# Ground Motion R & D Program

*Fred Asiri*

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## Acknowledgements


- SLAC Accelerator Physics:
  - Andrei Seryi, Fredric Le Pimpec
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- Parsons/Geovision team:
  - Bruce Shelton, Paul MacCalden
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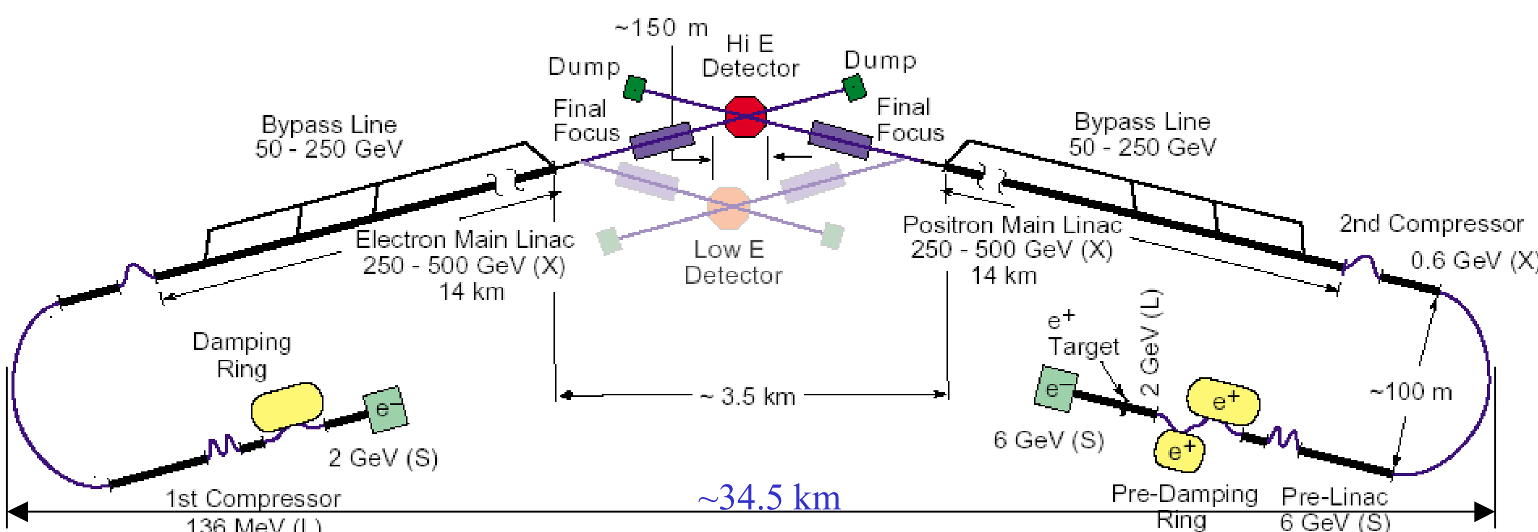
*All around us are material objects of many kinds, and it is quite difficult to move without shaking some of them more or less. If we walk about on the floor, it quivers a little under the fall of our feet; if we put down a cup on the table, we cannot avoid giving a small vibration to the table and the cup. If an animal walks in the forest, it must often shake the leaves or the twigs or the grass, and unless it walks softly with padded feet it shakes the ground. The motions may be very minute, far too small to see, but they are there nevertheless.*

*Sir William Bragg (1933), The World of Sound, p,1.*

## Goal

- To design, build and operate a facility with a footprint of about 35 km by one-half km wide including several buildings, some the size of a football field.
- *To operate the facility, it takes;*
  - several hundred mega watts of electricity to energize motion of one kind or another,
  - thousands of gallons of water per minute to keep it at a desirable temperature, and
  - hundreds of people to keep it running.



## Vibration stability requirements

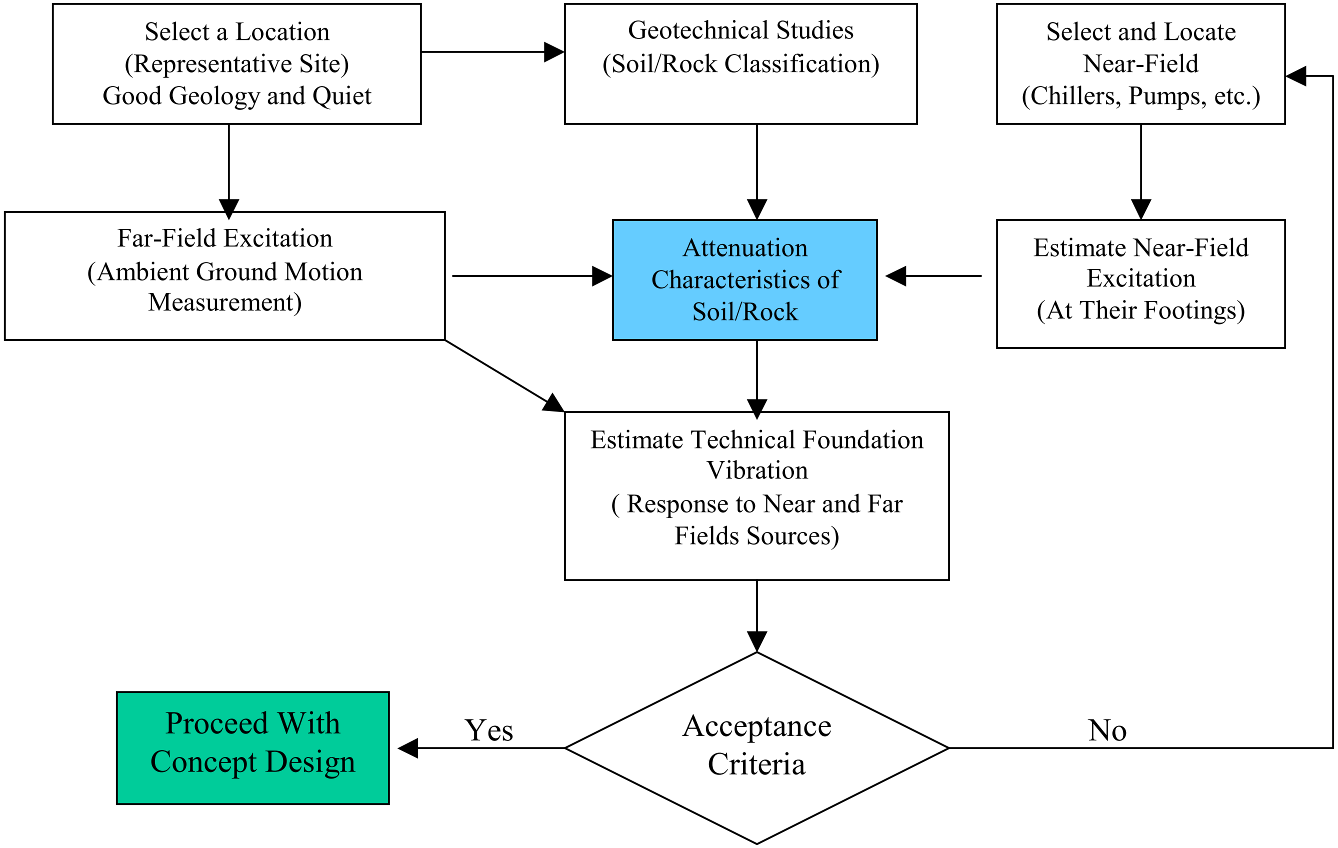
- To maintain the desired luminosity,
  - the focusing components of the main linac must control uncorrelated motions to within a few nanometers and a few Hz.
- Motion of these components are affected mainly by two sources;
  - far-field (external) sources, which are produced external to the facility, and
  - near-field (internal) sources, which are produced within the facility.

Below is an excerpt from MAC_Nov._Report:

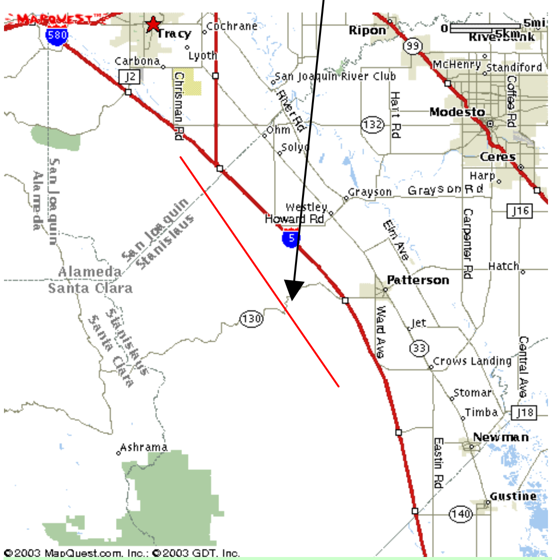
**4.1 Beam Dynamics, Ground Motion, and Stabilization Requirements**

These studies continue to yield important information concerning the viability of LC sites and the measures required to compensate for ground motion and vibration. *Measurements of noise transmission from the surface to the SLAC tunnel and between adjacent tunnels in the LA subway are an important step in developing tolerable noise level specifications for both the shallow and deep tunnel sites*

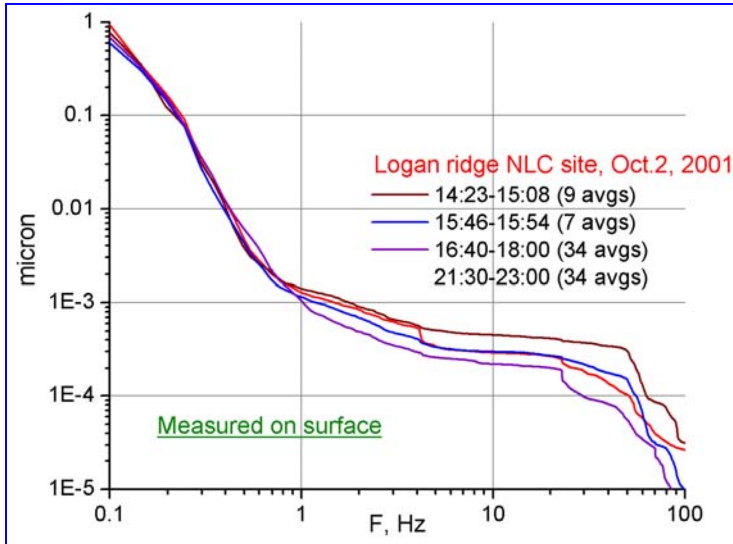
# How

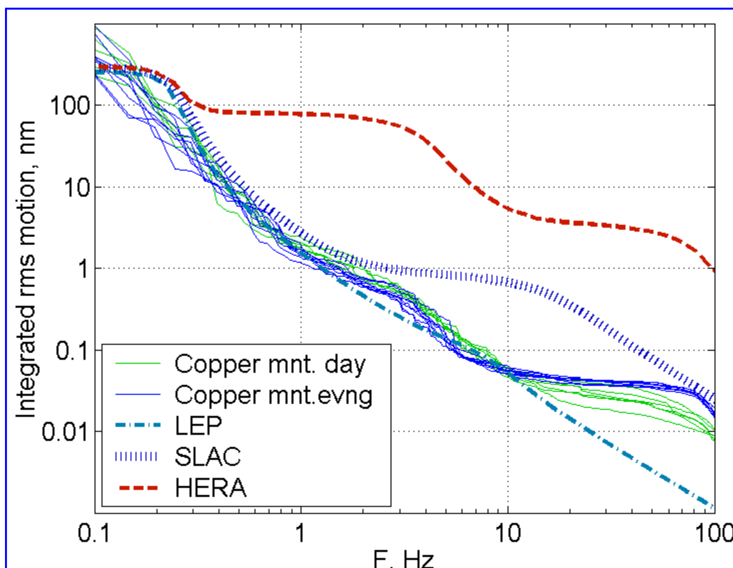


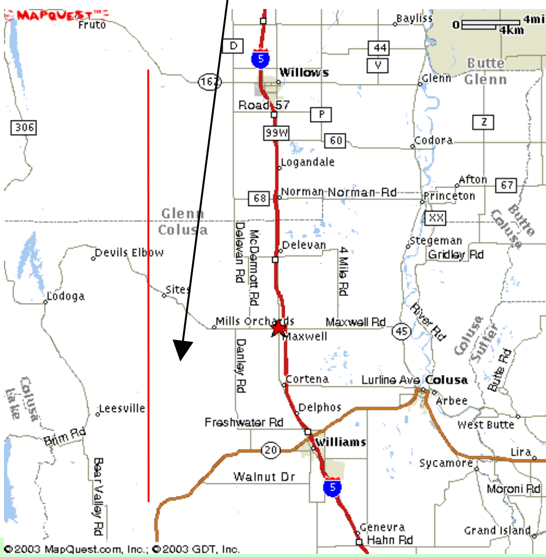

Technical Approach at pre-concept level



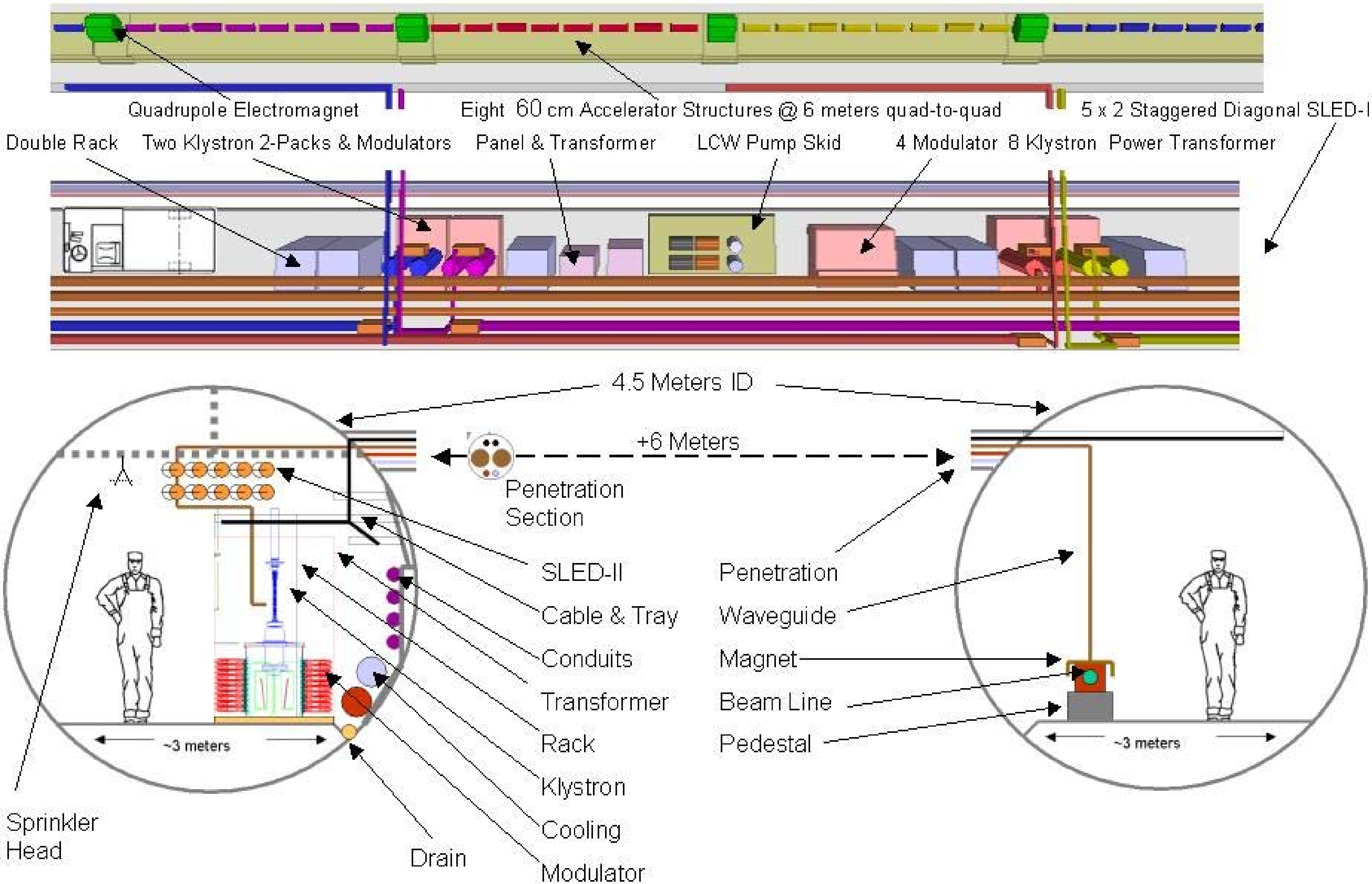

Sites are on suitable/stable geology for tunneling.



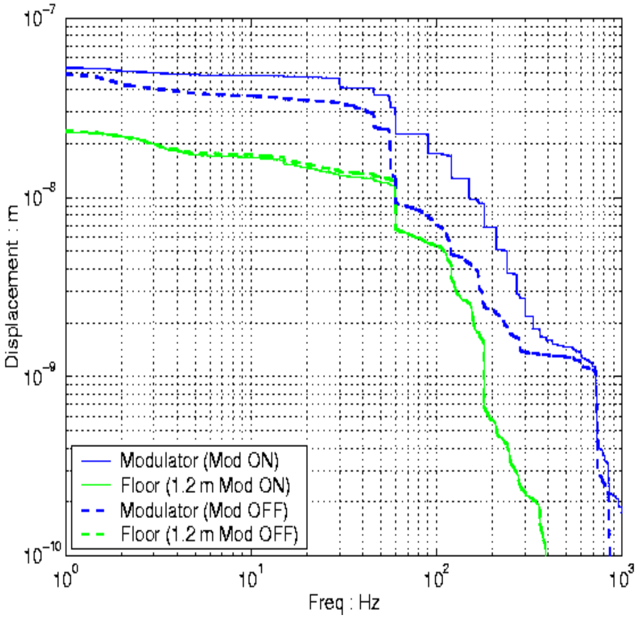



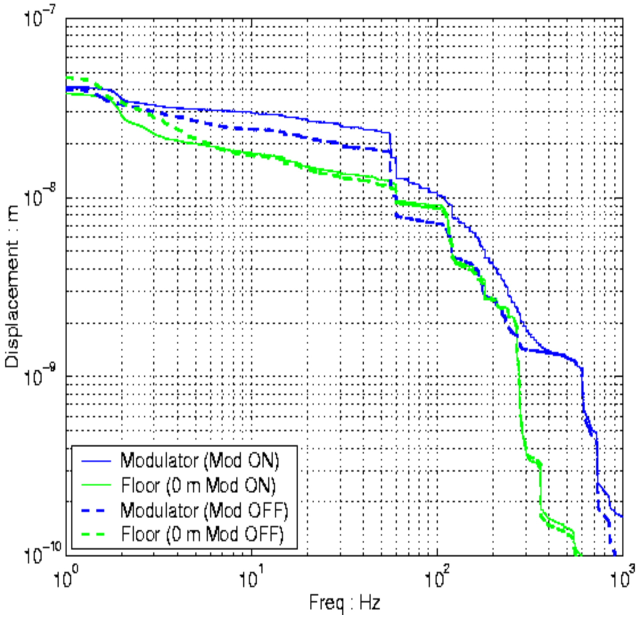



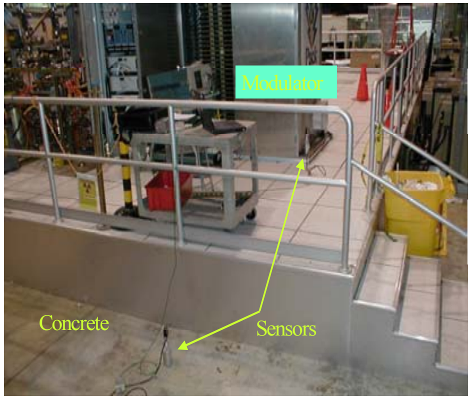

Sites are very quiet, with negligible contribution from cultural noise

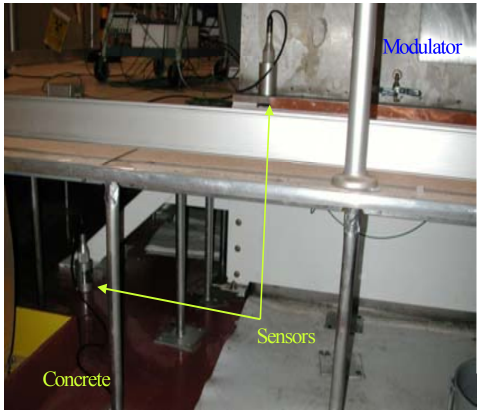

Quadrupole Electromagnet
Eight 60 cm Accelerator Structures @ 6 meters quad-to-quad
5 x 2 Staggered Diagonal SLED-II
Double Rack
Two Klystron 2-Packs & Modulators
Panel & Transformer
LCW Pump Skid
4 Modulator 8 Klystron Power Transformer
4.5 Meters ID
+6 Meters
Penetration
Section
SLED-II
Cable & Tray
Conduits
Transformer
Rack
Klystron
Cooling
Modulator
Penetration
Waveguide
Magnet
Beam Line
Pedestal
~3 meters
~3 meters
Sprinkler
Head
Drain

# Klystron and Modulator Vibration Characterization




Location of the Geophones Sensors at the Base of the Modulator and on Concrete Slab at 8-Pack in ESB

## Conclusion:

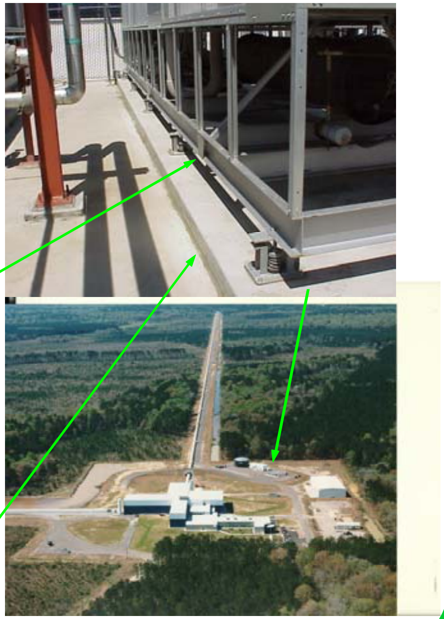
- Vibration transmitted by the RF generating equipment to the floor is nearly insignificant. *This could be because the floor background noise in the NLCTA was ~20 nm*.

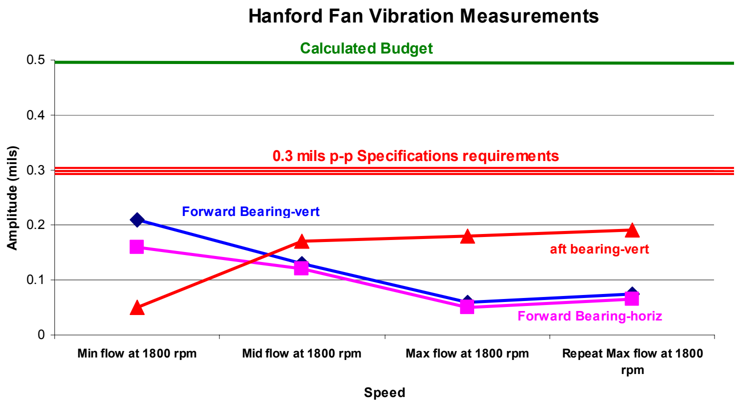
- The dominant sources of vibration are from electrical, rotating mechanical equipments, water flowing in pipes and people working in the area.

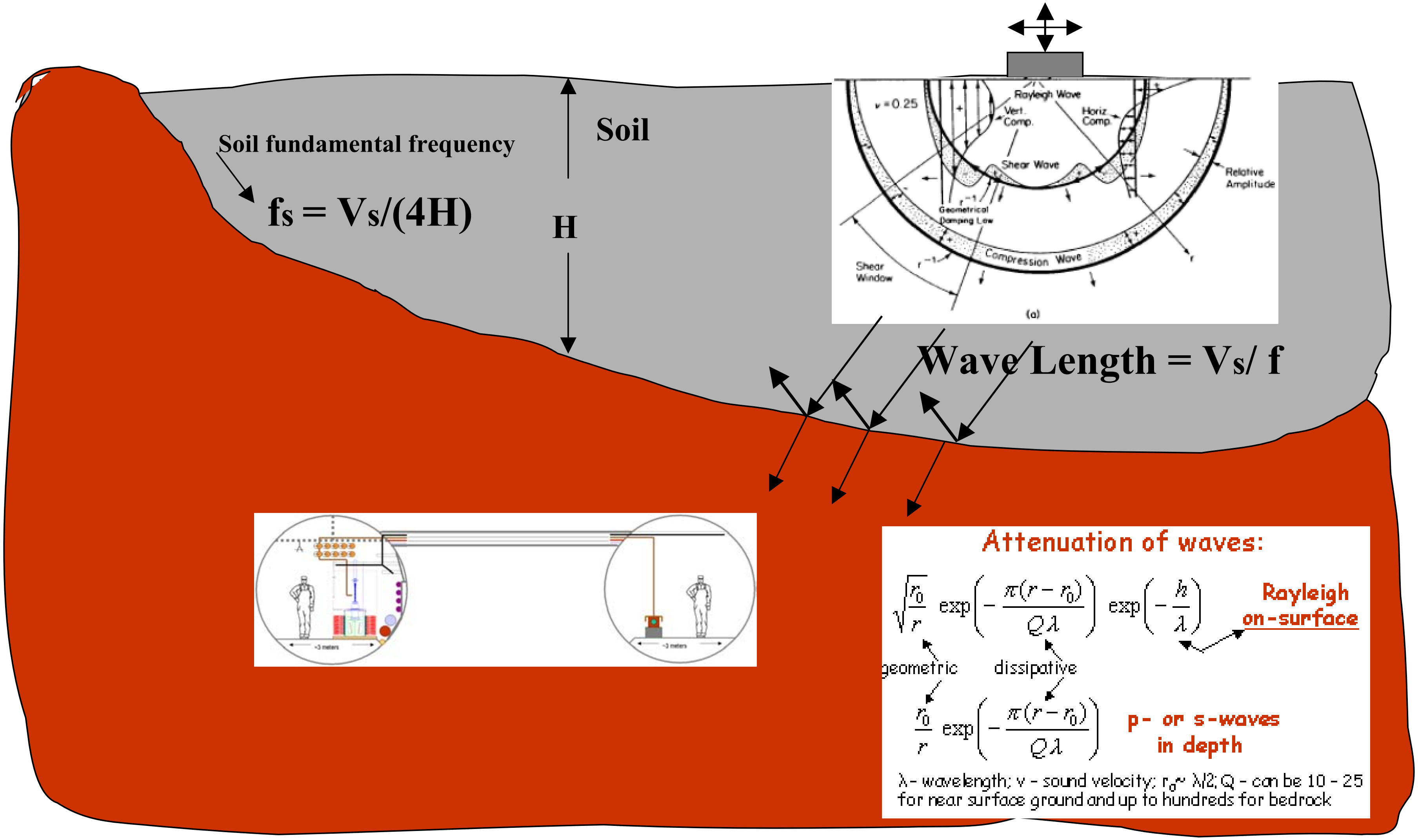
**Case in point: Assume a mechanical equipment pad similar to the LIGO**

- The speed of the rotating equipment is 3600 RPM (60 Hz).
- The mechanical equipment weighs about 21,400 pounds.
- A limit of 0.1 g is met at rotating equipment, thus the inertia force at the skid is about 2,140 lb (a minimum of 10% reduction).
- The mechanical equipment is mounted on a spring isolated skid. Generally, they have a natural frequency in the range of 4 Hz to 6 Hz which corresponds to a reduction factor of about 1%.

Thus, the transmitted dynamic force of the mechanical equipment at the top of equipment foundation is reduced by a factor of about 1,000.






Soil fundamental frequency
$f_s = V_s/(4H)$
Soil
H
$\nu = 0.25$
Rayleigh Wave
Vert. Comp.
Horiz. Comp.
Shear Wave
Relative Amplitude
Geometrical Damping Law
Compression Wave
Shear Window
(a)
Wave Length = $V_s/f$
~3 meters
~3 meters
Attenuation of waves:
$\sqrt{\frac{r_0}{r}}\exp\left(-\frac{\pi(r-r_0)}{Q\lambda}\right)\exp\left(-\frac{h}{\lambda}\right)$
Rayleigh on-surface
geometric
dissipative
$\frac{r_0}{r}\exp\left(-\frac{\pi(r-r_0)}{Q\lambda}\right)$
p- or s-waves in depth
λ - wavelength; v - sound velocity; $r_0 \sim \lambda/2$; Q - can be 10 - 25 for near surface ground and up to hundreds for bedrock

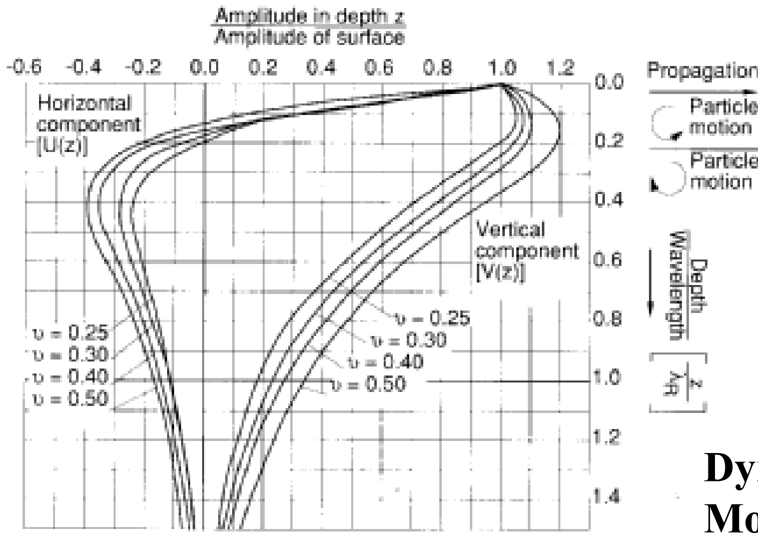
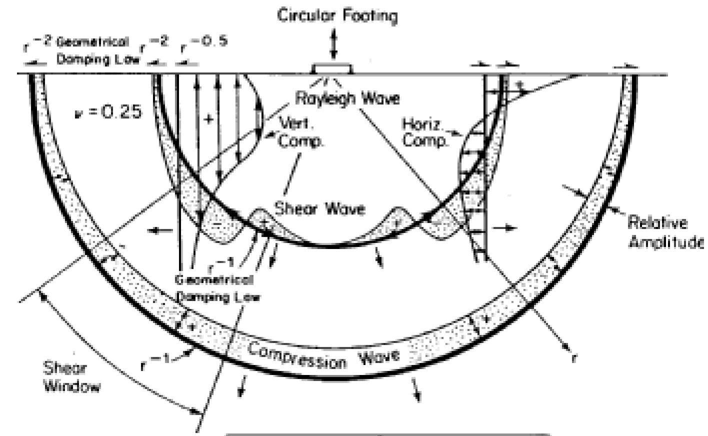



*Figure E.2: Relation between amplitude ratio and dimensionless depth for Rayleigh waves with ν as parameter*




| Wave Type | Per Cent of Total Energy |
|---|---|
| Rayleigh | 67 |
| Shear | 26 |
| Compression | 7 |

**Figure 3-16. Distribution of displacement waves from a circular footing on a homogeneous, isotropic, elastic half-space (*from* Woods, *1968*).**

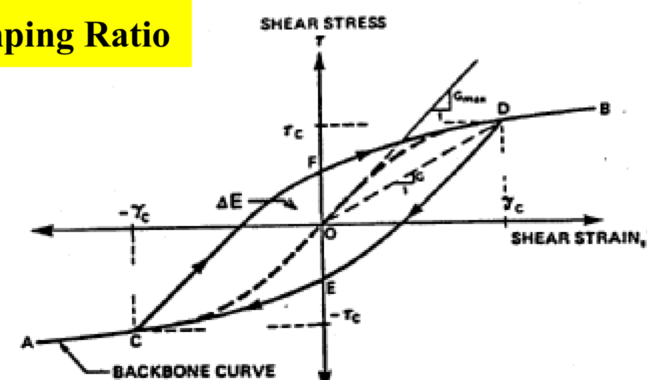
**Dynamic Shear Modulus:** $G = \dfrac{\tau_c}{\gamma_c}$

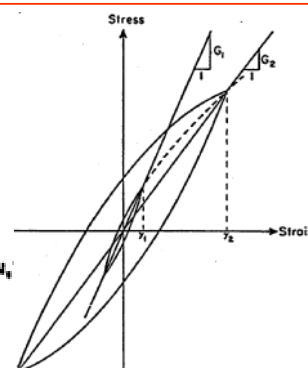
$$v_p = \sqrt{\frac{(\lambda + 2\mu)}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

$$v_S = \sqrt{\mu/\rho} = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{G/\rho}$$

*the higher the soil damping, The more slow motion results from fast vibration source*

**Soil Damping Ratio**



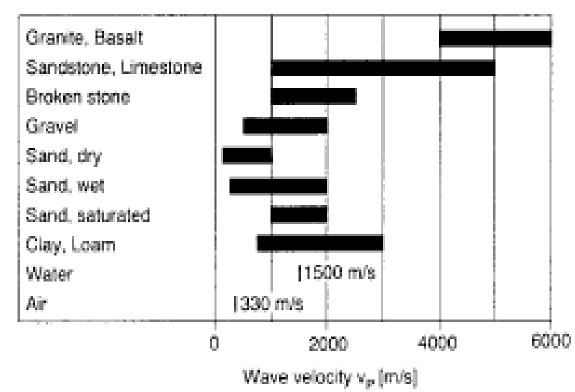



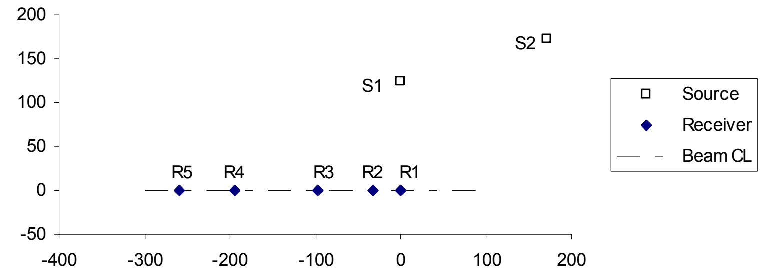

*Figure E.3: Typical velocities of compression waves (P-waves) for rocks and soils*

## Objectives:

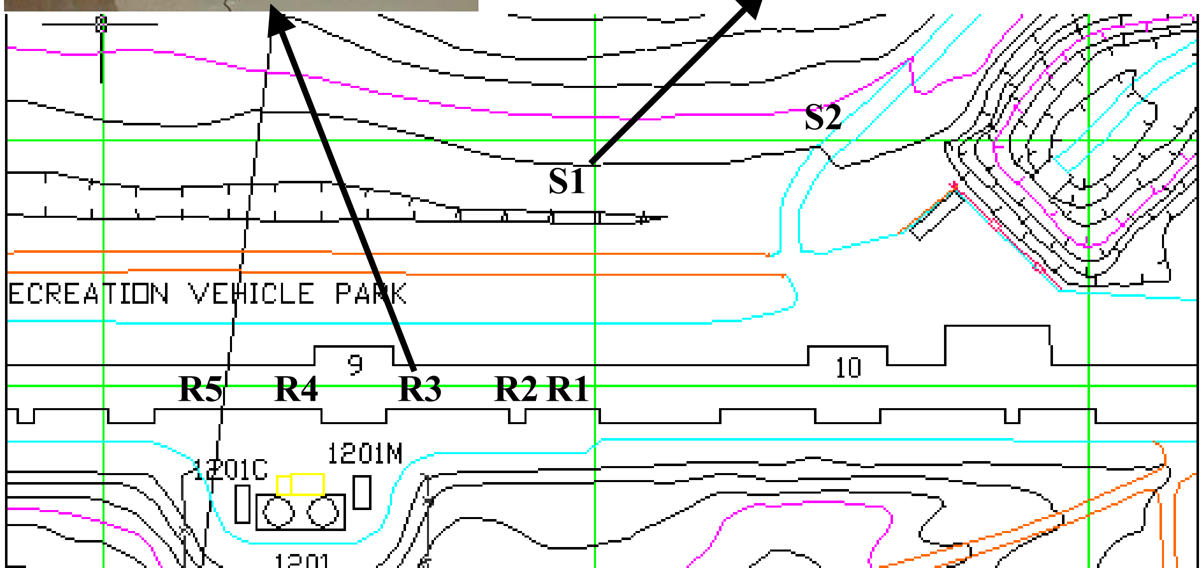
- To experimentally determine the vibration transmissibility in geological kinds similar to that at representative Next Linear Collider CA sites.
  - *Cretaceous sandstone with claystone (shear velocity > 760 m/sec)*

## Vibration transmissibility was measured at two locations:

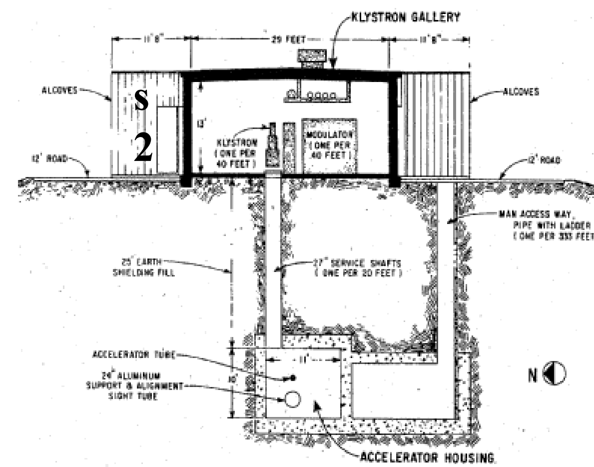
- At SLAC along Sector 9 and 10
  - *Eocene sandstone and claystone (shear velocity of ~720 m/se*
- At the Los Angeles County Metropolitan Transportation Authority (MTA) Red Line tunnels near the Universal City Station.
  - *Miocene sandstone and shale (shear velocity of ~950 m/sec)*




Location Plan View of Sources S# and Receptors R#

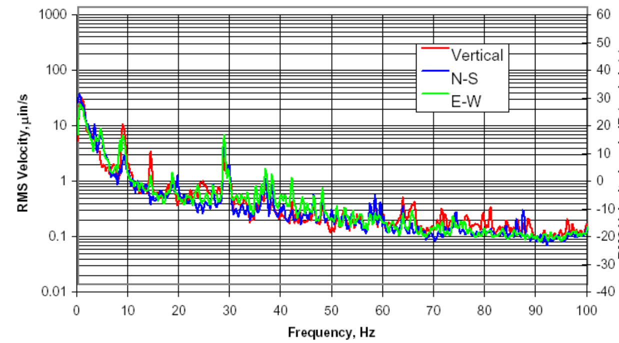



Plan Layout of Sector 9 and 10 at SLAC




Typical Cross Section of Accelerator Housing and Klystron Gallery at SLAC

| Source | Receiver | Distance, ft | Attenuation at Given Frequency | | | |
|---|---|---|---|---|---|---|
| | | | 10 Hz | 20 Hz | 30 Hz | 60 Hz |
| S1 | R1 | 130 | 0.014 | 0.0084 | 0.012 | 0.005 |
| | R2 | 134 | 0.012 | 0.012 | 0.014 | 0.004 |
| | R3 | 162 | 0.011 | 0.0084 | 0.006 | 0.001 |
| | R4 | 233 | 0.010 | 0.004 | 0.002 | 0.001 |
| | R5 | 289 | 0.005 | 0.002 | 0.0009 | 0.0003 |

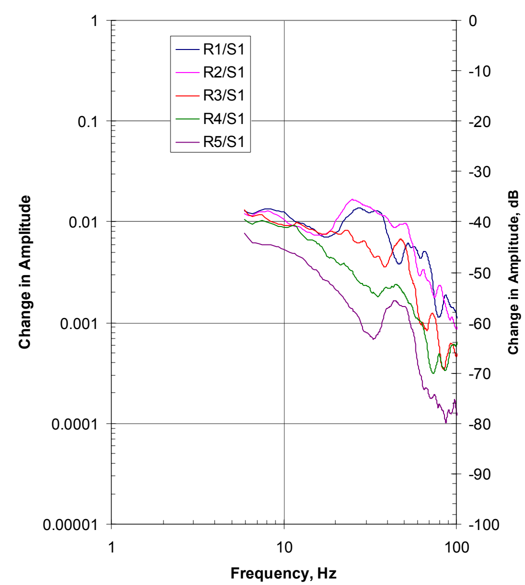



**Ambient Vibration at Receiver Location R5**

**The figures in the above table represent the attenuation Factor for a vibration with its source near S1 propagating along the same path.**

**Example 1: Suppose a pump is installed at S1, and it produces a vibration at 60 Hz with an amplitude of X.**
**The amplitude at 60 Hz that we measure at R5 would be the greater of either ambient or 0.0003X.**

**Example2: If we want to place a pump at S1 and not to exceed ambient at R5 (0.6μ in/sec), then we need to impose a limit on the resulting vibration at S1 of 0.6/0.0003=0.002 in /sec.**



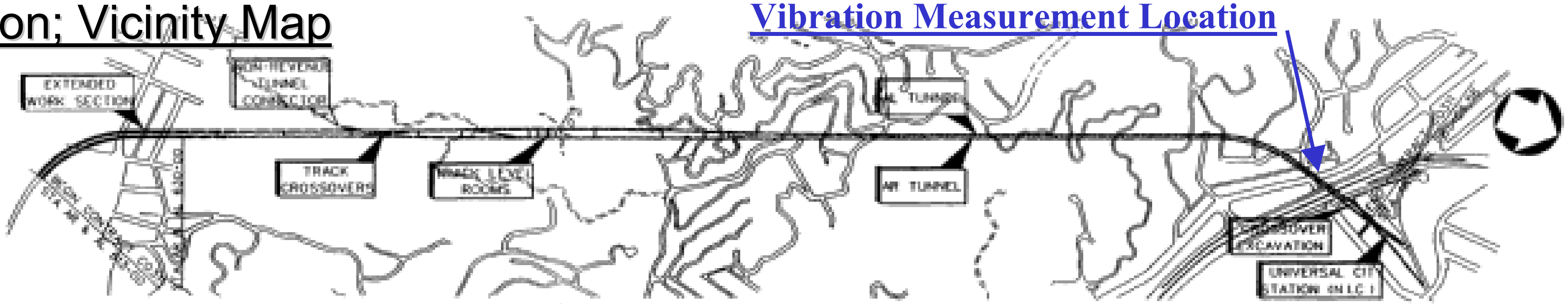

Log Mean Transmission From Drive Point S!

# Vibration Measurements in the MTA Tunnels

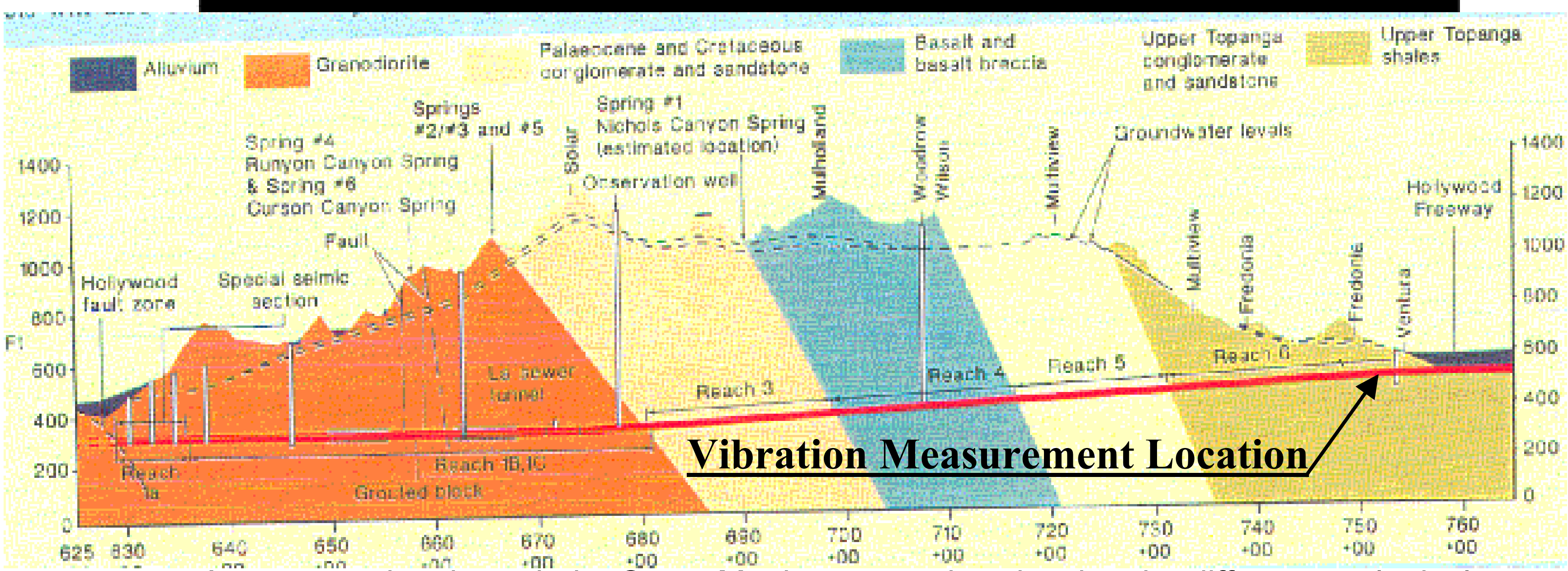
- Retained Services of the Parsons/Geovision team to perform these vibration measurements.
  - Parsons/Geovision team brought decades of vibration measurement, analysis, design and implementation experience.
  - Their most resent experience were with NIF and LIGO projects.
- Performed the following five (5) tests:

1. Ambient (traffic) source, measurements in both Tunnel A and on surface above
2. Source on surface, measurements near source and in Tunnel A below source
3. Source in Tunnel A, measurements along Tunnel A
4. Source in Tunnel A, measurements in both Tunnels A and B
5. Train source, measurements in Tunnel (cross-passage between A and B) and on surface above

Location; Vicinity Map

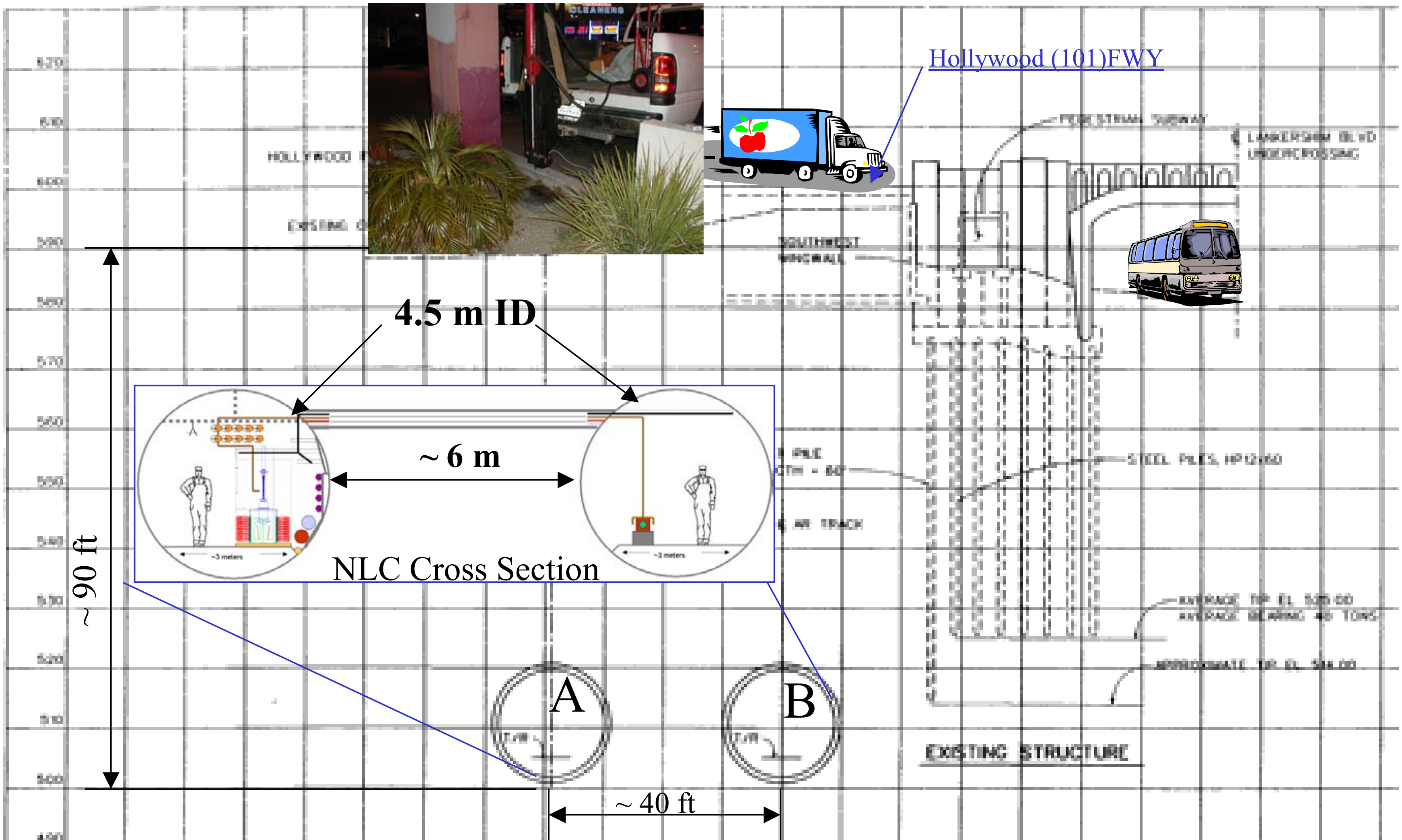



## METRO RED LINE PROJECT




A cross-section through the Santa Monica mountains showing the different geological conditions.

# Typical Cross-Section of the MTA Tunnels



Entrance to MTA Universal City Station looking south


Looking south at corner of Ventura Blvd and Lankershim Blvd.


Dry run at Universal City Station at 11 PM (5/11/03)

Testing of the vibration source and measuring the ambient

## Measurements along the Tunnel - 11 May 03

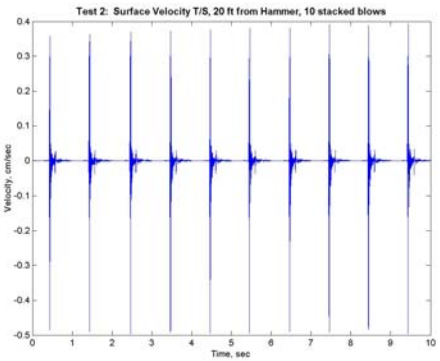
- Digital recorders (Geometrics “Geode” and Kinematrics SSR)
- Vertical 1-Hz Seismometers (Kinemetrics SS-1 and Geospace GS-1)
- Vertical 10-Hz Seismometers (Geospace GS-20DM)
- Accelerated weight (200 lb)drop seismic source, mounted on back of pickup
- Vertical accelerometer on drop weight to measure force impulse

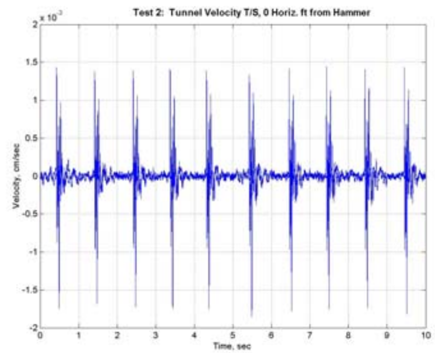
Typical receivers set-up
Geophone & Accelerometer

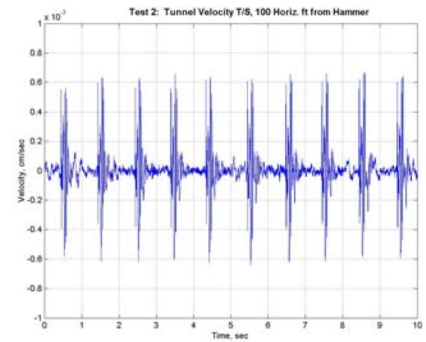
Set-up of recording instrument at the source location

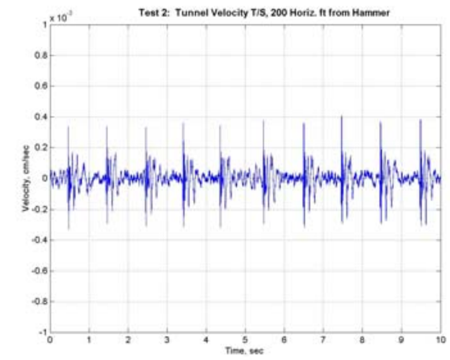
Vibration test measurements in progress in tunnel “A”

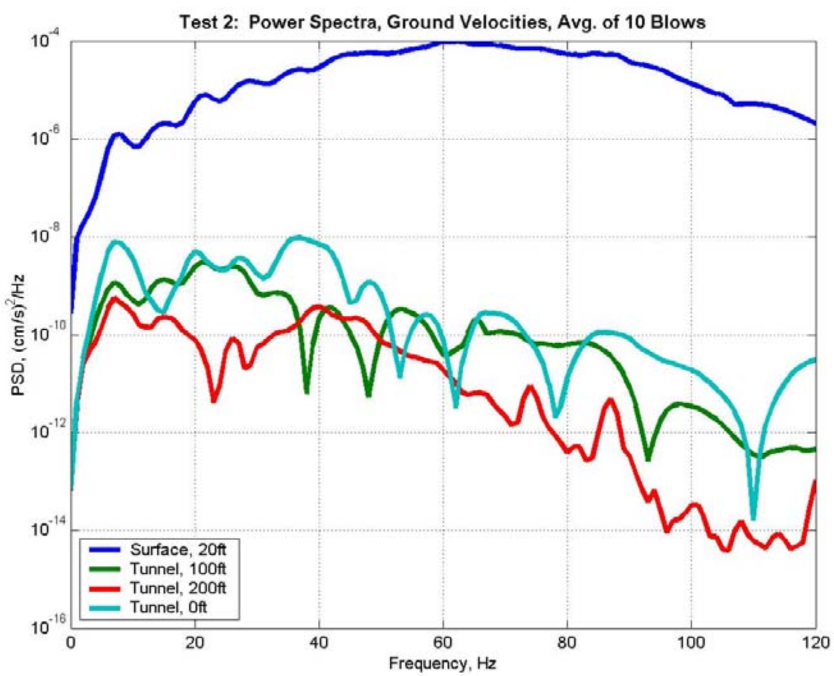
# Test 2: Controlled Source at Surface

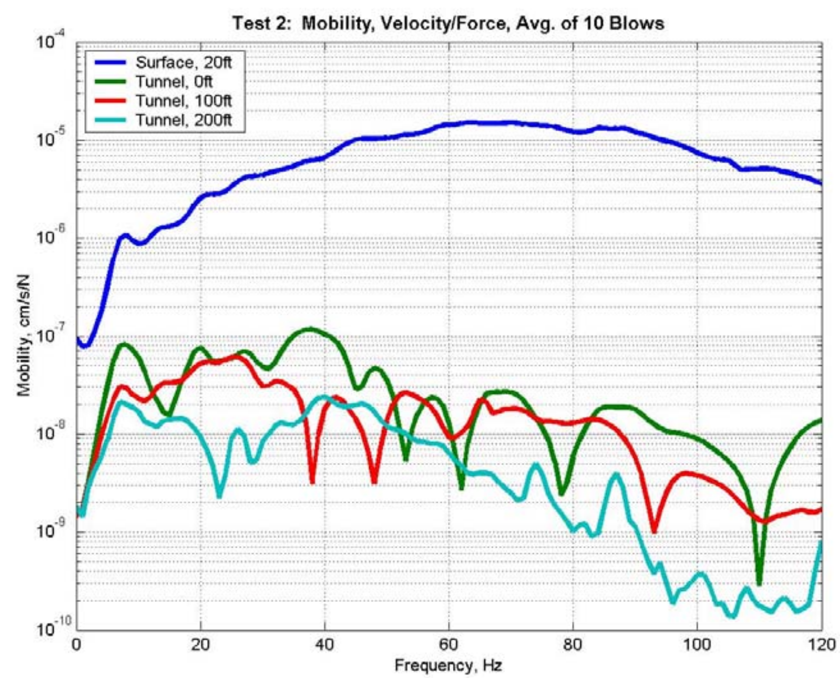


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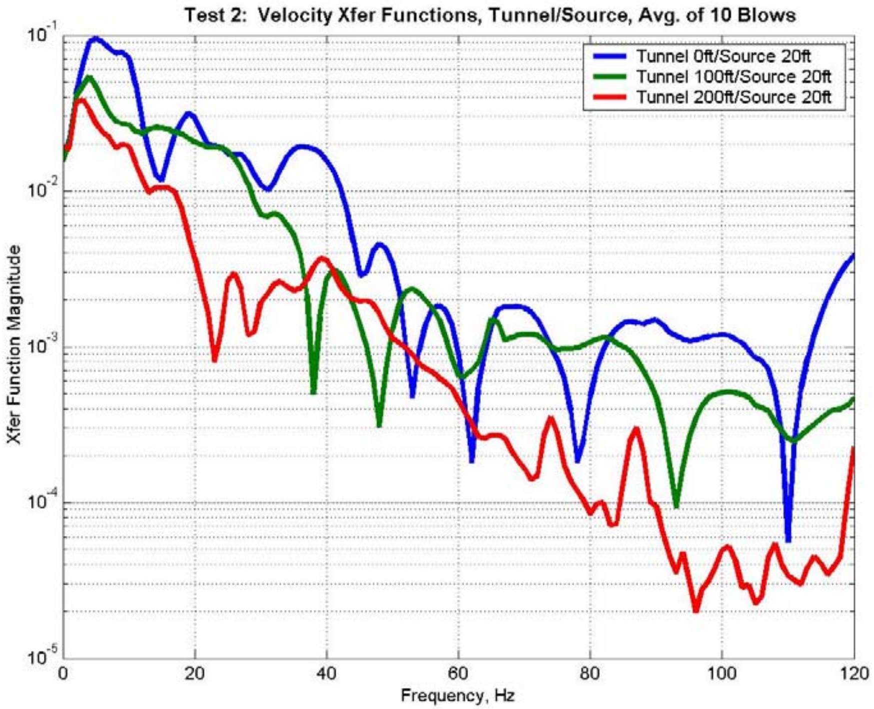
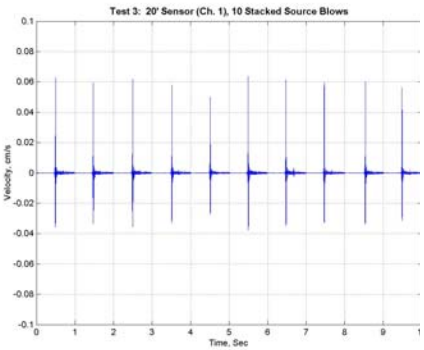


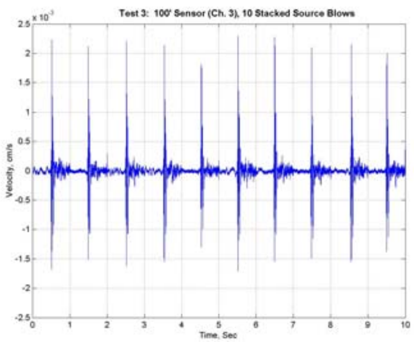

| Receiver Location | Path Length [Feet] | Attenuation/ XFER Magnitude | | | |
|---|---|---|---|---|---|
| | | 10 Hz | 20 Hz | 30 Hz | 60 Hz |
| Tunnel A- 0 ft | 87 | 0.0800 | 0.0300 | 0.0110 | 0.0009 |
| Tunnel A-100 ft | 133 | 0.0275 | 0.0210 | 0.0070 | 0.0006 |
| Tunnel A- 200 ft | 219 | 0.0200 | 0.0040 | 0.0020 | 0.0004 |

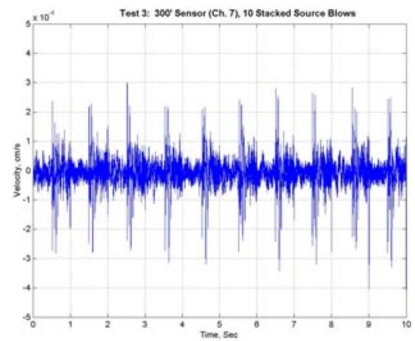
## Results:

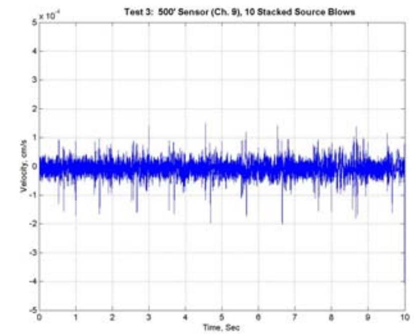
- Coherence between surface and tunnel low due to unsynchronized recordings
- Signal quality is good for the 1-Hz seismometers, suggesting that data can be useful in estimating tunnel motions from a surface source
- Transfer functions (tunnel/surface) show attenuation vs. frequency
- Mobility (velocity/force) useful for estimating future tunnel vibrations from known surface sources

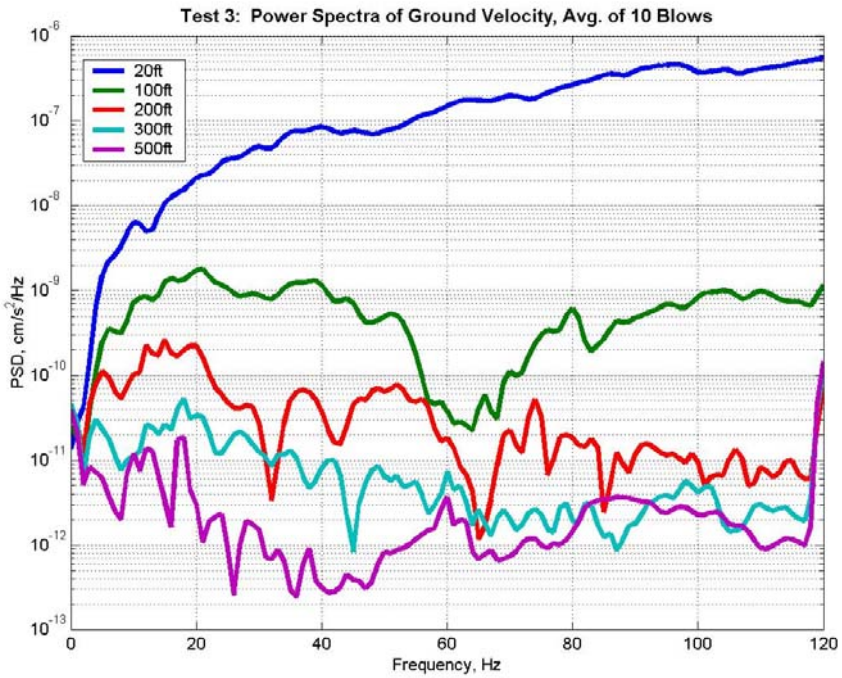
# Test 3: Controlled Source in Tunnel A, Measurements Along Tunnel A

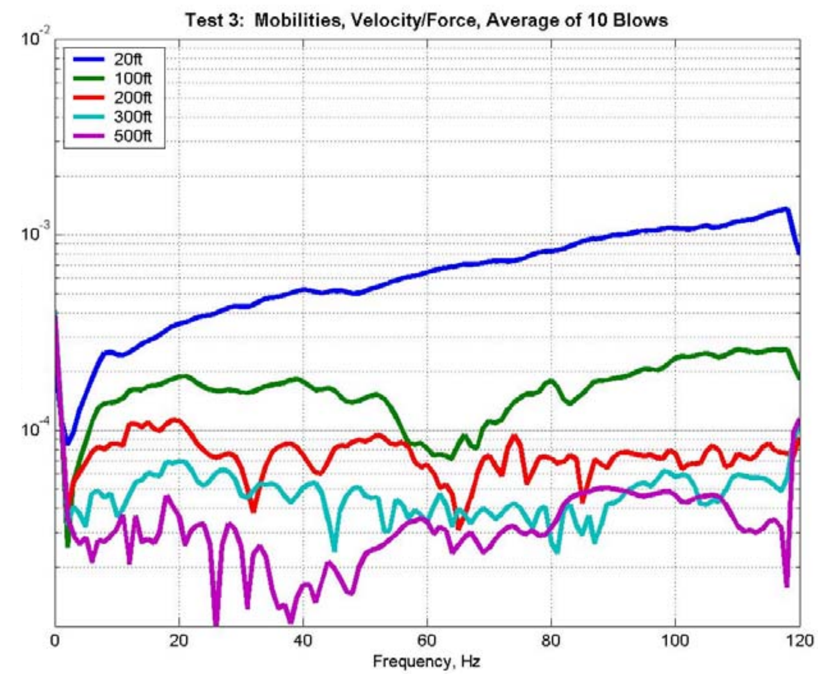


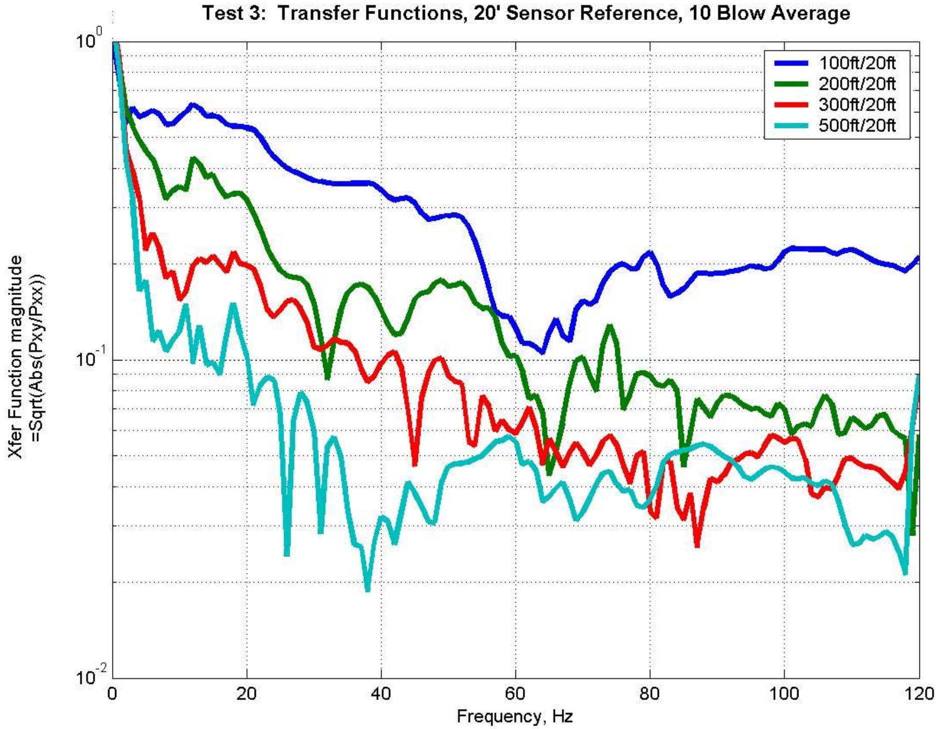





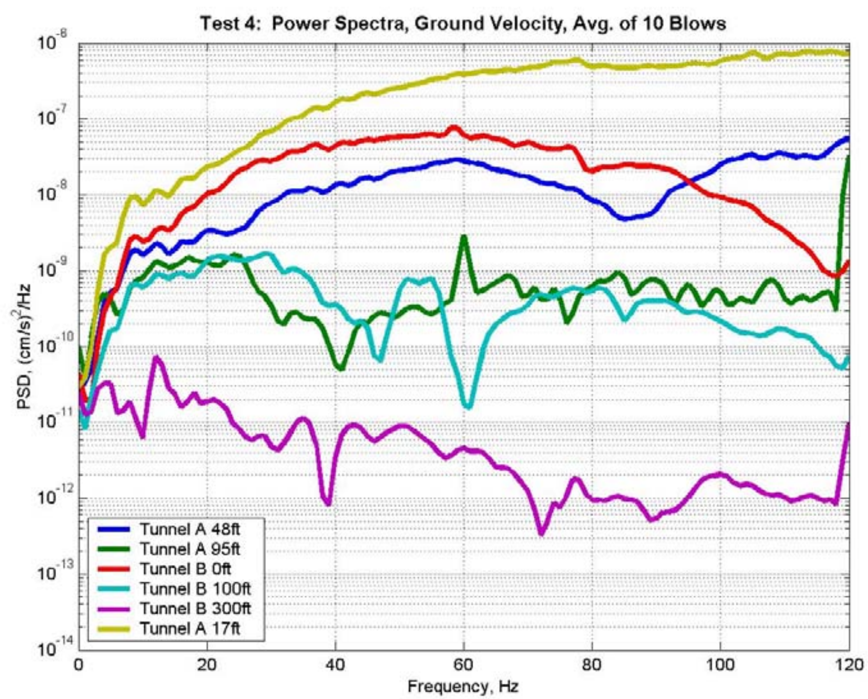

| Receiver Location | Path Length [Feet] | Attenuation/ XFER Magnitude | | | |
|---|---|---|---|---|---|
| | | 10 Hz | 20 Hz | 30 Hz | 60 Hz |
| Tunnel A- 100 ft | 100 | 0.600 | 0.5300 | 0.380 | 0.130 |
| Tunnel A-200 ft | 200 | 0.300 | 0.320 | 0.175 | 0.100 |
| Tunnel A- 300 ft | 300 | 0.160 | 0.200 | 0.120 | 0.060 |
| Tunnel A-500 ft | 500 | 0.140 | 0.100 | 0.060 | 0.048 |

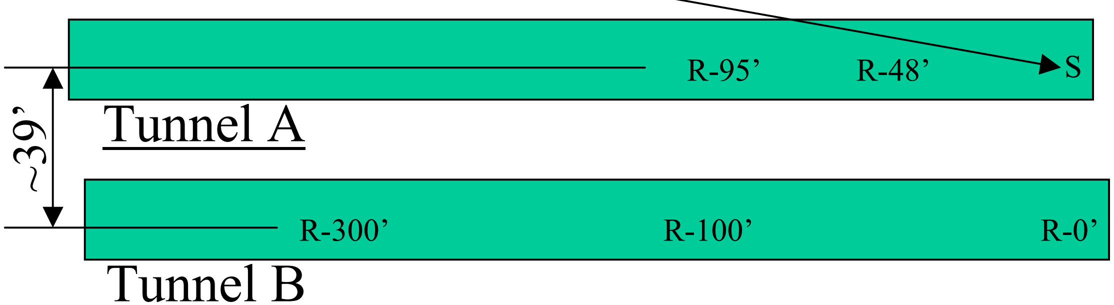
## Test 3- Results:

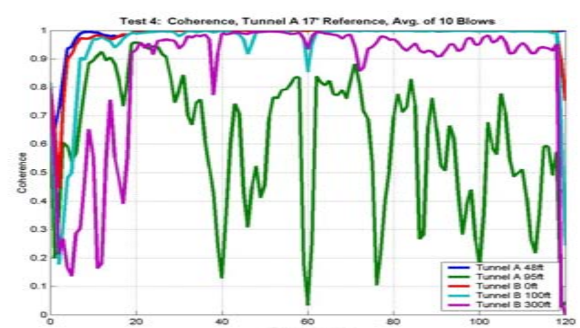
- Coherence between sensors is high
- Signal quality is good for the 1-Hz seismometers, suggesting that data can be useful in estimating tunnel motions from a tunnel source
- Transfer functions (velocity/reference velocity at 20') show attenuation vs. frequency
- Mobility (velocity/force) can be used to estimate vibration from a known source force

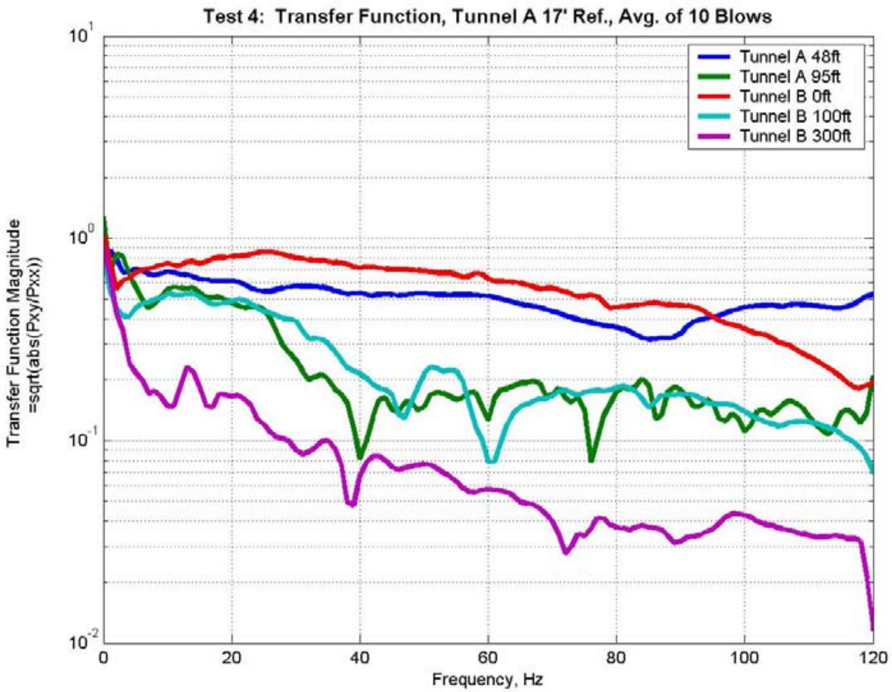
# Test 4: Controlled Source in Tunnel A, Measurements in Tunnels A & B

- Measurements on May 13 morning
- Simultaneous in-tunnel vibration measurements
  - (Tunnel A: 17’, 48’, and 95’ horizontally from source;
  - Tunnel B: 0’, 100’, and 300’ along tunnel from source projection
- 10 Source blows stacked and averaged



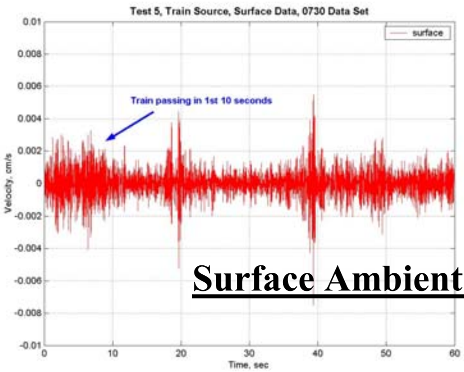



| Receiver Location | Path Length [Feet] | Attenuation/ XFER Magnitude | | | |
|---|---|---|---|---|---|
| | | 10 Hz | 20 Hz | 30 Hz | 60 Hz |
| Tunnel A- 48 ft | 48 | 0.70 | 0.60 | 0.60 | 0.50 |
| Tunnel A-95 ft | 95 | 0.6 | 0.40 | 0.25 | 0.15 |
| Tunnel B- 0 ft | 39 | 0.75 | 0.80 | 0.80 | 0.60 |
| Tunnel B-100 ft | 107 | 0.50 | 0.50 | 0.40 | 0.08 |
| Tunnel B-300 ft | 303 | 0.15 | 0.17 | 0.10 | 0.058 |

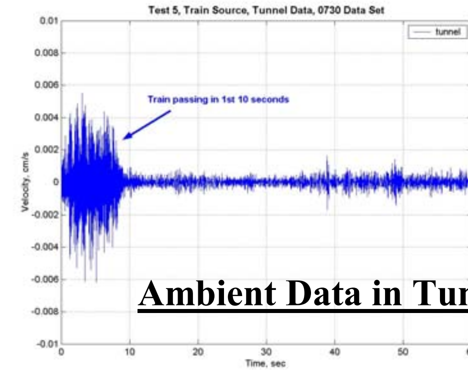
## Test 4-Results:

- Signal quality is good for the 1-Hz seismometers, suggesting that data can be useful in estimating tunnel motions from a tunnel source
- Transfer functions (velocity/reference velocity at 17') show attenuation vs. frequency
- Mobility not measured due to failure of source accelerometer
- Attenuation between the tunnels is rather low, and not more than 0.5 to 0.7 for across the tunnel

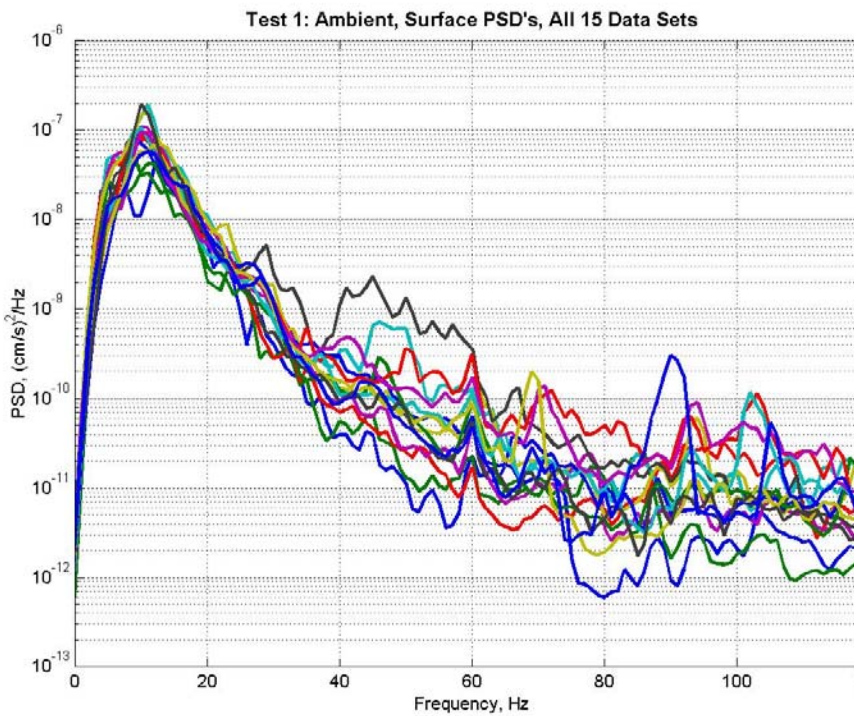
# Test 1: Ambient (traffic) source



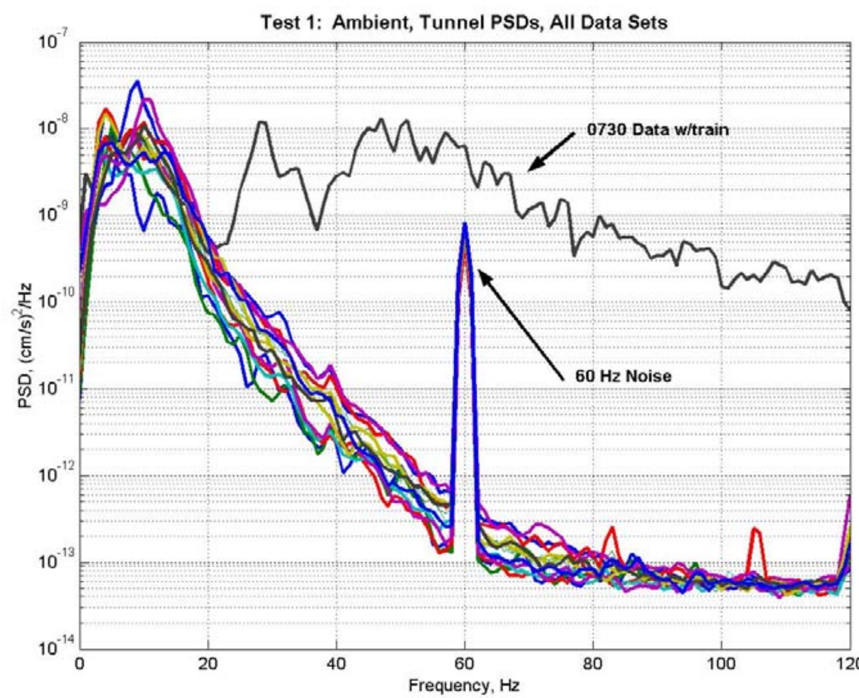

**Surface Ambient Data**




**Ambient Data in Tunnel-A**




**Measured Surface Power Spectra**

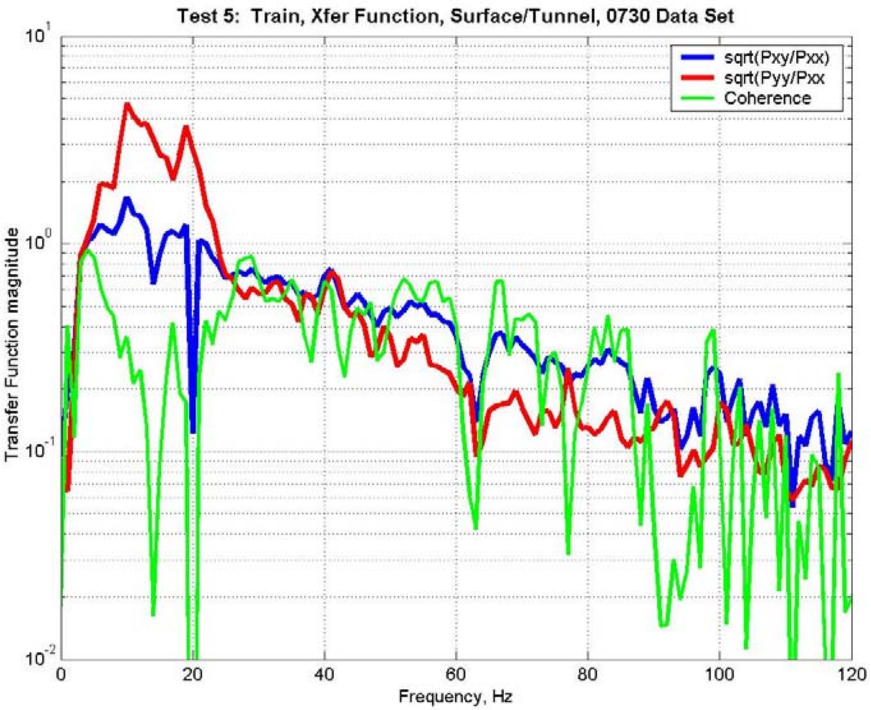



**Measured Tunnel Power Spectra**

# Test 5:Train as Vibration Source (same measurements as Test 1)

## Results:

- Only one train passing recorded by both surface and tunnel
- Train vibrations are similar in magnitude to freeway traffic at surface, but well above ambient in the tunnel
- Transfer functions (surface/tunnel) show attenuation of upgoing energy vs. frequency
- Strong site amplification observed at ~10-20 Hz, probably due to a weathered rock layer




Transfer Function, Surface/Tunnel

- Coherence is moderate, suggesting a partial input-output relationship with the train as input
- These results should be applied with care, with the limitations (only one train, moderate coherence, possible site response) these data only generally define the attenuation for an in-tunnel source

# Comparison of Vibration Measurement Results

MTA Tunnel Vibration Measurements

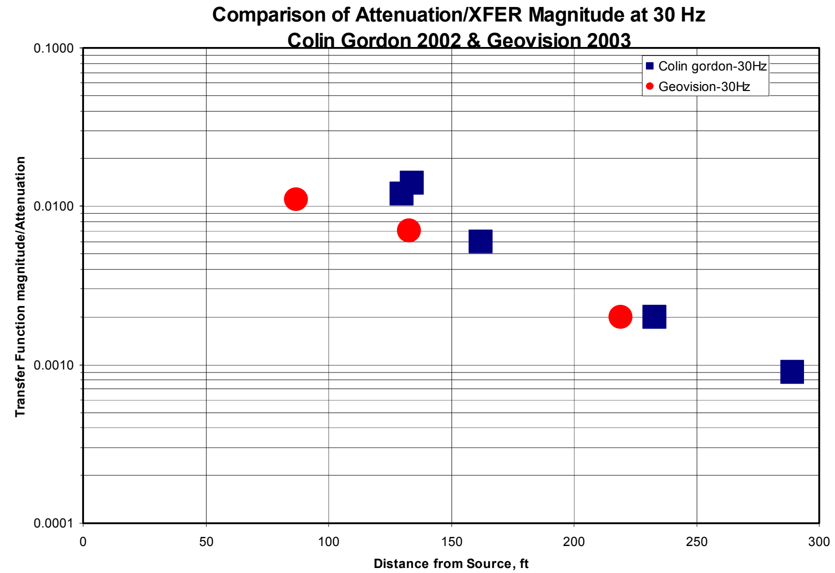
Comparison of Geovision & Colin Gordon Results

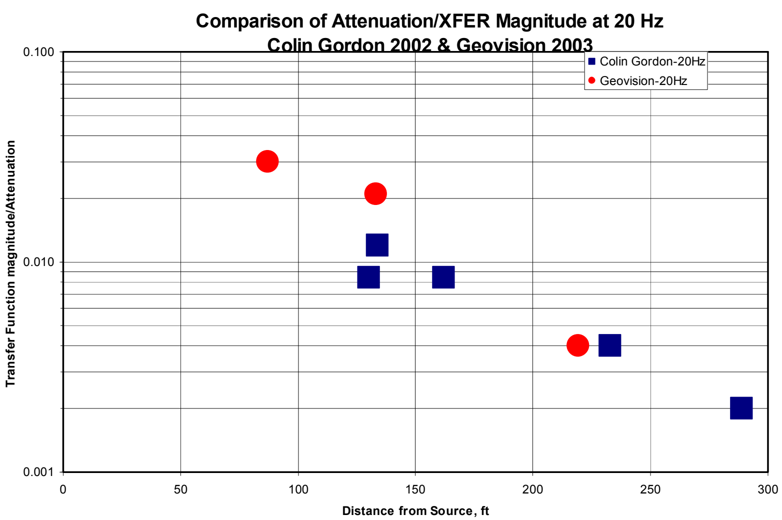
**Attenuation, Tunnel Receiver/Surface Source**

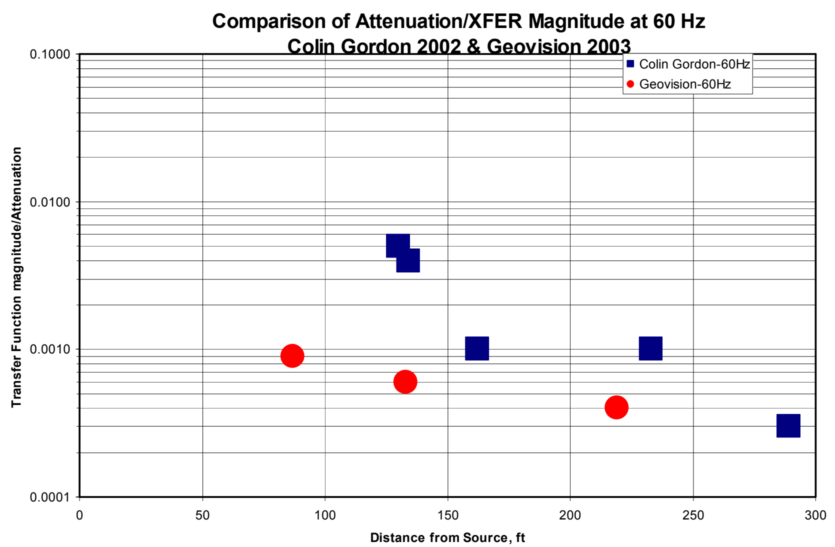
*Colin Gordon Data from Page 6 of 7 August 2002 Report (S1 Data)*

*Geovision Data from Test 2 Transfer Functions*

| | | Attenuation/XFER Magnitude | | |
|---|---|---|---|---|
| **Data Source** | **Path Length, ft** | **20 Hz** | **30 Hz** | **60 Hz** |
| **Colin Gordon** | **130** | **0.0084** | **0.0120** | **0.0050** |
| **8/2002** | **134** | **0.0120** | **0.0140** | **0.0040** |
| | **162** | **0.0084** | **0.0060** | **0.0010** |
| | **233** | **0.0040** | **0.0020** | **0.0010** |
| | **289** | **0.0020** | **0.0009** | **0.0003** |
| **Geovision** | **87** | **0.0300** | **0.0110** | **0.0009** |
| **6/2003** | **133** | **0.0210** | **0.0070** | **0.0006** |
| | **219** | **0.0040** | **0.0020** | **0.0004** |



**Proposal:** **(In collaboration with Nick Simos of BNL )**

• to utilize an integrated procedure used for 3-D modeling and dynamic soil analysis of Fault-Soil-Structure interaction.

• to generate ground motion and spatial distribution of soil properties using spectral representation based procedure.

• to assess the response of technical foundation from near and far field sources.