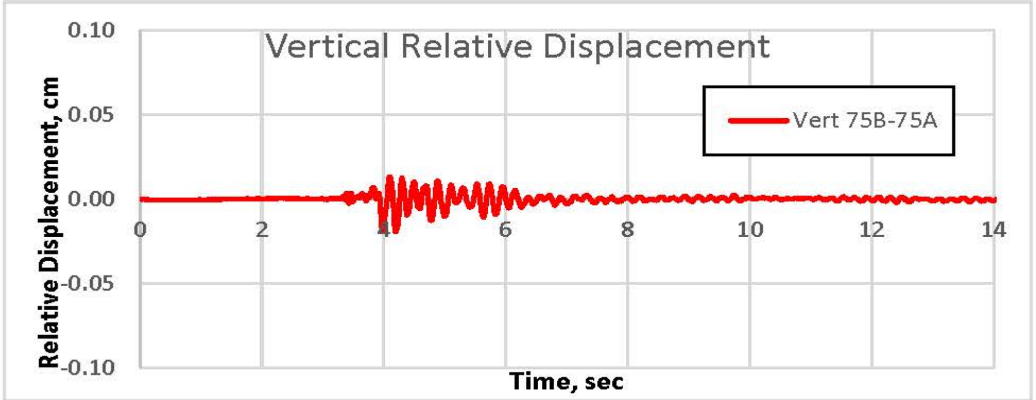


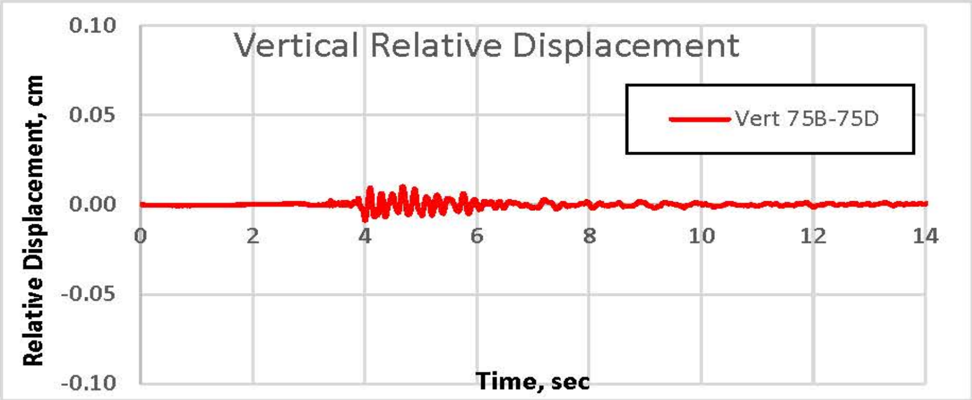
Tangential





Vertical

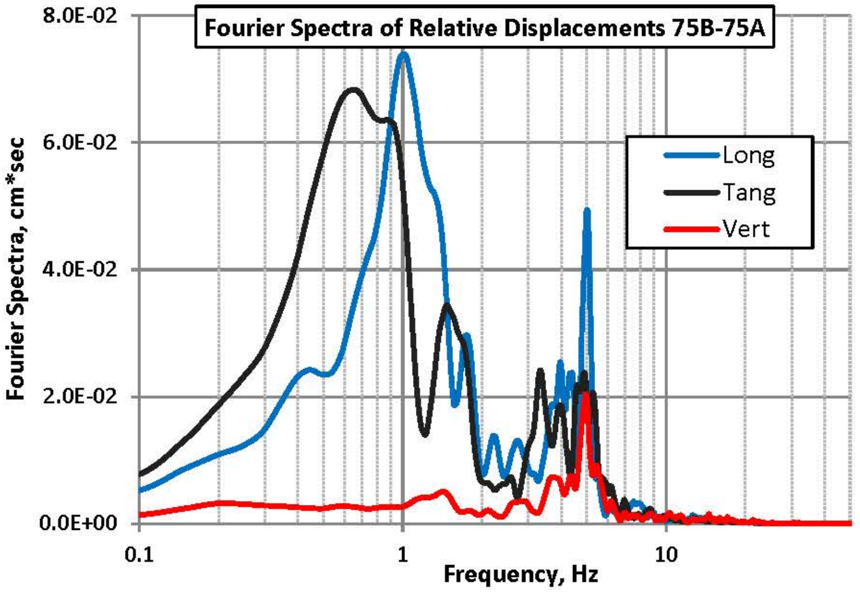




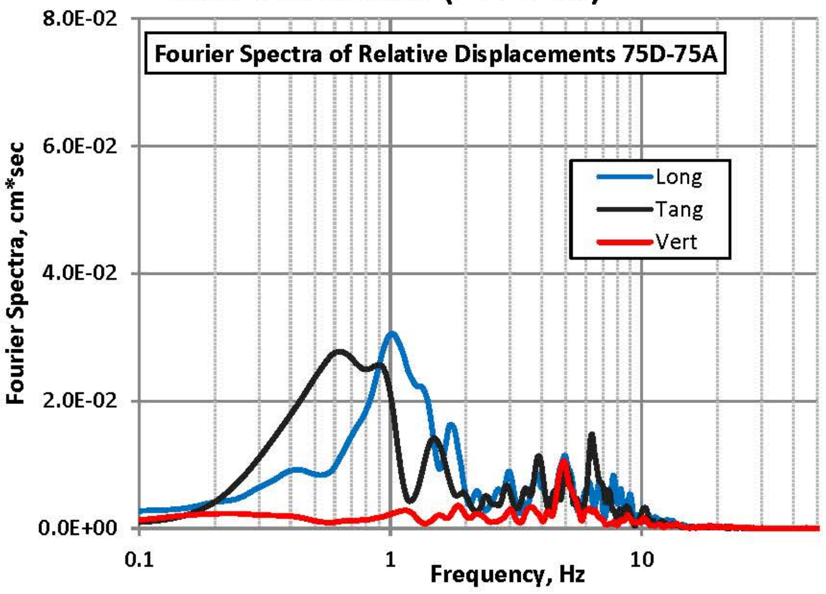
Fourier and Response Spectra of Relative Displacements

Fourier Spectra

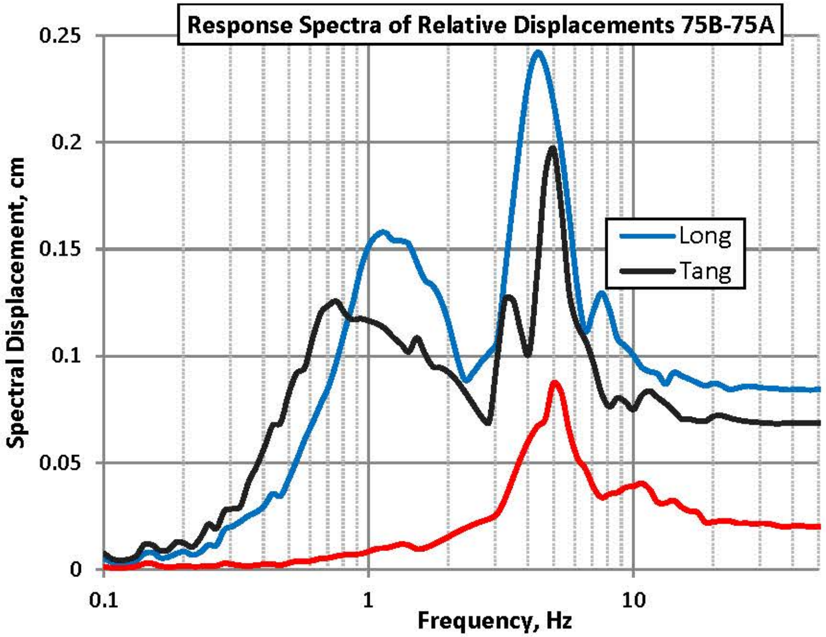
Base (El. 703 ft) and Floor (757 ft) in Containment

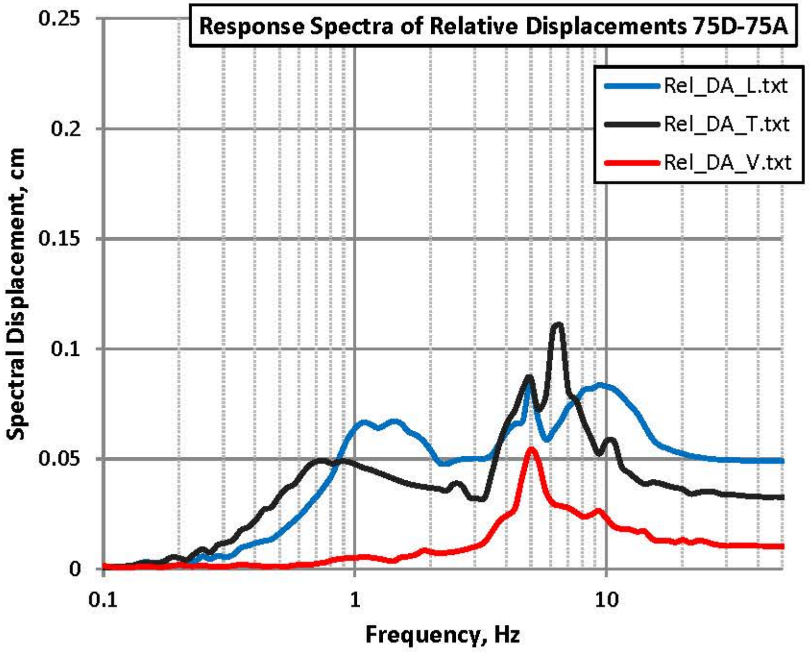


Base of Containment (El. 703 ft) and Diesel Generator (El. 742 ft)



5% damped Response Spectra





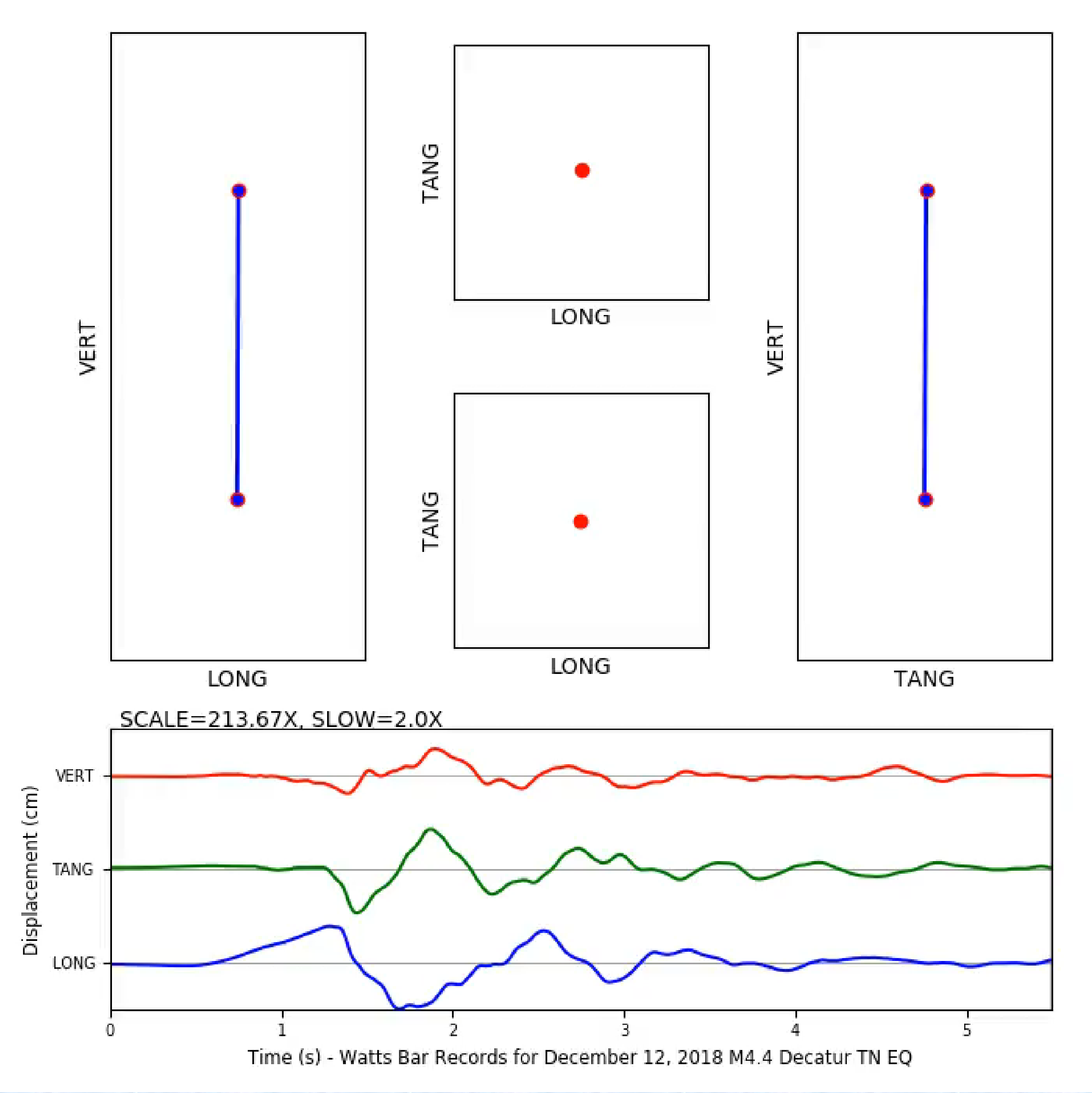
Observations Based on Relative Displacements

RDs between base and the higher elevation in the containment structure are higher than those of between the containment base and the diesel generator building. RDs between the two structures are in phase and have similar shapes.

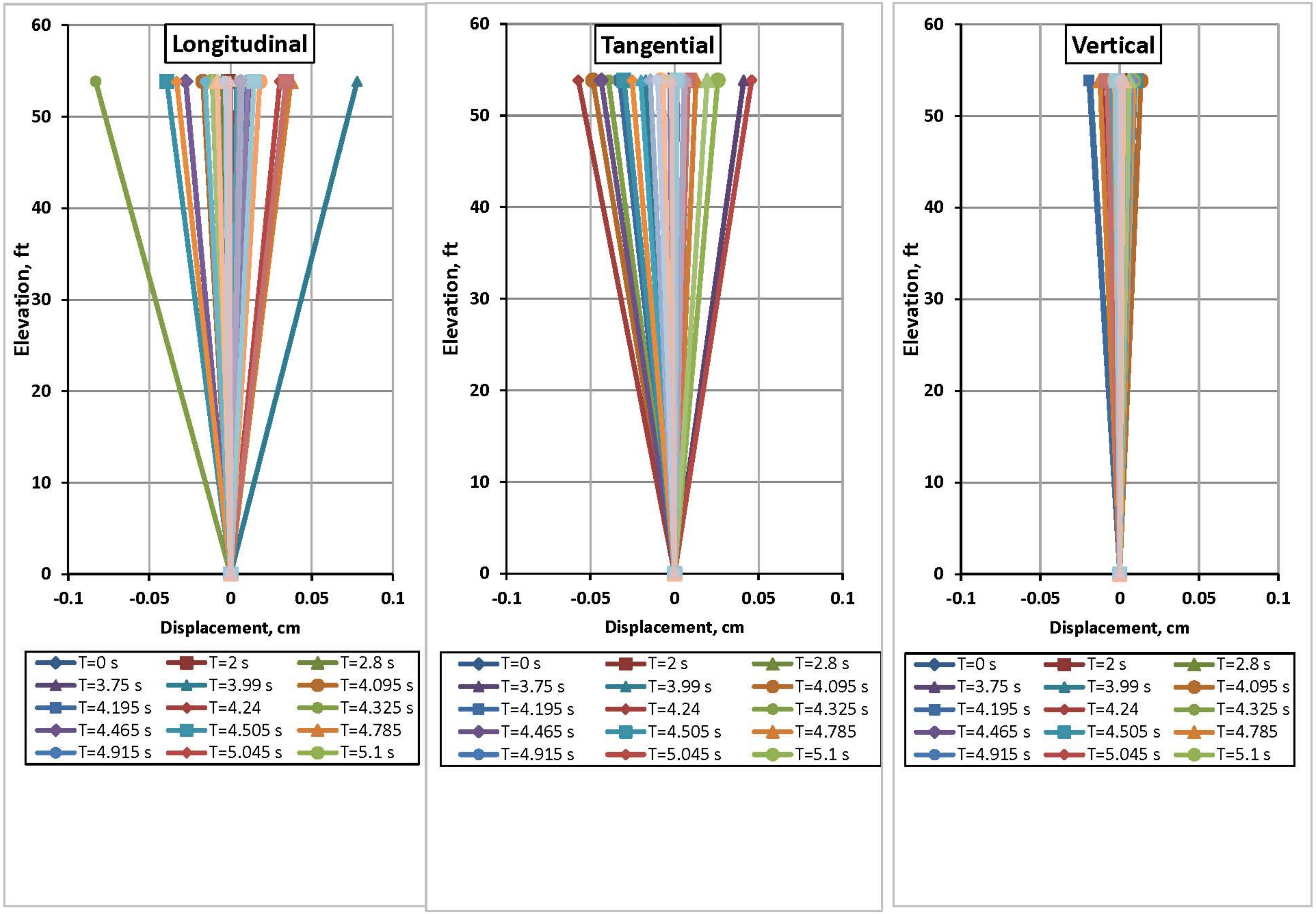
Vertical RDs between the reactor base and a higher elevation floor in the containment structure, as well as between the reactor base and the diesel generator building as expected, are a few times lower than the horizontals. Vertical RDs are similar in shape and predominantly only high-frequency 5 Hz motions.

Resonance frequencies observed in the longitudinal direction are at 1 and 4.5–5 Hz and at 0.6–0.7 and 5 Hz in the tangential direction. High-frequency peaks near 5 Hz can most likely be associated with the natural frequencies of the reactor building floor or internal structures whereas low-frequency peaks at 0.6–1 Hz can most likely be associated with a rocking motion of the containment building.

Animation of Relative Motion of Containment



Relative Displacements between Base (El. 703 ft) and Floor (757 ft) in Containment



Deformation

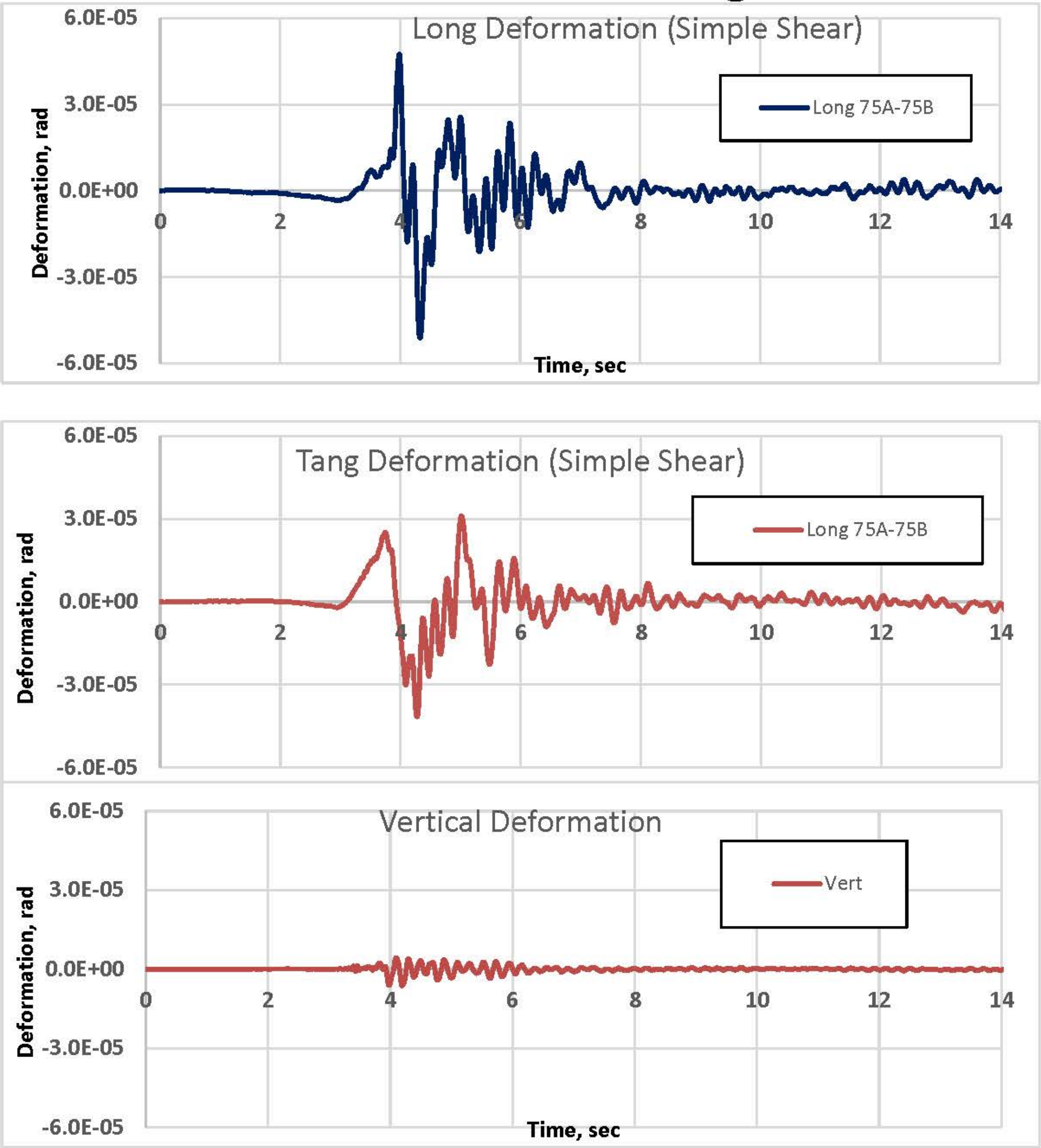
Deformation (simple shear) in the structure along the *x*-axis

$$\gamma(t) \approx \frac{x_n(t) - x_{n-1}(t)}{L}$$

where $x_n(t)$ *and* $x_{n-1}(t)$ are amplitudes of horizontal ground motions at the same time t at different elevations in the structure, and L is the distance between those elevations measurements (base).

Simple shear strain with the rate γ is the combination of pure shear strain with the rate γ/2 and rotation with the rate of α=γ/2.

Deformation in Reactor Bldg. between El. 703 and 757 ft



Maximum deformation:

- Longitudinal 5.12E-05
- Tangential 4.17E-05
- Vertical 6.28E-06

Lessons Learned

- **Availability of recordings helped making quick decision of ground motions non-exceeding OBE and no need of plant shutdown.**

- Availability of multiple synchronized seismic records allowed to identify structural resonances at 5 and 14 Hz within the containment and other important features of structural response.

- Setting up trigger level at 1% g, while RG 1.12 Rev.2 (1997) required not more than 2% g allowed to have clean and complete recordings not missing any key portions of the waveforms.

- Absence of a free-field recording limited the seismic analysis not allowing to calculate CAV and estimate some input motion parameters for direct comparison with ground motion models. Having more dense seismic instrumentation in the free-field and in structures as recommended by the RG 1.12 Rev. 3 (2017) can help with post-earthquake engineering analysis.

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