Center for Development
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INTERNATIONAL INSTITUTE OF EARTHQUAKE ENGINEERING AND SEISMOLOGY

IIEES

بسم الله الرحمن الرحیم

Importance of site effects in post-disaster reconstruction

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Assistant Professor at the Geotechnical Research Center

International Institute of Earthquake Engineering and Seismology



- Entering the Topic
- Theoretical background
- Factors affecting site response analysis
- Site Response Analysis and Resilience
- Regulations
- Some Examples
- Codes and Events
- Soil constitutive model in site response analysis

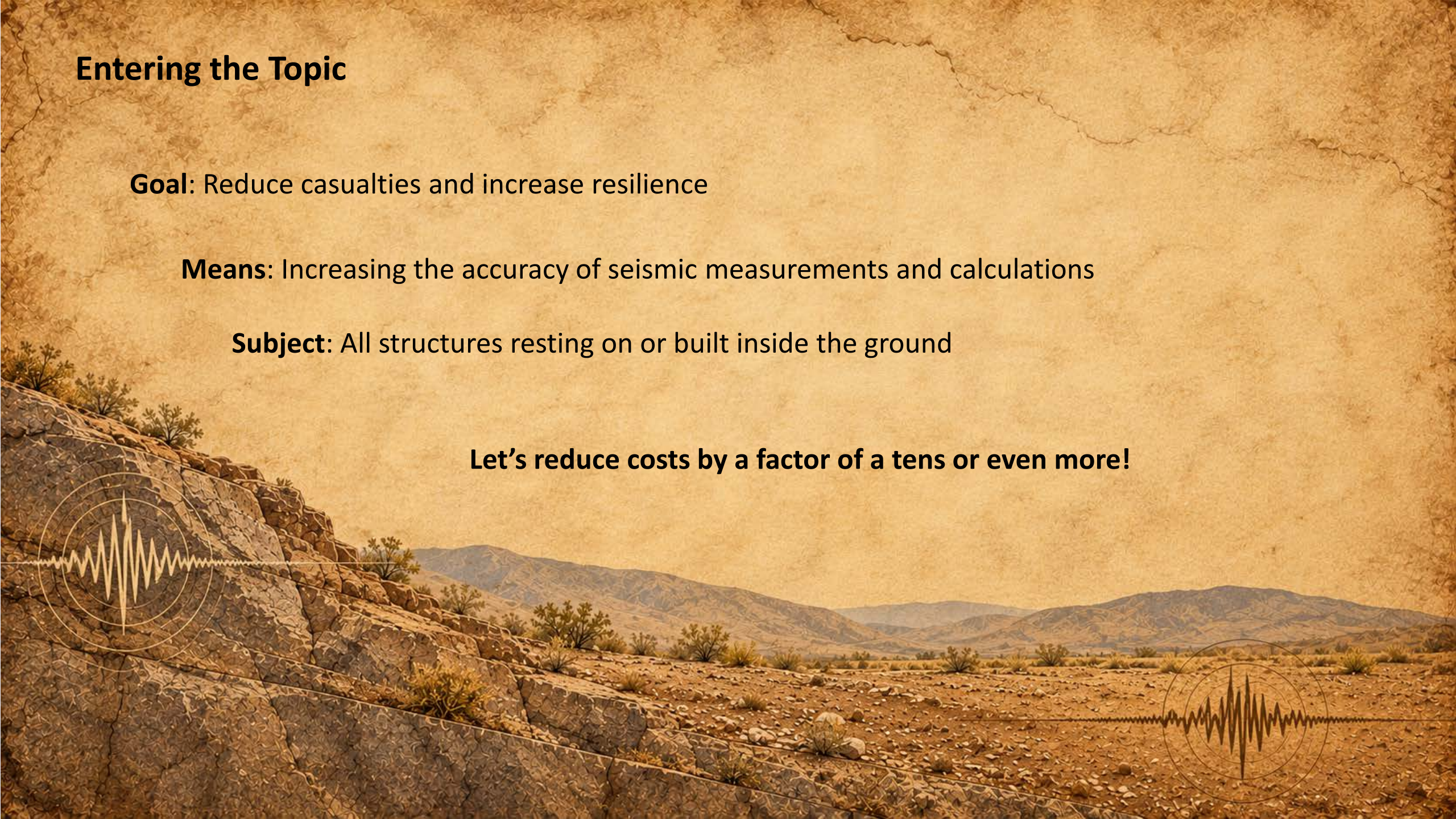
Entering the Topic

Goal: Reduce casualties and increase resilience

Means: Increasing the accuracy of seismic measurements and calculations

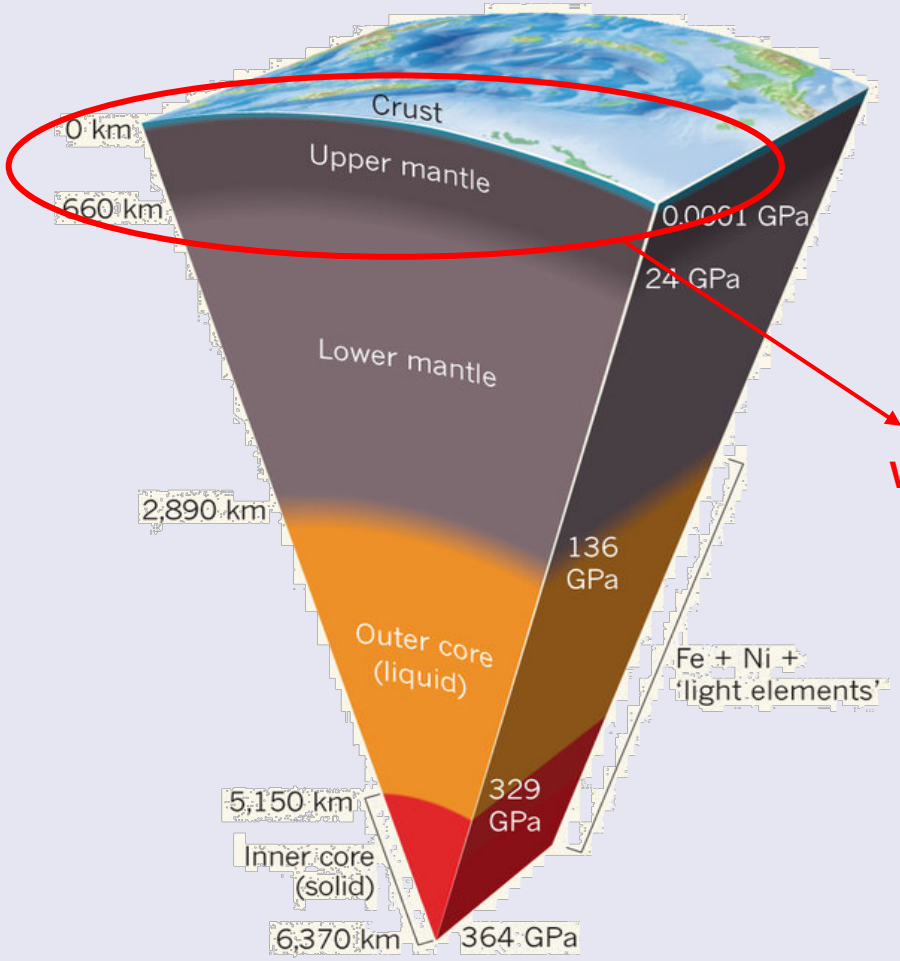
Subject: All structures resting on or built inside the ground

Let’s reduce costs by a factor of a tens or even more!



- Entering the Topic ✓
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- Soil constitutive model in site response analysis

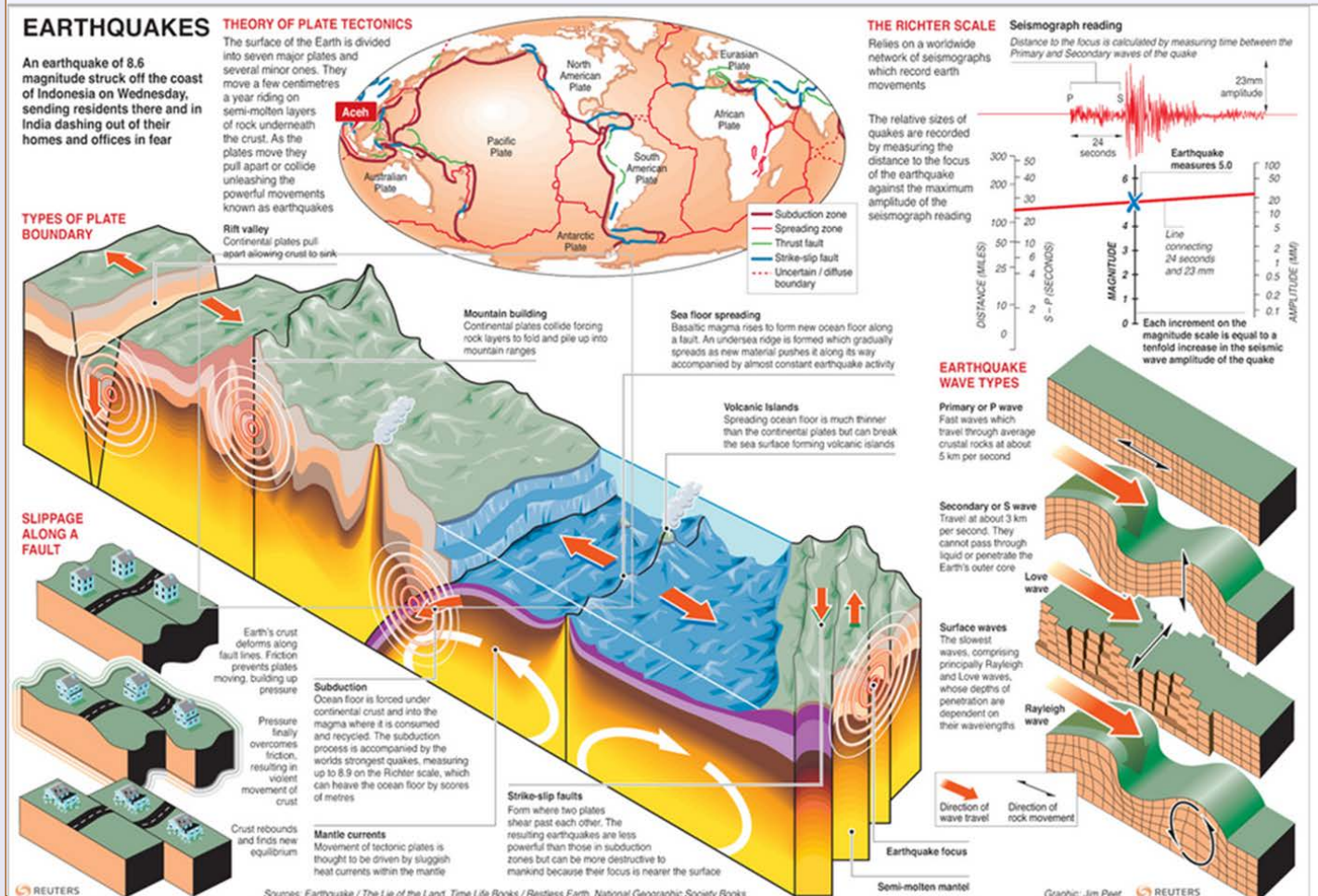
Site Effect



We are here!

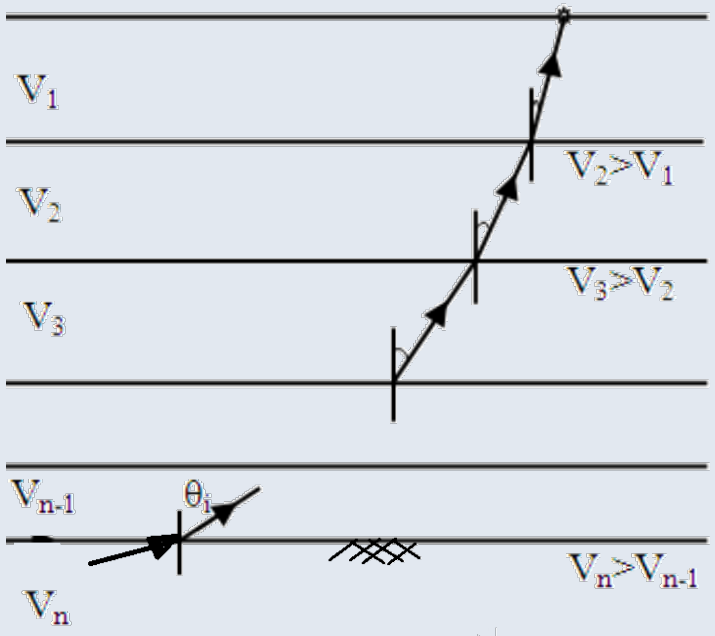
Earthquake

- Source
- Path
- Site

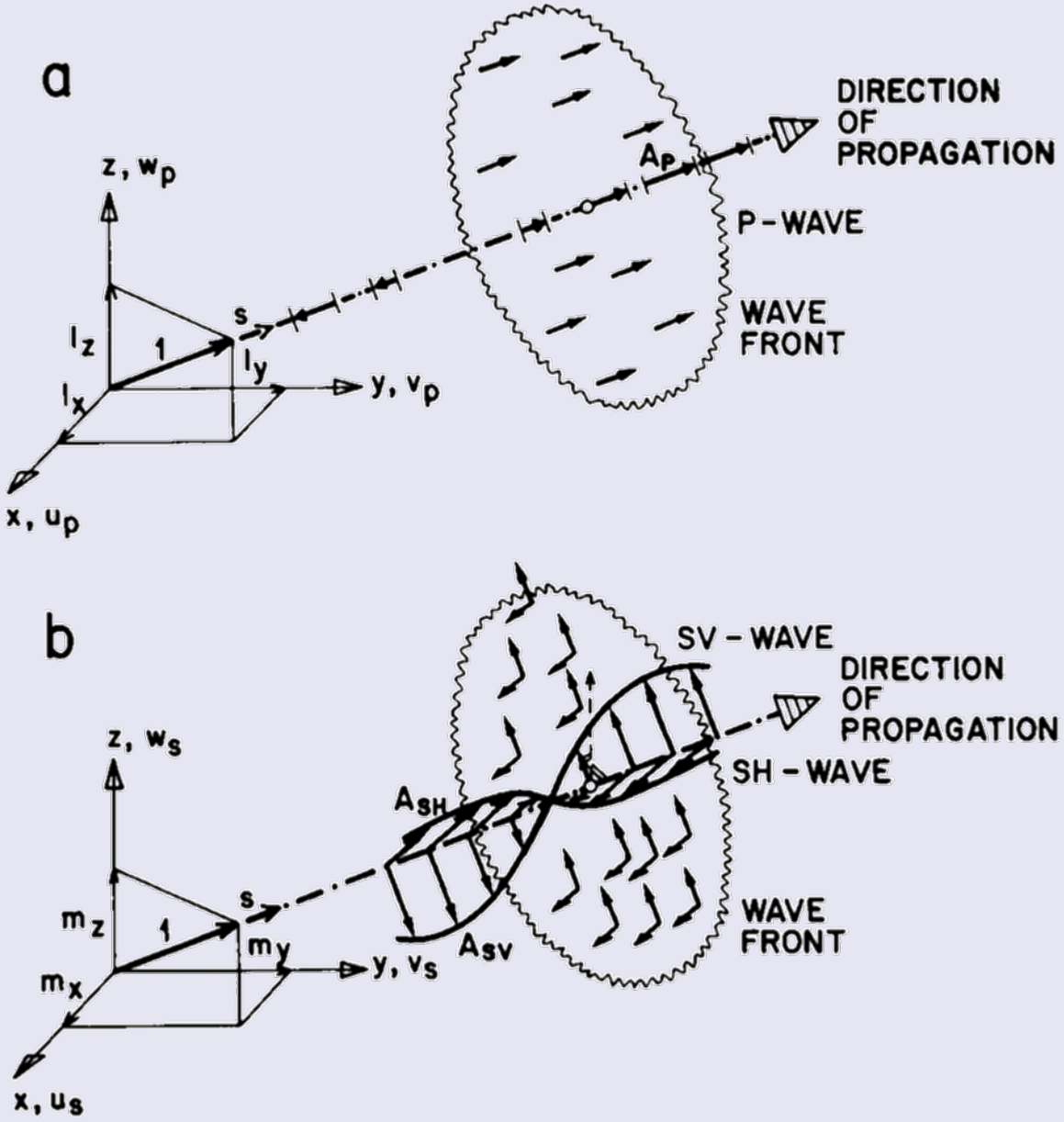


Site Effect

Earthquake — **Source**, **Path**, **Site**



Traveling Body Waves



Sever Inertial Forces

Failures of Retaining Walls Due to Earthquake



Caused by Kobe Earthquake in 1995

Landslide

Wenchuan Earthquake
China



Liquefaction

1964 Niigata earthquake



Surficial Movements



Figure. 1-20 Ground uplift along the fault in the 1999 Chi-Chi Earthquake (Photo by Dr. Farzad Naeim).

Tsunami

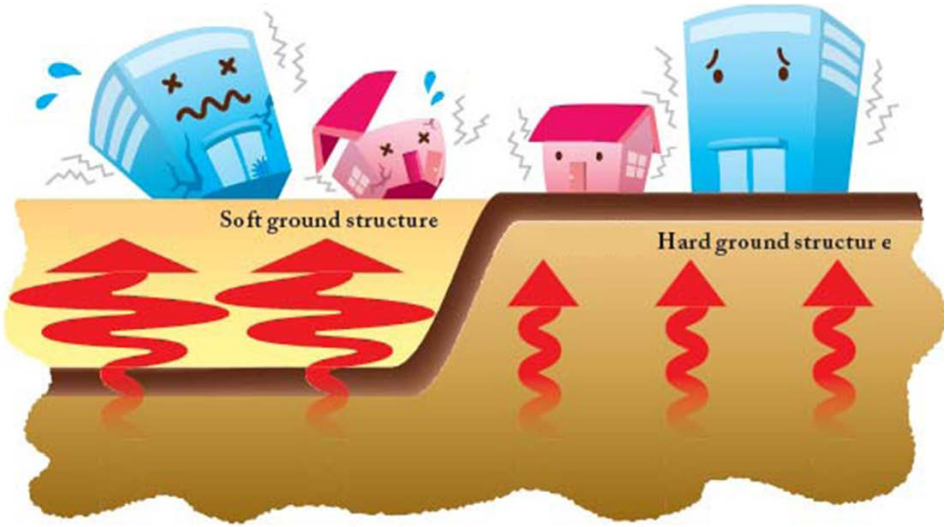


2011 Tohoku Earthquake

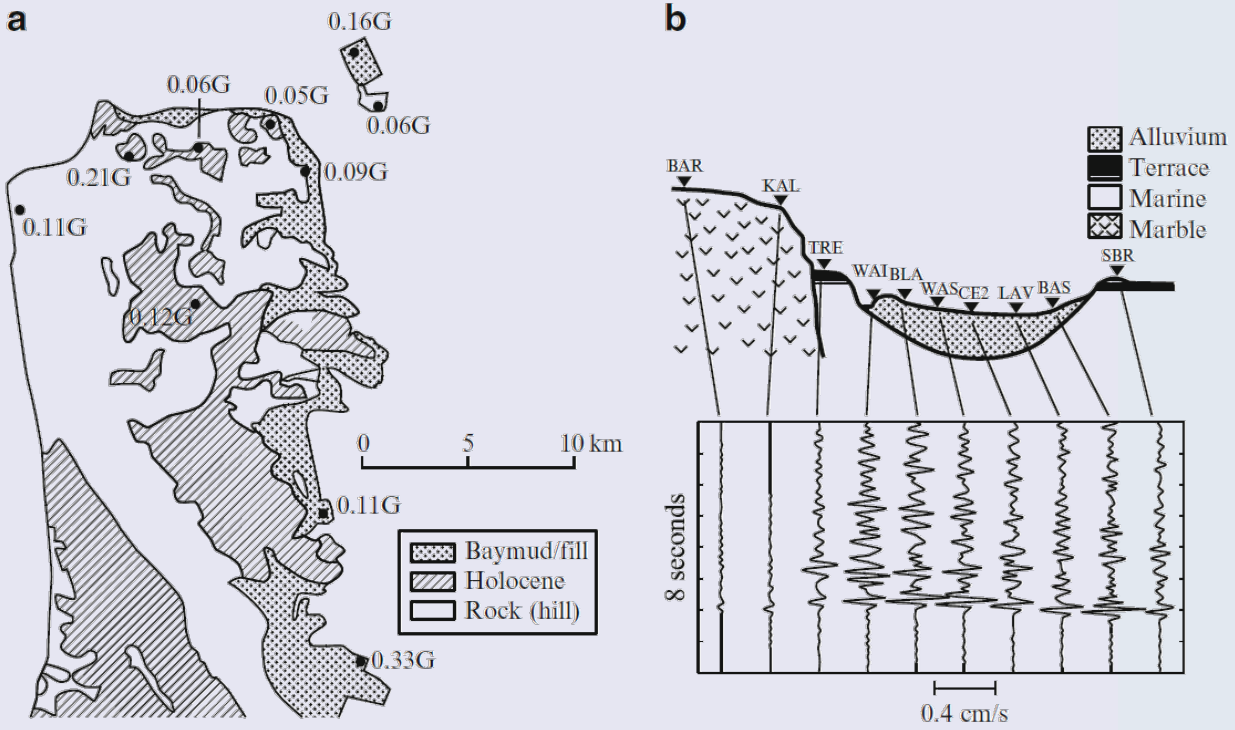


Site Effect

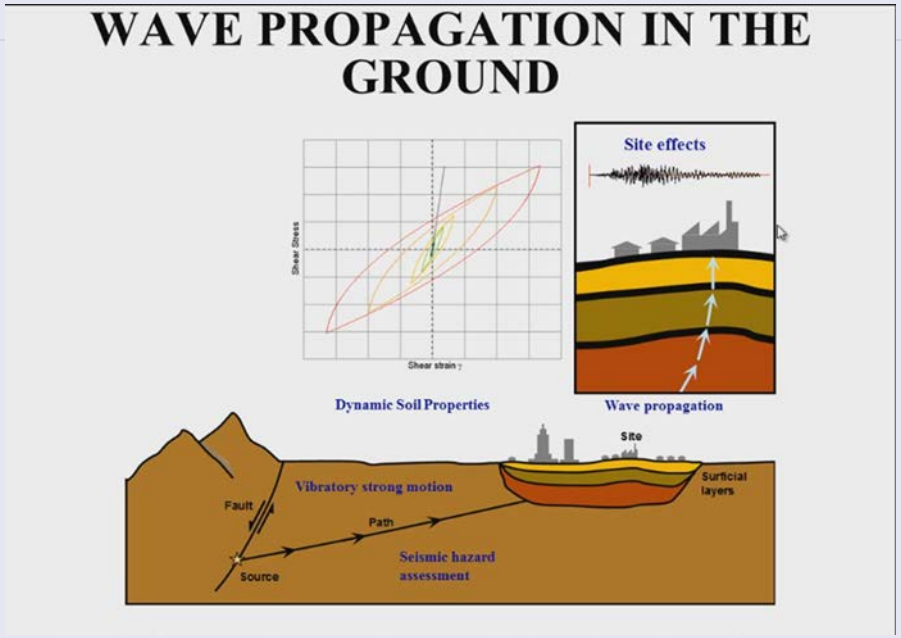


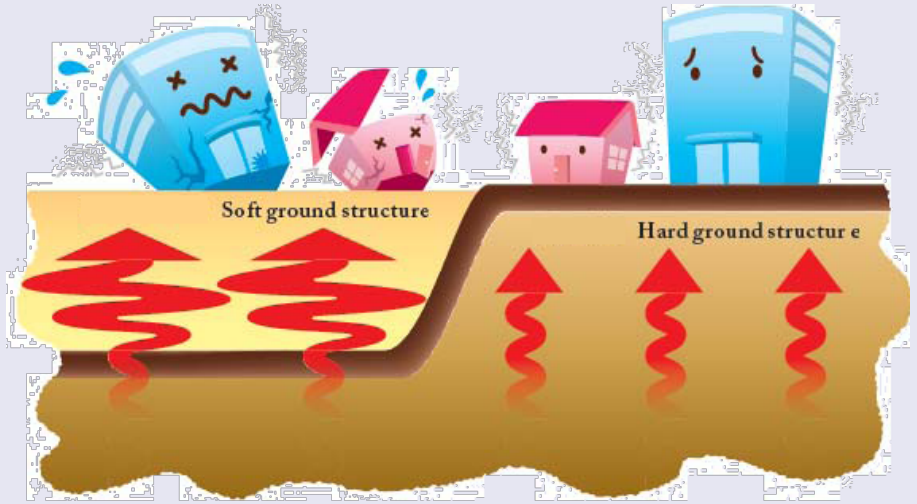


Site Effect

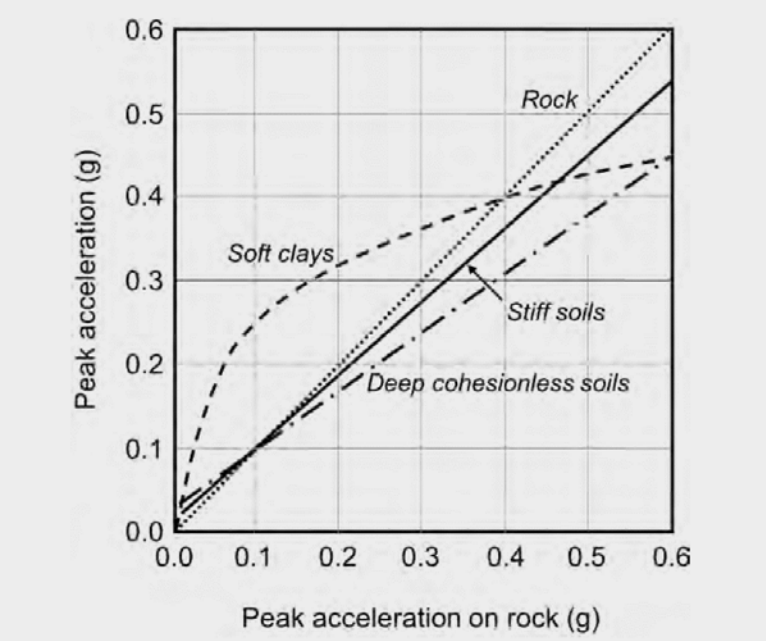


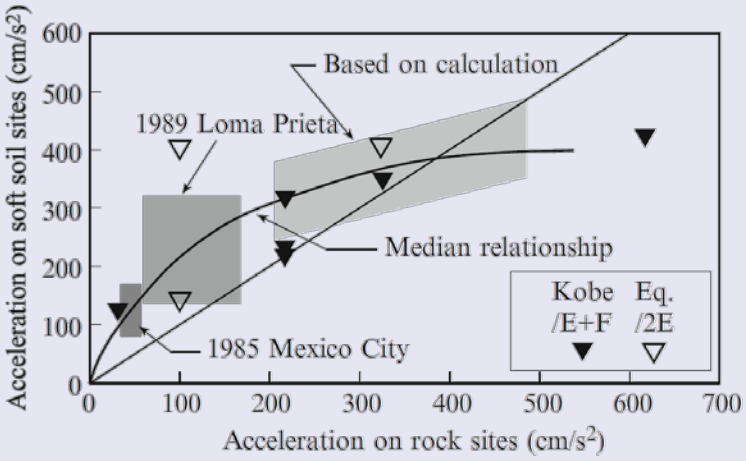
Earthquake observation in the 1989 Loma Prieta earthquake. (**a**) PGA at main shock (Tokyo Prefecture 1990). (**b**) Aftershock (Modified from Kameda 1990)





Site Effect



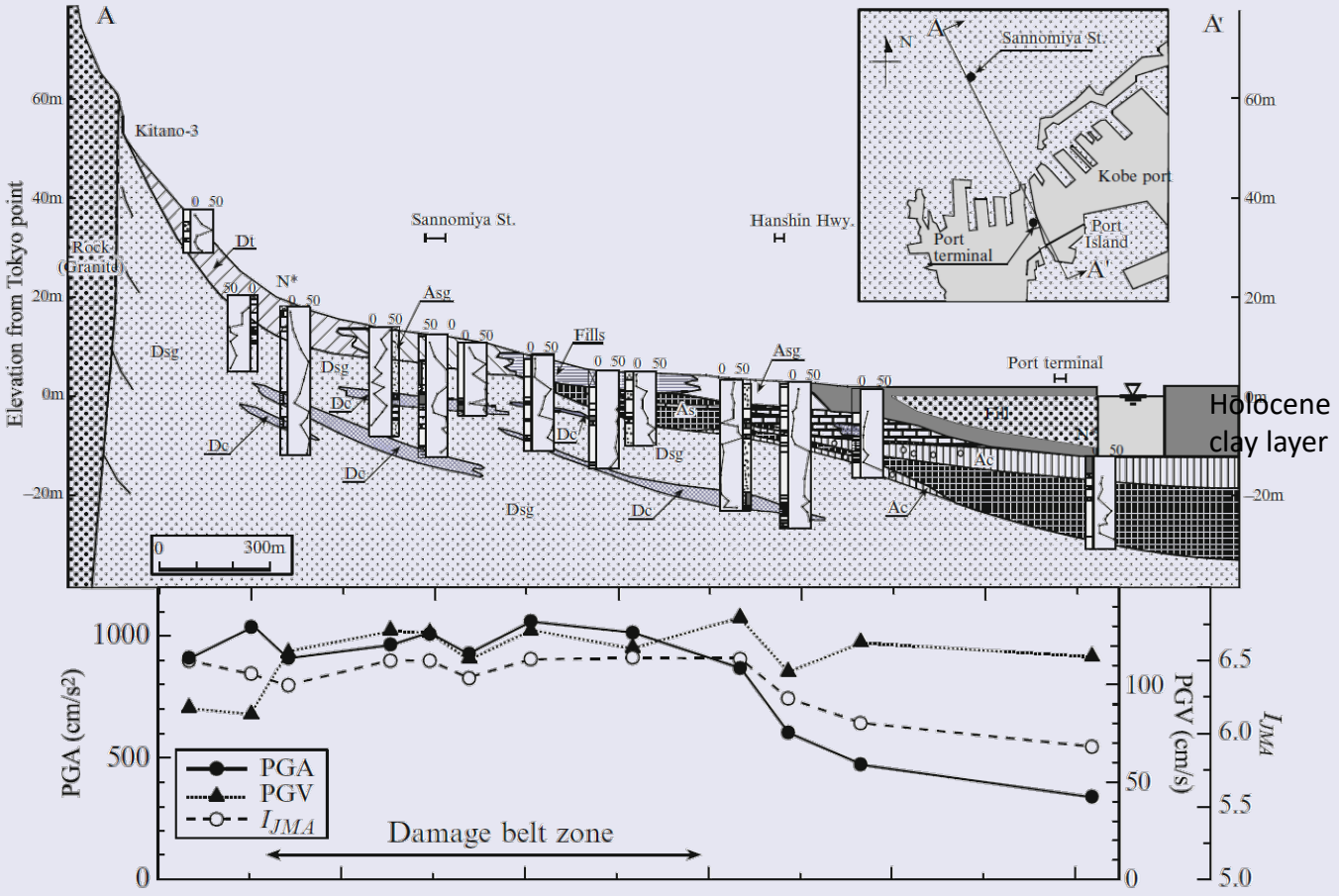


Amplification or Attenuation

1-D Site Response Analysis

Wave propagation from bedrock through soil layers

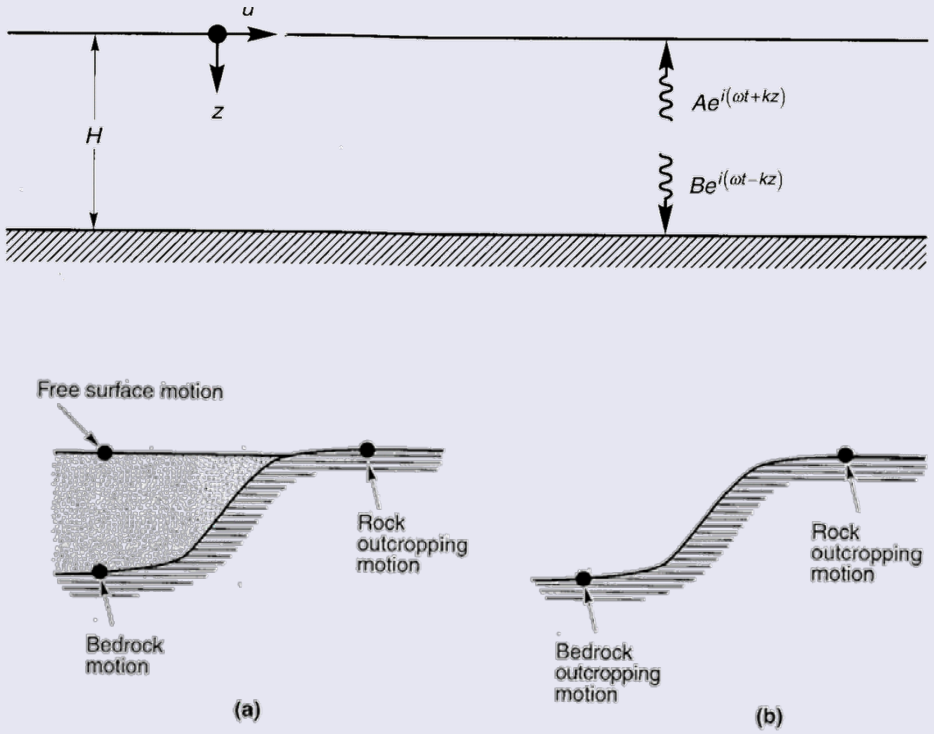
1995 Kobe earthquake



Soil profiles and earthquake motion indices along section passing Sannomiya (Modified from Suetomi and Yoshida 1998)

Site Effect

Damped Soil on Rigid Bedrock

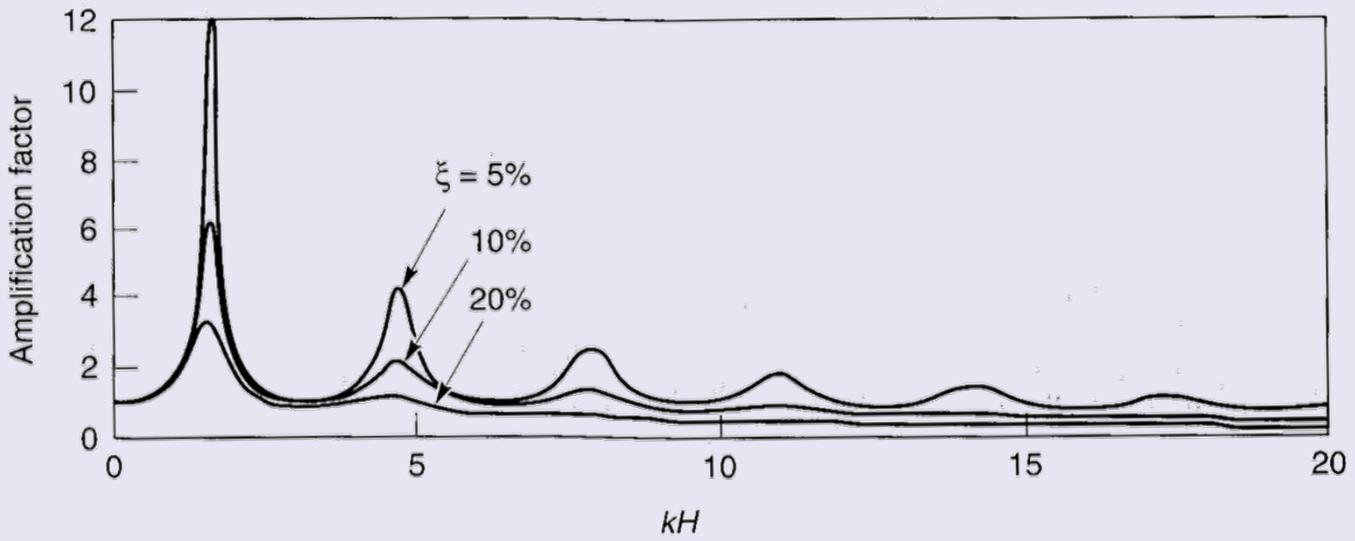


1-D Site Response Analysis

Kelvin-Voigt solid

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial z^2} + \eta \frac{\partial^3 u}{\partial z^2 \partial t}$$

$$|F_2(\omega)| \approx \frac{1}{\sqrt{\cos^2 kH + (\xi kH)^2}} = \frac{1}{\sqrt{\cos^2 (\omega H/v_s) + [\xi(\omega H/v_s)]^2}}$$



Amplification Function

Site Effect

Damped Soil on Elastic Bedrock

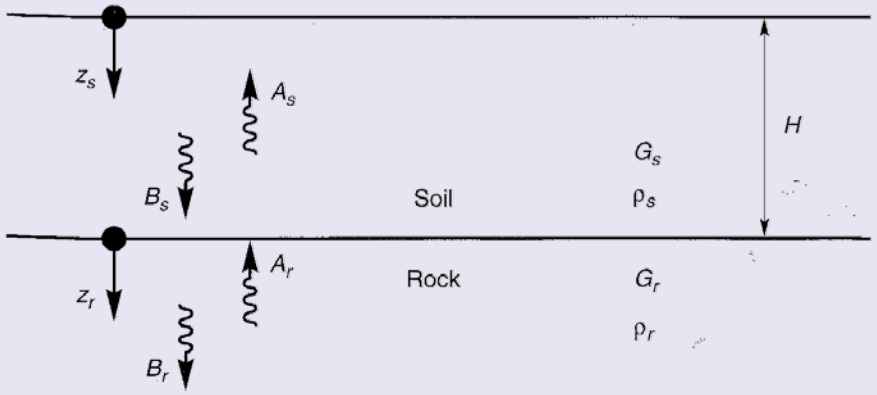
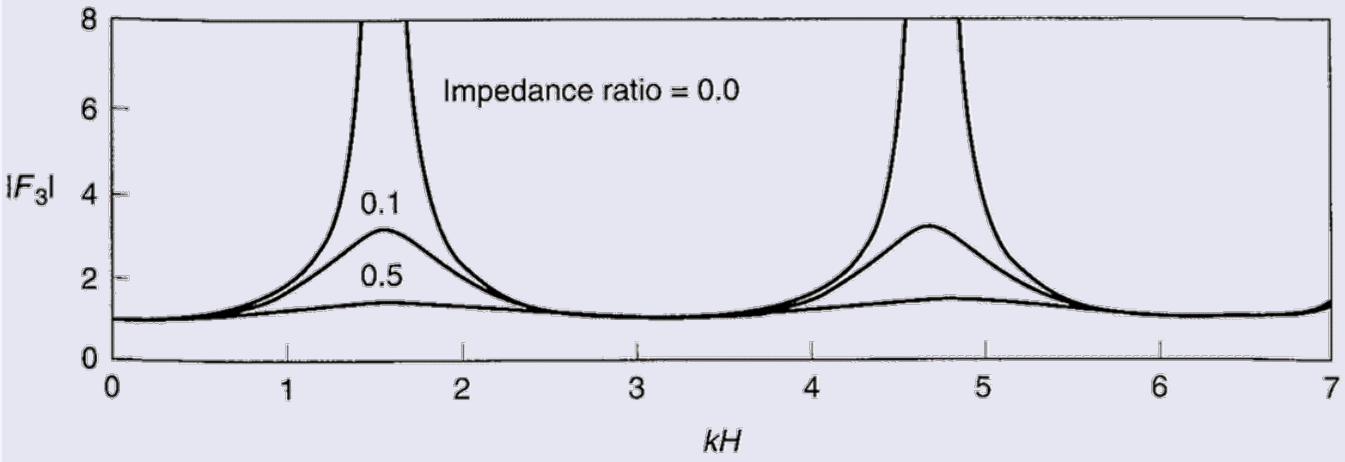


Figure 7.7 Nomenclature for the case of a soil layer overlying a half-space of elastic rock.

1-D Site Response Analysis

Kelvin-Voigt solid

$$|F_3(\omega, \xi = 0)| = \frac{1}{\sqrt{\cos^2 k_s H + \alpha_z^2 \sin^2 k_s H}} \qquad \frac{\rho_s v_{ss}^*}{\rho_r v_{sr}^*} = \alpha_z^*$$



Effect of impedance ratio on amplification factor for case of undamped soil.

Amplification Function

Site Effect

Layered Soil on Elastic Rock

Codes

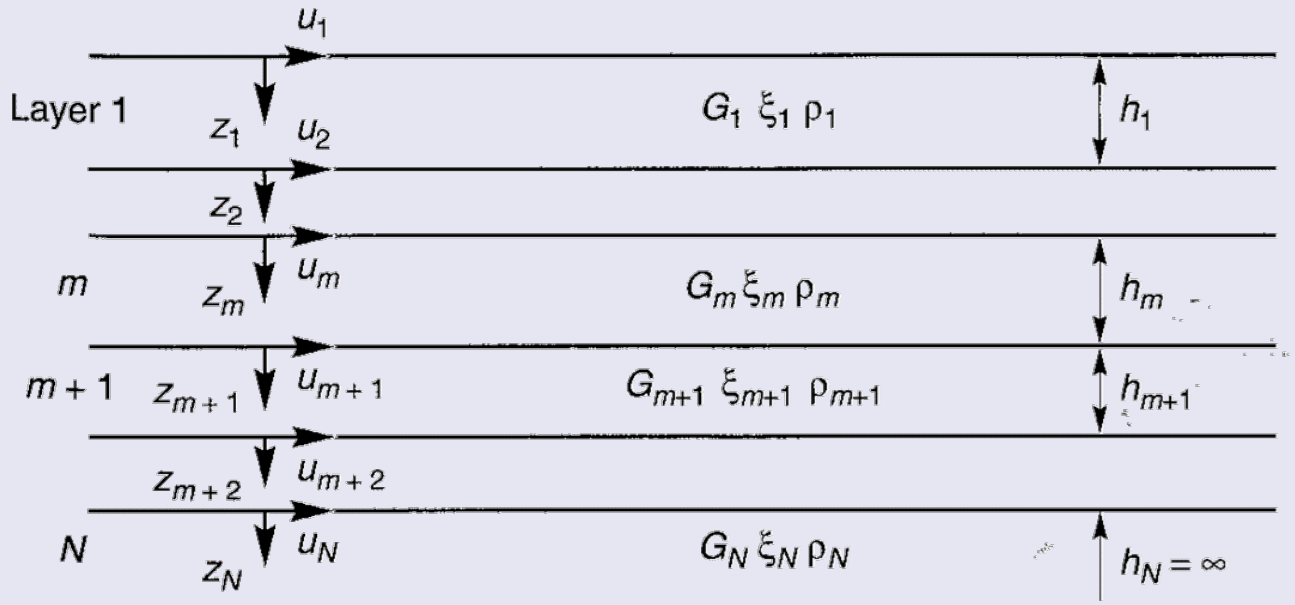
Iranian Journal of Science and Technology, Transactions of Civil Engineering
https://doi.org/10.1007/s40996-023-01232-5

RESEARCH PAPER

A Newly Generated Seismic Ground Response Analysis Software Package -SeisGRASP- by International Institute of Earthquake Engineering and Seismology

Javad Jalili[1] · Mojtaba Moosavi[1] · Shima Pakniat[1]

1-D Site Response Analysis



Nomenclature for layered soil deposit on elastic bedrock.

Site Effect

Layered Soil on Elastic Rock

Codes

Iranian Journal of Science and Technology, Transactions of Civil Engineering
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1-D Site Response Analysis

Site response analysis software used in highway engineering practice (Matasovic and Hashash 2012)

No	Software	Website	References
1	SHAKE2000	http://www.geomotions.com	Ordonez (2000)
2	PROSHAKE	http://www.proshake.com	EduPro Civil Systems (1999)
3	D-MOD2000	http://www.geomotions.com	Matasovic (2006) (D-MOD_2); Matasovic and Ordonez (2008)
4	DEEPSOIL	http://deepsoil.cee.illinois.edu	Hashash and Park (2001; 2002), Hashash et al. (2011)
5	CyberQuake	http://www.brgni.fr	Modaressi and Foerster (2000)
6	OpenSees	http://opensees.berkeley.edu	Ragheb (1994); Parra (1996); Yang (2000)
7	SIREN	http://www.oasys-software.com/products/seismic/siren/	Oasys (2006); Heidebrecht et al. (1990,1991)
8	FLAC	www.itascacg.com	Itasca (2005)
9	PLAXIS	http://w ww.plaxis.nl	PLAXIS-B.V. (2002)
10	ABAQUS	http://www.abaqus.com	ABAQUS (2005)
11	TNO Diana	http://www.midas-diana.com/gts/	MIDAS (2008)
12	VERSAT 1-D	http://www.wutecgco.com/v-2d.htm	Wu (2010)
13	VERSAT 2-D	http://www.wutecgeo.com/v-2d.htm	Wu (2010)
14	QUAKE/W	www.geo-slope.com	GSI (2006)
15	EERA	http://gees.usc.edu/GEES/Software/EERA2000/Default.htm	Bardet et al. (2000)
16	NERA	http://gees.usc.edu/GEES/Software/NERA/2001/Default.htm	Bardet and Tobita (2001)
17	QUAD4M	http://nisee.berkeley.edu/elibrary/getpkg?id=QUAD4	Idriss et al. (1973); Hudson et al. (1994)
18	Cyclic 1-D	http://cyclic.ucsd.edu/	Elgamal et al. (2004)
19	DESRAMUSC		Qiu (1997)
20	SHAKE91		Idriss and Sun (1992)
21	LS Dyna		LSTC (1988)
22	Dyna 1-D		Prevost (1989)
23	DESRAMOD		Vucetic (l986)
24	TESS		Pyke (2000)
25	D-MOD		Matasovic (1993)
26	PSNL		Kramer (2010)
27	SPECTRA		Borja and Wu (1994)
28	AMPLE		Pestana and Nadim (2000)
29	SUMDES		Li et al. (1992)
30	DYSAC2		Muraleetharan et al. (1991)
31	FLUSH		Lysmer et al. (1975)
32	MASH		Martin and Seed (1978a)
33	SUPER SASSI		SAI (1995)
34	SASSI2000	http://nisee.berkeley.edu/elibrary/Text/200703021	N1SEE—Univ. of California, Berkeley
35	PLAXIS 3D	http://www.plaxis.nl	PLAXIS-B.V. (2002)
36	TARA-2		Finn and Yogendrakumar (1987)
37	WinMOC		Ray (2008)
38	MARDESRA		Martin (1990), Personal Communication
39	WAVES		Hart and Wilson (1989)
40	CHARSOIL		Liouetal. (1977)
41	UFSHAKE		Urzua (1995), Personal Communication
42	SAF-DYNA		Urzua (1995), Personal Communication
43	DYNAFLOW		Prevost (1998), Personal Communication
44	LIQCA		No Information
45	Dyneq		No Information
46	FLIP		No Information
47	ShearBeam		No Information

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Factors affecting site response analysis

Geotechnical Issues

Layer geometry

Thickness, groundwater depth

General properties

Unit weight, OCR, PI, K0, C, ϕ

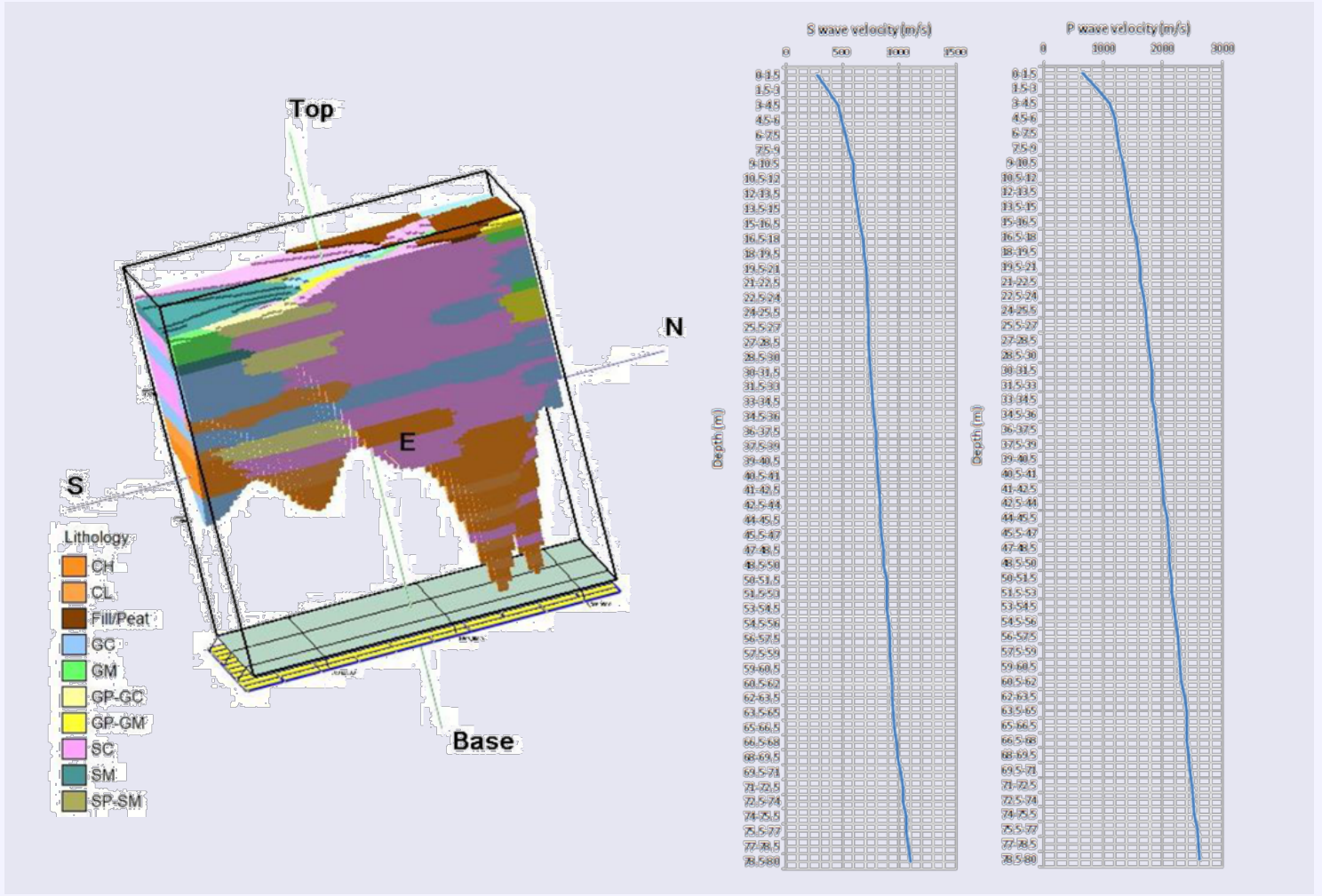
Dynamic properties

Measured or defensible shear-wave velocities, with uncertainty carried into the model
Modulus reduction and damping curve

Seismic Bedrock

Where to place the input motions?

Journey to the Depths of the Earth, to meet the seismic bedrock!



Factors affecting site response analysis

Geotechnical Issues

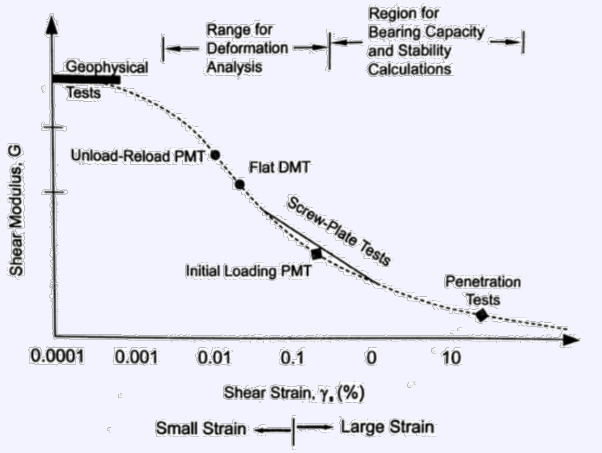
Laboratory Tests

Small Strain
Non-Linear Strain

Field Tests

Seismic Geophysical Survey
Microtremor

Empirical estimations



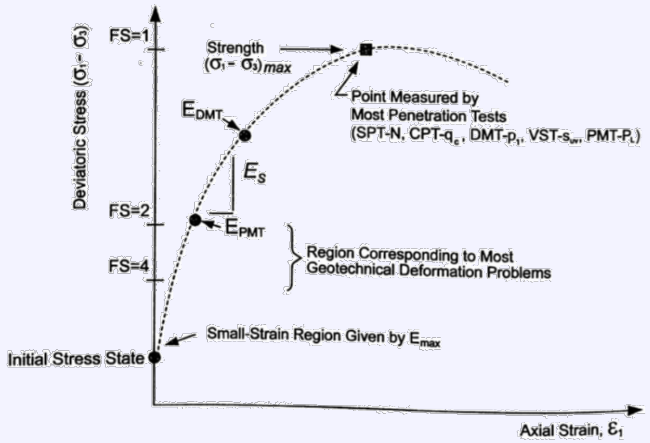
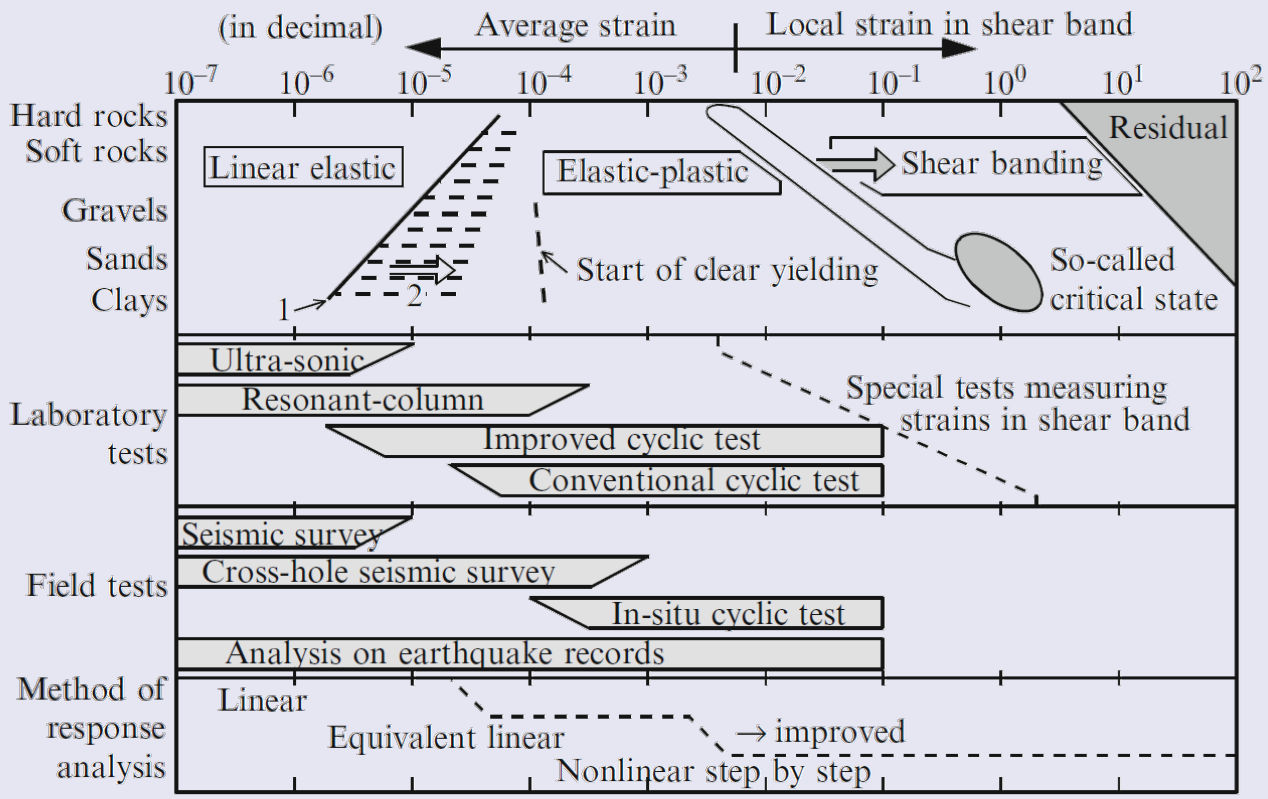


Figure 11.2 Variation of modulus with strain level (Sabatani et al., 2002).



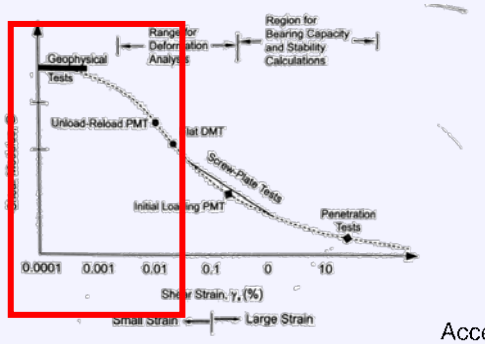
1. For normally consolidated soils subjected to monotonic loading
2. Increases as OCR increases and with cyclic loading

Factors affecting site response analysis

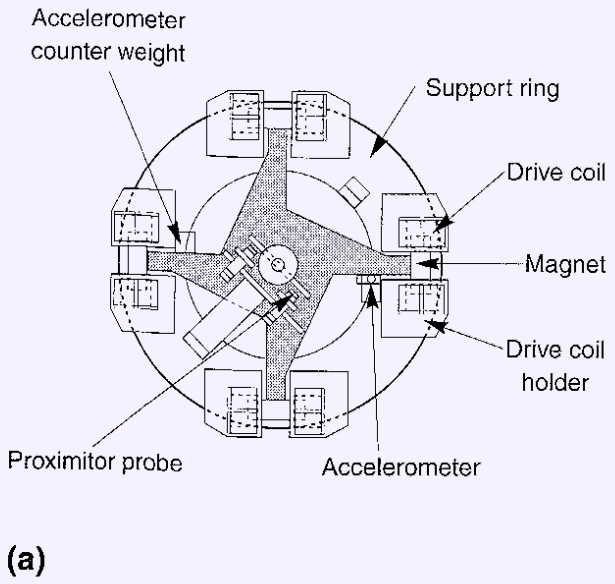
Geotechnical Issues

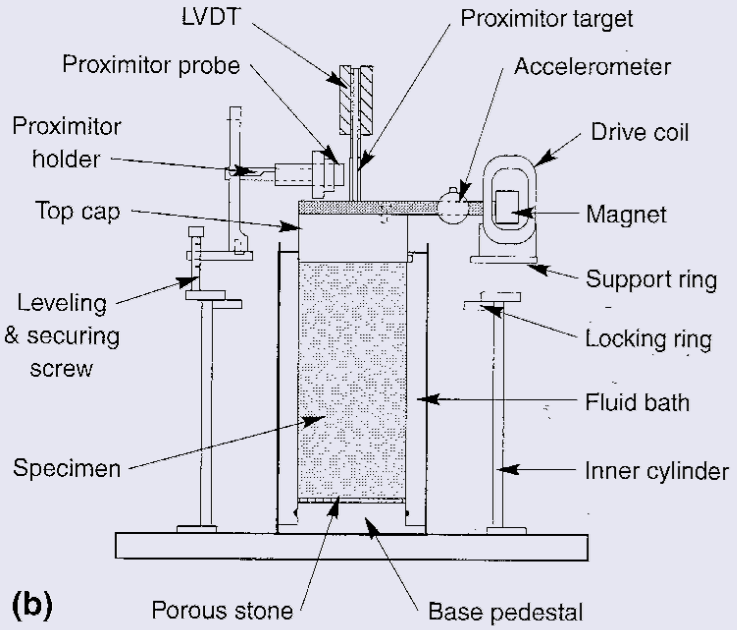
Laboratory Tests

Small Strain



Resonant Column





Bender Element

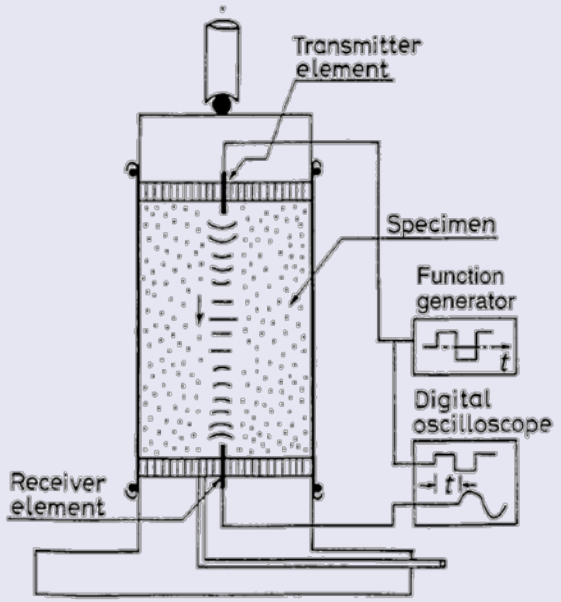


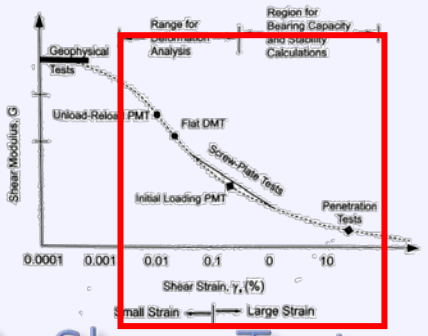
Fig. 4.13 Use of bender elements in the triaxial test apparatus.

Factors affecting site response analysis

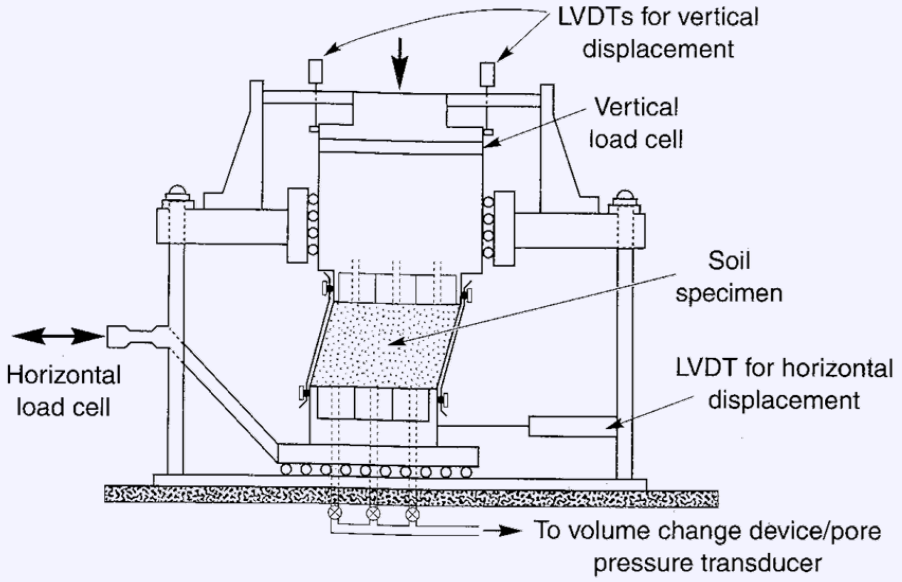
Geotechnical Issues

Laboratory Tests

Large Strain



Cyclic Simple Shear Test



Cyclic Triaxial

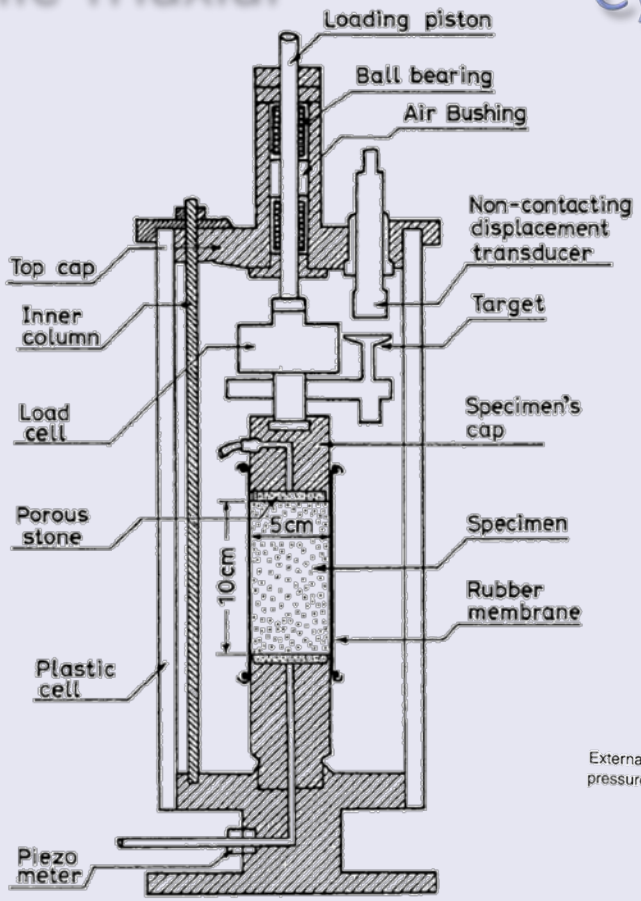
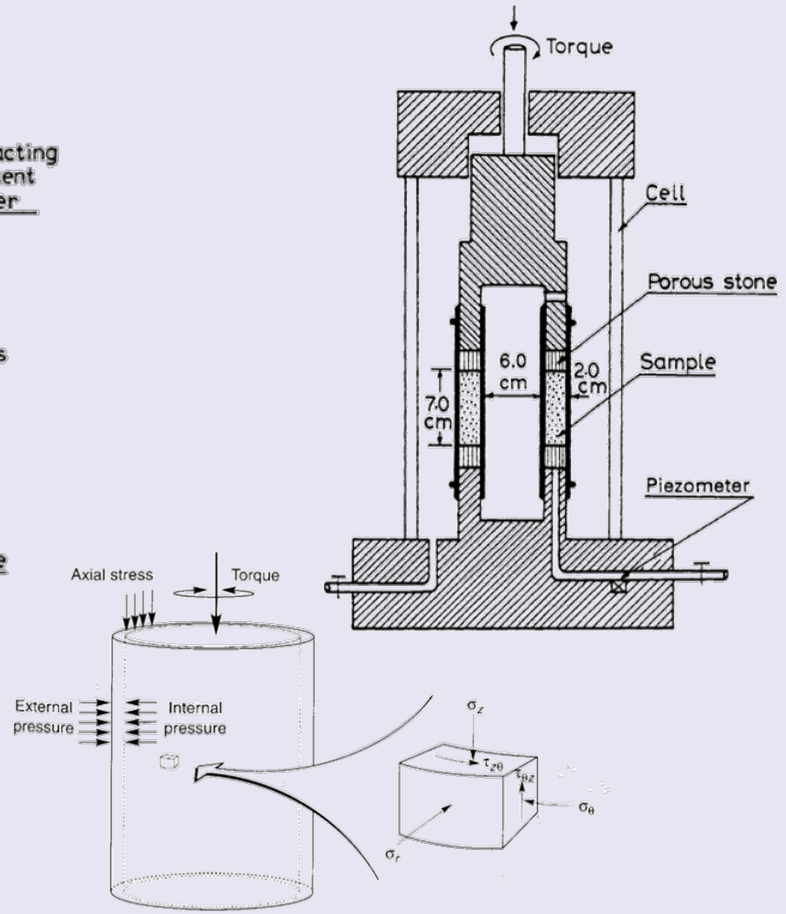


Fig. 4.1 Triaxial test apparatus.

Cyclic Torsional Shear Test

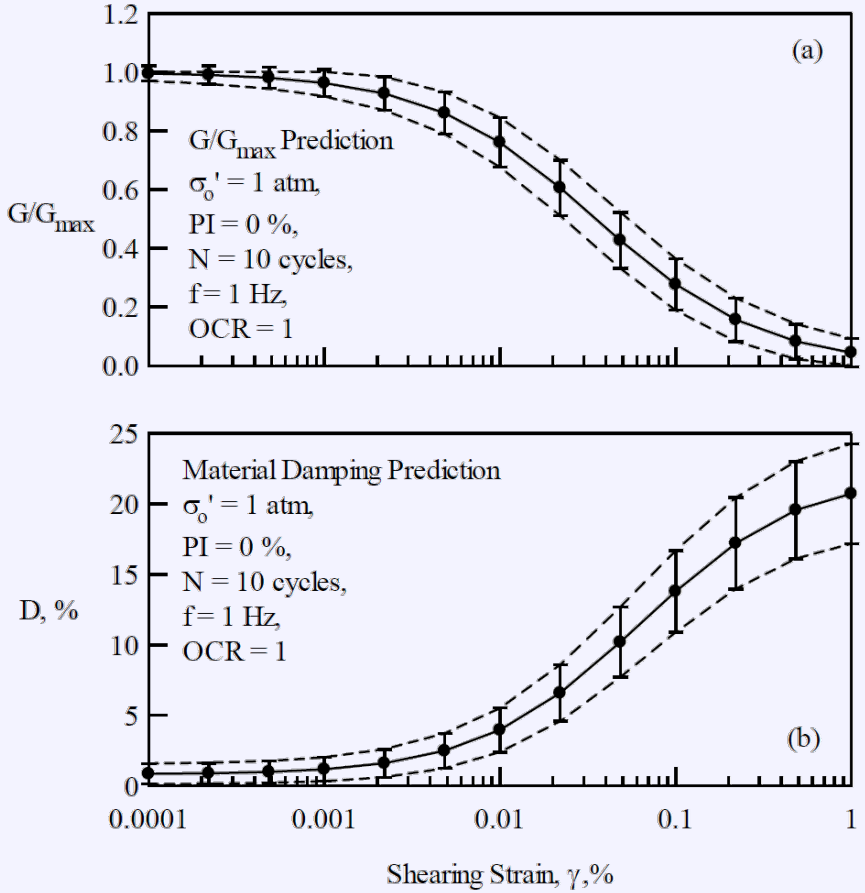


Factors affecting site response analysis

Geotechnical Issues

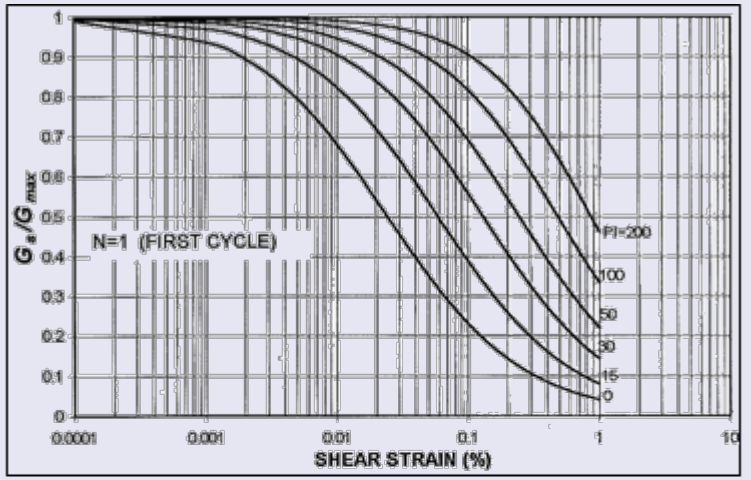
Empirical estimations

Large Strain

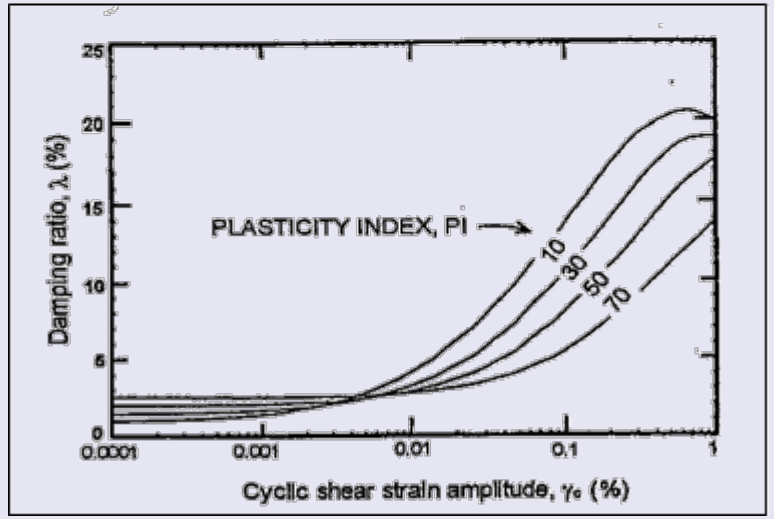


Darendeli, 2001

Presented curves correspond to relatively constant rate of straining for all γ_c (Doroudian and Vucetic, 1997)



Damping ratios at small γ_c are correctly presented (EPRI report, 1993 – suggested by Pyke after Vucetic, 1986)



Factors affecting site response analysis

Geotechnical Issues

Seismic Bedrock

Seismic Refraction, Down-hole, Microtremor

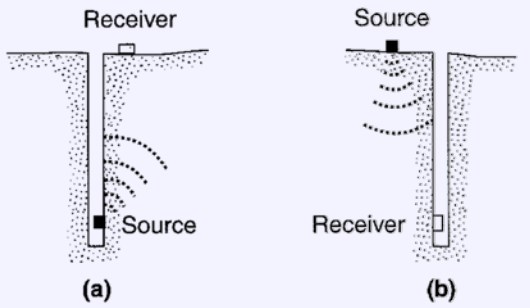
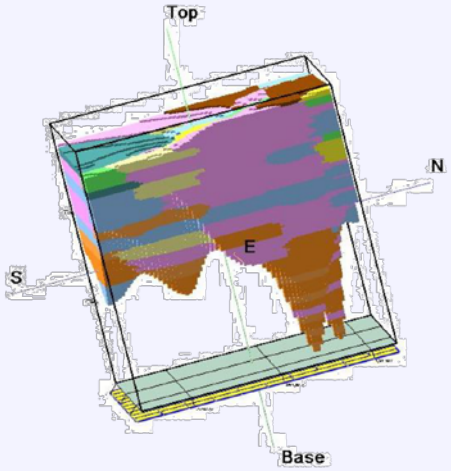
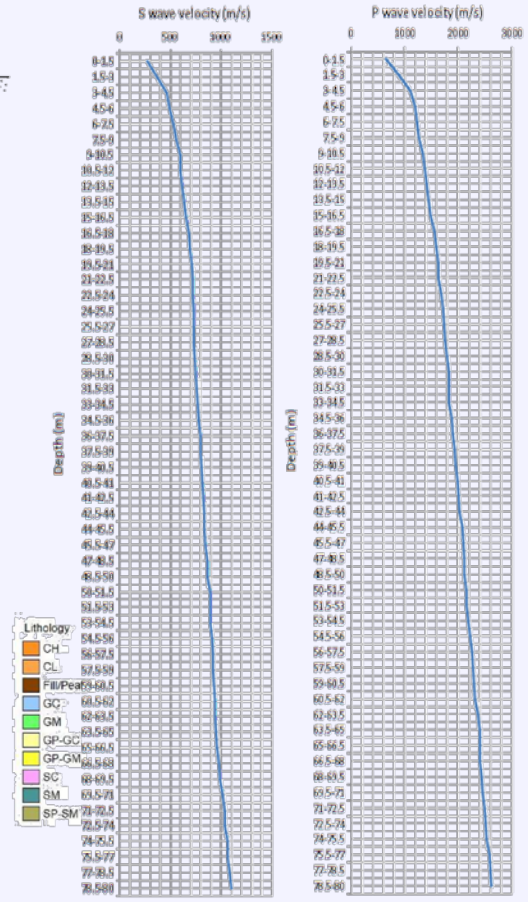
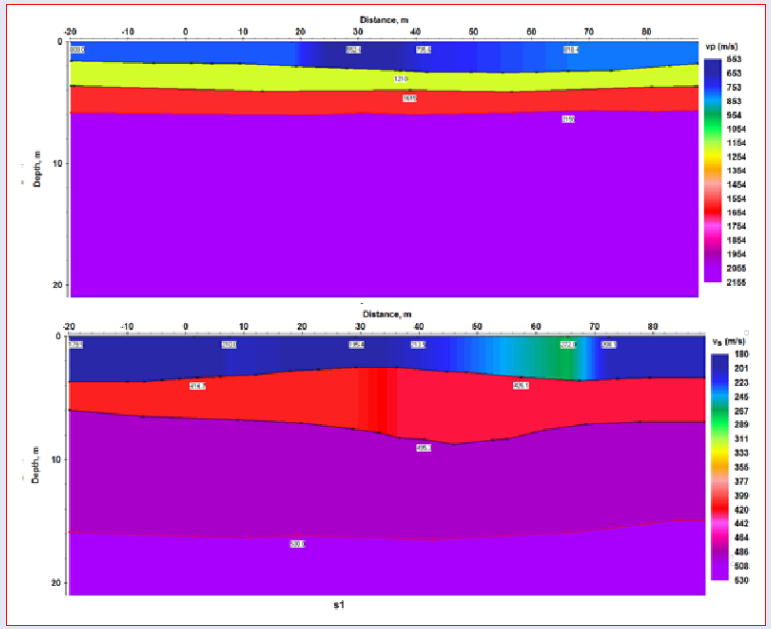


Figure 6.22 (a) Seismic up-hole test, and (b) seismic down-hole test.







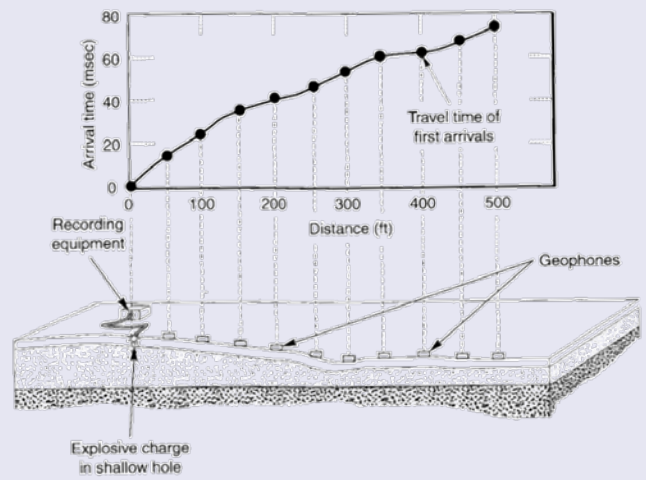


Figure 6.11 Seismic refraction test setup. (After Redpath, 1973.)

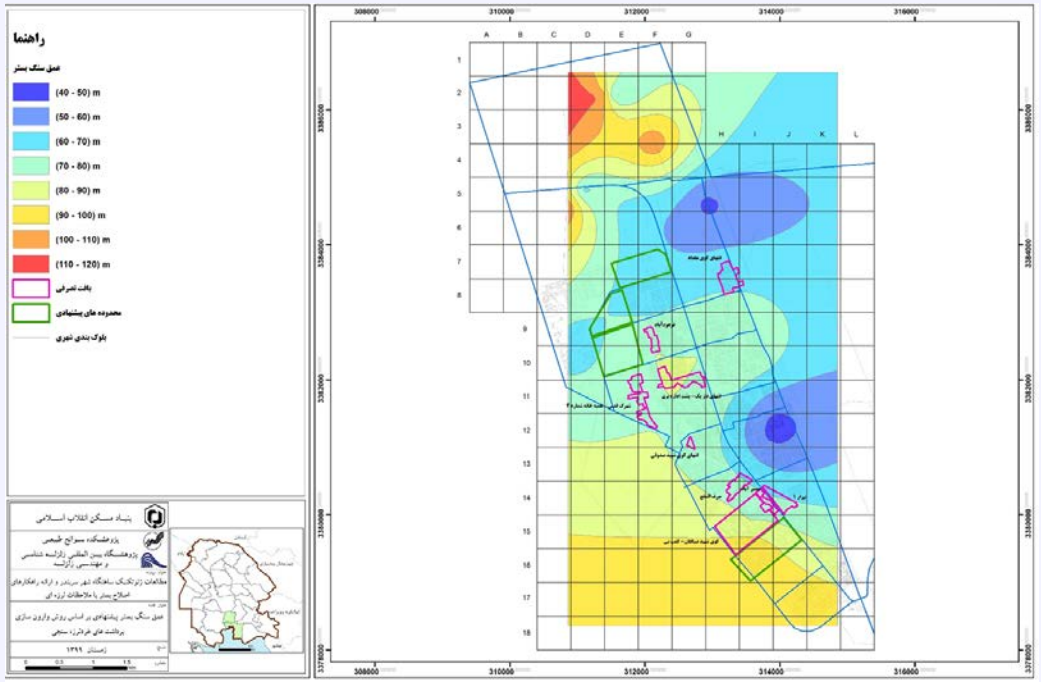


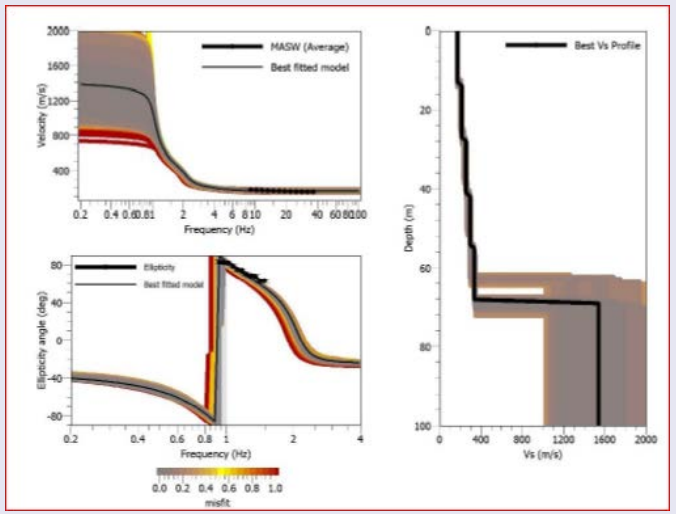
Factors affecting site response analysis

Geotechnical Issues

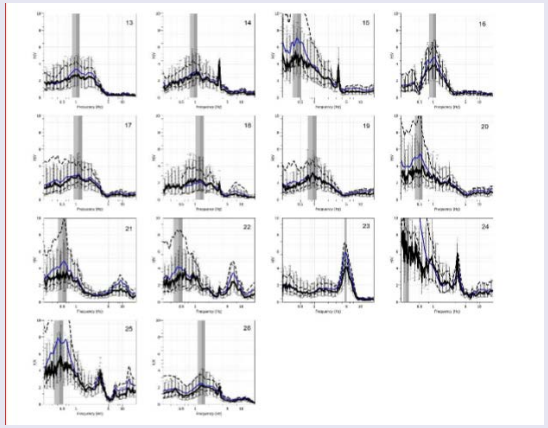
Seismic Bedrock

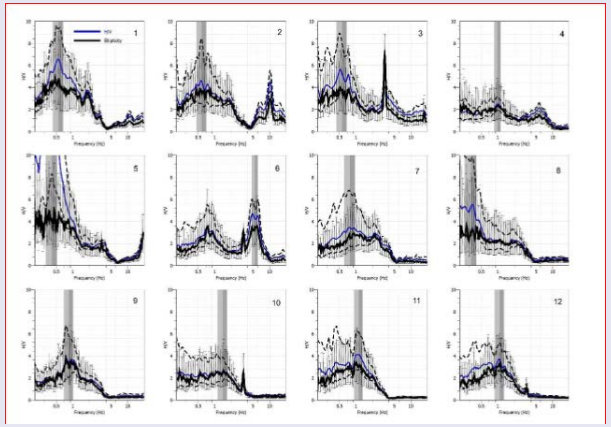
Microtremor





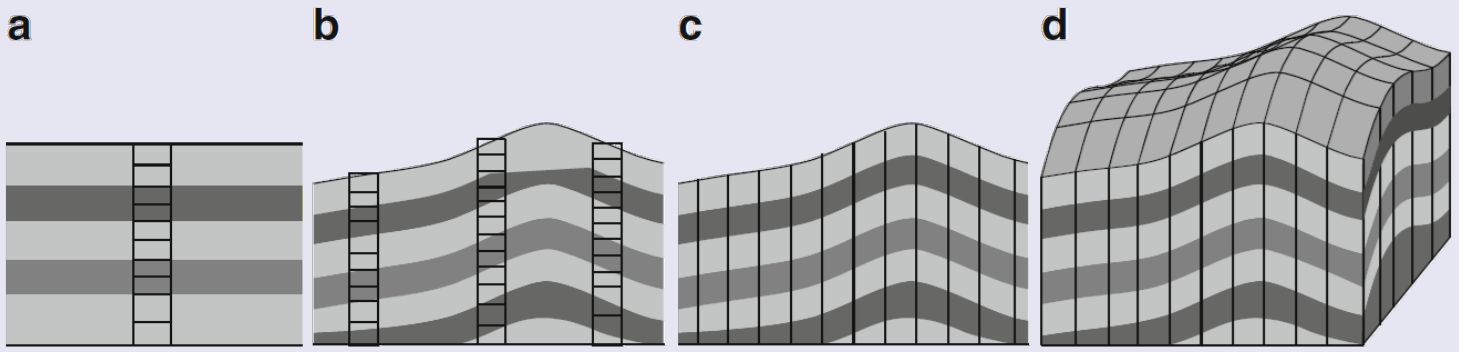




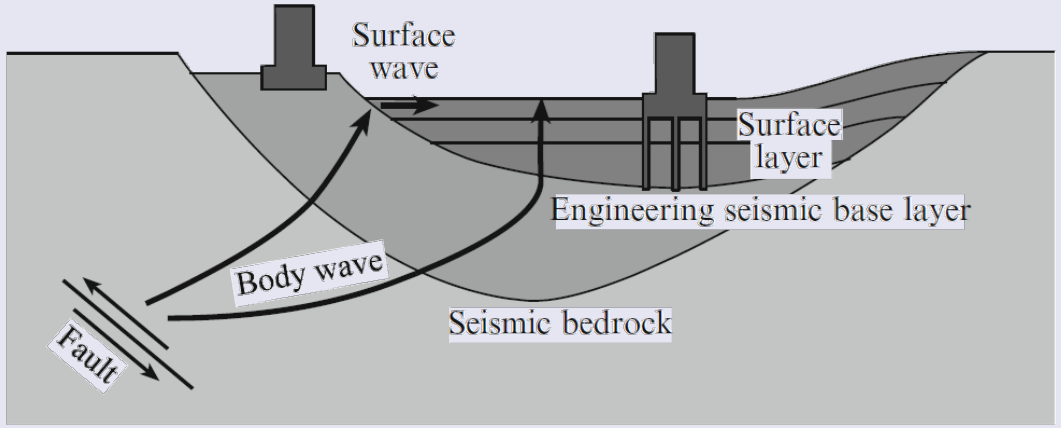


Factors affecting site response analysis

Dimensionality



Various modeling of ground. (**a**) Horizontal. (**b**) One dimension. (**c**) Two dimension. (**d**) Three dimension



- Entering the Topic ✓
- Theoretical background ✓
- Factors affecting site response analysis ✓
- Site Response Analysis and Resilience ⟸
- Regulations
- Some Examples
- Codes and Events
- Soil constitutive model in site response analysis

Cost and Benefit

Site Response Analysis and Resilience

Imagine if the buildings were not damaged!



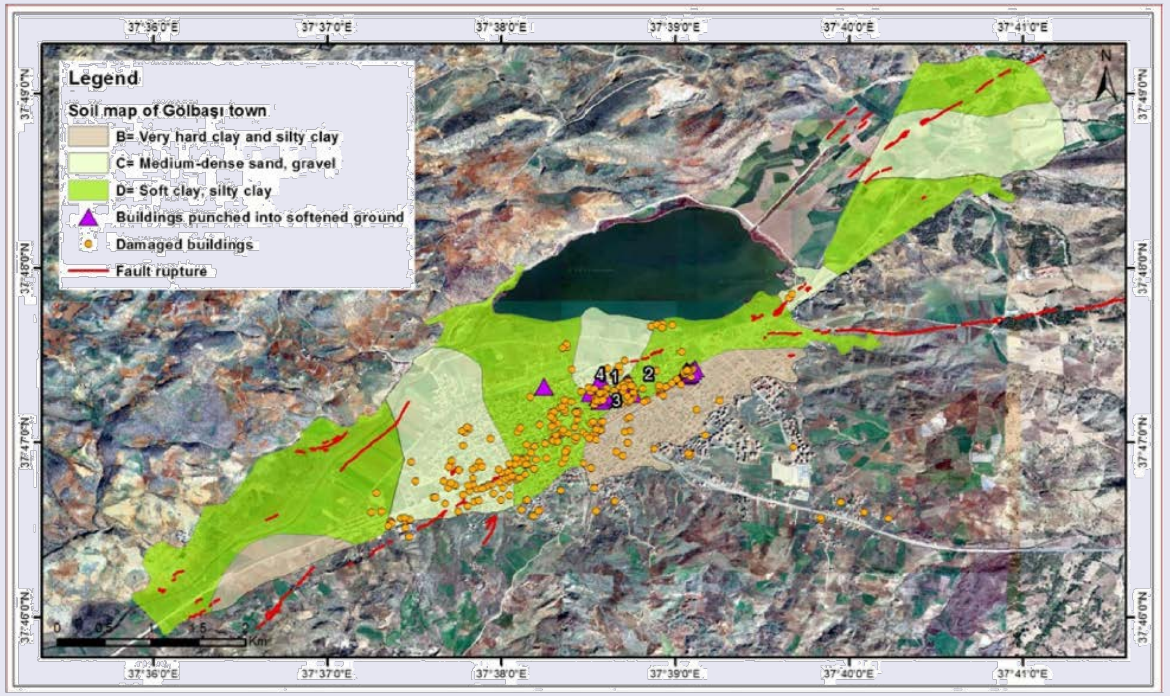
Buildings subjected to excessive foundation tilting (district 12).

Bakir, B. S., Sucuoglu, H., & Yilmaz, T. (2002). An overview of local site effects and the associated building damage in Adapazari during the 17 August 1999 Izmit earthquake. Bulletin of the Seismological Society of America, 92(1), 509-526.

Cost and Benefit

Site Response Analysis and Resilience

Imagine if the buildings were not damaged!



Location of site mostly covered by thick clayey soils around Gölbaşı in Türkiye



Buildings punched into the ground softened by the Türkiye–Syria earthquake, located in areas that are covered with clayey soils

Jalili, J., Moosavi, M., Safari, S., Haghshenas, E., Jafari, M. K., Askari, F., ... & Rakhshandeh, M. (2026). Investigation of cyclic softening hazard of low-plastic clays: two case studies–northern and southern Iran. Asian Journal of Civil Engineering, 1-20.

Cost and Benefit

Site Response Analysis and Resilience

Imagine if the buildings were not damaged!

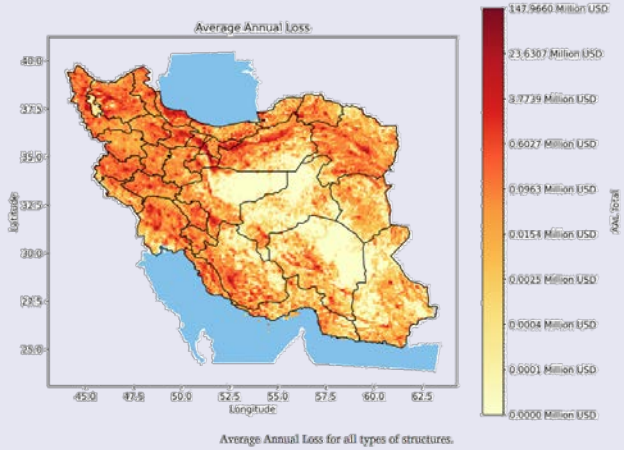
Benefit

probabilistic seismic-risk modelling:

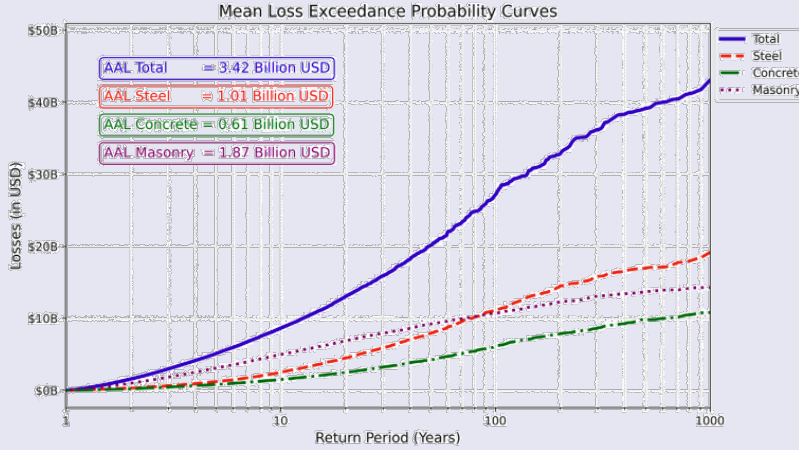
- Annual **repair and reconstruction losses** for Iran's residential buildings :approximately **USD 2.7 billion**
- The cost of **upgrading buildings during reconstruction included**: the estimate rises to approximately **USD 3.3 billion**

Shahbazi, P., et al. (2020). Introducing loss transfer functions to model seismic financial loss: A case study of Iran. International Journal of Disaster Risk Reduction, 51, 101883.https://doi.org/10.1016/j.ijdrr.2020.101883

Benefit



Average Annual Loss for all types of structures.



Mean loss exceedance probability curve for residential units.

Shahmohammadian, A., Ghafory-Ashtiany, M., Mansouri, B., Motamed, H., & Nasserasadi, K. (2025). FiCat-EQ: An integrated system-based tool for assessing financial vulnerability and economic impact of seismic risk, case study: Housing sector of Iran. *International Journal of Disaster Risk Reduction*, *123*, 105474.

Cost and Benefit

Site Response Analysis and Resilience

Imagine if the buildings were not damaged!

Cost

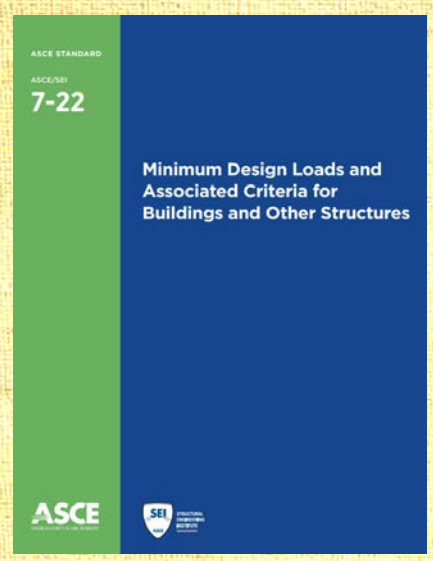
- ~ 10% Increase in Construction cost
- Conventional geotechnical investigation: drilling, sampling and testing required for foundation design;
- Additional seismic characterization: Vs measurements, engineering-bedrock depth;
- Site-response analysis: dynamic soil modelling and calculation of surface ground motion and response spectra.

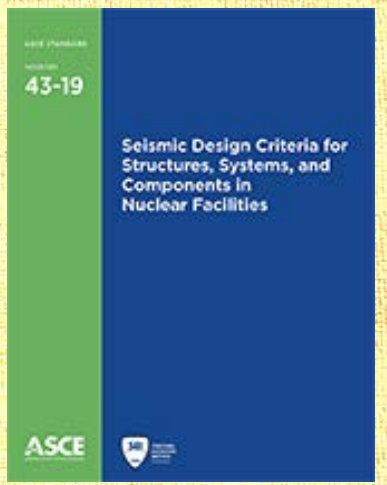
- Entering the Topic ✓
- Theoretical background ✓
- Factors affecting site response analysis ✓
- Site Response Analysis and Resilience ✓
- Regulations ⟸
- Some Examples
- Codes and Events
- Soil constitutive model in site response analysis

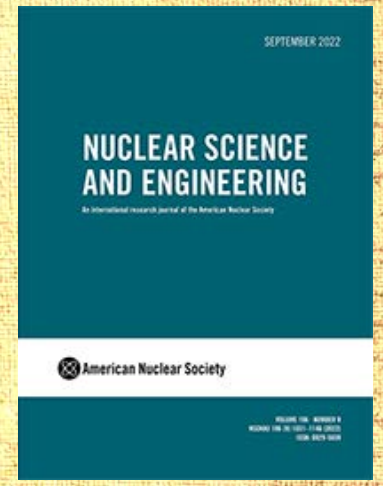
Regulations

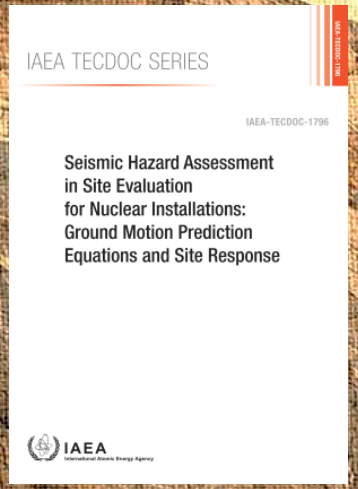






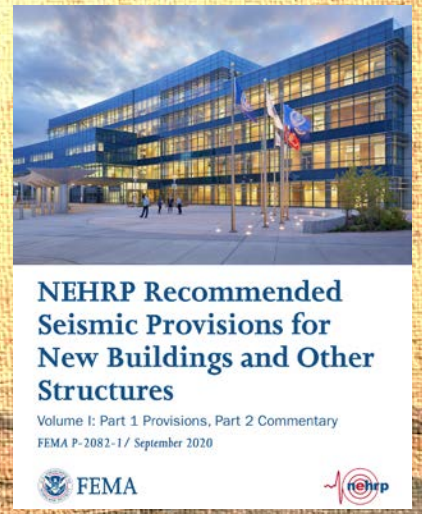








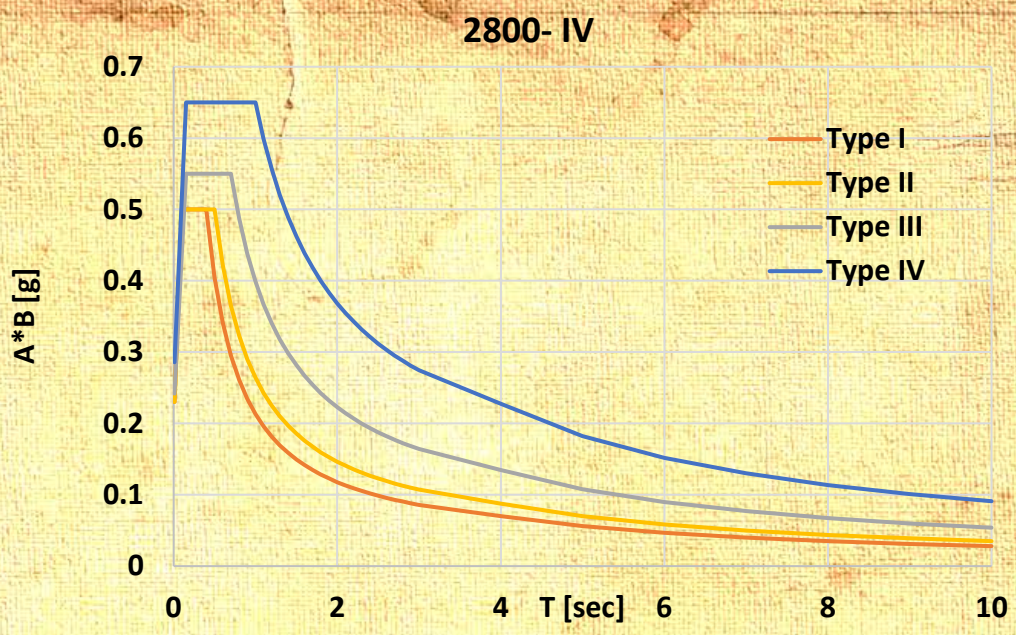


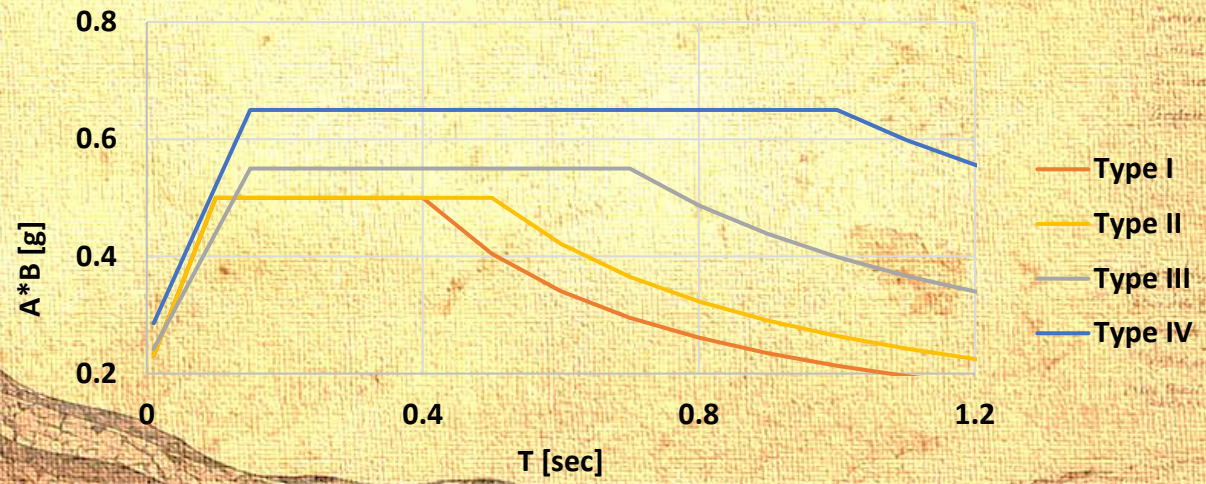


Regulations

جدول ۲-۳ طبقه‌بندی نوع زمین

نوع زمین	توصیف لایه‌بندی زمین	پارامترها		
		$\overline{v}_s(m/s)$	$\overline{N}_{1(60)}$	$\overline{C}_u(kPa)$
I	**سنگ و شبه سنگ**،شامل سنگ‌های آذرین، دگرگونی و رسوبی و خاک‌های سیمانته بسیارمحکم با حداکثر ۵ متر مصالح ضعیف‌تر تا سطح زمین	>۷۵۰	-	-
II	**خاک خیلی متراکم یا سنگ سست**، شامل- شن و ماسه خیلی متراکم، رس بسیار سخت با ضخامت بیشتر از ۳۰ متر که مشخصات مکانیکی آن با افزایش عمق به‌تدریج بهبود یابد. سنگ‌های آذرین و رسوبی سست، مانند توف ویا سنگ متورق و یا کاملاً هوازده	۳۷۵ -۷۵۰	>۵۰	>۲۵۰
III	**خاک متراکم تا متوسط** ، شامل شن و ماسه متراکم تا متوسط یا رس‌های سخت با ضخامت بیشتر از ۳۰ متر	۱۷۵ -۳۷۵	۱۵-۵۰	۷۰-۲۵۰
IV	**خاک متوسط تا نرم**، لایه‌های خاک غیر چسبنده یا با کمی خاک چسبنده با تراکم متوسط تا کم، لایه‌های خاک کاملاً چسبنده نرم تا محکم.	<۱۷۵	<۱۵	<۷۰

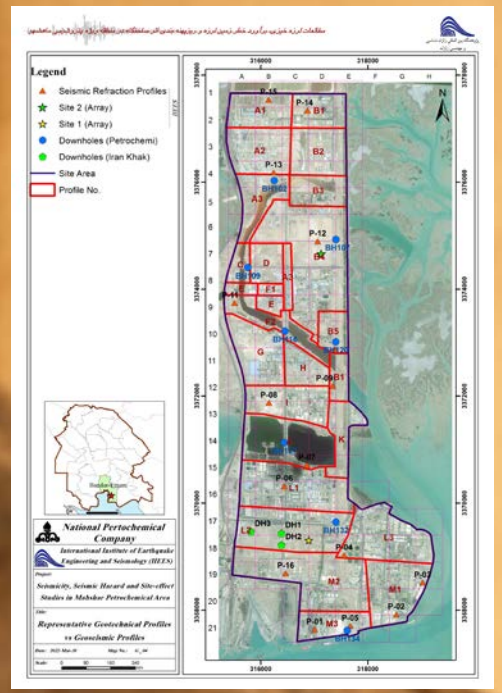


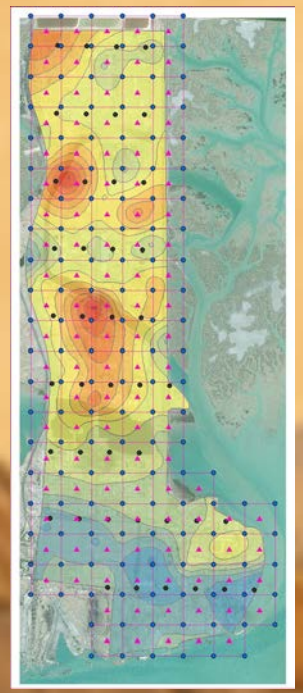


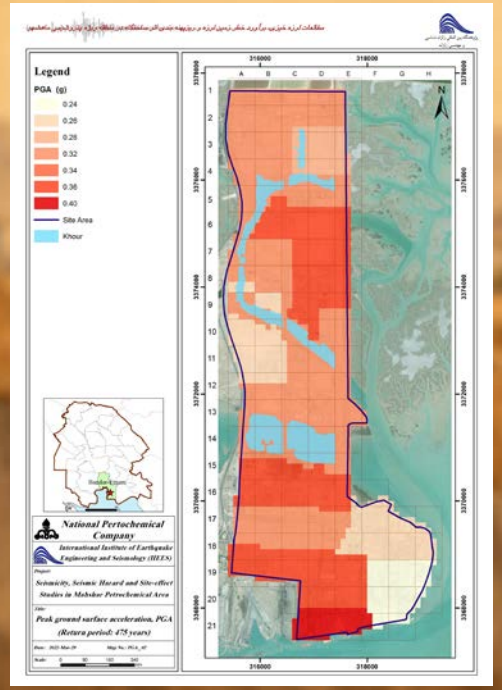
- Entering the Topic ✓
- Theoretical background ✓
- Factors affecting site response analysis ✓
- Site Response Analysis and Resilience ✓
- Regulations ✓
- Some Examples
- Codes and Events
- Soil constitutive model in site response analysis

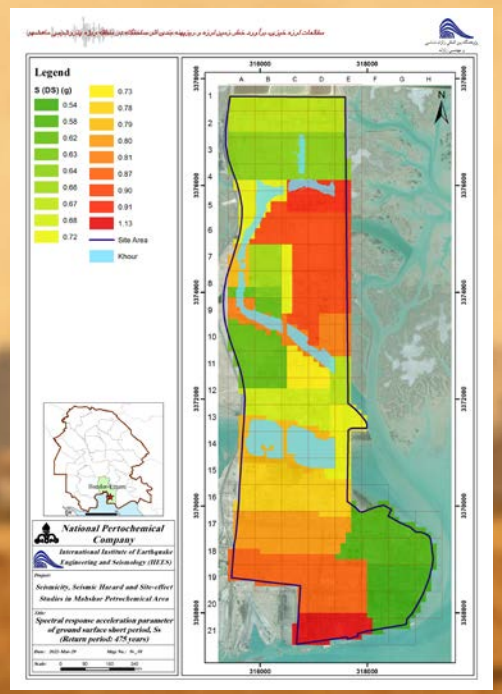
Examples

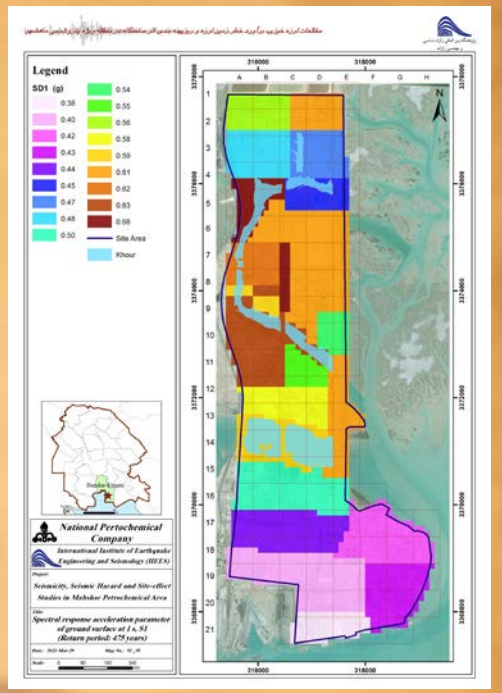
A Petrochemical Area





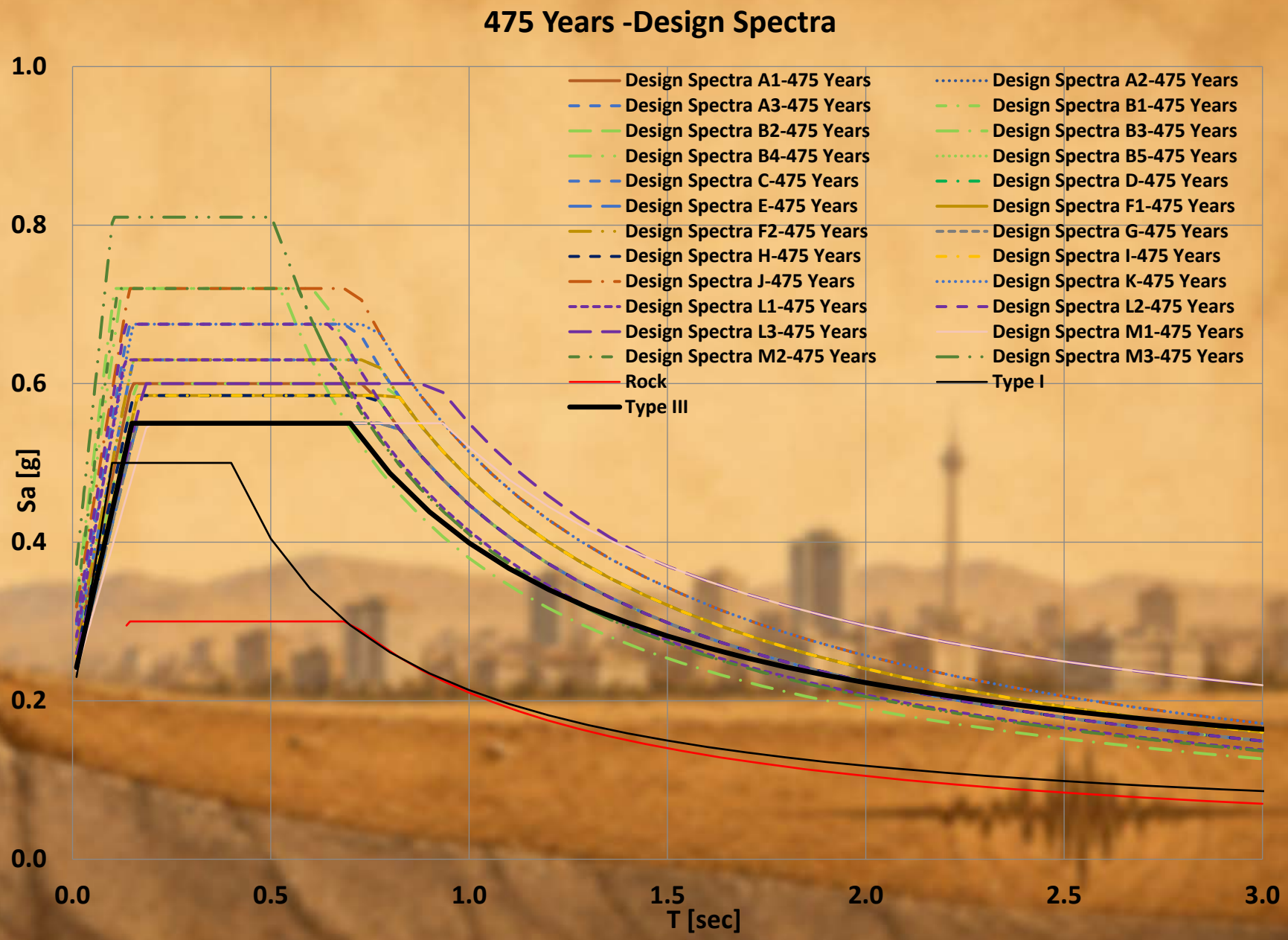






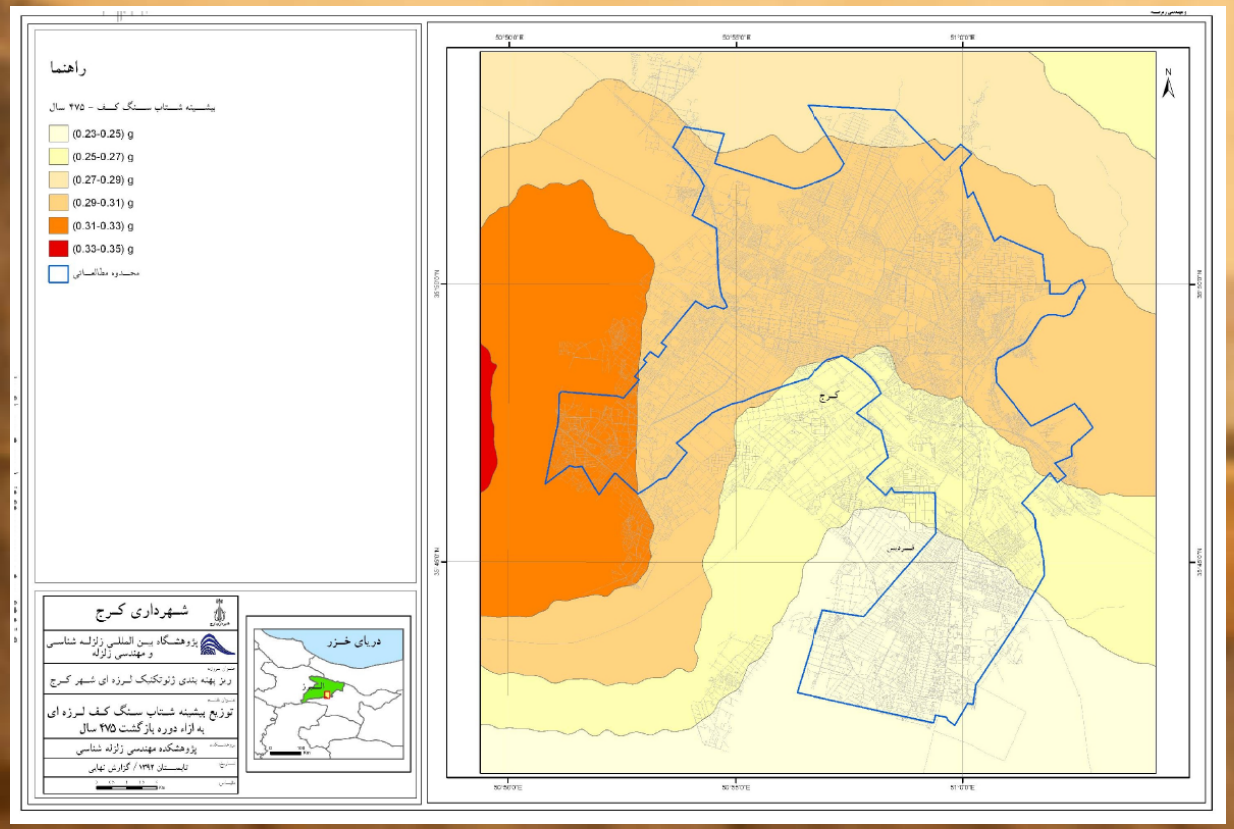
Examples

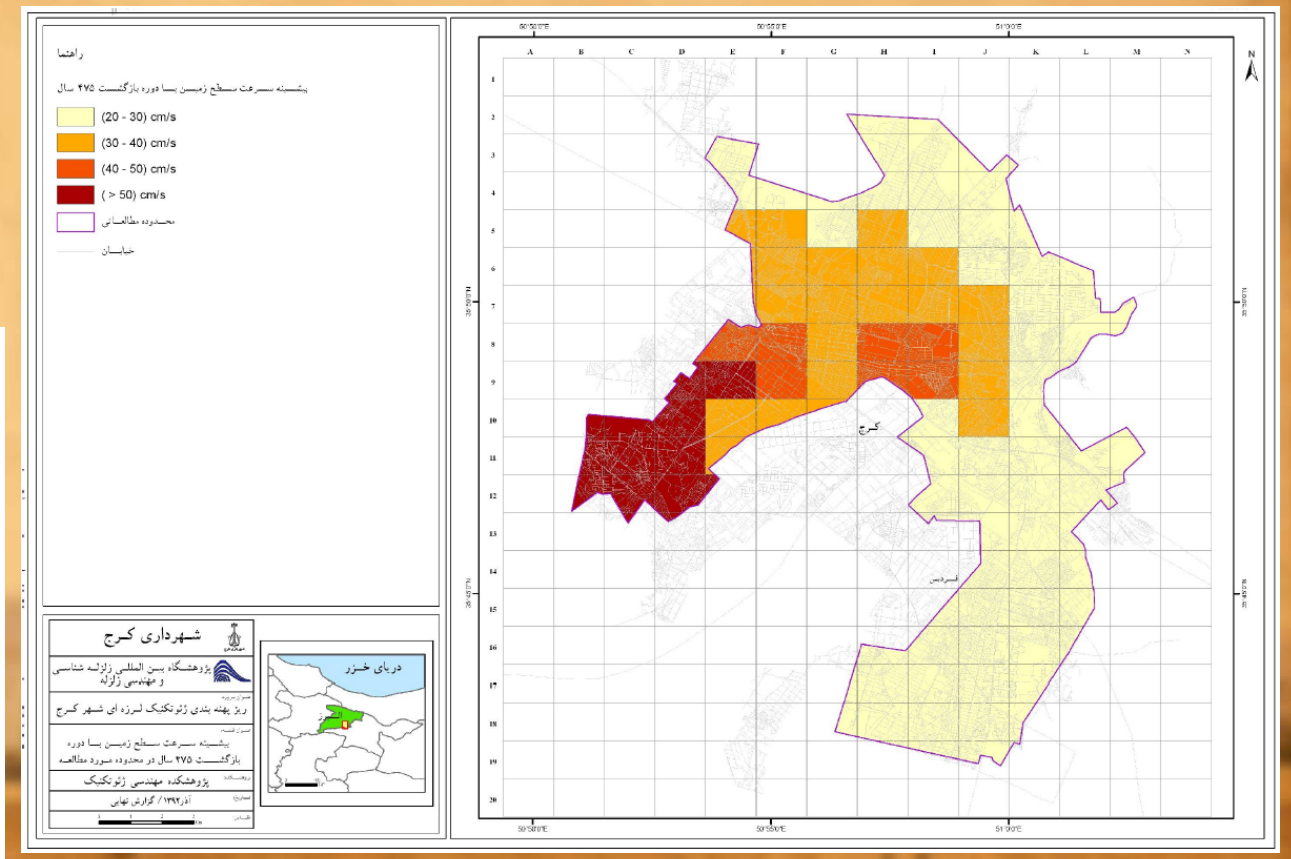
A Petrochemical Area



Examples

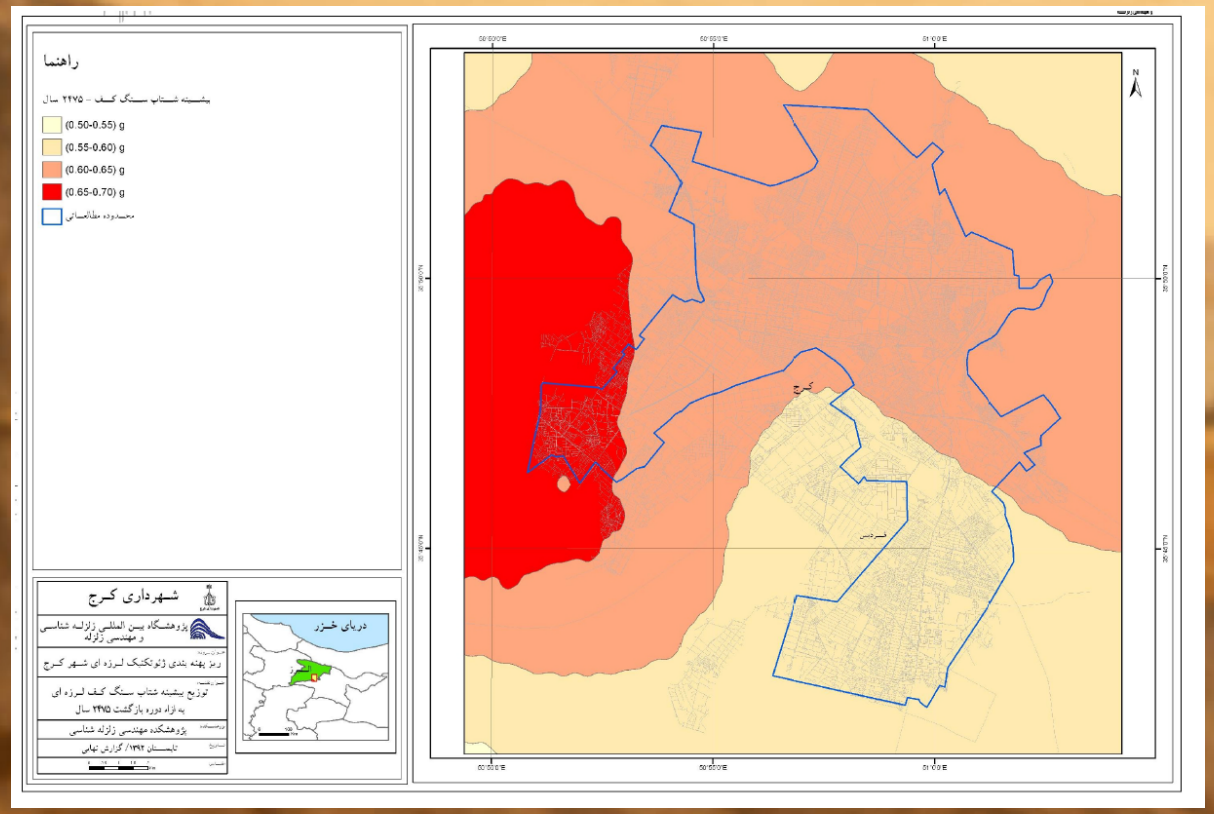
A City

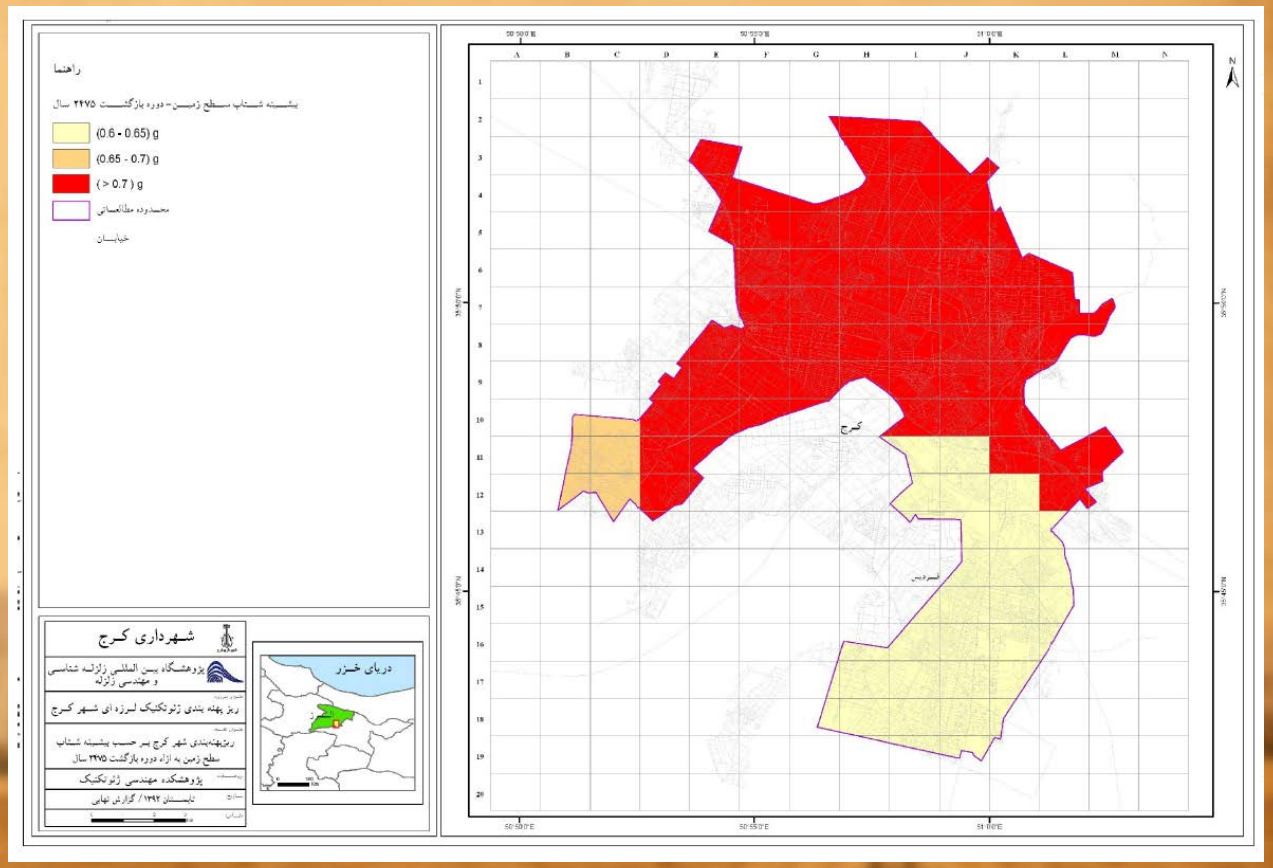




Examples

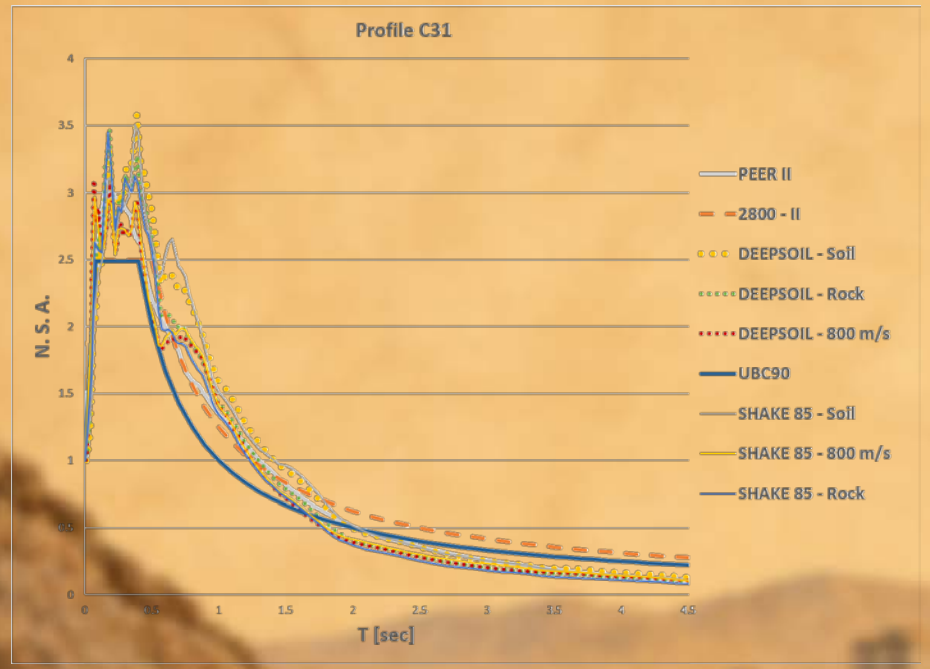
A City

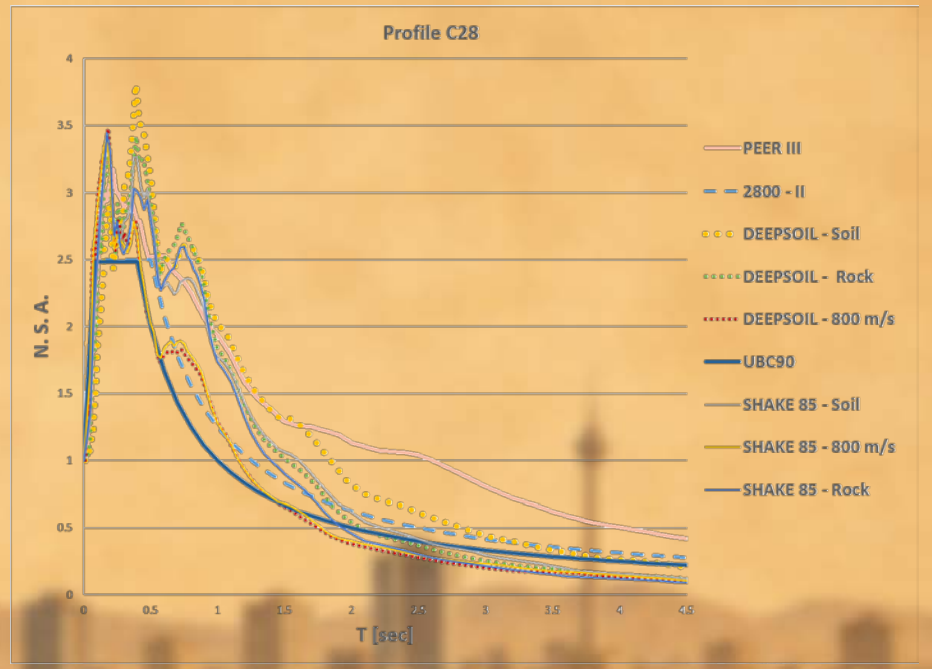




Examples

A City

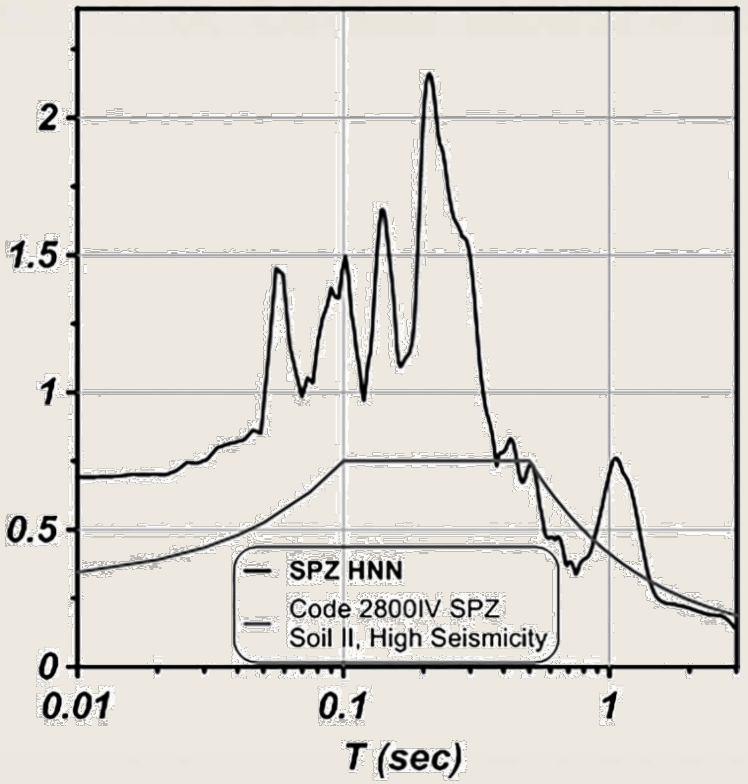




- Entering the Topic ✓
- Theoretical background ✓
- Factors affecting site response analysis ✓
- Site Response Analysis and Resilience ✓
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- Some Examples ✓
- Codes and Events
- Soil constitutive model in site response analysis

Codes and Events

Sarpol-e Zahab M 7.3 (2017)



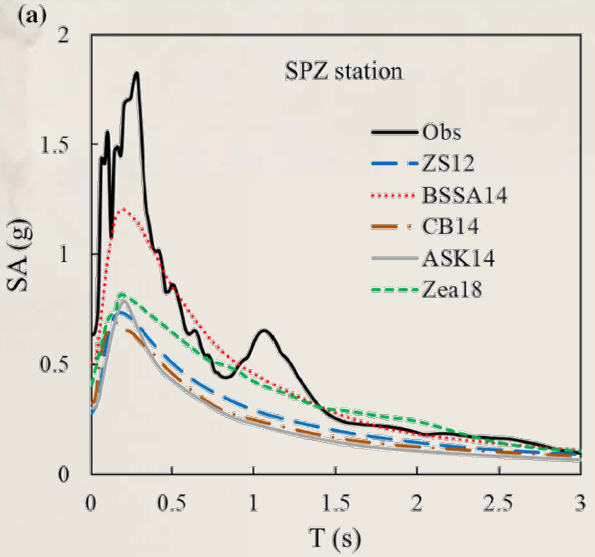
Code-based acceleration response spectrum versus recorded spectrum (5% damped) at the Sarpol Zahab (SPZ) station, Horizontal north–south component (HNN). Image created using the acceleration time history data publicly available from the IRCS-UT.

Roudbari, S., Heris, M., Hakhamaneshi, M., & Dashti, S. (2020). Mediating design claims: The social media and housing disaster of the 2017 Halabja earthquake. *Natural Hazards Review*, *21*(2), 04020012.

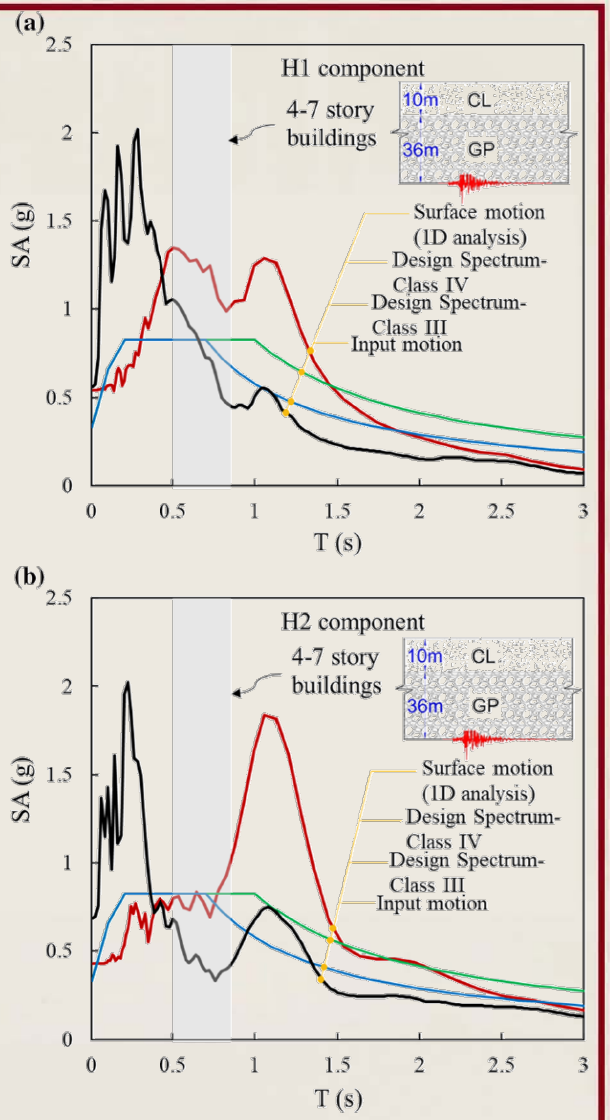
Codes and Events

Sarpol-e Zahab M 7.3 (2017)

Comparison of observed and predicted spectral accelerations in SPZ and KRD stations. *Obs* observed data, *Zea18* Zafarani et al. (2018), *BSSA14* Boore et al. (2014), *CB14* Campbell and Bozorgnia (2014), *ASK14* Abrahamson et al. (2014), *ZS12* Zafarani and Soghrat (2012)



Comparison of acceleration response spectra of input motion, soil surface, and the BHRC14 design spectra for the horizontal components **a** east–west **b** north–south

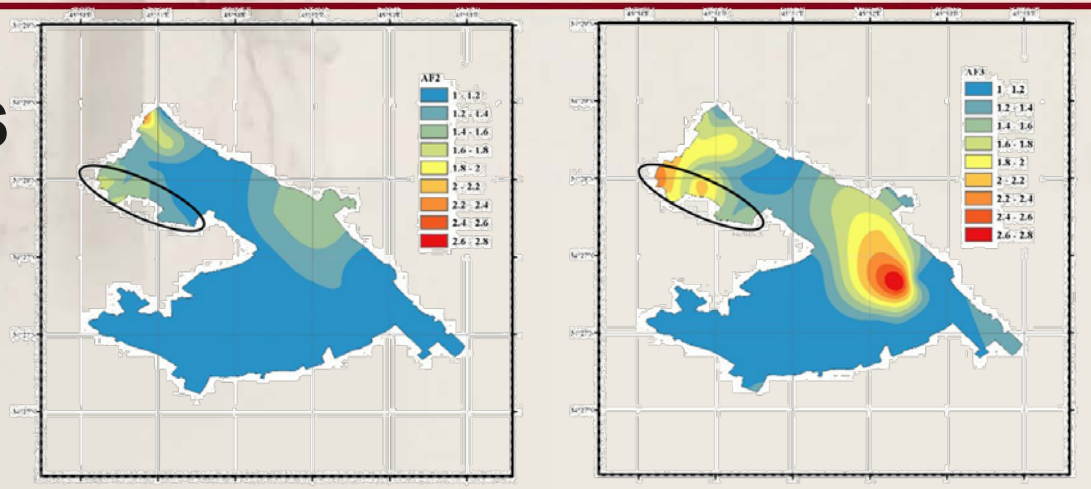


Zafarani, H., Jafarian, Y., Eskandarinejad, A., Lashgari, A., Soghrat, M. R., Sharafi, H., & Afraz-e Haji-Saraei, M. (2020). Seismic hazard analysis and local site effect of the 2017 M w 7.3 Sarpol-e Zahab, Iran, earthquake. *Natural Hazards*, *103*(2), 1783-1805.

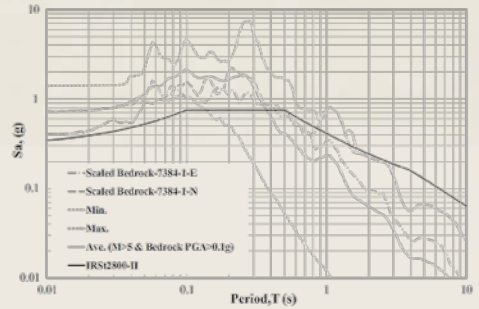
Codes and Events

Sarpol-e Zahab M 7.3 (2017)

$$AF_i = \frac{\int_{f_1}^{f_2} S_a^{ground}(f)}{\int_{f_1}^{f_2} S_a^{bedrock}(f)}$$



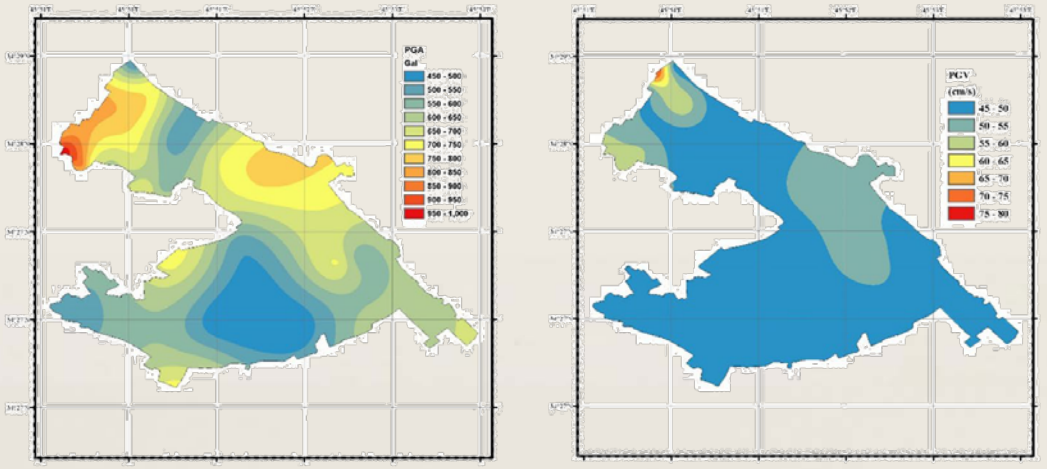
Amplification factors for Mw 7.3 earthquake; AF_2 (left) and AF_3 (right). Black circled region shows the concentration of damages of 3 to 7 stories buildings



Response spectra of 32 scaled bedrock motions at ISMN-SPZ and design spectra of IRSt2800, ground type II

Different frequency bands for the amplification factor, AF_i and approximate building height corresponding to each frequency band accompanied with the Max. AF_i at Sarpol-e-zahab city

Frequency range	i	f_1 (Hz)	f_2 (Hz)	Approximate building height (m) (IRSt2800)	Max. AF_i
Very low	1	0.5	1	25 to 75	1.53
Low	2	1	2	12 to 30	2.48
Intermediate	3	2	5	4 to 15	2.89
High	4	5	10	2 to 5	2.50
Very high	5	10	20	Special equipment or facility	2.65



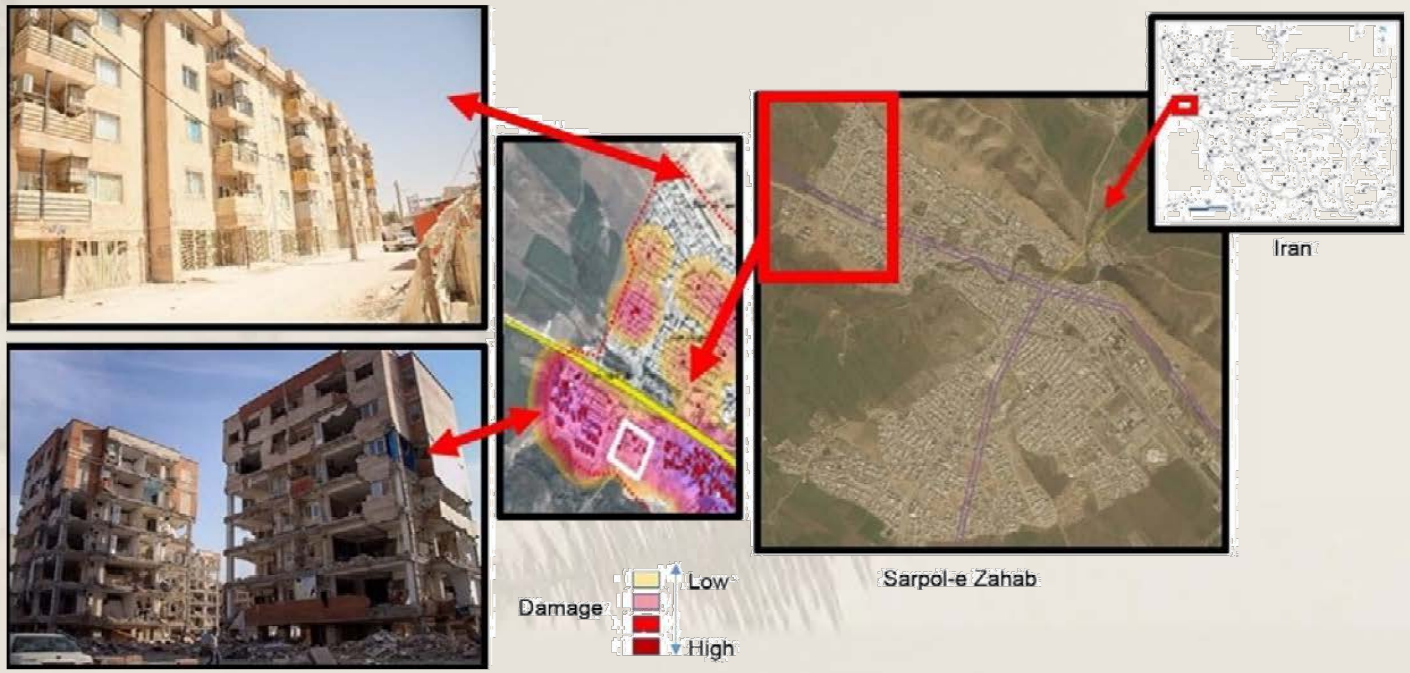
Shakemaps of PGA (left) and PGV (right) for Mw 7.3 earthquake at Sarpol-e-zahab

Ashayeri, I., Memari, M. A., & Haghshenas, E. (2021). Seismic microzonation of Sarpol-e-zahab after Mw 7.3 2017 Iran earthquake: 1D-equivalent linear approach. *Bulletin of Earthquake Engineering*, *19*(2), 605-622.

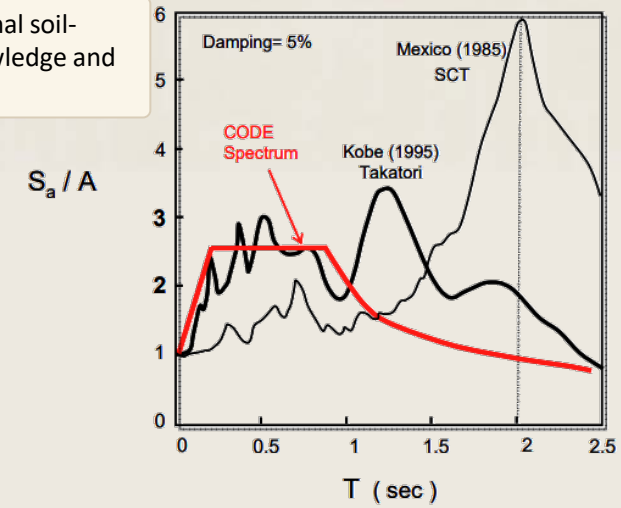
Gazetas, G., & Ziotopoulou, A. (2010). Binormalized response spectrum for a rational soil-structure interaction analysis. In Workshop on Soil Structure Interaction (SSI) Knowledge and Effect on the Seismic Assessment of NPPS Structures and Components (pp. 6-8).

Codes and Events

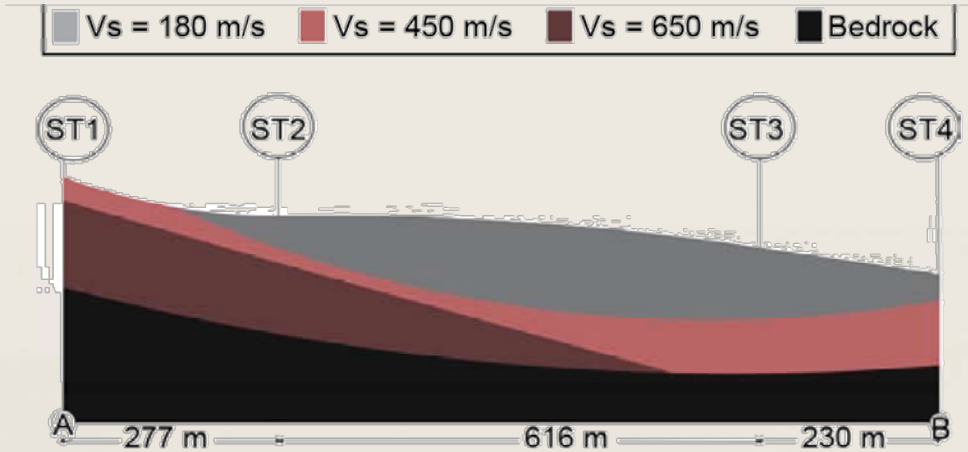
Sarpol-e Zahab M 7.3 (2017)



Study location and destructing trend in north and south of the study area in west of Sarpol-e Zahab town (damage assessment based on Unitar [10]).



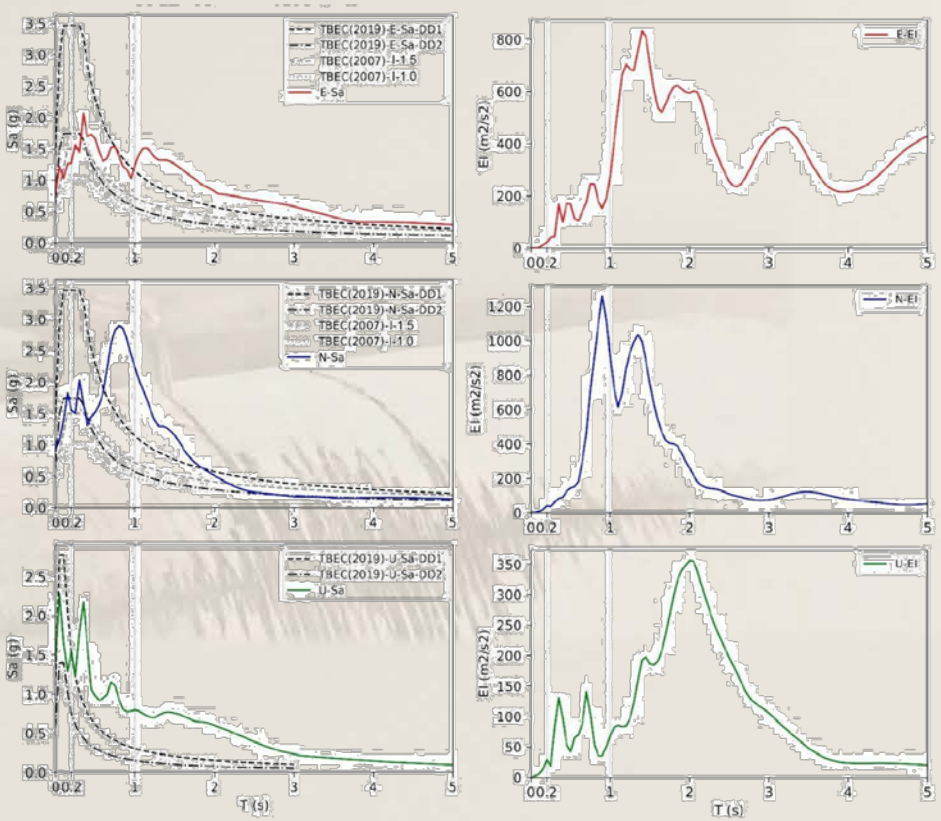
The discrepancy between a Code Design Spectrum, typical for soft soils, and the response spectra of two actual soil amplified motions.

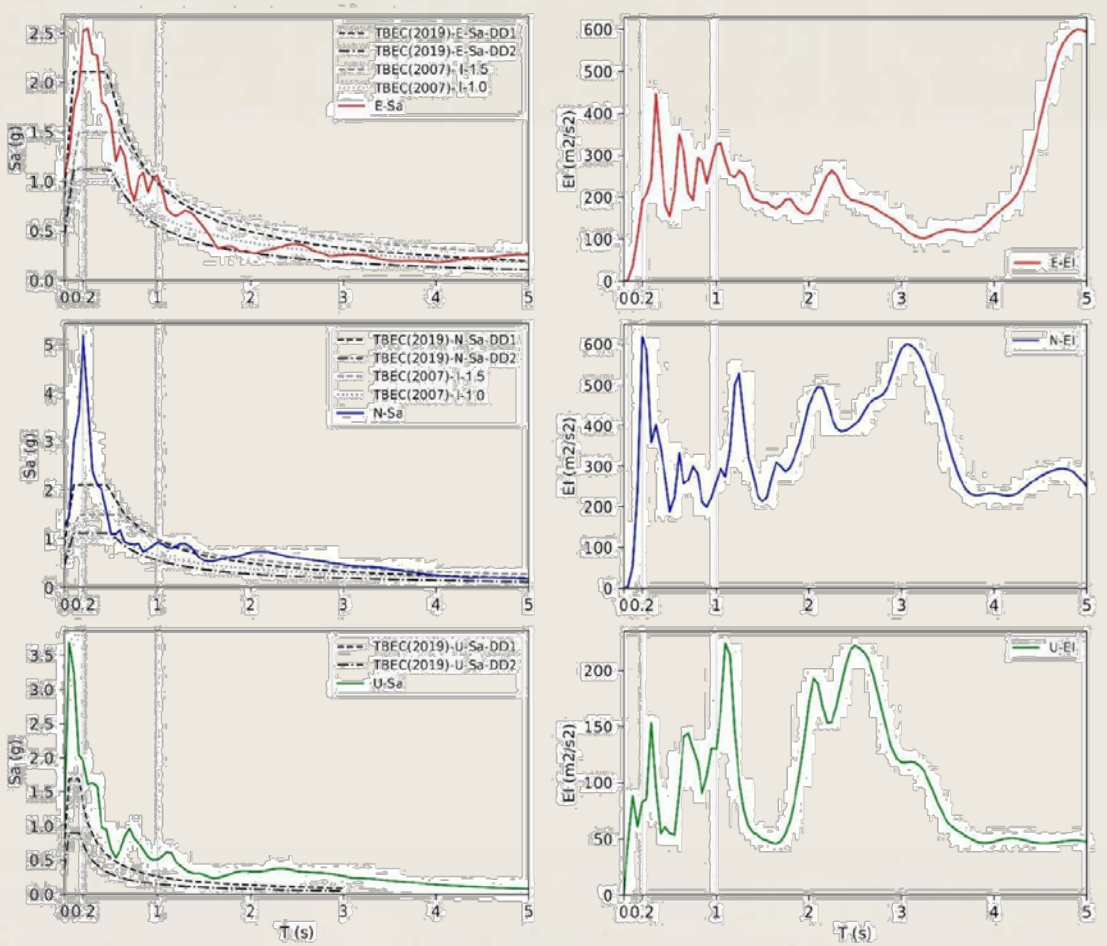


Moosavi, M., Taleshi, H., & Hosseinian, O. (2018). Investigation of Site Response Analyses of the Ezgeleh-Sarpol-e Zahab Earthquake, Iran, inWest of Sarpol-e Zahab Town. *Journal of Seismology and Earthquake Engineering*, *20*(4), 33-43.

Codes and Events

Kahramanmaraş earthquakes, Turkey (2023)



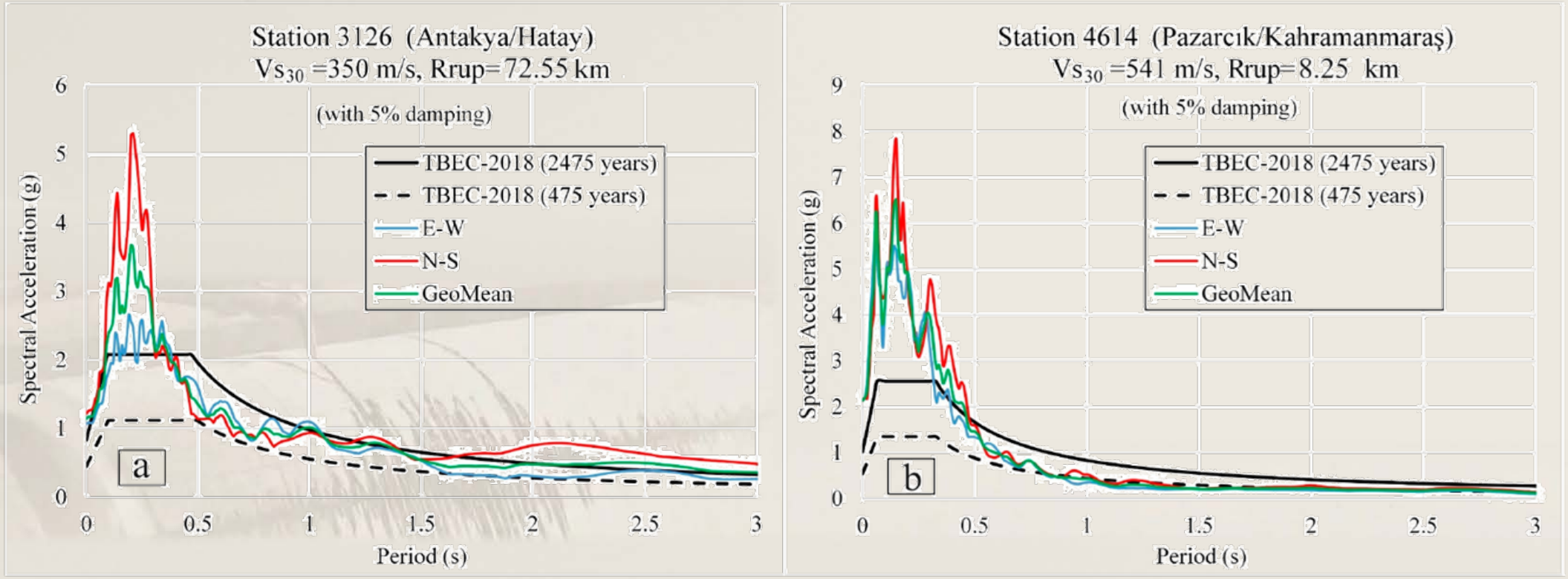


Comprehensive view of the seismic data, showcasing the recorded three-component ground accelerations. The figure includes acceleration response spectra (with 5% damping) with the previous and most recent building code (TBDY, 2018) for comparison, and the energy spectra. Specifically, the selected stations, namely 3126 (upper panel), and 3138 (lower panel) from the Pazarcik (Mw7.8) mainshock, are examined

Akinci, A., Dindar, A. A., Bal, I. E., Ertuncay, D., Smyrou, E., & Cheloni, D. (2025). Characteristics of strong ground motions and structural damage patterns from the February 6th, 2023 Kahramanmaraş earthquakes, Türkiye. *Natural Hazards*, *121*(2), 1209-1239.

Codes and Events

Kahramanmaraş earthquakes, Turkey (2023)



Response spectra compared with TBEC-2018 at stations (**a**) 3126 and (**b**) 4614, in relation to the Pazarcık earthquake (*Mw* = 7.7).

Alpyürür, M., & Ulutaş, H. (2024). Comparison of performance analysis results with developed site-specific response spectra and Turkish seismic design code: A case study from the SW türkiye region. Buildings, 14(5), 1233.

Soil constitutive model in site response analysis

Importance of investigating local materials

Engineering Behavior and Constitutive Modeling
of Sandy Dolomite: Intelligent Characterization

Dr. Meiqian Wang