



Searching for reference stations and reference ground motions in the Greek seismic networks

Αναζητώντας σταθμούς για κινήσεις αναφοράς στο εθνικό δίκτυο

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Athens – 30 October 2025



The challenge

Reference ground motions:

- important for **many cascading applications** in both seismology / eng. seismology and EQ eng
- if inappropriate: **can introduce bias** in amplitude, frequency content and duration
- can be selected based on various criteria & proxies – **or not...!**

Usual criterion: choose stations are **installed on “rock”**:

- usually **no effort to characterise** or challenge their quality as ref stations
- assumed to be free of any site effect... this we now know is **untrue!**

The challenge

- How do we define a reference station in a **consistent & holistic way**?
- Aim to **provide the user engineer** with a framework to:
 - select input GMs in an informed and controlled way
 - reduce uncertainties and bias or double-counting of site effects
 - ultimately improve quality / reliability of downstream analyses

A long time ago, in a ΠΣΑΜΤΣ far, far away...

 Πανελλήνιο συνέδριο
**ΑΝΤΙΣΕΙΣΜΙΚΗΣ ΜΗΧΑΝΙΚΗΣ
ΤΕΧΝΙΚΗΣ ΣΕΙΣΜΟΛΟΓΙΑΣ**
Αθήνα 5-7 Σεπτεμβρίου 2019

Βελτιώνοντας την κατανόηση
της σεισμικής απόκρισης
σε σταθμούς του Εθνικού Αστεροσκοπείου



**Όλγα-Τζόαν Κτενίδου
Ιωάννης Καλογεράς**

Εθνικό Αστεροσκοπείο Αθηνών





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The quest for reference stations at the National Observatory of Athens, Greece

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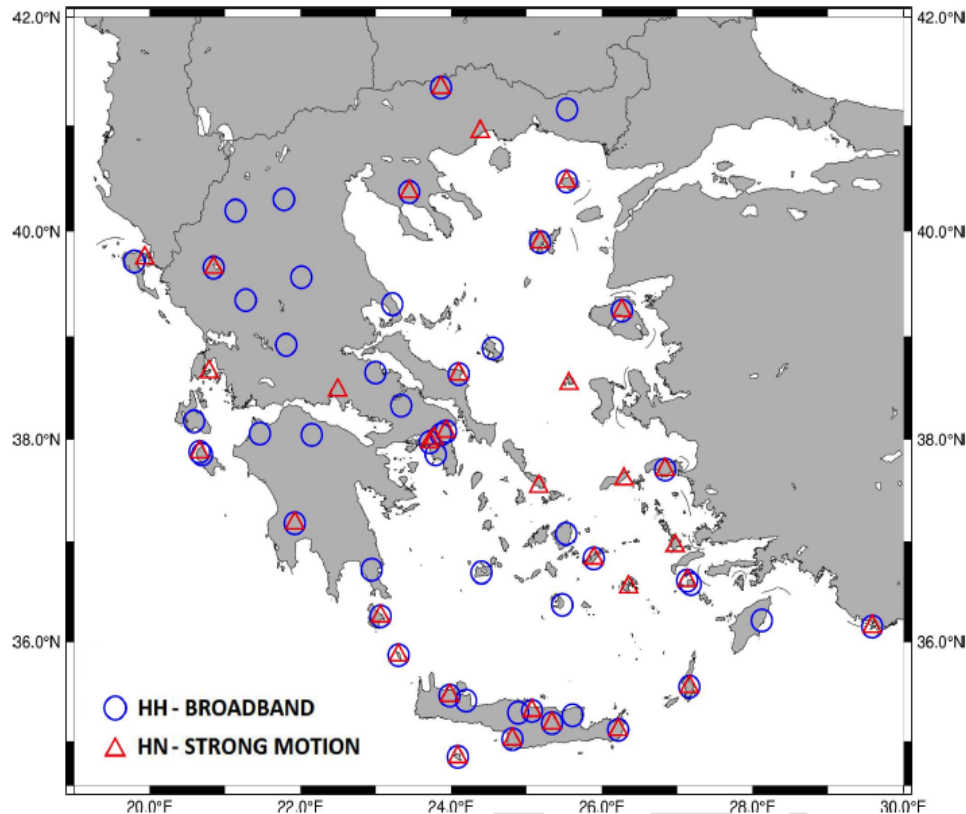
What would we like to know?

- **waveform (data)**-derived parameters
- parameters based on the analysis of all **external sources**
- **operator's observations** from site visits

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NOA 'rock' stations

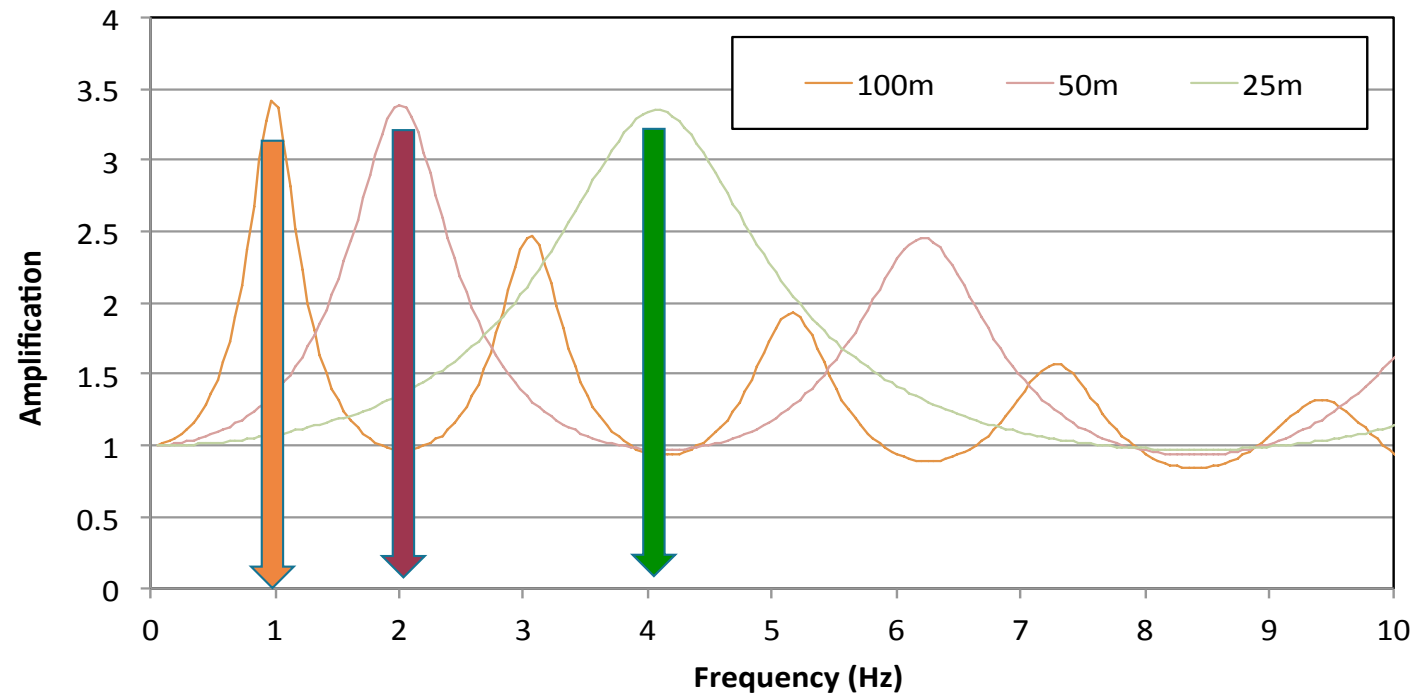


- BB stations (HH channels)
- Collocated BB/SM (HH and HN)
- SM stations for which some indication exists:
 - literature and online resources
 - geological map info
 - proxy-based info
 - operator's/site-visit info
- publicly accessible via the EIDA@NOA node
- enough recordings

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Site resonance

Soil resonance is an accepted fact (simplified effect in GMPEs etc.)



Soil resonance is an accepted fact (simplified effect in GMPEs etc.)

Rock resonance is not yet such a well-accepted fact although...

	Ground class	Stiff	Medium stiff
Depth class	$V_{s,H}$ range H_{800} range	$400 \text{ m/s} \leq V_{s,H} < 800 \text{ m/s}$	$250 \text{ m/s} \leq V_{s,H} < 400 \text{ m/s}$
Very shallow	$H_{800} \leq 5 \text{ m}$	A	A

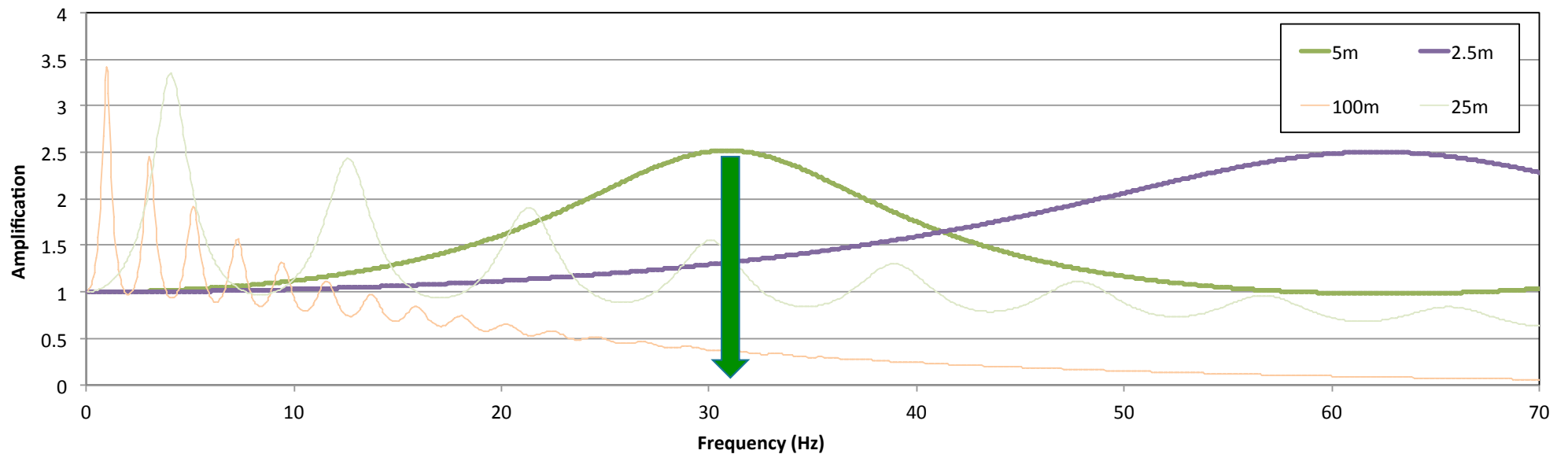
EC8 new draft
CEN/TC 250/SC 8 (2021)

Labbe & Paolucci (2022)

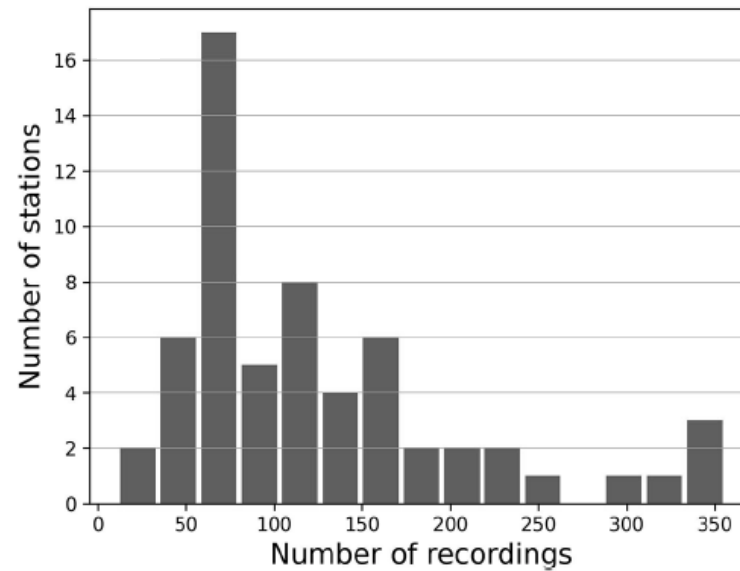
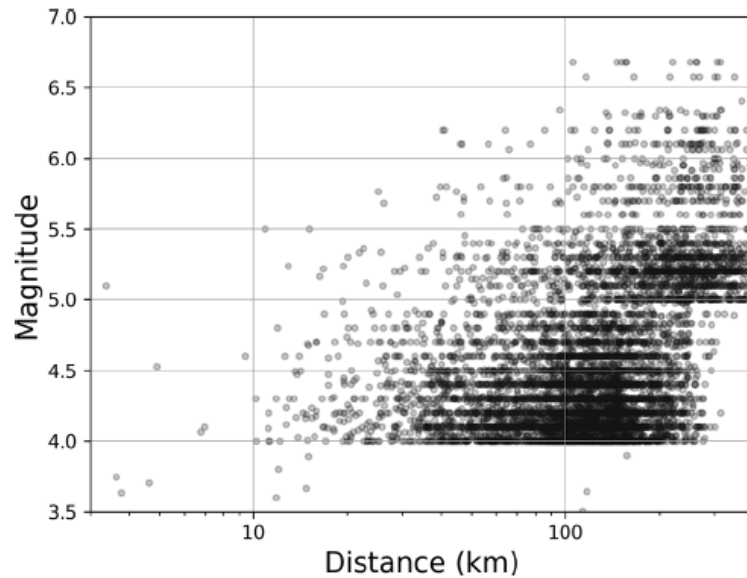
Combination of f_0 (Hz) and $V_{s,H}$ (m/s)	Site category
$f_0 > 10$ and $V_{s,H} \geq 250$	A

Soil resonance is an accepted fact (simplified effect in GMPEs etc.)

Rock resonance is not yet such a well-accepted fact although...

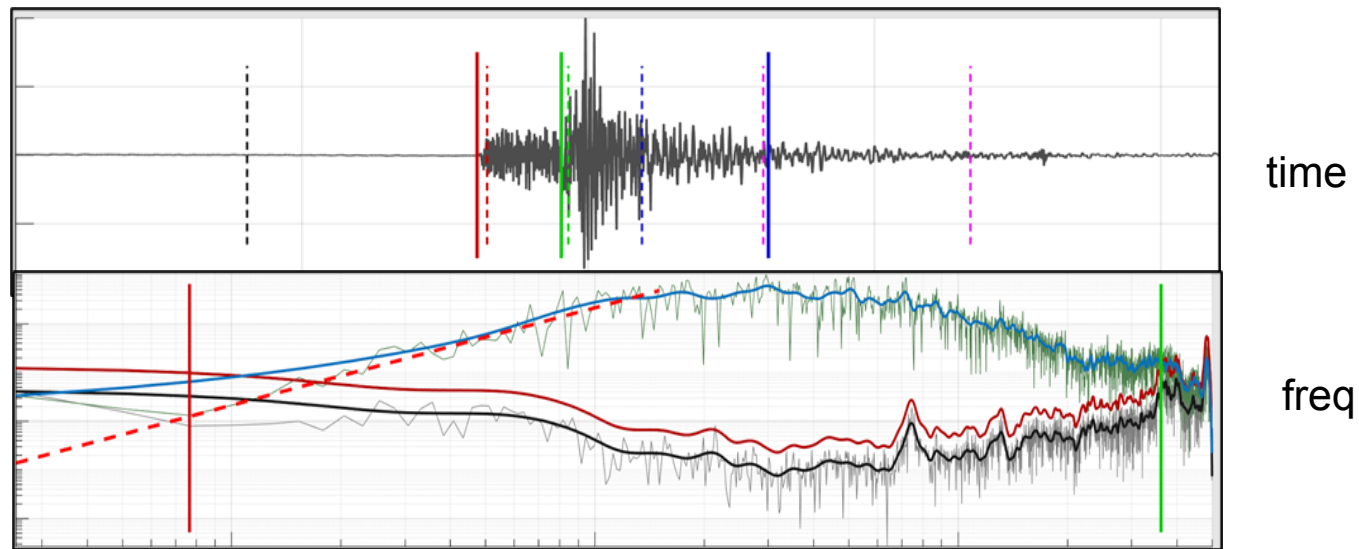


Waveform-derived parameters



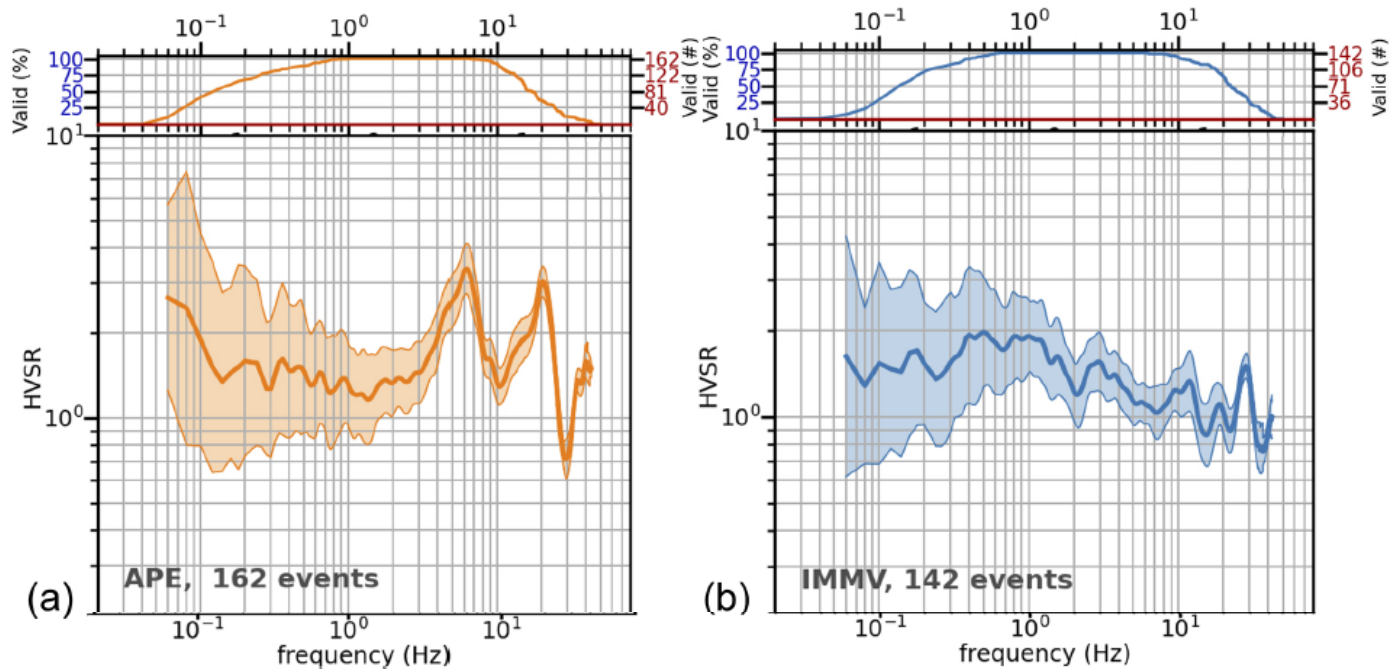
digital era (EIDA – Evangelidis et al., 2021)
>7500 recordings, M4+, till 31/12/2023
2+ years' worth of processing

1. Visual inspection
2. Quality assessment
3. Waveform-specific processing in the time and frequency domain



Mean HVSR

Combine horizontal components in an orientation-independent estimate



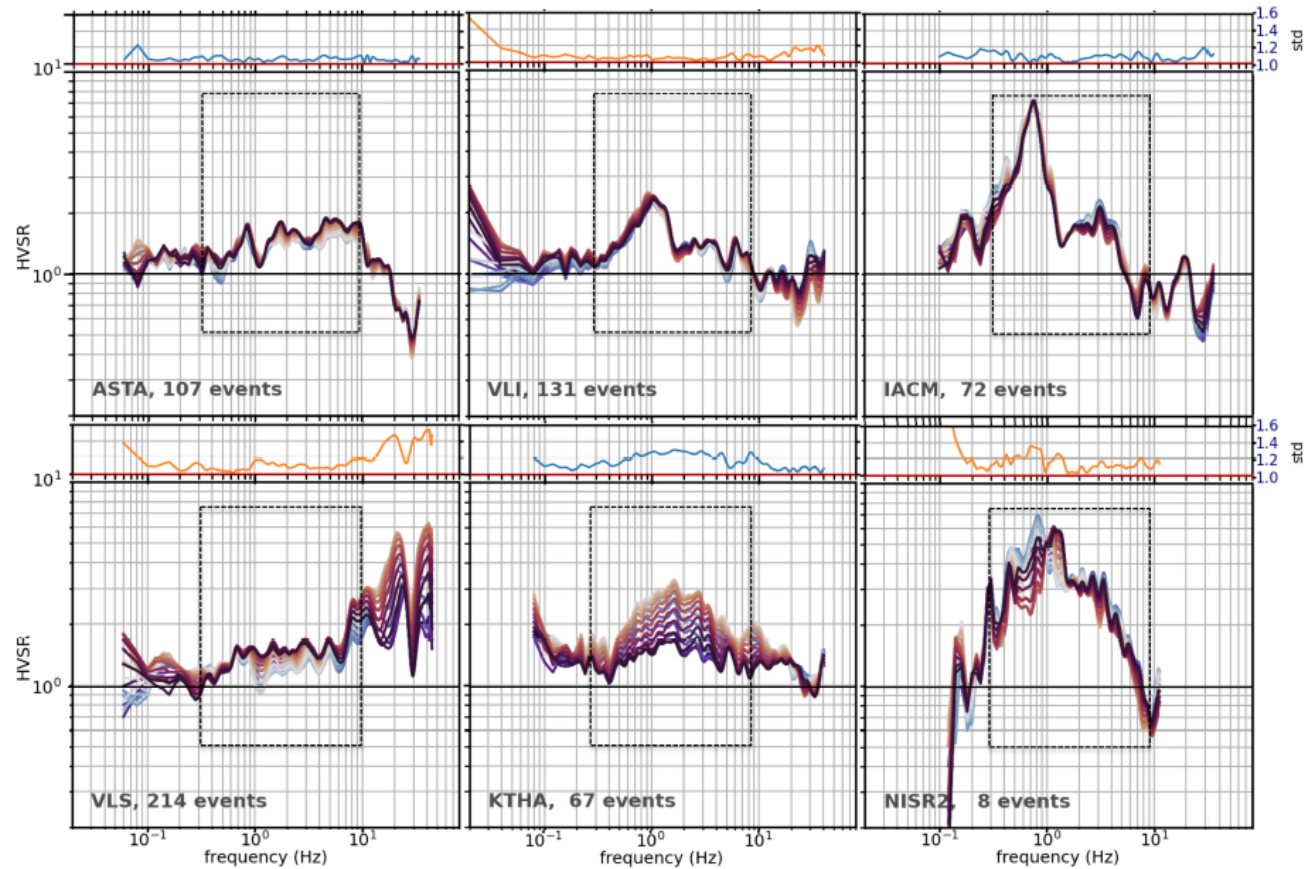
Strong amplification
at 6 & 20Hz



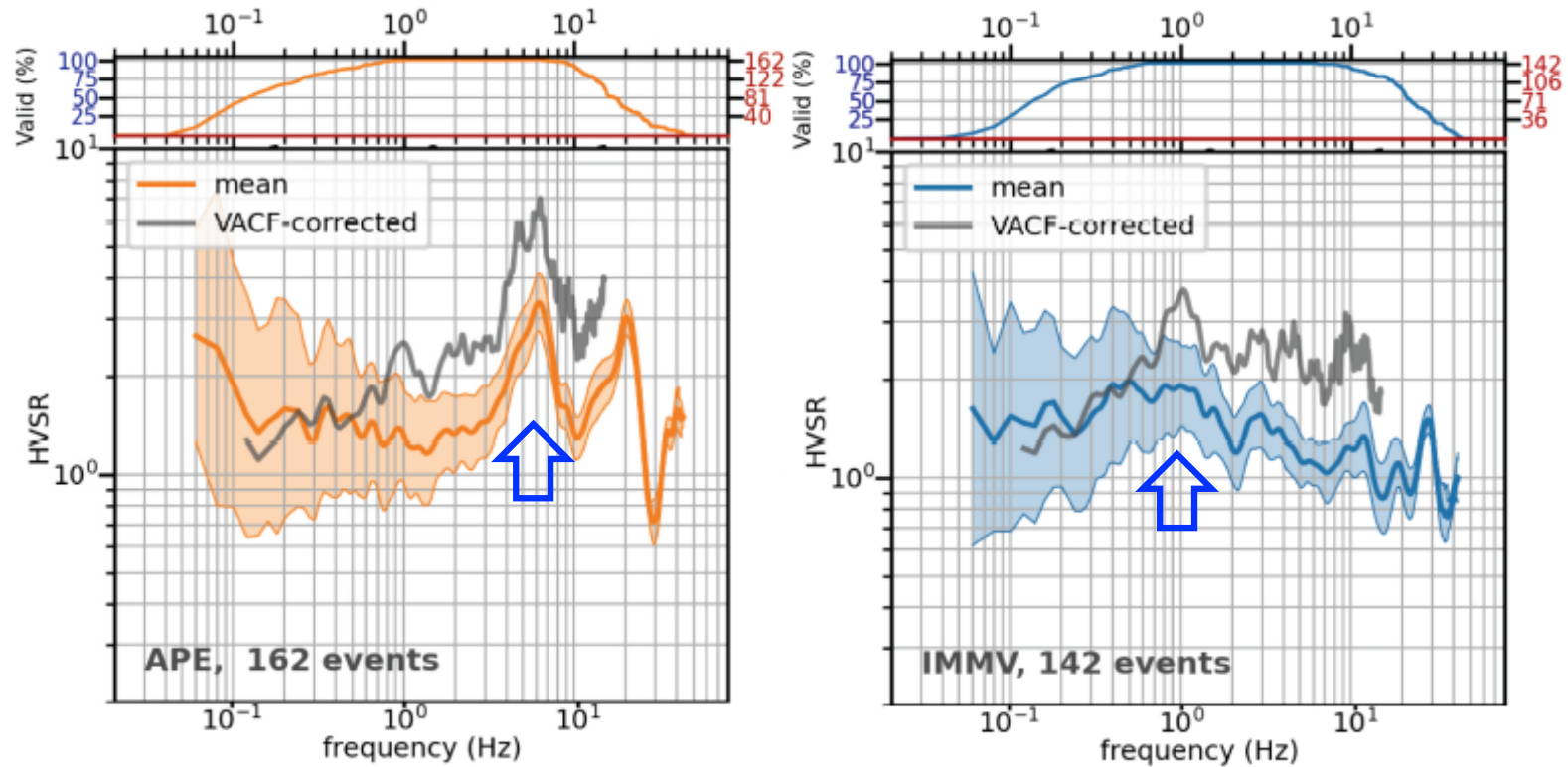
flat without clear
resonant peaks

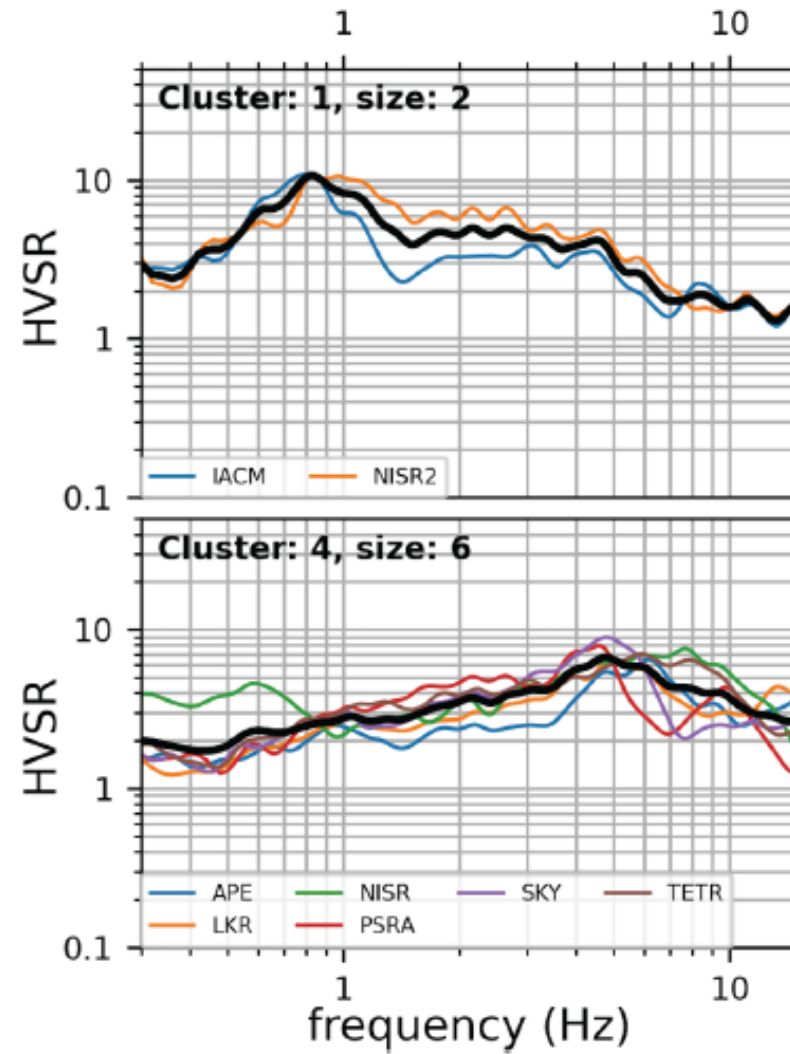
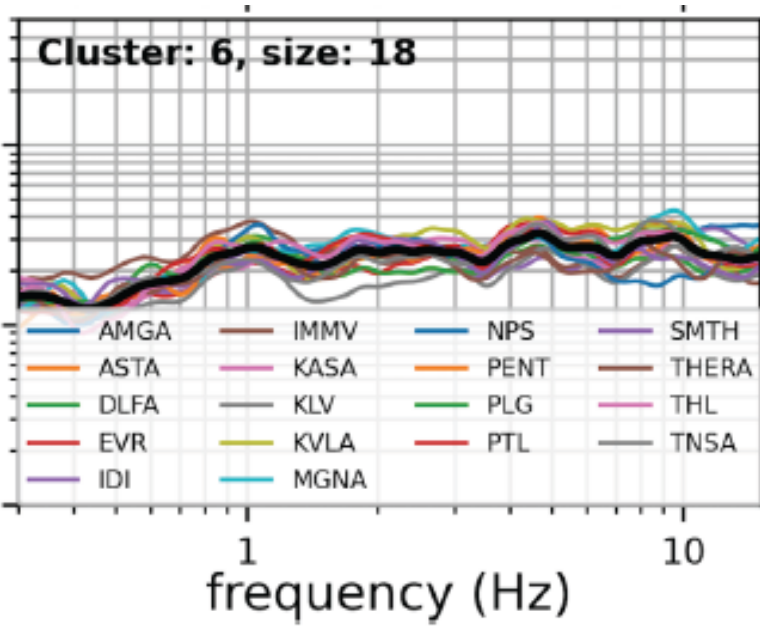
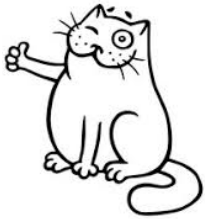
Rotational HVSR

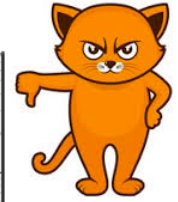
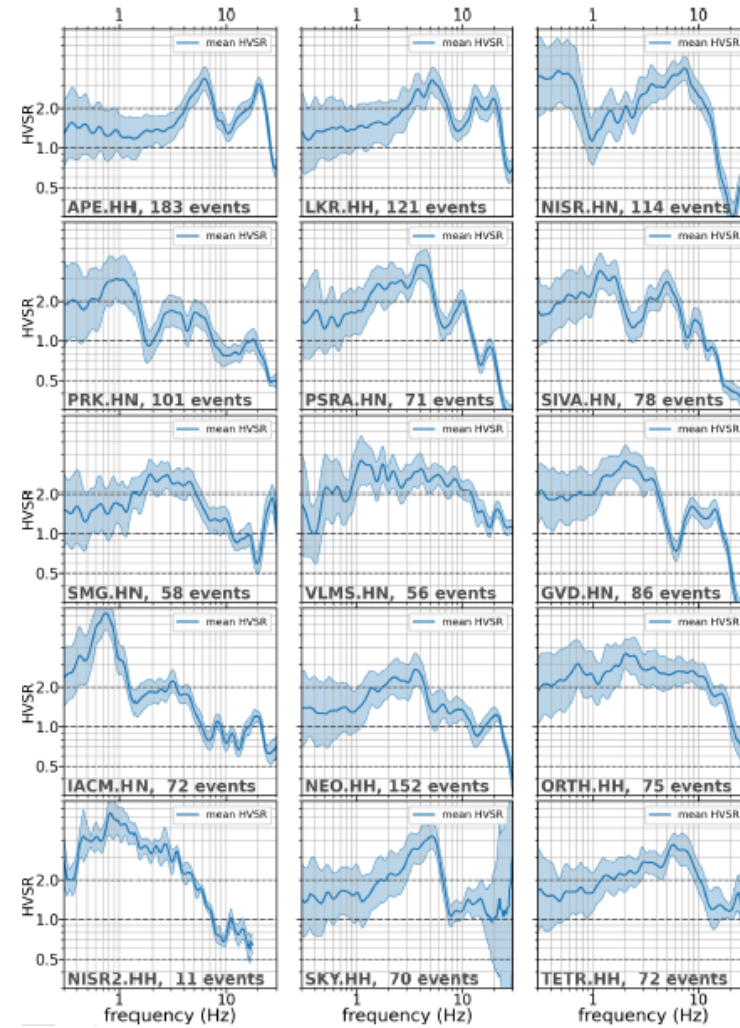
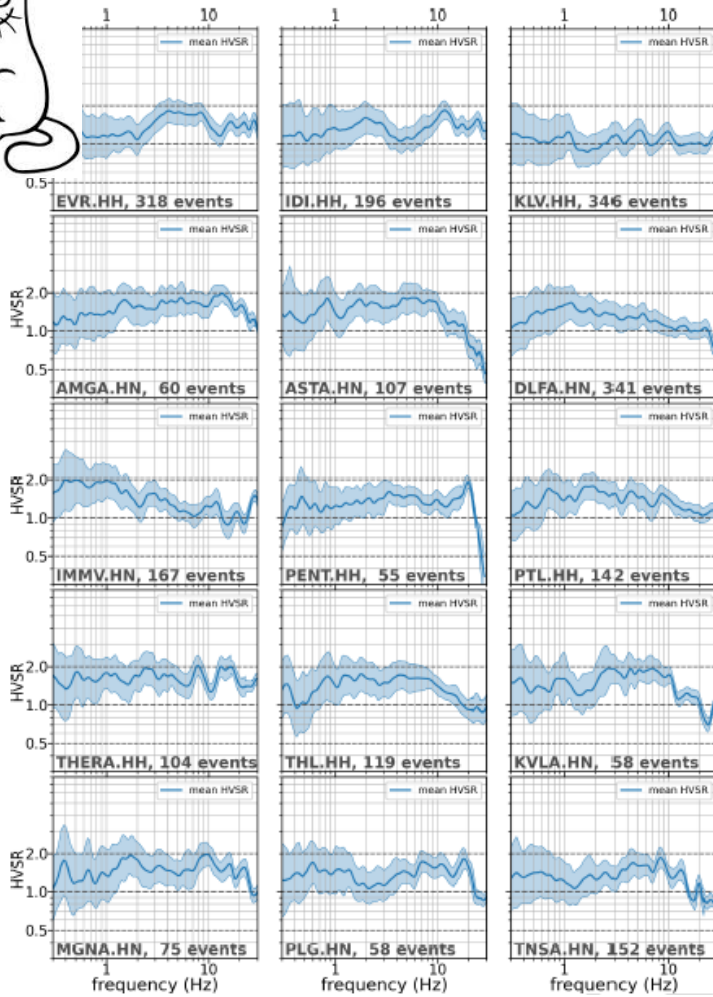
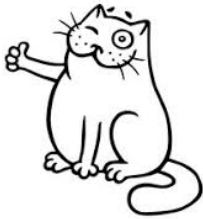
Strong directional effects may indicate departure from 1D behaviour due to local geomorphology

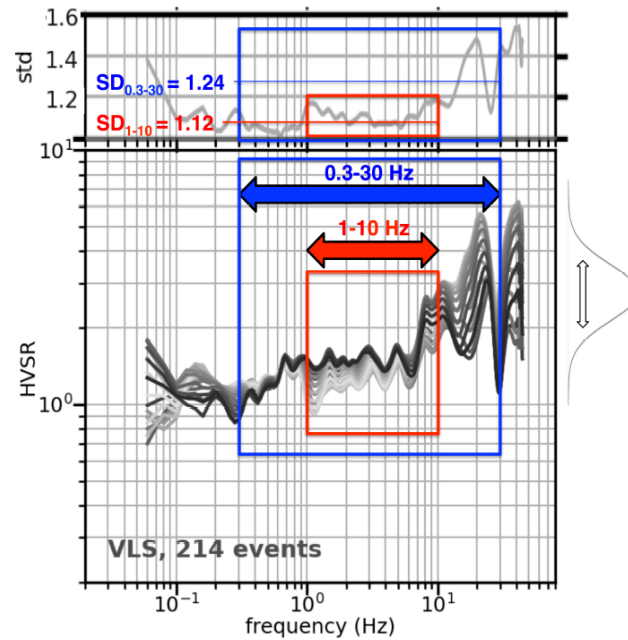


Rough correction for the implicit amplification of the vertical (Ito et al., 2020)









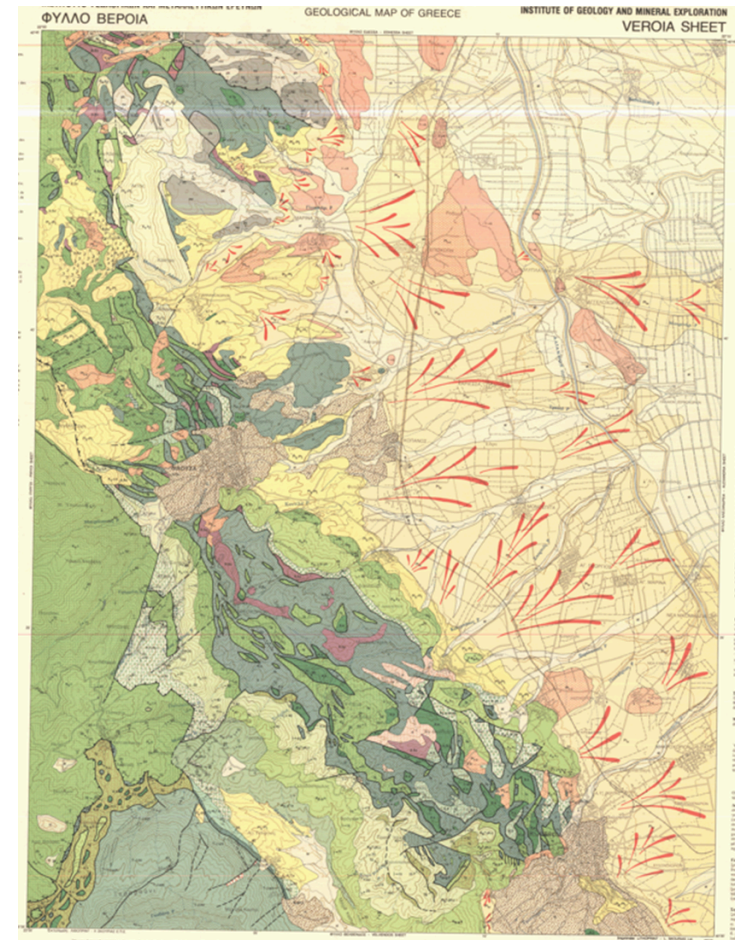
No.	Station code	f_0 inspected > 2.7 (Hz)	A_0	Peak/flat	f_0 automatic (Hz)	f_1 (Hz)	A_1	$f_{0,corr}$ if not seen in HVSR (Hz)	$A_{0,corr}$ ($A_{1,corr}$)	SD (f_0)	SD (1-10 Hz)	Directional (0.3-30 Hz)	Directional variability < 10 Hz	Cluster variability - HF	Cluster no. from mean HV	no. from HV_corr	Potential response description (mean HV)	Potential reference site (directionality)	Reference site (mean HV)
1	AMGA	-	-	f	13.5	-	-	-	-	1.04	1.05	Low	Low	Low	6	5	Reference station	Yes	Yes
2	ANKY	0.8	2.9		0.8	-	-		5	1.08	1.06	1.11	Low		3	2	Low amp, down trending	Yes	OK
3	APE	6.3	3.2		6.3	20	3		7/NA	1.20	1.09	1.19		High	4	1	HF amp	Not > 10 Hz	No
4	ARG	-	-	p	3.0	-	-	4.5	4.8	1.20	1.13	1.18		High	5	5	Flat, near reference	No	OK

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- waveform-derived parameters
- **parameters based on the analysis of all external sources**
- operator's observations from site visits

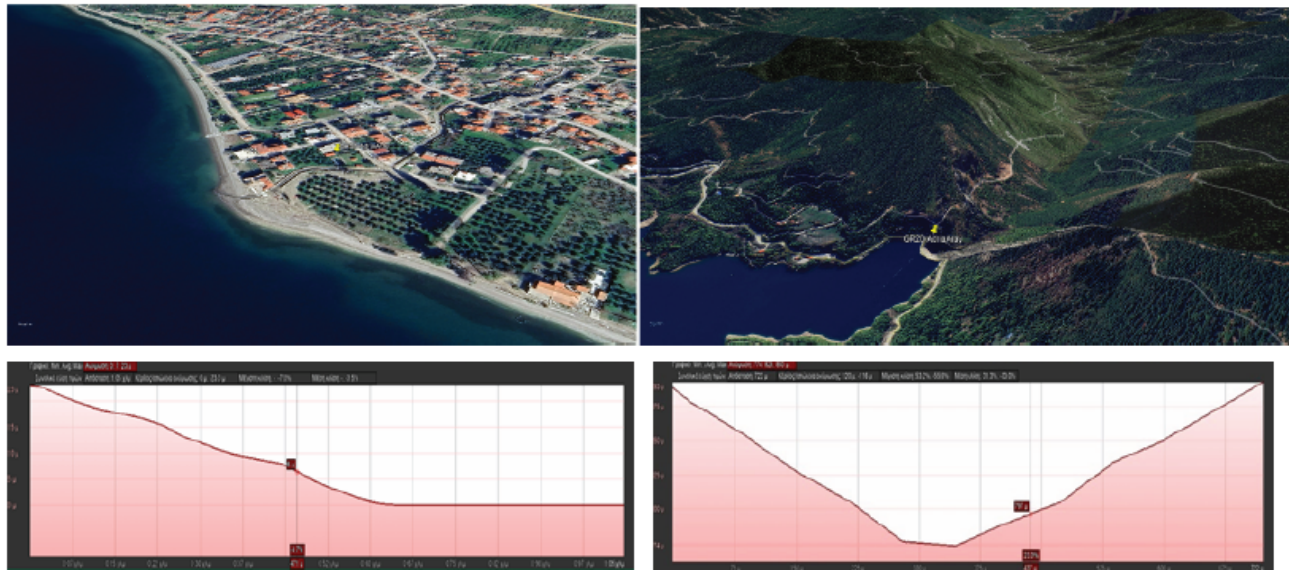
Parameters from external sources

- We studied 1:50,000 scale geological maps & compiled info on **geological units and age**
- Not always straightforward depending on age of map, accessibility of area, complexity and lateral variability, etc.
- Not to mention accessibility of maps...
- YES / NO / likely



Parameters from external sources

- Characterising **topography and slope** regime near the stations based on digital elevation models, maps of various scales, etc.
- Steepness means hard material... but...
- **Topo also amplifies!**
- Even **structure** characteristics



Parameters from external sources

Vs30 / EC8 / topo / geological unit-age / etc...

No.	Station code	EC8 from ESM	Vs30 from ESM Database (m s ⁻¹)	Measured Vs30 (Marg2021) (m s ⁻¹)	Profile site code (Stew2014)	Vs30 from geology/slope proxy (Marg2021)	Vs30 from terrain proxy (Marg2021)	Preferred Vs30 (Marg2021)	Measured Vs30 (HELPOS)	Potential reference site
1	AMGA	B	502	–	–	589	475	529		No
2	ANKY	B	760	–	–	589	475	529		Yes – ESM Database

No.	Station code	Station elevation (m)	Topography code (ESM Database)	Slope angle (°) (ESM Database)	Slope (Marg 2021)	Slope angle (°) based on Marg2021	Topography assessment by site visits	Potential reference site
1	AMGA	308	T1	3	0.047	3	Flat/shallow (< 15) within 200 m	Yes
2	ANKY	143	T1	8	0.138	8	Flat/shallow (< 15) within 200 m	Yes

No.	Station code	Station elevation (m)	Building type (from AccelNet)	Installation conditions – site visit	Potential reference site
1	AMGA	308	One-floor RC	Not free field	No
2	ANKY	143	–	Free field only for HH	No
3	APE	608	–	Vault in building	Yes

What would we like to know?

- waveform-derived parameters
- parameters based on the analysis of all external sources
- **operator's observations from site visits**

Insights from operator

Network operator's first-hand experience is very important:

- **housing/installation info!**
(potential SSI effects....)



Insights from operator

Network operator's first-hand experience is very important:

- **geological** maps constructed at a national scale (by different teams, over several decades) inevitably contain errors and simplifications
 - site visit more reliable & to scale
- satellite-based estimates of **slope/topo** invariably include approximation/homogenisation and lack specificity/granularity
 - site visit leaves little doubt as to the exact nature of the landscape at the station



Compiling all

General						Operator			External sources					
No.	Name	Station code	StLa (deg)	StLo (deg)	StEl (m)	Topography /slope from operator	Installation/ housing conditions from operator municipal	Photos from operator	Slope from DEM or other	Geol. symbol	Geological unit	Geol. age	Good based on geology?	Good based on slope?
											Pindos Zone:	Eocene,		

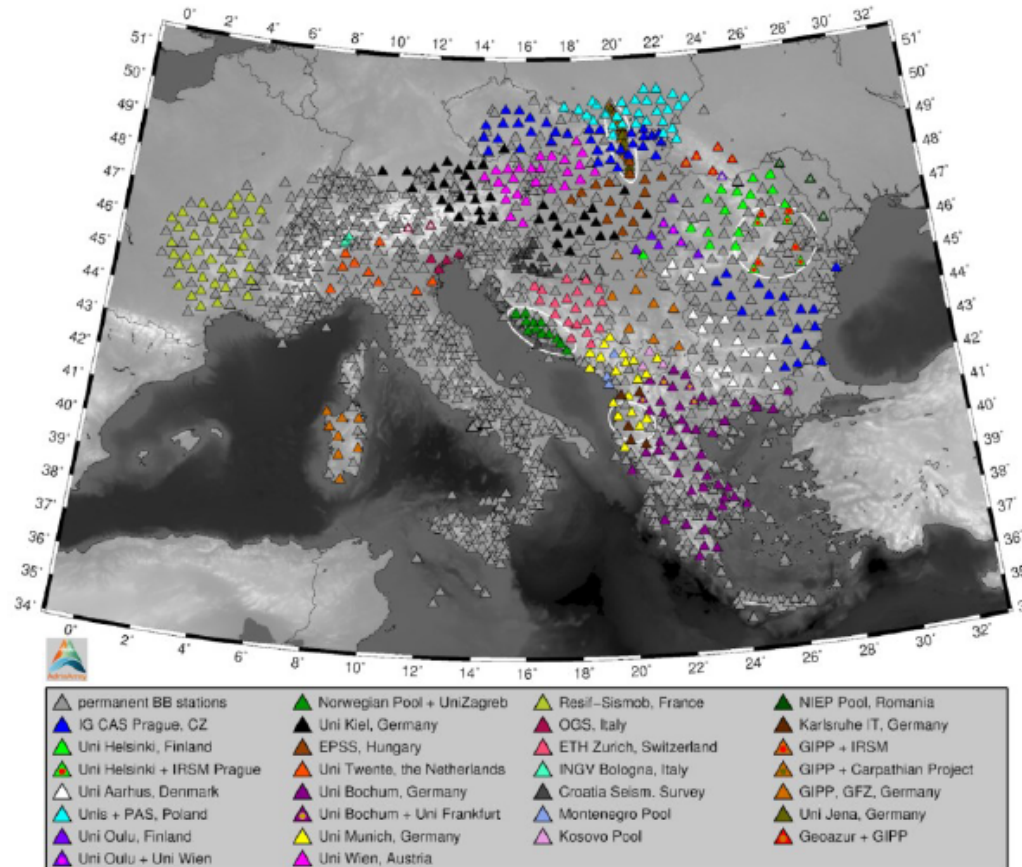
Data-derived

No. recs	Data from	Data till	ML range	Repi range (km)	Az. gap (deg)	f0 (Hz)	A0	std_f0	std_01-10	Comment: mean HV shape	Good based on HV?	Place holders
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No.	Station code	Installation/ housing	Topography/ slope	Vs30	Geology 1 : 50 000	HVSR: shape and amplitude	HVSR: directionality	Final disposition
1	AMGA	No	Yes	No	Yes	Yes	Yes	Very good
2	ANKY	No	Yes	Yes – ESM Database	Likely	OK	Yes	Good
3	APE	Yes	Yes	–	Yes	No	Not > 10 Hz	Good < 10 Hz
4	ARG	Yes	Yes	No	No	OK	No	

Other datasets: Adria Array

- Suggested methodology for a larger European effort



Other datasets: Adria Array

1  ANNALS OF GEOPHYSICS, VV, NV, PPPP, YYYY; doi:10.4401/ag-xxxx
2 OPEN ACCESS

3

4 A study of site conditions and amplification for 5 Greek AdriaArray stations

6 Olga- Joan Ktenidou¹, Antonia Papageorgiou^{*,1}, Vasilis- Erion Pikoulis², Kalliopi-
7 Elli Fragouli¹, Spyros Liakopoulos¹ and Fanis Halaris¹

8 ⁽¹⁾ Institute of Geodynamics, National Observatory of Athens, Lofos Nymfon-Thiseion, Athens, 11850, Greece

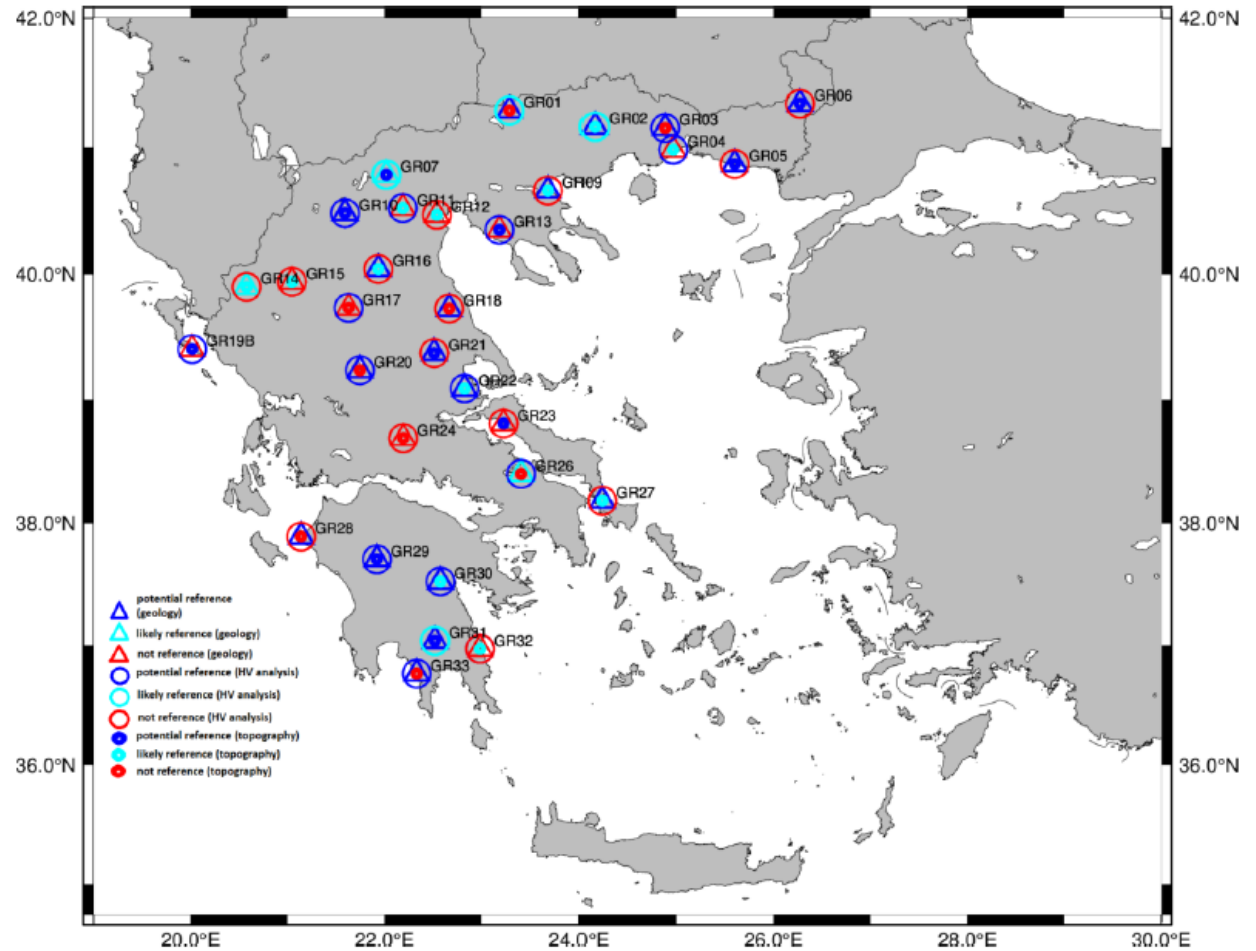
9 ⁽²⁾ University of Patras, Patras, 26504, Greece

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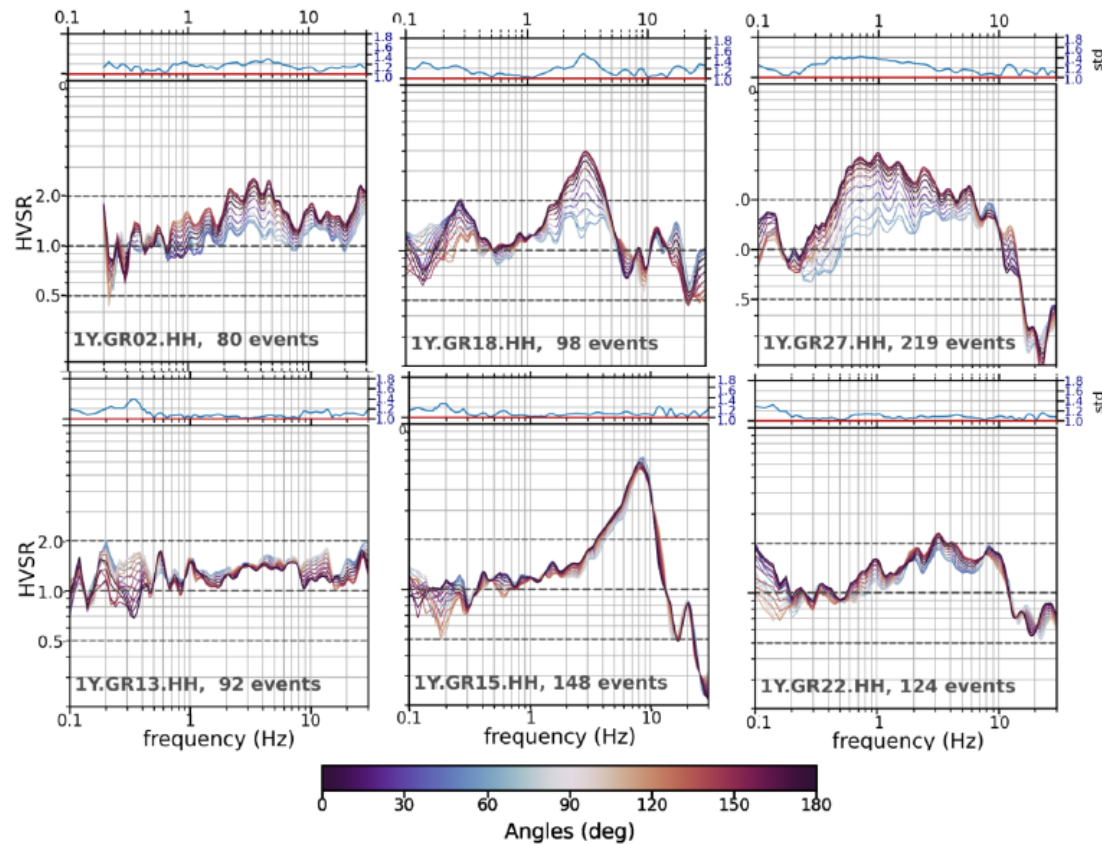
11 Article history: received Month DD, YYYY; accepted Month DD, YYYY

Other datasets: Adria Array

- △ potential reference (geology)
- △ likely reference (geology)
- △ not reference (geology)
- potential reference (HV analysis)
- likely reference (HV analysis)
- not reference (HV analysis)
- potential reference (topography)
- likely reference (topography)
- not reference (topography)



Other datasets: Adria Array

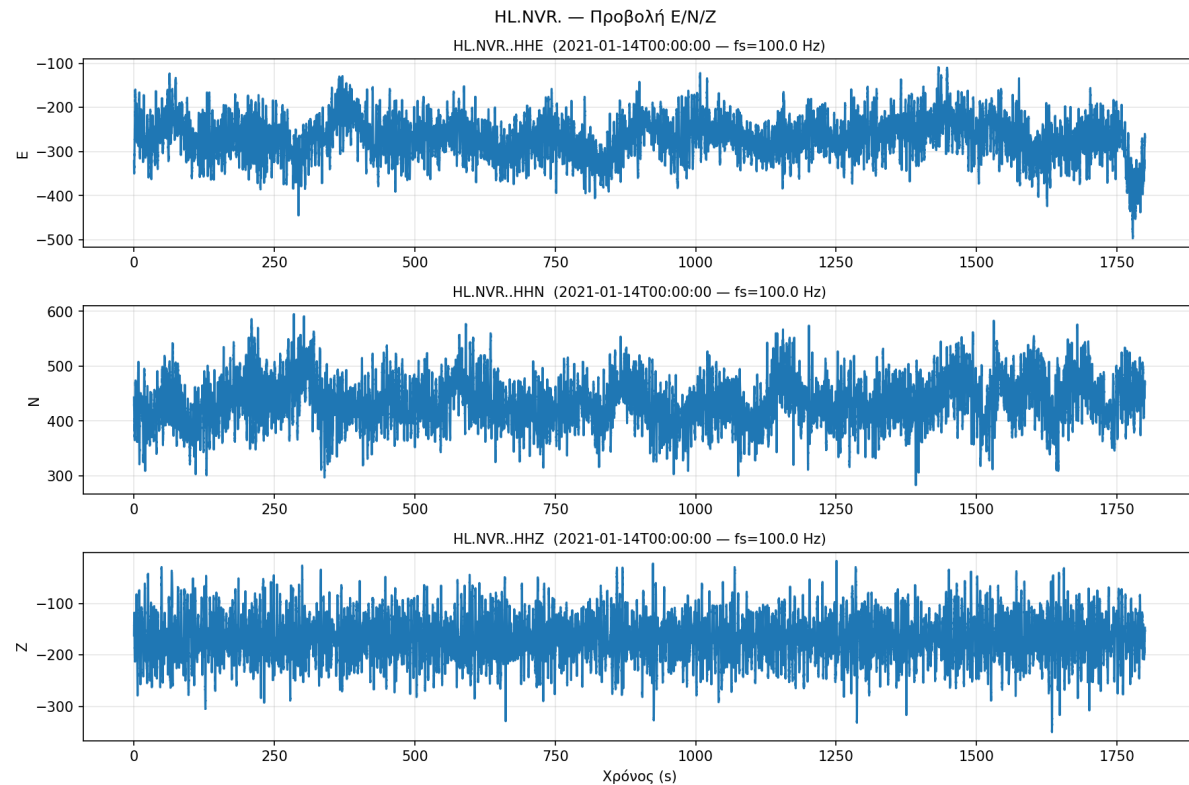


*I think I'll
take the NS
component...*



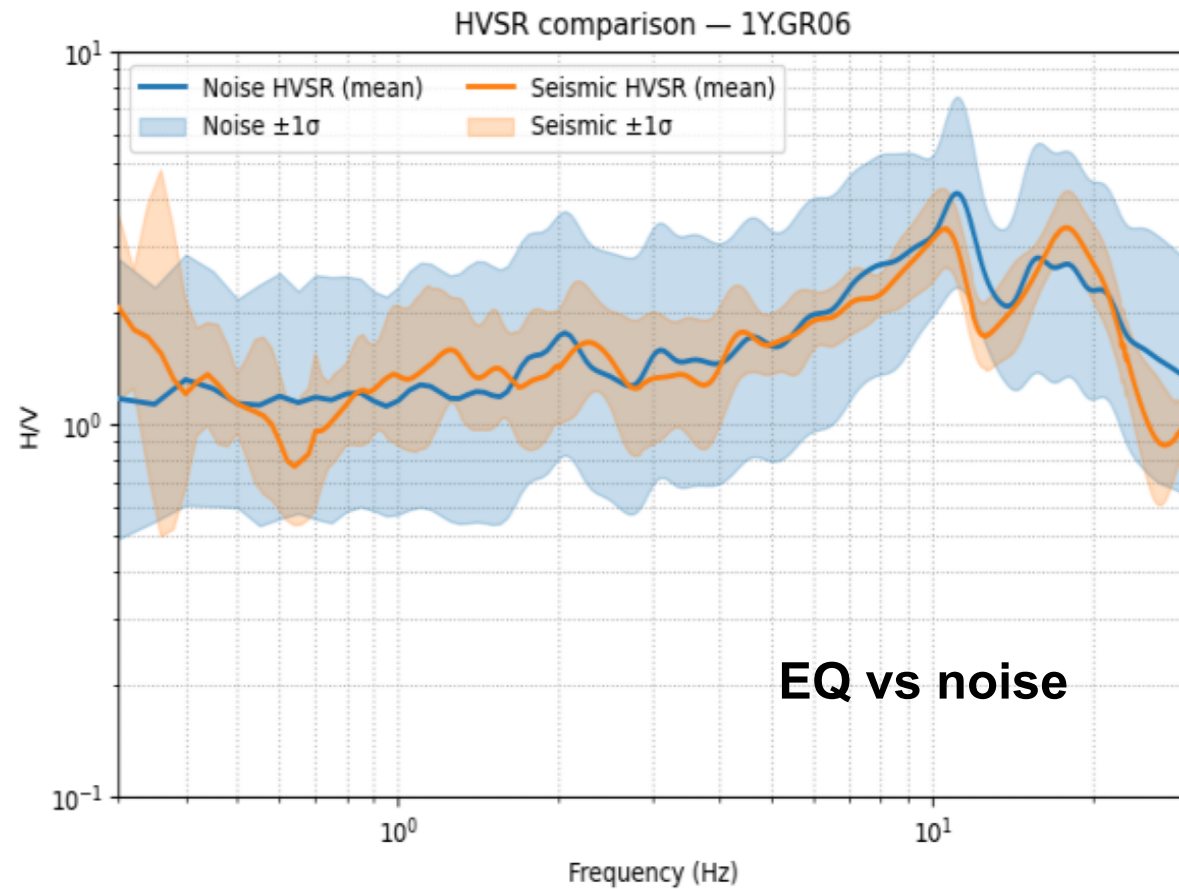
Other datasets: Adria Array

- BTW... for new stations..
- no time to wait for Enceladus?
- noise vs EQ amps



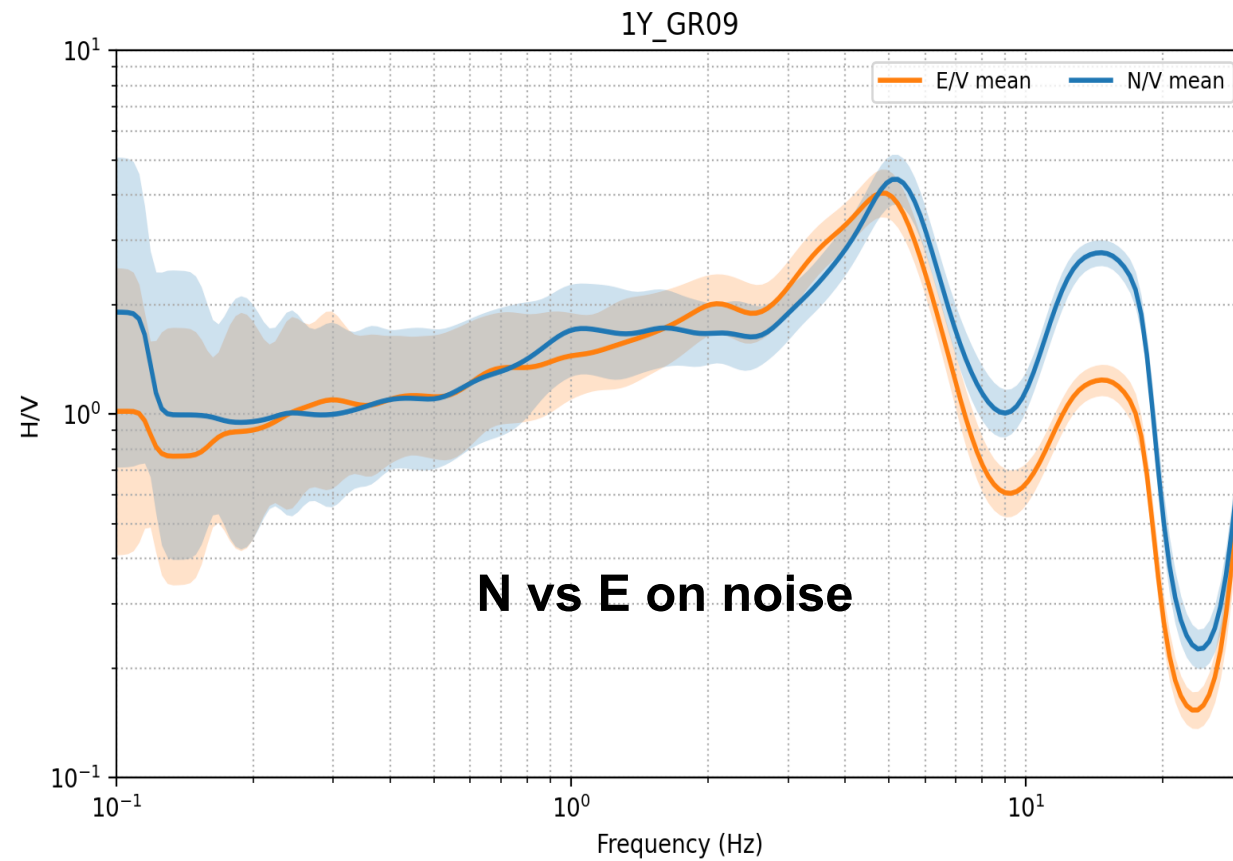
Other datasets: Adria Array

- BTW... for new stations..
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Other datasets: Adria Array

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- noise vs EQ amps



Wrap-up

We have proposed a more **inclusive / holistic framework for selecting reference stations** and GMs, combining:

- **DATA**: amplification at rock stations + rich metadata exceeding typical analyses
- input from **public sources** (housing, topo, geology, Vs30)
- insights & corrections from operators based on **site visits**

We have shown that:

- not all rock sites should be treated equally or trusted blindly
- the **selection process matters**
- one size / criterion does not fit all

Wrap-up

Compile & **openly challenge** / contrast all info:

- offer overall **qualitative assessment** of reference site potential
- **offer transparency** of all criteria and the possibility for potential user to **prioritise / tailor to individual needs**, rather than blindly accept
- combine criteria: a single source of info may carry **larger risks**

Hope to allow future EQ engineering studies to:

- select input ground motions in an **informed and controlled way**
- **reduce uncertainties** and bias
- ultimately improve the quality **and reliability of analyses** using recorded data as input

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