THE 55TH TERZAGHI LECTURE

RESPONSE OF SOIL SITES DURING EARTHQUAKES A 60-YEAR PERSPECTIVE

by

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KARL VON TERZAGHI (1883 –1963)

Father of Soil Mechanics

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TOPICS FOR TODAY

1. ***Why site response***
2. ***Recorded earthquake ground motion data***
3. ***Comparison with empirical earthquake ground motion models (GMMs) & need for analytical approaches***
4. ***Historical perspective***
5. ***Currently available analytical procedures***
6. ***Concluding Remarks/Recommendations***

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TOPIC 1

WHY SITE RESPONSE

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The New East Span of the San Francisco Oakland Bay Bridge

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Nuclear Plant in California

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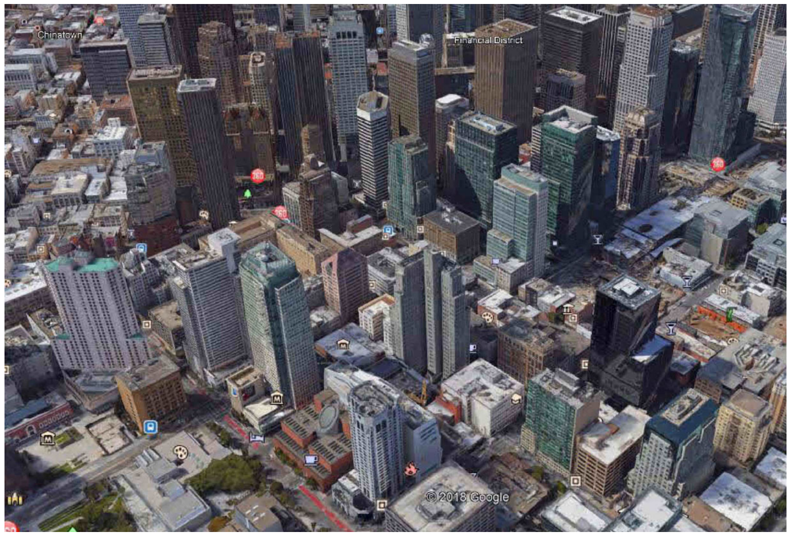

Portion of Downtown San Francisco

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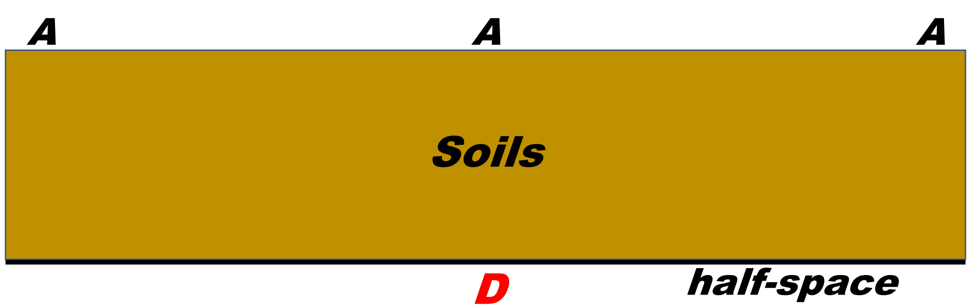

Idealized soil profile to represent free field conditions

"D" corresponds to the earthquake ground motion needed as the "within" rock motion to use in a dynamic response

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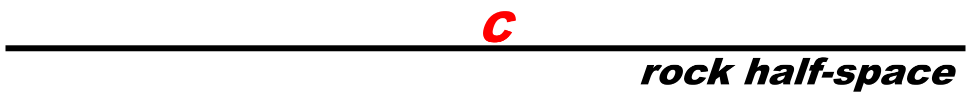

Idealized outcrop

"C" corresponds to earthquake ground motion recorded on a rock outcrop

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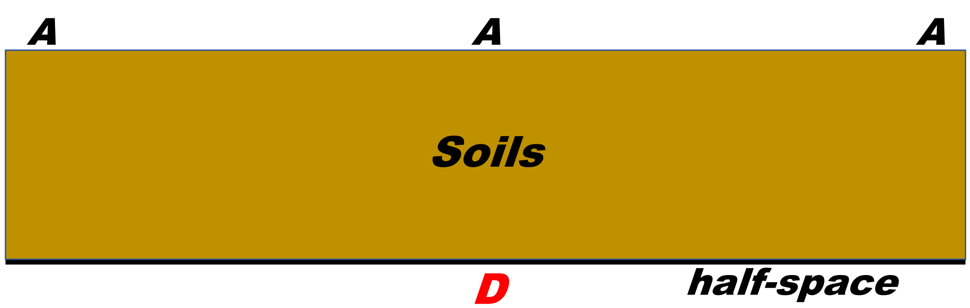

Idealized soil profile to represent free field conditions

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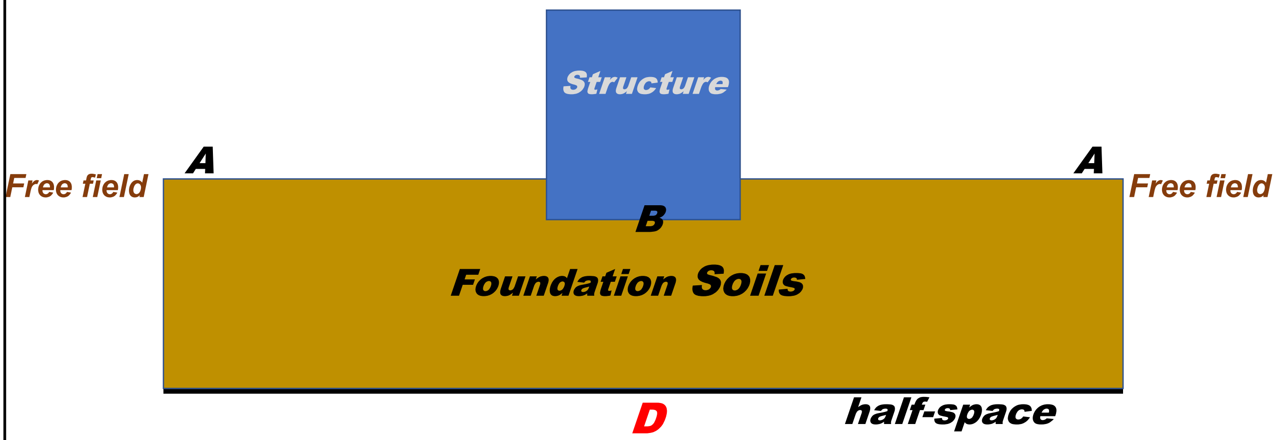

Idealized soil-foundation-structure (SFS) system

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Embankment Dam

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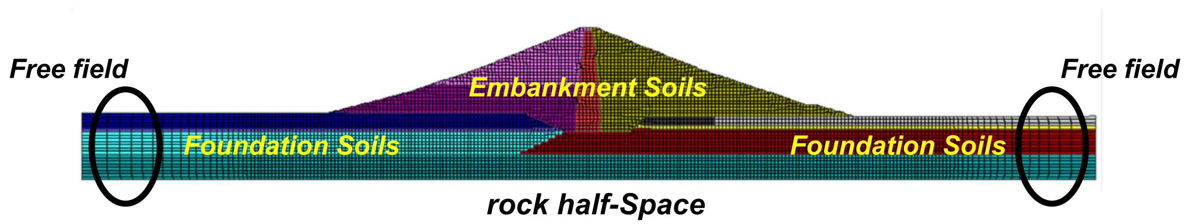

Finite difference mesh courtesy of Dr. Michael Beaty

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Why Site Response

A ground response analysis provides a means to check the results in the free field of dynamic analyses that incorporate SSI or SFSI … etc.

Therefore, it is important to have in our "Computation–Tool Bucket" procedures and computer programs that we can rely on to provide us with reasonably reliable estimates that correlate well with measured values and are physically meaningful.

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TOPIC 2

RECORDED EARTHQUAKE GROUND MOTION DATA

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Recorded Earthquake Ground Motion Data

The New Generation Attenuation (NGA) Project was initiated in 2004 and resulted in accumulating, checking, organizing and disseminating tens of thousands of motions recorded during earthquakes as follows:

- ***Shallow crustal earthquakes in active tectonic regions (such as California); designated NGA West2.***
- ***Shallow crustal earthquakes in stable continental tectonic regions (such as Central and East North America); designated NGA East.***
- ***Subduction zone earthquakes; designated NGA Subduction.***

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RECORDED EARTHQUAKE GROUND MOTION DATA

NGA West2

- Total Number of Recordings 21,540
- Usable FF Number of Recordings 19,572

Range of Data: M = 3 to 7.9
R_{rup} = 0.1 to 1,500 km
V_{S30} = 89 to 2,100 m/sec

Rock Sites → $V_{S30} \geq 600$ m/sec

Soft soil sites → $V_{S30} \leq 210$ m/sec

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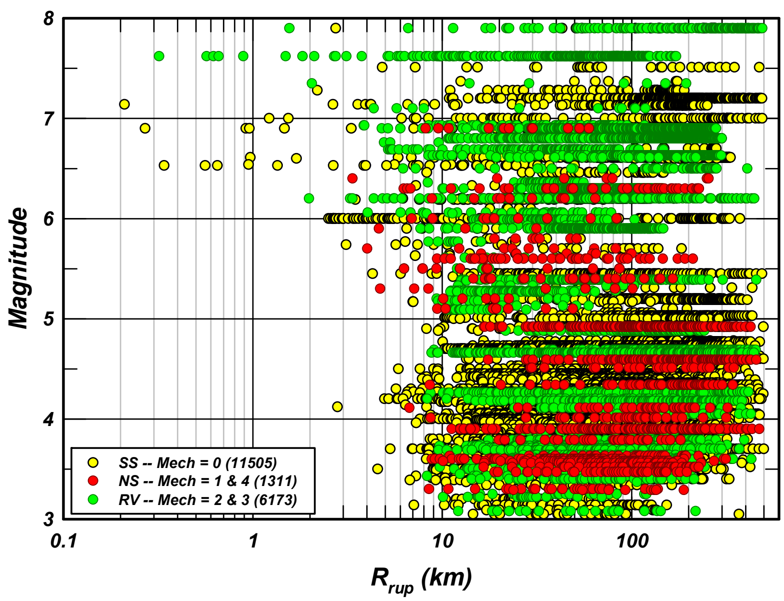

Magnitude – R_{rup} plot of Recordings obtained during crustal earthquakes
$R_{rup} \leq 500$ km; $M \geq 3$

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RECORDED EARTHQUAKE GROUND MOTION DATA

NGA East

- ***Total Number of Recordings 9,382***
- ***Usable FF Number of Recordings 8,918; 59 events***

Range of Data: ***M = 3.1 to 5.85***
R_{rup} = 4.2 to 3,510 km
V_{S30} = 144 to 2,000 m/sec

Plus one recording – M = 6.8 at 5.5 km; V_{S30} = 300 m/sec
& three recordings – M 6.76 at 4.9 to 9.6 km; V_{S30} = 1700 m/sec

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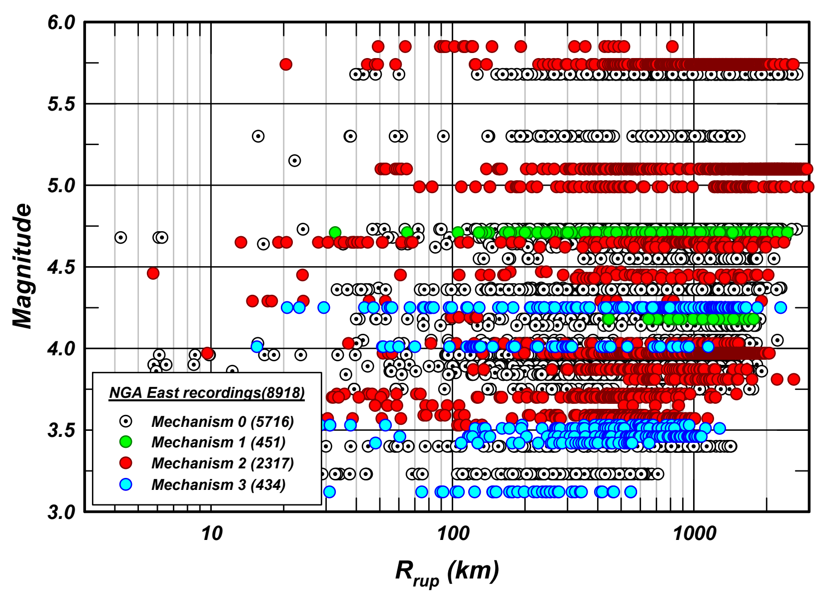

Magnitude – R_{rup} plot of Recordings obtained during earthquakes in CENA*
R_{rup} ≤ 3000 km; M ≥ 3

** Central and East North America*

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RECORDED EARTHQUAKE GROUND MOTION DATA

NGA Subduction

- *Total Number of Recordings:* 71,343
- *Usable FF Number of Recordings:* 49,259; 736 events

Range of Data:

Interface:	M	= 4 to 9.1
	R_{rup}	= 8 to 6,500 km
	V_{S30}	= 53 to 2,230 m/sec
Intraslab:	M	= 3.3 to 8.4
	R_{rup}	= 17 to 5,400 km
	V_{S30}	= 88 to 2,100 m/sec

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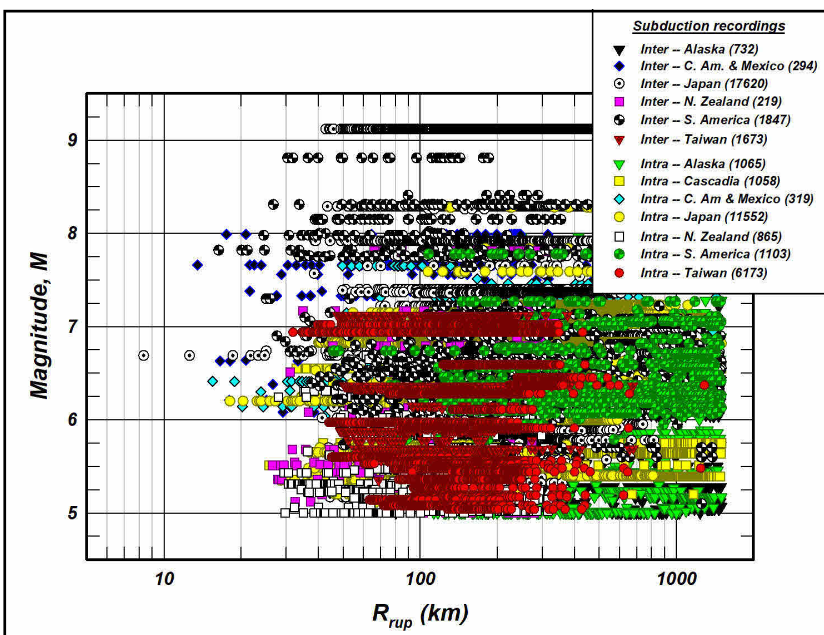

Magnitude – R_{rup} plot of Recordings obtained during subduction earthquakes $R_{rup} \leq 1500$ km; $M \geq 5$

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WHAT WE CAN GLEAN FROM RECORDED EARTHQUAKE GROUND MOTION DATA

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LEARNING FROM RECORDED DATA

Will examine spectra, in terms of spectral shapes

Spectral shape is the ratio of the spectral acceleration, PSA, at period, T, divided by the spectral acceleration at T = 0.01 sec, which typically corresponds to the maximum acceleration of the record, i.e., PGA.

Key metrics to examine are:

- ***Plot of PSA/PGA versus T***
- ***The maximum ratio PSA/PGA***
- ***The period, $T_{@max}$ at which this maximum occurs***

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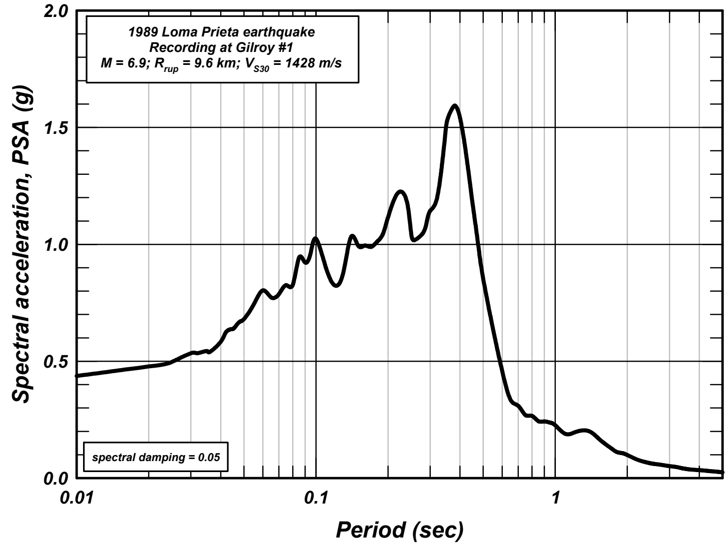

Plot of spectral acceleration versus period

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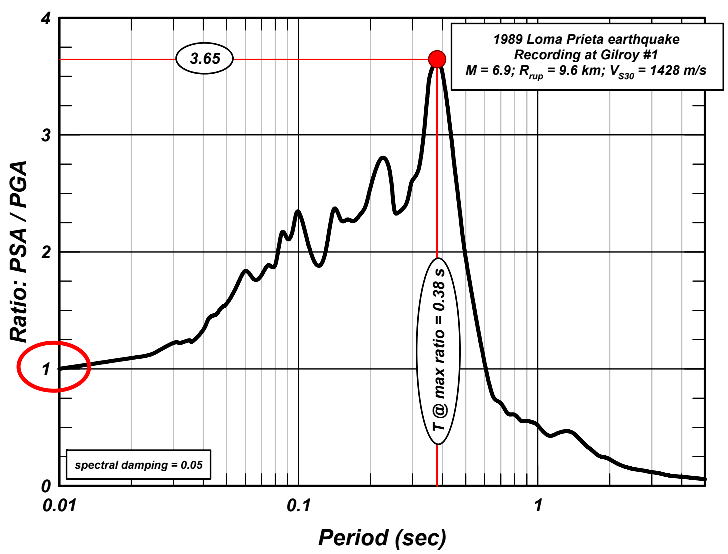

Spectral Shape

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EXAMINATION OF THE PERIOD, $T_{@max}$, AT WHICH THE MAXIMUM RATIO OF PSA/PGA OCCURS

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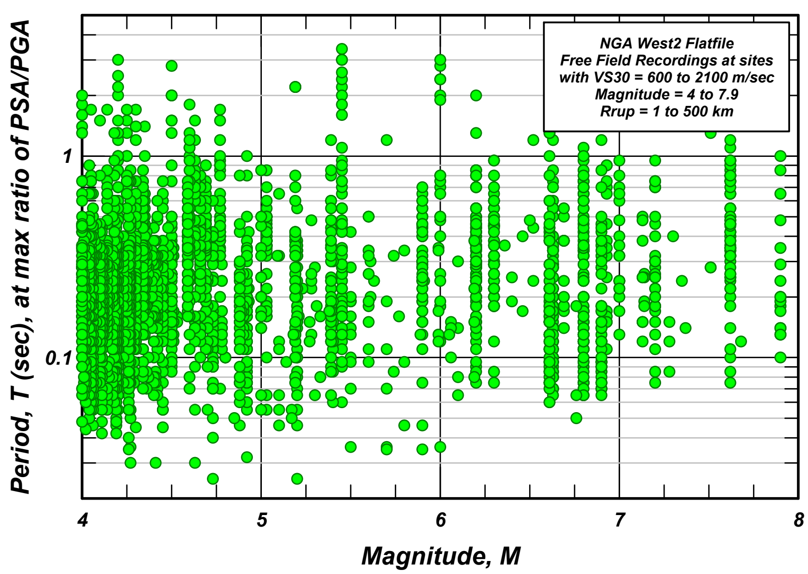

Rock sites – Plot of T at max ratio of PSA/PGA versus M

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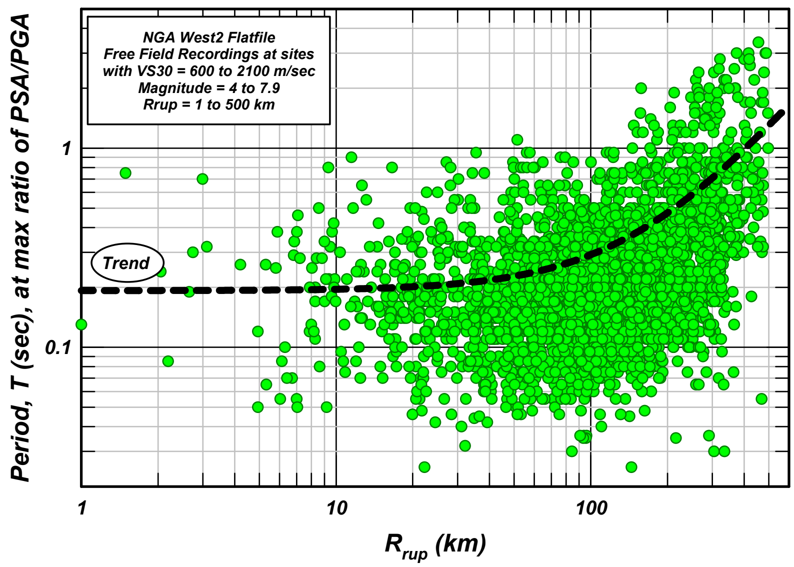
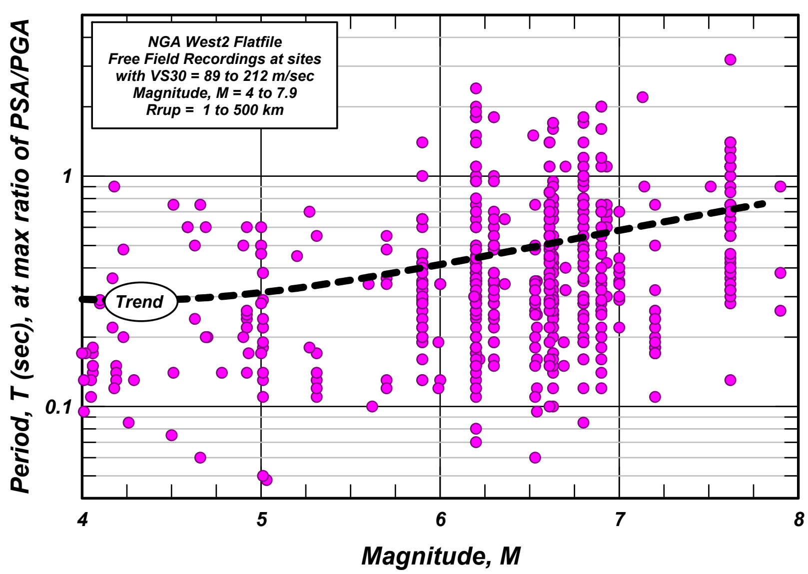
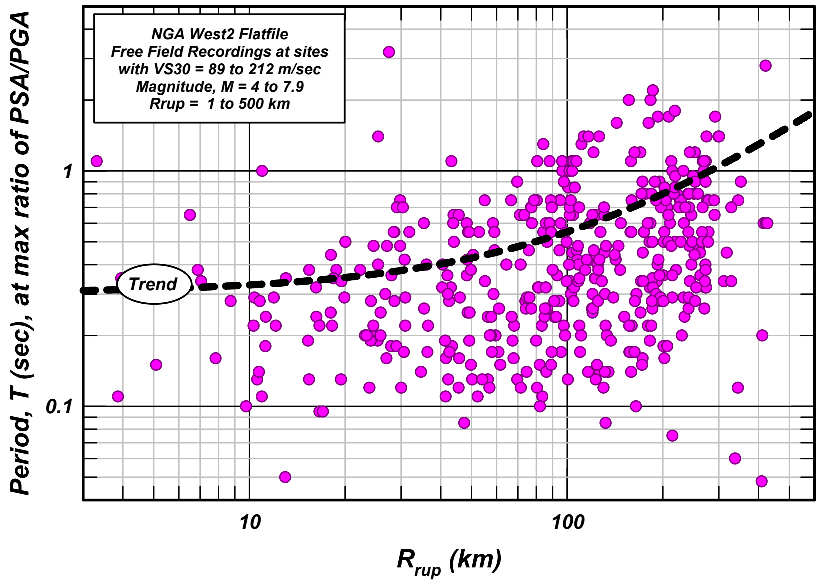


Rock sites – Plot of T at max ratio of PSA/PGA versus R_{rup}



Soft Soil sites – Plot of T at max ratio of PSA/PGA versus M



Soft Soil sites – Plot of T at max ratio of PSA/PGA versus R_{rup}

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LEARNING FROM RECORDED DATA

Conclusions regrading the period, $T_{@max}$, at which the max ratio of PSA/PGA occurs can be summarized as follows:

1. ***Rock Sites [$V_{S30} \geq 600$ m/sec]***
   - ***$T_{@max}$ is essentially independent of magnitude, M, and V_{S30}.***
   - ***$T_{@max}$ increases with R_{rup}.***

2. ***Soft Soil Sites [$V_{S30} \leq 212$ m/sec]***
   - ***$T_{@max}$ is essentially independent V_{S30}.***
   - ***$T_{@max}$ increases with of magnitude, M, and R_{rup}.***

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EXAMINATION OF THE MAXIMUM RATIO OF PSA/PGA

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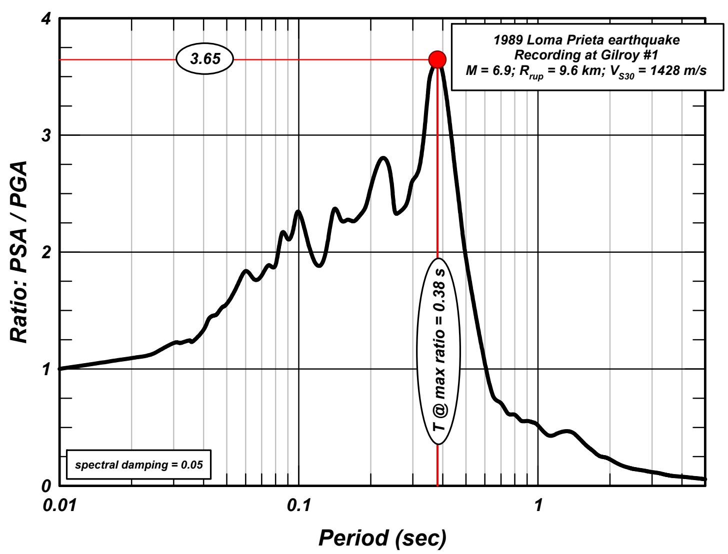

Spectral Shape

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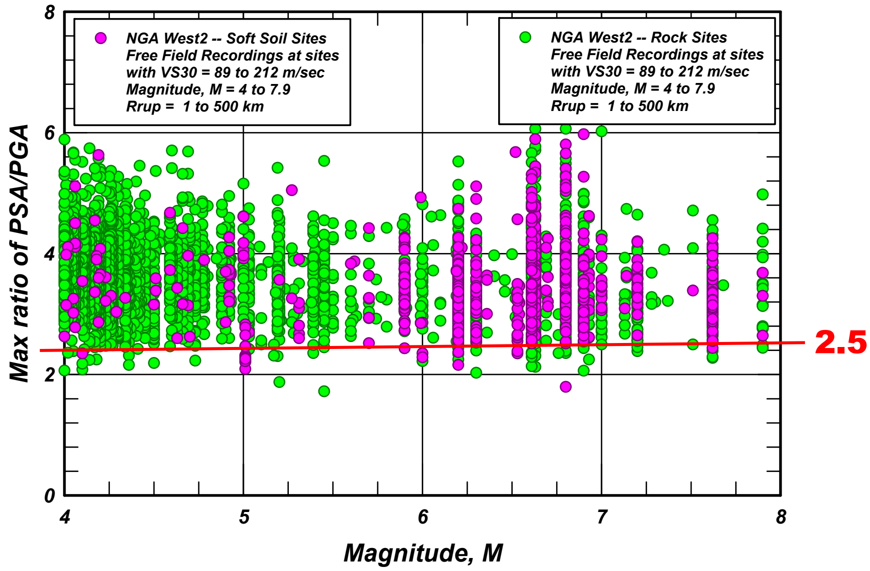

Rock and Soft Soil sites – Plot of the max ratio of PSA/PGA versus M

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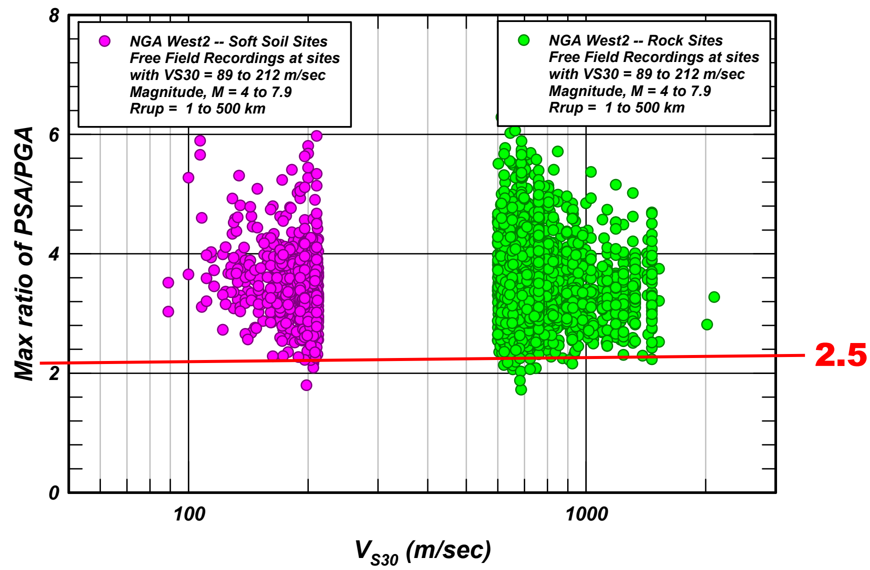

Rock and Soft Soil sites – Plot of the max ratio of PSA/PGA versus V_{S30}

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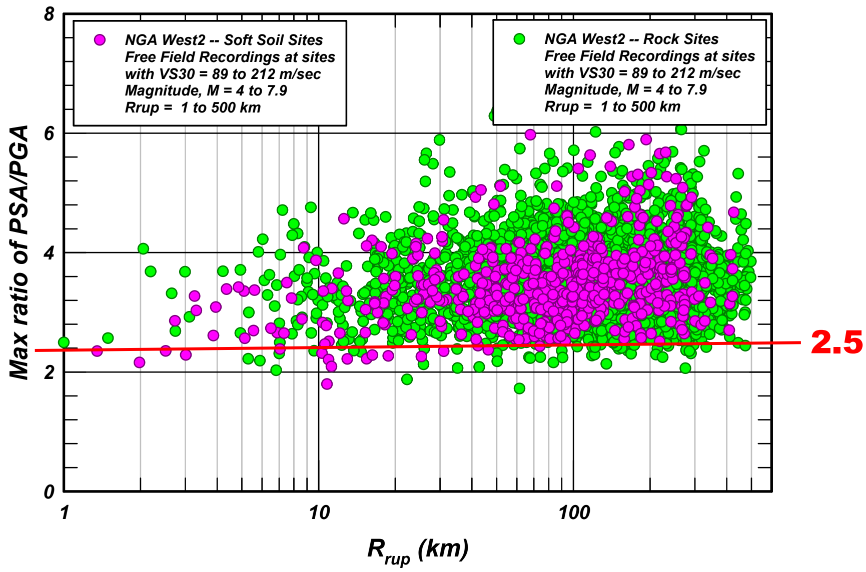

Rock and Soft Soil sites – Plot of the max ratio of PSA/PGA versus R_{rup}

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LEARNING FROM RECORDED DATA

Conclusions regarding the max ratio of PSA/PGA can be summarized as follows:

The max ratio of PSA/PGA appears to be essentially independent of magnitude, M, or V_{S30}. There is an apparent hint that this metric may increase with R_{rup}.

The range of this ratio is from 2 to about 6. This ratio exceeds 2.5 for about 97% of the recordings.

These conclusions apply at rock as well as at soft soil sites.

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TOPIC 3

EMPIRICAL EARTHQUAKE GROUND MOTION MODELS

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EMPIRICAL EARTHQUAKE GROUND MOTION MODELS

Conclusions regarding the use of empirical earthquake ground motion models (GMMs) can be summarized as follows:

- ***The spectral shapes obtained for a rock site [V_{S30} = 760 m/sec] using the NGA West2 GMM are generally consistent with the recorded data.***
- ***However, those obtained for a soft soil site are not as well constrained.***

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EMPIRICAL EARTHQUAKE GROUND MOTION MODELS

Differing results were obtained for the soft soil site [V_{S30} = 180 m/sec] using the other three NGA West2 GMMs. The conclusion stated above, however, applied to each.

Accordingly, it is appropriate to use the empirically-derived earthquake ground motion models (GMMs) to estimate spectral values at a rock site, which becomes the "rock outcrop" for a specific application.

Such spectra can then be used to represent the target spectrum at a rock outcrop in a seismic analysis.

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TOPIC 4

HISTORICAL PERSPECTIVE

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The 1906 San Francisco Earthquake

The performance of various sites during the 1906 San Francisco earthquake highlighted the importance of site response during earthquakes and, as noted by Lawson (1908), emphasized the effects of local site conditions.

Although some attempts were made to explain these effects using wave propagation theories, it was not possible, at that time, to go beyond qualitative explanations.

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Professor Kanai's Contributions

In 1952 – 1956 Professor Kanai proposed the use of the continuous solution to the wave equation to study site effects on earthquake ground motions.

Professor C. Martin Duke brought Kanai's work to attention of US researchers & practitioners in 1958.

This was met with strong resistance from structural engineers in the USA.

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Activities in the 1960s

The late Professor Seed presented a paper at the WCEE advancing the concerns with the behavior of soils during earthquakes and the potential effects of local site conditions on earthquake ground motions -- 1960.

Donald Hudson (Caltech) proposed the use of values of damping that are dependent on the level of deformation in structural elements – 1963.

Penzien, Parmelee & Seed developed a bilinear procedure & wrote a computer program to calculate the response of soft soil sites – 1963.

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Activities in the 1960s (Cont'd)

G. R. Martin suggested the need to incorporate the influence of the level of shaking in calculating response of earth dams – 1965.

Idriss examined the laboratory test results by Thiers & Seed and suggested the use of strain-compatible modulus & damping values in site response calculations – 1966

Idriss & Seed used the bilinear solution to show that strain-compatible modulus & damping values can be used in a linear program to produce comparable results; i.e. <u>Equivalent Linear Solution</u> -- 1968

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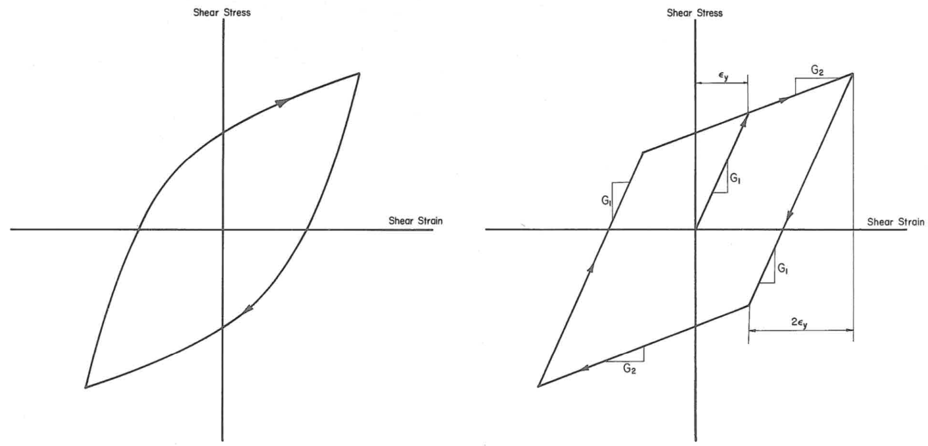

(a) Stress-Strain Curve (b) Bilinear Idealization

FIG. 15 STRESS-STRAIN CHARACTERISTICS OF SOIL

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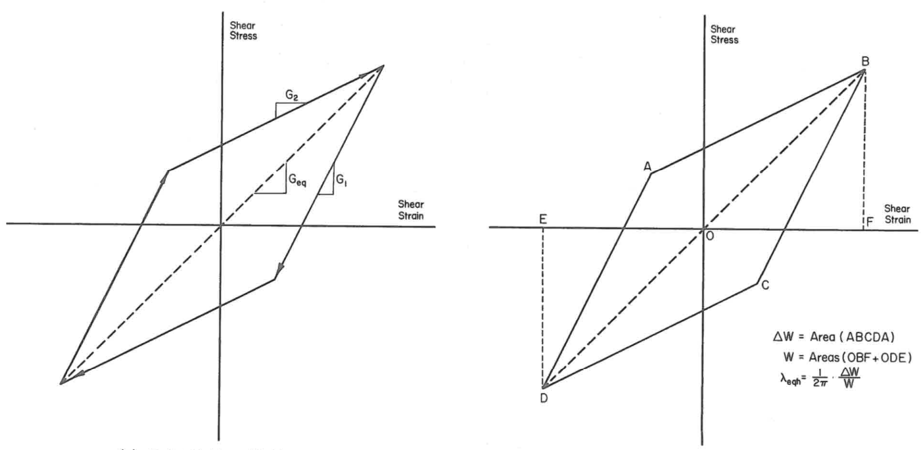

(a) Equivalent Linear Modulus (b) Equivalent Viscous Damping Ratio

FIG. 20 EVALUATION OF EQUIVALENT LINEAR PARAMETERS FROM BILINEAR HYSTERETIC STRESS-STRAIN CYCLE.

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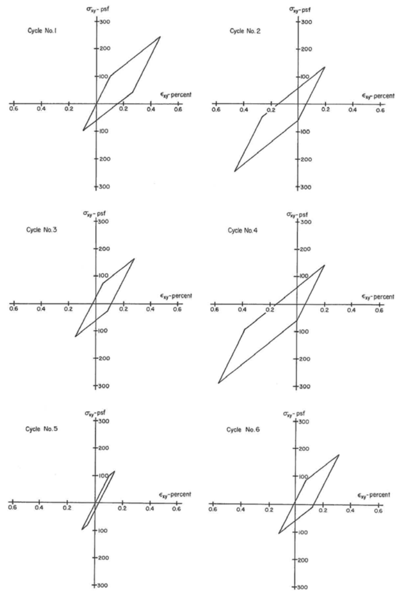

FIG.19 HYSTERETIC CYCLES DEVELOPED AT MIDHEIGHT OF LAYER WITH BILINEAR STRESS-STRAIN CHARACTERISTICS.

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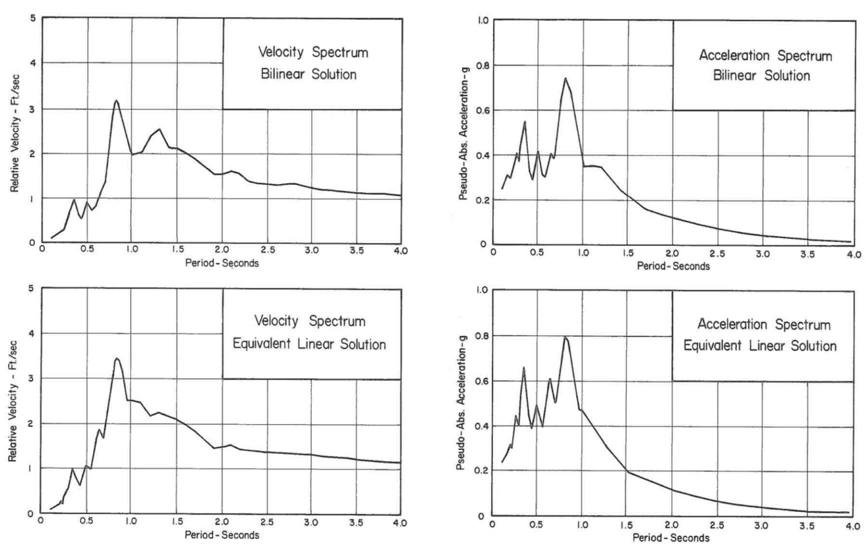

FIG. 21 RESPONSE SPECTRA FOR BILINEAR AND EQUIVALENT LINEAR SOLUTIONS.

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Activities in the 1960s

Researchers at the University of Michigan (under the leadership of Professor Richart) carried out a comprehensive testing program to measure modulus & damping values. They showed dependence of these values on amplitude of vibration – this work was initiated beginning in the early 1960s.

The late Professor Seed and I began to compile the dynamic laboratory tests on sands, which included free vibration and resonant column tests. This effort began in 1968 and culminated in the preparation of the Report summarizing these results and introducing the concept of using G/G_{max}. This Report was published by EERC in 1970.

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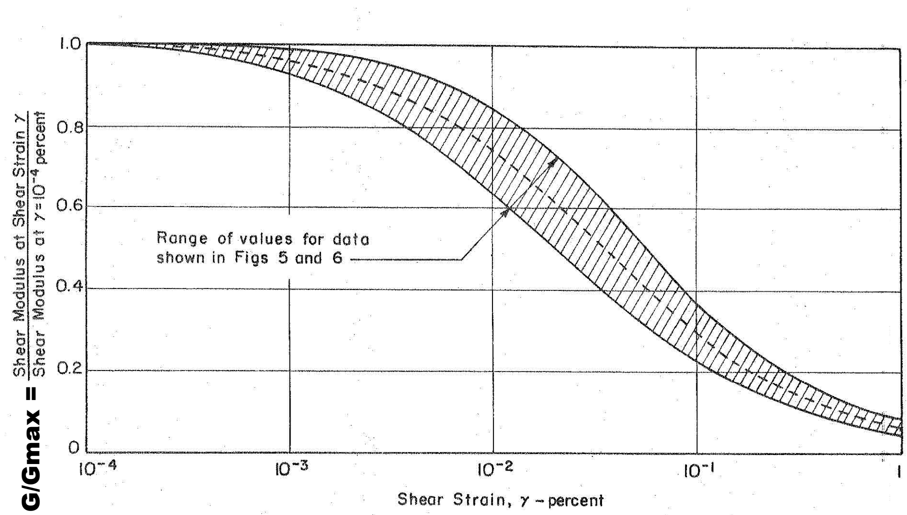

Fig. 7 VARIATION OF SHEAR MODULUS WITH SHEAR STRAIN FOR SANDS.

From Seed and Idriss (1970)

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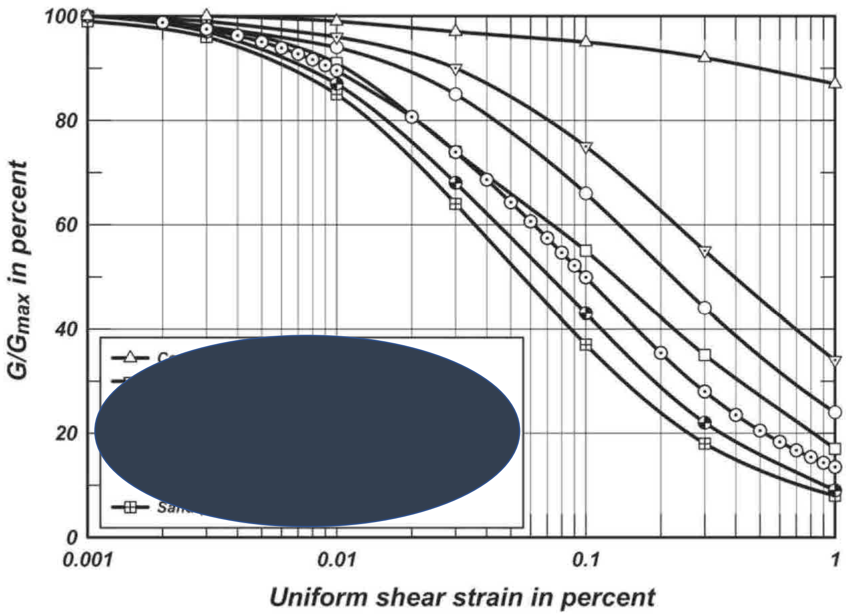

Examples of G/Gmax Curves published over the years

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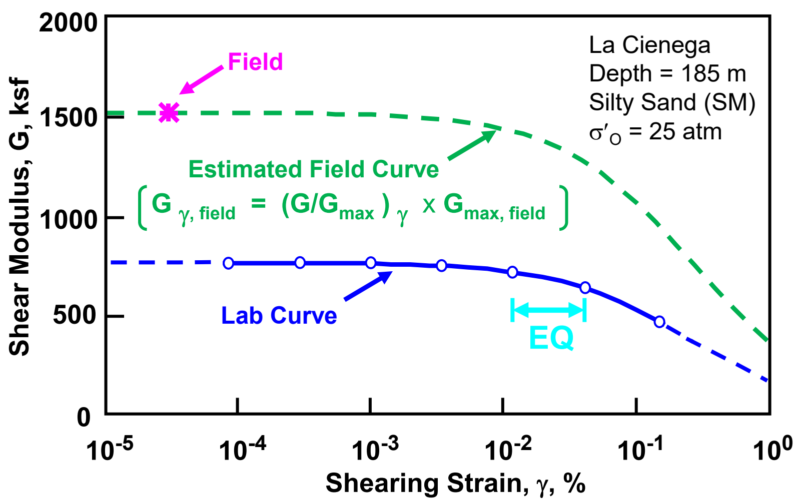
Link Between Field and Lab:

Estimating the Field G – log γ Relationship (Soil)



Courtesy of Professor K. Stokoe

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Activities in late 1960s and early 1970s

Analyses of shaking table tests on earth slopes suggested the need to have the ability to use different damping values in various parts of the slope & to the development of a variable damping FE program – 1969, which was later named QUAD4.

Schnabel started his research using the FE program developed in 1969 and initiating comparisons using a continuous solution to check accuracy – 1970.

Both approaches (the time-domain FE and the frequency-domain continuous formulations) introduce high damping. When Schnabel and I discussed this issue with Professor Lysmer, who had up to that time concentrated on working on foundation vibration issues, he suggested a novel approach to overcome this issue.

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Activities in the1970

Professor Lysmer suggested that the viscosity coefficient in the complex modulus expression be replaced by the damping ratio; thus making the damping ratio frequency-independent – 1971.

These developments & using Cooley & Tukey fast Fourier transform made it possible to have an efficient continuous solution that can be programmed to provide for incorporating strain-compatible modulus & damping values – 1972

Thus, the birth of the Computer Program SHAKE.

Professor Lysmer "converted" to geotechnical earthquake engineering and introduced the Computer Programs LUSH, FLUSH culminating in the Program SASSI, which has been widely used in evaluating SSI for nuclear plant structures since its introduction some 40 years ago.

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TOPIC 5

SITE RESPONSE ANALYSES

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Site Response Calculations

A large number of recordings were obtained at many sites during the 1989 Loma Prieta earthquake (M = 6.9). Many of these sites were in the San Francisco Bay Area, including the site at Treasure Island.

Calculation of the response of the Treasure Island site will be covered as follows:

1. ***Loma Prieta – equiv. linear analyses (EQL)***
2. ***Downhole Array -- Comparison with other programs (EQL)***
3. ***Loma Prieta – Comparison with other programs (EQL & NL)***

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TREASURE ISLAND SITE

1. ***Loma Prieta – equiv. linear analyses (EQL)***
2. ***Loma Prieta – Comparison with other programs (EQL & NL)***

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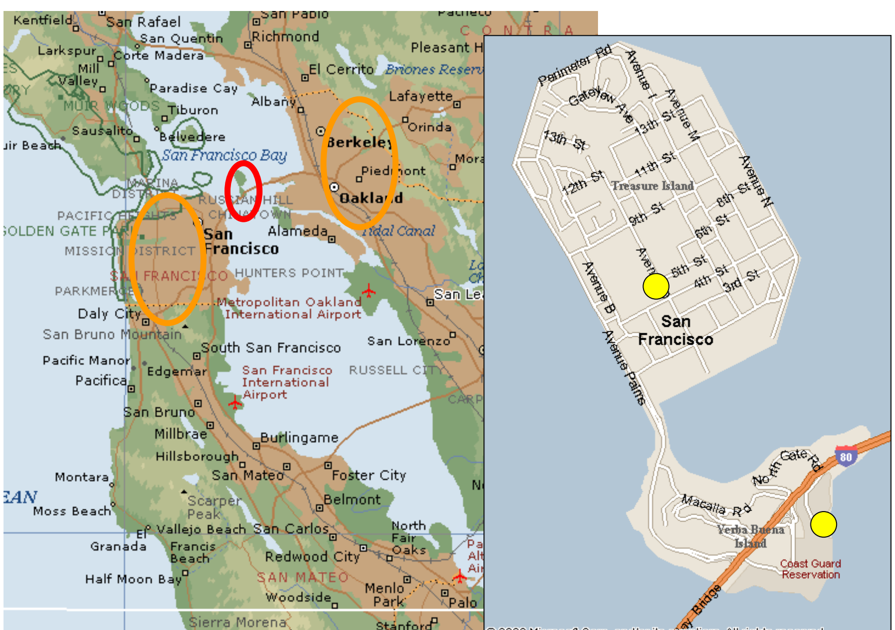

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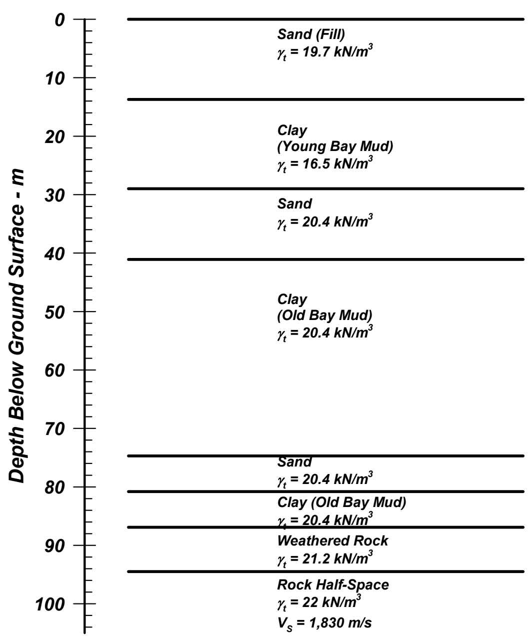

Subsurface layers at the Treasure Island site

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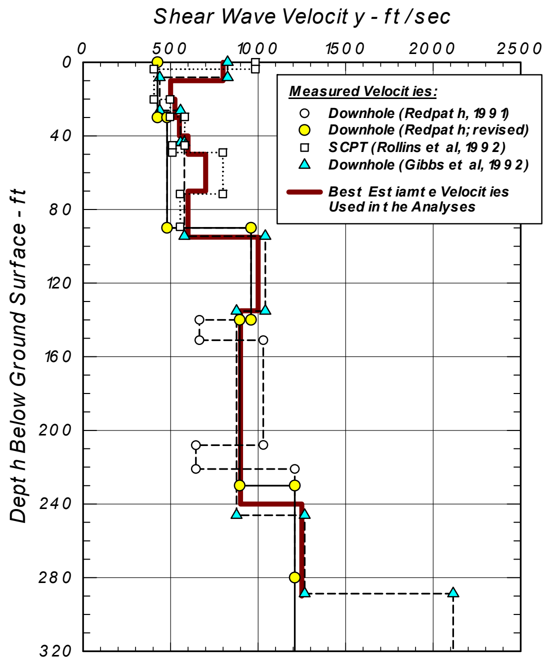

Range of shear wave velocities
Measured at the Treasure Island site

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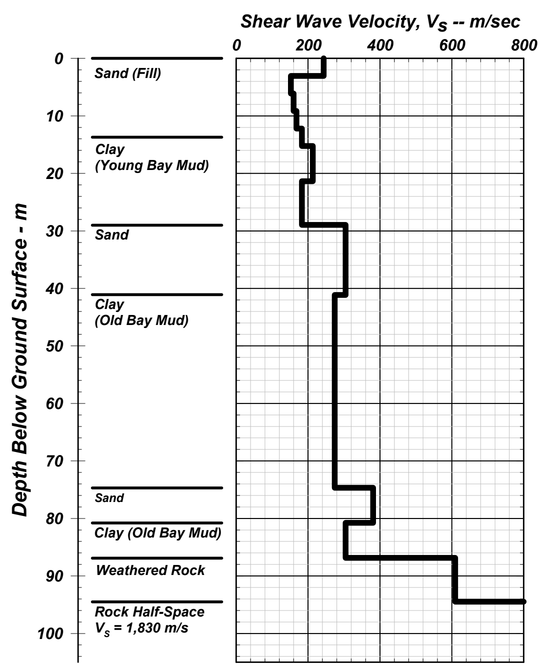

Best estimate
Shear wave velocity profile at the
Treasure Island site

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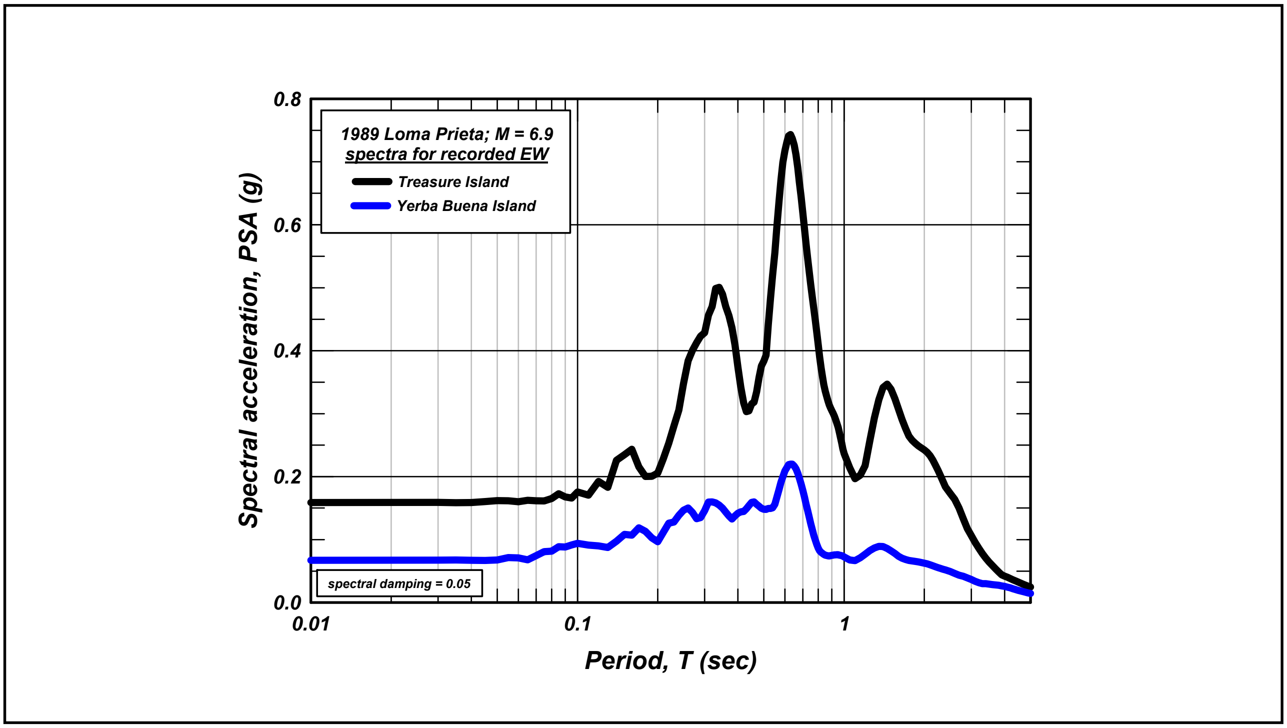
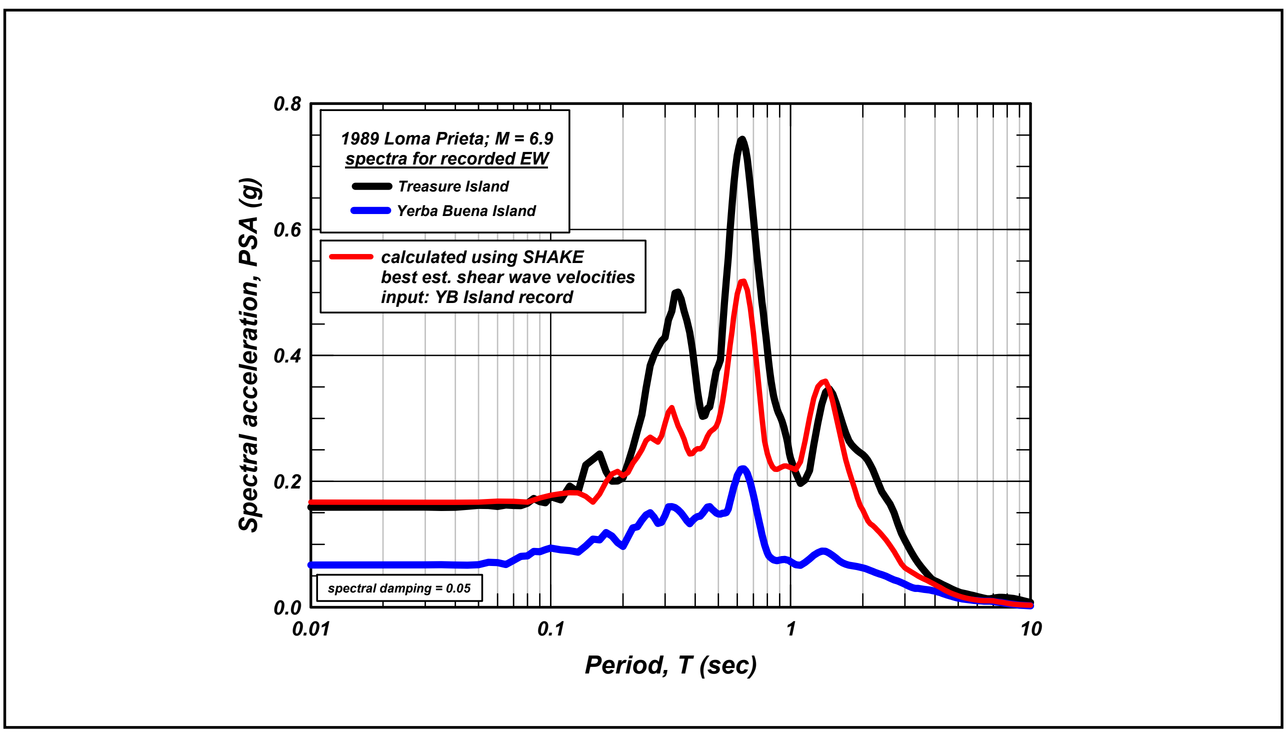

1989 Loma Prieta; M = 6.9
spectra for recorded EW
Treasure Island
Yerba Buena Island
spectral damping = 0.05
Spectral acceleration, PSA (g)
Period, T (sec)
0.0
0.2
0.4
0.6
0.8
0.01
0.1
1

65


1989 Loma Prieta; M = 6.9
spectra for recorded EW
Treasure Island
Yerba Buena Island
calculated using SHAKE
best est. shear wave velocities
input: YB Island record
spectral damping = 0.05
Spectral acceleration, PSA (g)
Period, T (sec)
0.0
0.2
0.4
0.6
0.8
0.01
0.1
1
10

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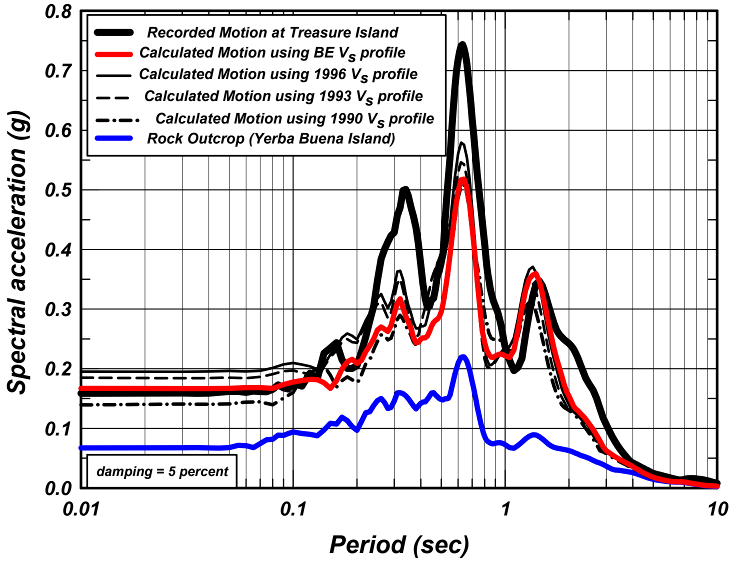

Effects of varying dynamic soil Properties On calculated surface Response – Treasure Island site

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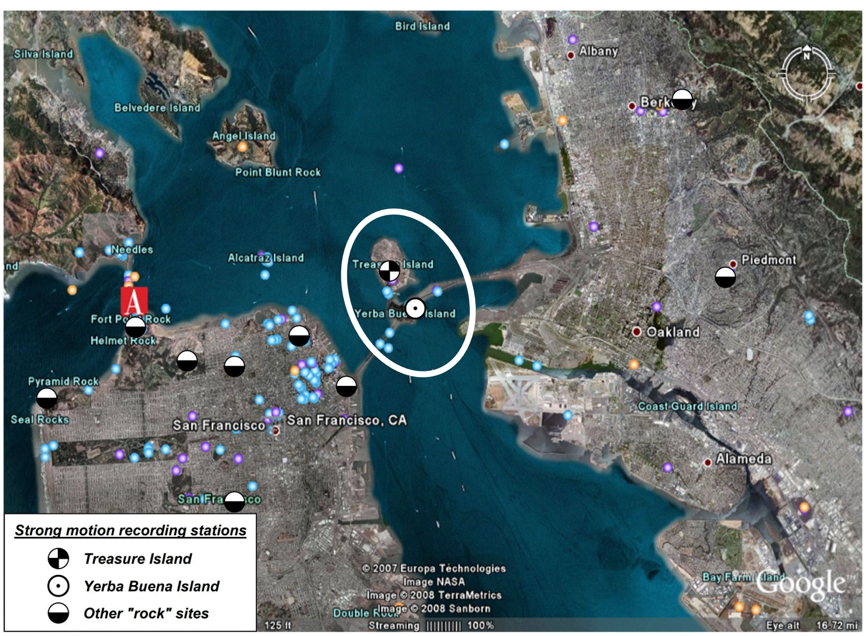

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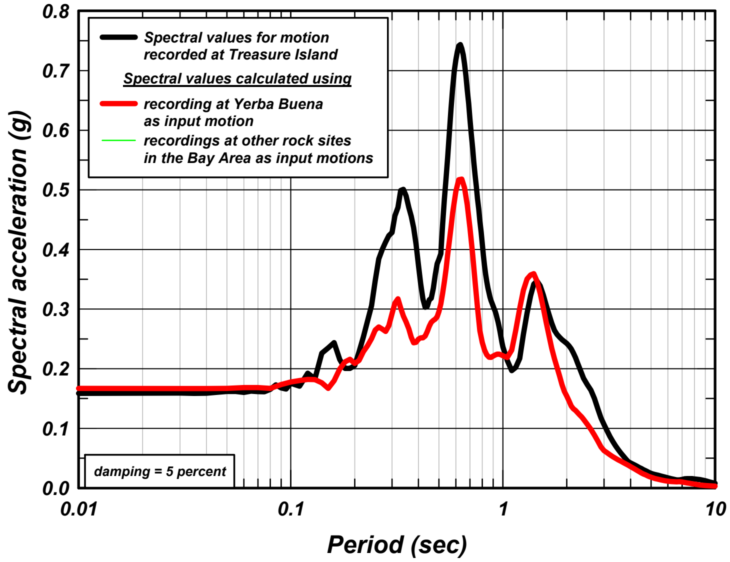

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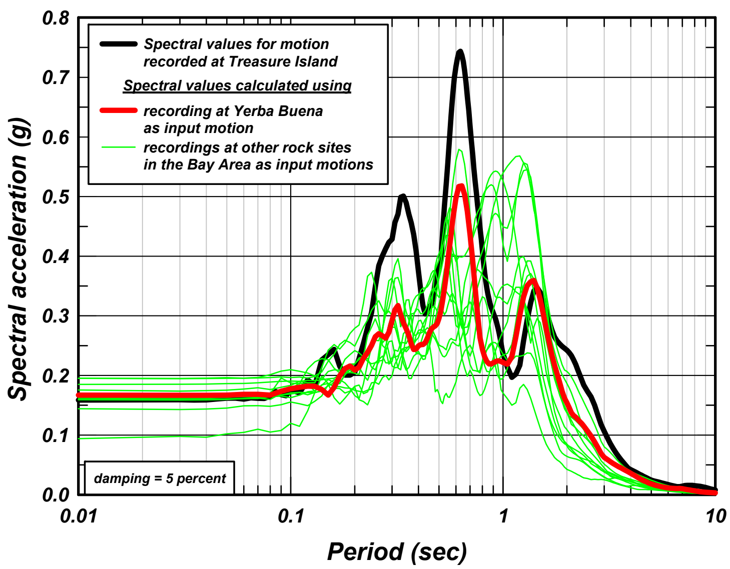

Effects of varying input motion on calculated surface response Treasure Island site

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TREASURE ISLAND SITE

1. Loma Prieta – equiv. linear analyses (EQL)
2. Loma Prieta – Comparison with other programs (EQL & NL)

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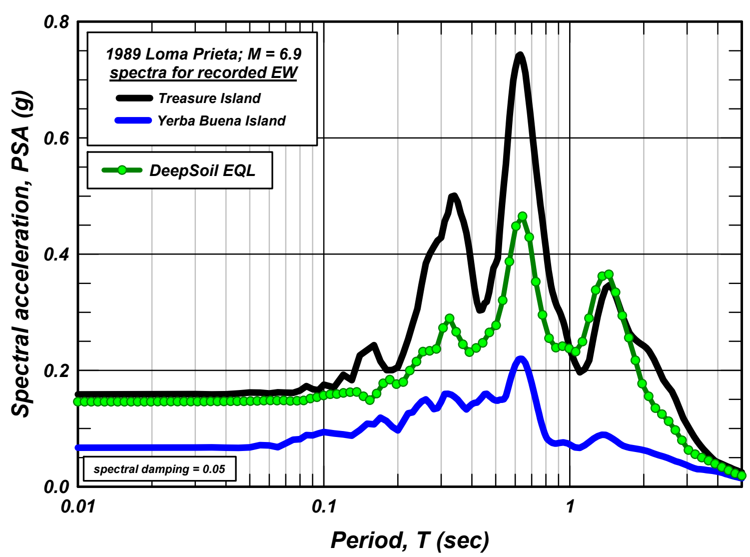
Loma Prieta – Comparison with DeepSoil (EQL)



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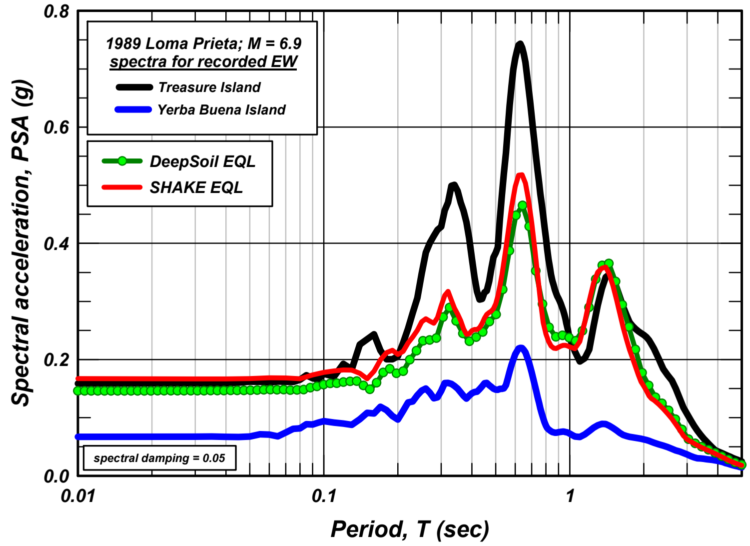
Loma Prieta – Comparison with DeepSoil & SHAKE (EQL)



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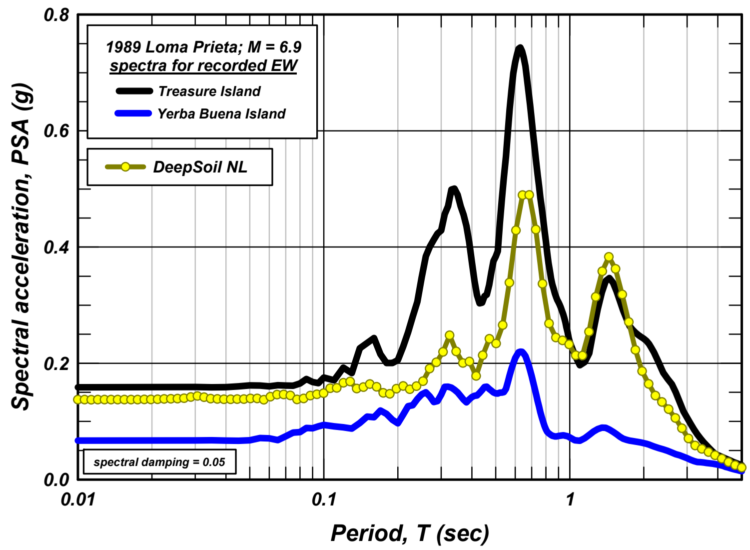
Loma Prieta – Comparison with DeepSoil (NL)



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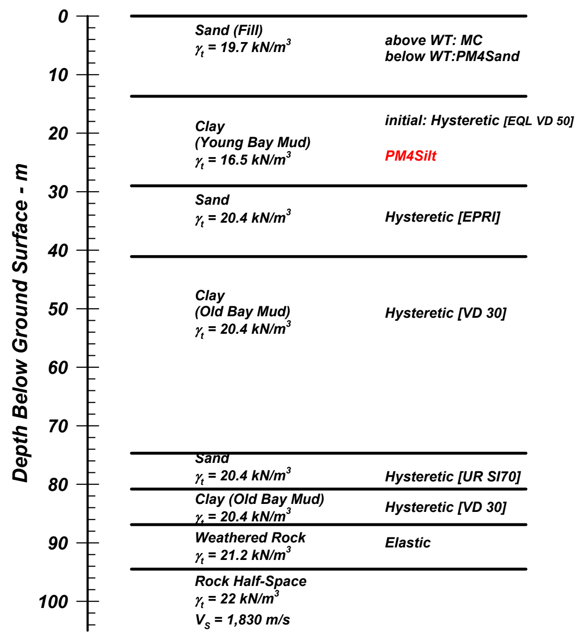


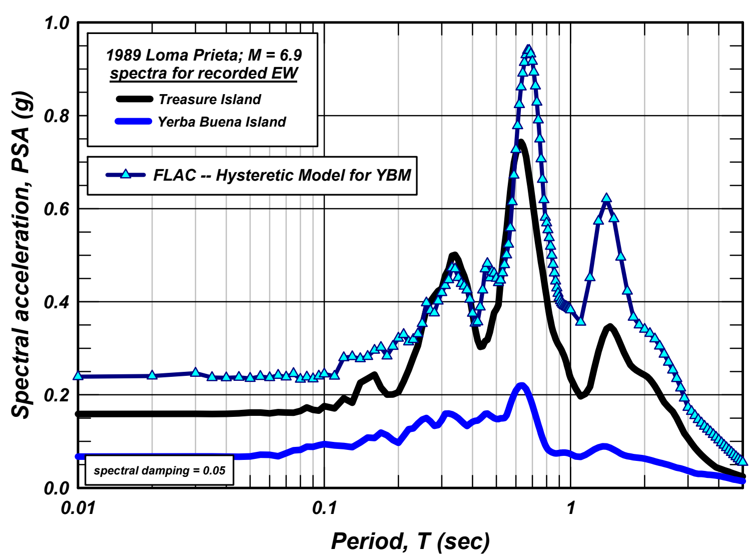
Subsurface layers at the Treasure Island site

&

Const. Models assigned for FLAC Analyses

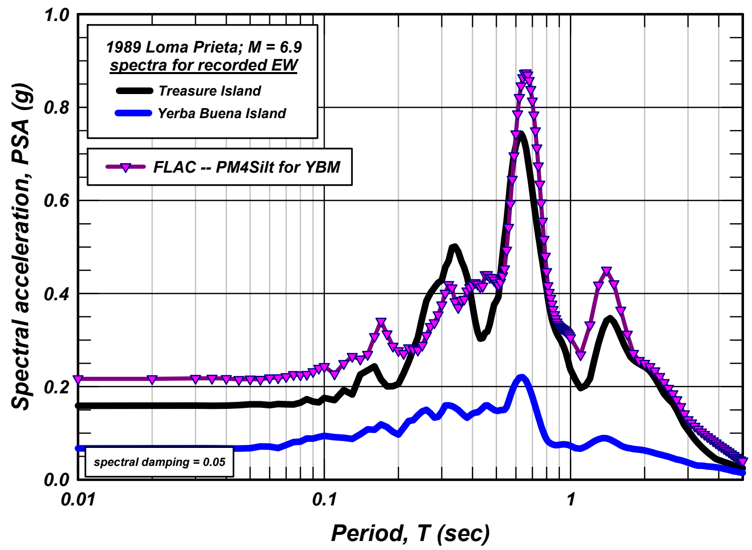
75

Loma Prieta – Comparison with FLAC Hysteretic Model for YBM



76

Loma Prieta – Comparison with FLAC using PM4Silt for YBM



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Spectral Shapes

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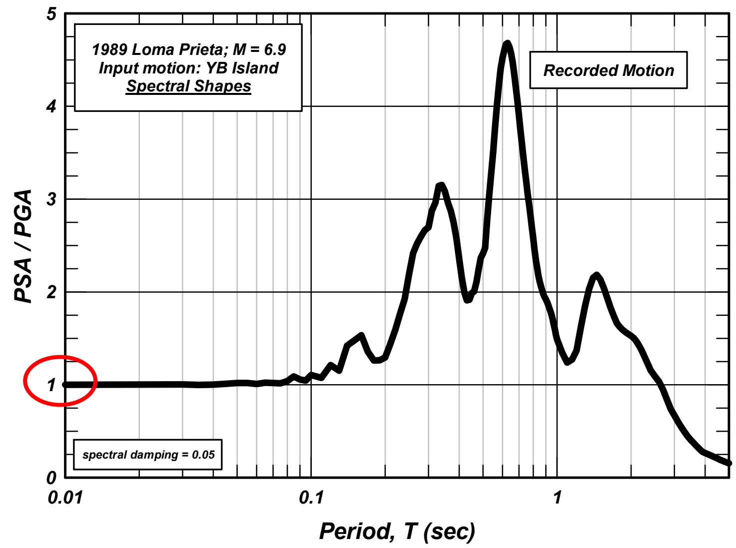
Spectral Shape – Recorded Motion at TI



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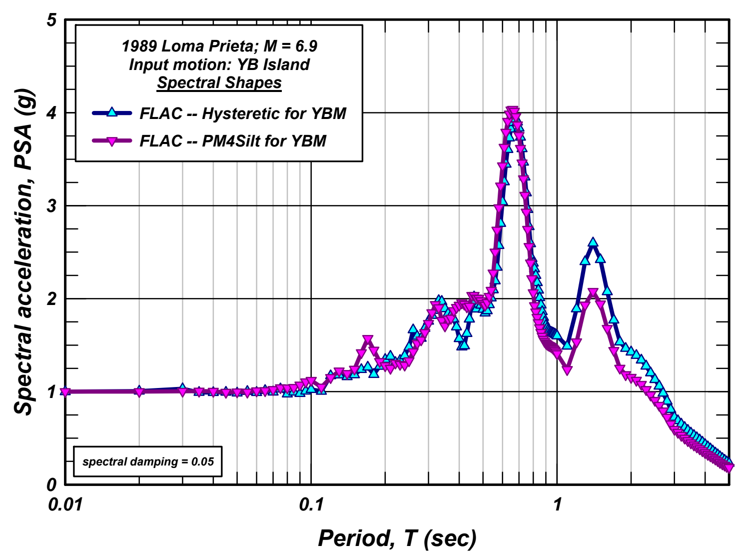
Spectral Shapes – FLAC Analyses



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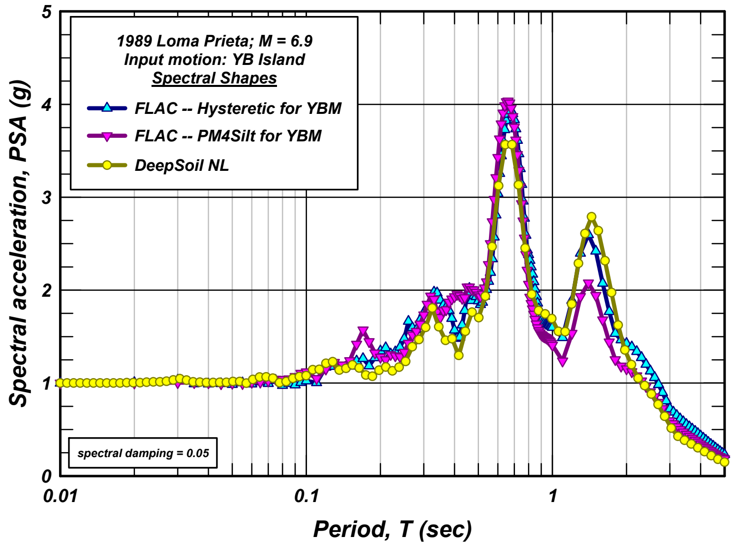
Spectral Shapes – FLAC Analyses and DeepSoil NL



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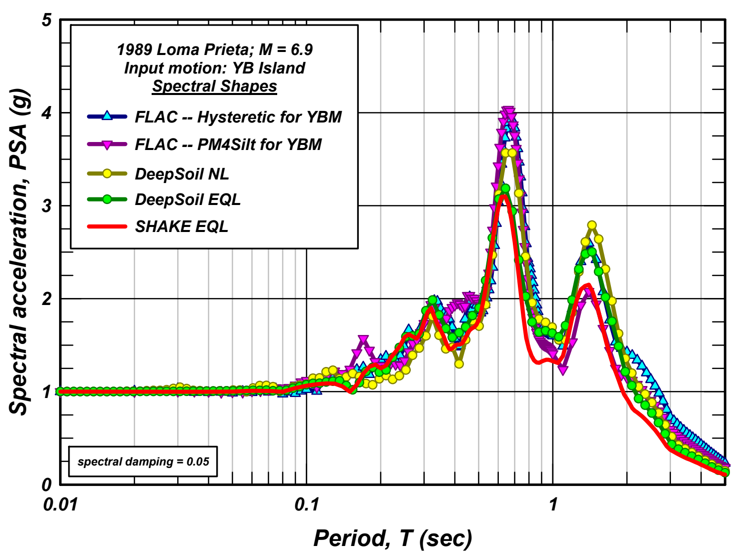
Spectral Shapes – NL and EQL Analyses



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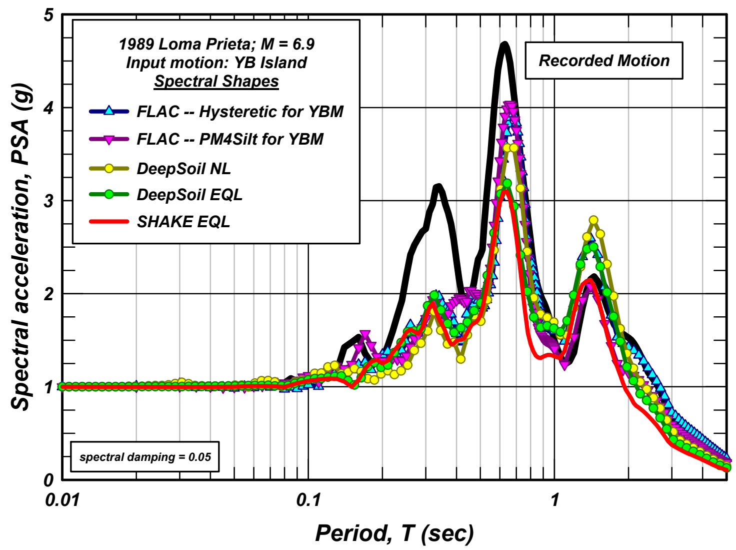
Spectral Shapes – Recorded Motion and NL & EQL Analyses



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FLAC ANALYSES – DEVELOPMENT OF EXCESS PWP

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FLAC Analyses – Excess PWP Induced during Shaking

The use of PM4Sand for the sand layers and PM4Silt for the Young Bay Mud layers provides the means to calculate the excess pore water pressure (PWP) induced in these layers during shaking, as illustrated at a depth of 10.5 m within the upper sand layer and a depth of 20.5 m within the YBM layer.

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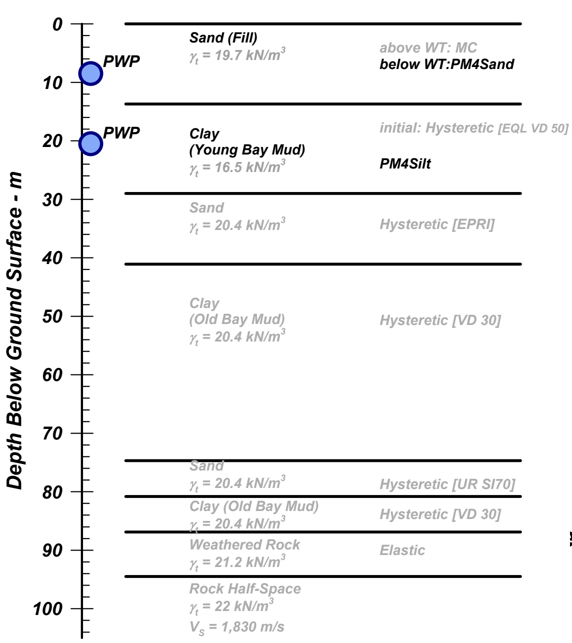

Treasure Island Site
FLAC Analysis -- depths at which PWP
neration/dissipation are shown in next figures

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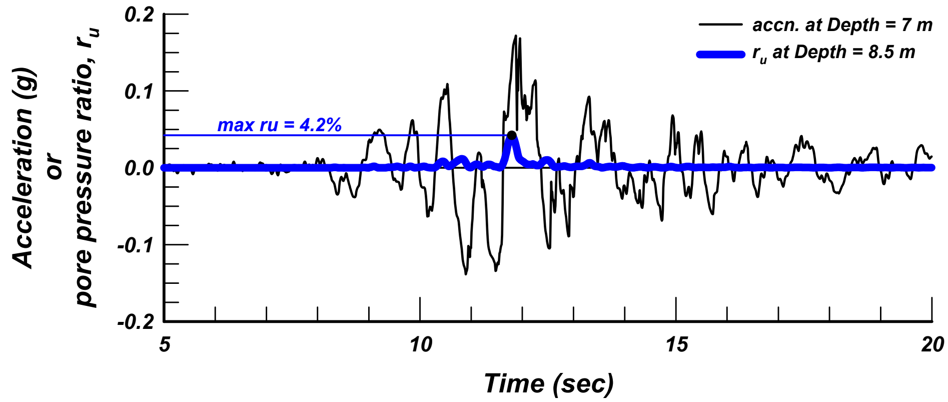
FLAC Analyses – Excess PWP Induced during Shaking

Sand Fill – Depth = 8.5 m



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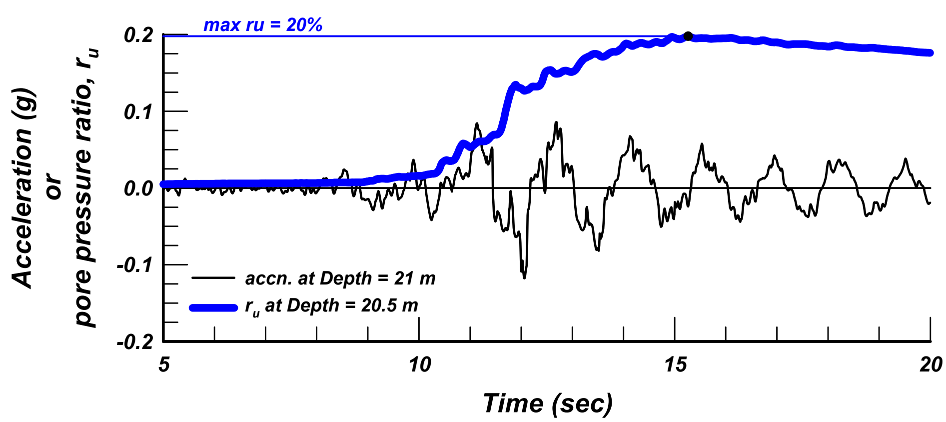
FLAC Analyses – Excess PWP Induced during Shaking

Young Bay Mud – Depth = 20.5 m



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CONCLUDING REMARKS

The equivalent linear procedure has been & continues to be widely used procedure in practice for calculating site response & for developing site specific earthquake ground motions and design parameters.

It has also been widely used for evaluating existing and new earth structures and for assessing SSI aspects.

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CONCLUDING REMARKS

Advances in nonlinear analyses are encouraging and the results presented today highlight the values of using such analyses.

Care must be exercised in selecting appropriate constitutive models for the various soil layers comprising the profile under considerations.

Calibration of the selected constitutive model with relevant test data and empirical correlations is essential. Professor Hashash and his collaborators have done that for the model built into DeepSoil. Professors Boulanger and Ziotopoulou and their collaborators have done that extensively for PM4Sand and are continually adding to that effort for PM4Silt.

The results for the Treasure Island site, using PM4Silt for the Young Bay Mud layer, highlight the importance of accounting for pwp generation and cyclic softening during shaking.

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CONCLUDING REMARKS

The key factors that affect a site response calculation are:

1. ***The <u>input motion</u> can have a profound influence on calculated site response, as evidenced from the results shown earlier for the Treasure Island site.***
2. ***The <u>soil profile</u> also will influence the calculated site response.***
3. ***The <u>soil properties</u> also influence the calculated site response, but to a lesser degree than input motion or soil profile.***
4. ***The <u>method of analysis</u> will influence the results, depending on the level of shaking and the selection of parameters. For the Treasure Island site, the effect was minimal for the level of shaking experienced in the Loma Prieta earthquake.***

A FEW RECOMMENDATIONS

1. ***PLEASE limit the use of the equivalent linear procedure to those in which the calculated effective strain is less than about 0.6%, which corresponds to a maximum strain < 1%.***

2. ***For a "deconvolution" analysis, I have found it useful to get the strain-compatible properties by completing the analysis with a low cuff-off frequency (say 5± Hz, depending on the level of shaking), then using the resulting strain-compatible modulus and damping values for one iteration and the desired cuff-off frequency (typically 20 to 30± Hz).***

A FEW RECOMMENDATIONS

3. *Allow for variations in shear wave velocities and in modulus reduction and damping curve **within physically meaningful ranges.***

4. *When using a randomizing process to allow for variations in these properties, **be sure to check that any realization is physically meaningful.***

5. *Casagrande, in his Terzaghi Lecture (No. 2), emphasized the need to select a "probable range of pertinent soil properties guided by judgement and experience". This is a valuable and timeless advice. We should all heed it.*

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PARTING THOUGHTS

Confucius said

"Life is really simple, but we insist on making it complicated"

Einstein said

"Everything should be made as simple as possible, but no simpler"

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Acknowledgments

I am most grateful to My Family for continuing love, support and tolerance.

I am eternally grateful to numerous very talented friends and colleagues
Let me just mention a few

Colleagues and clients on various projects over the past 30 + years

And finally, to ASCE & G-I for this great honor – I appreciate it.

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THANK YOU very much

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