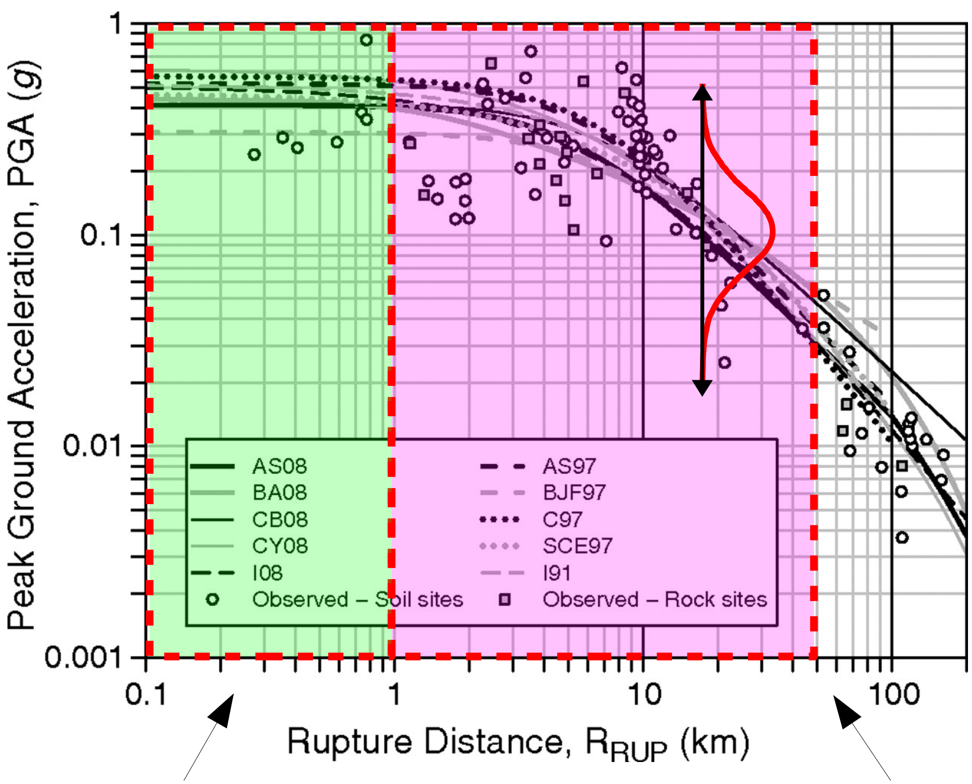
GMPE site term and Soil Proxies

GMPE - Ground Motion Prediction Equations

Given a specific source scenario (e.g. magnitude, fault mechanism...), GMPEs predict the shaking level at a given location (e.g. at distance R)

GM Amplitude = **Source term** * **Path term** * **Site term**



Lack of data in near field...

Important distances < 50Km

Often source, path and site terms are described by a simple **regressive model** (e.g. high order polynomials) using a merely empirical approach and **single predictors** (**PGA, PGV, Intensity**)

PRO: generally quite easy to use, often calibrated on world-wide datasets

CONS: based just on observation, (little) physical justification, large epistemic uncertainty

The Generic Site Amplification Term

GMPEs represent a simple and convenient way to predict ground motion level over wide areas and sites of different characteristic

In order to predict site response for a specific site and in case of **lack of direct recordings**, a **site amplification model** is then necessary

This can be done in two ways, using:

Numerical models and closed analytical solutions

Possible, but impractical over large scales, due to high costs in obtaining detailed site parameters....

Empirical prediction based on soil proxies

Simple and convenient, although empirical models are still calibrated on **direct analysis of earthquakes**

Soil classification and proxies

Present **GMPEs** and **building codes** use simplified approaches to map the variability of local site response over wide areas by means of **statistical models** based on **ground types** (or classes) and **empirical observations**

Ground types are identified by appropriate **near-surface proxies**, such as:

- → **the average velocity over the first 30 meters (Vs_{30})**
- → the fundamental frequency of resonance
- → results from SPT/CPT tests
- → geological/geotechnical classification...

Ground Class	Description	v_s [m/s]	N_{SPT}	s_u [kN/m^2]	S	T_B [s]	T_C [s]	T_D [s]
A	firm rock (e.g. granite, gneiss, quartzite, siliceous limestone, limestone) or soft rock (e.g. sandstone, conglomerate, Jura marl, Opalinus claystone) beneath a maximum soil cover of 5 m	> 800	–	–	1.00	0.15	0.4	2.0
B	deposits of extensive cemented gravel and sand and/or overconsolidated soils with a thickness exceeding 30 m	400…800	> 50	> 250	1.20	0.15	0.5	2.0
C	deposits of normally consolidated and uncemented gravel and sand and/or moraine with a thickness exceeding 30 m	300…500	15…50	70…250	1.15	0.20	0.6	2.0
D	deposits of unconsolidated fine sand, silt and clay with a thickness exceeding 30 m	150…300	< 15	< 70	1.35	0.20	0.8	2.0
E	alluvial surface layer of Ground Classes C or D, with a thickness of 5 to 30 m lying above a stiffer layer of the Ground Classes A or B	–	–	–	1.40	0.15	0.5	2.0
F	deposits of structurally-sensitive and organic deposits (e.g. peat, lake marl, slide material) with a thickness exceeding 10 m	–	–	–	–	–	–	–

SIA261 - Example of soil classification using Vs_{30}

Some Considerations on the Use of Soil Proxies

⇨ Proxies are a convenient way to characterize soil types of "*expected*" similar seismic response using just a single parameter

⇨ Soil proxies can be obtained by direct measure or (very often) by **indirect extrapolation** from other direct observations (e.g. geology, topography)

⇨ However, despite of their simplicity, these proxies:

① do not fully describe the **vertical/lateral variability** of the soil structure

② can hardly describe the **frequency dependent** amplification behavior

③ cannot account for site-specific phenomena like **soil non-linearity** and **resonance amplification**

What Vs_{30} actually is?...

- Vs_{30} is the **travel-time average shear-wave velocity** over the first 30m.
- It is computed in such a way:

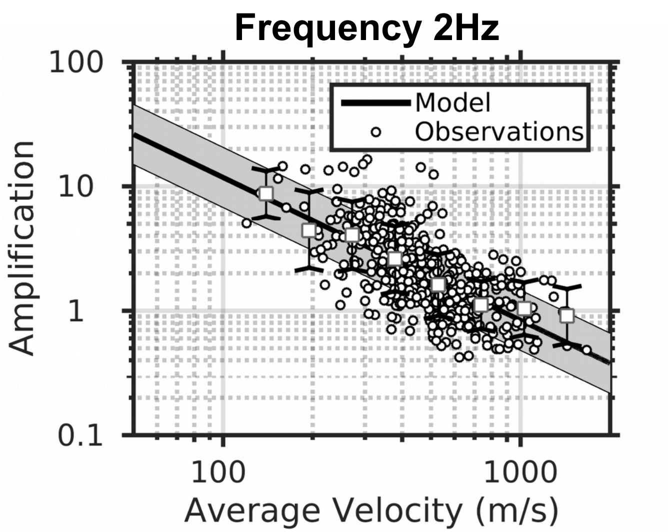
$$Vs30 = \frac{30}{\sum_{i=1,N} \frac{h_i}{v_i}}$$

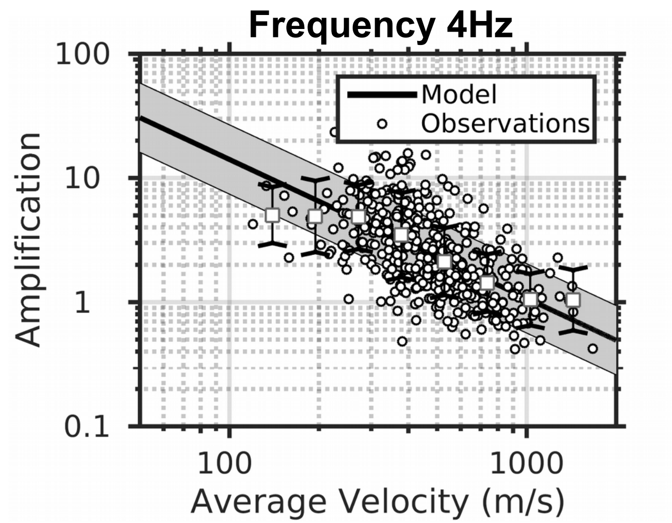
...but why using 30m, and not 10, 25 or 50m?

- Simply because ~30m (**100ft!**) was the standard penetration depth of most of the direct logging techniques of the past (at least in US).

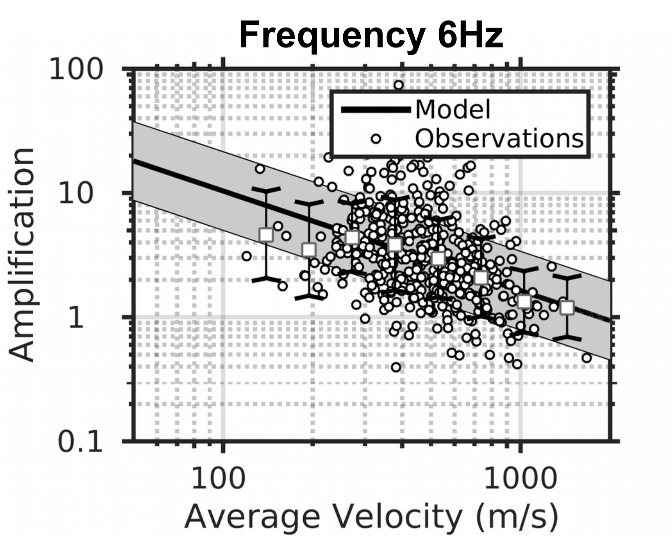
Consequently...

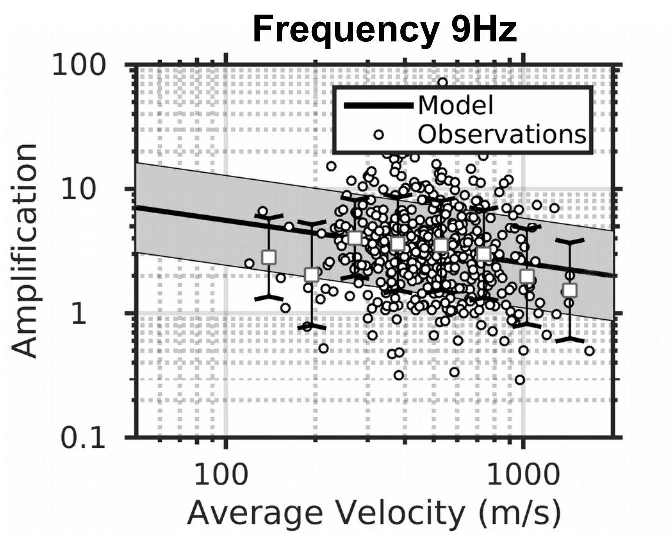
- The large availability of log data within this depth range imposed this parameters as **de facto standard** (but without a clear **physical meaning**)





Nonetheless Vs_{30} is a parameter **highly correlated** with site amplification...





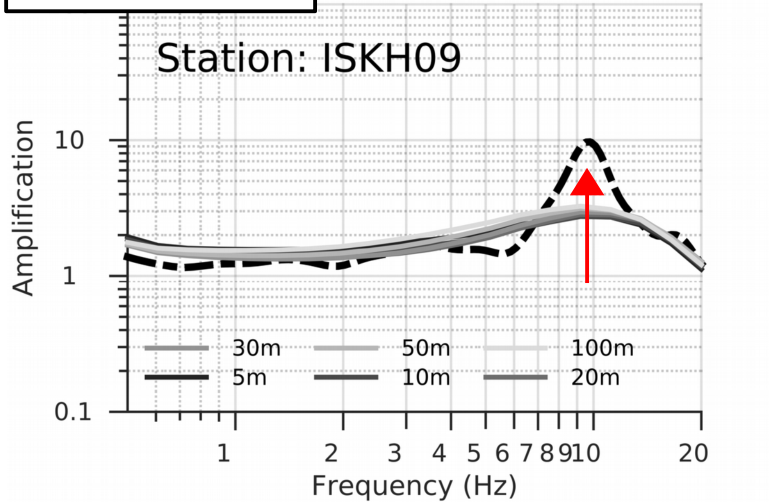
...even if prediction **uncertainty** is quite large

Source of Uncertainty of the Predictor

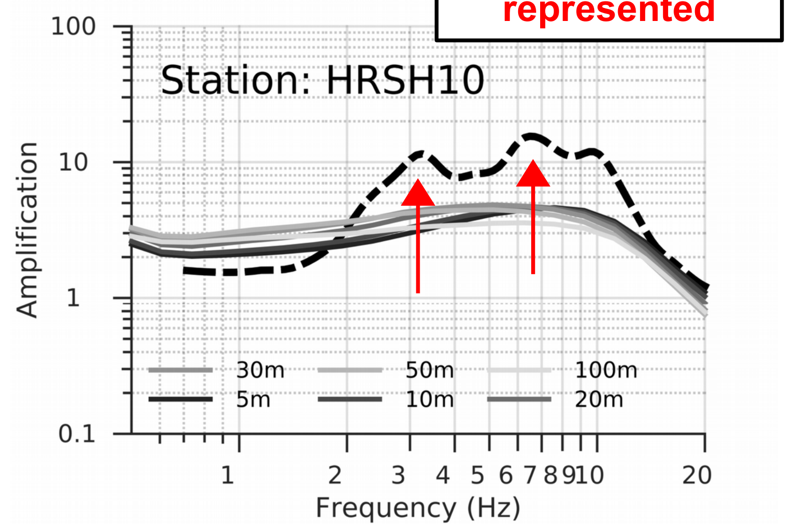
- Vs_{30} is basically a proxy for the contrast of seismic impedance between the **basement** (source condition) and the **uppermost (average) soil**, which is controls the average amplification level of the site

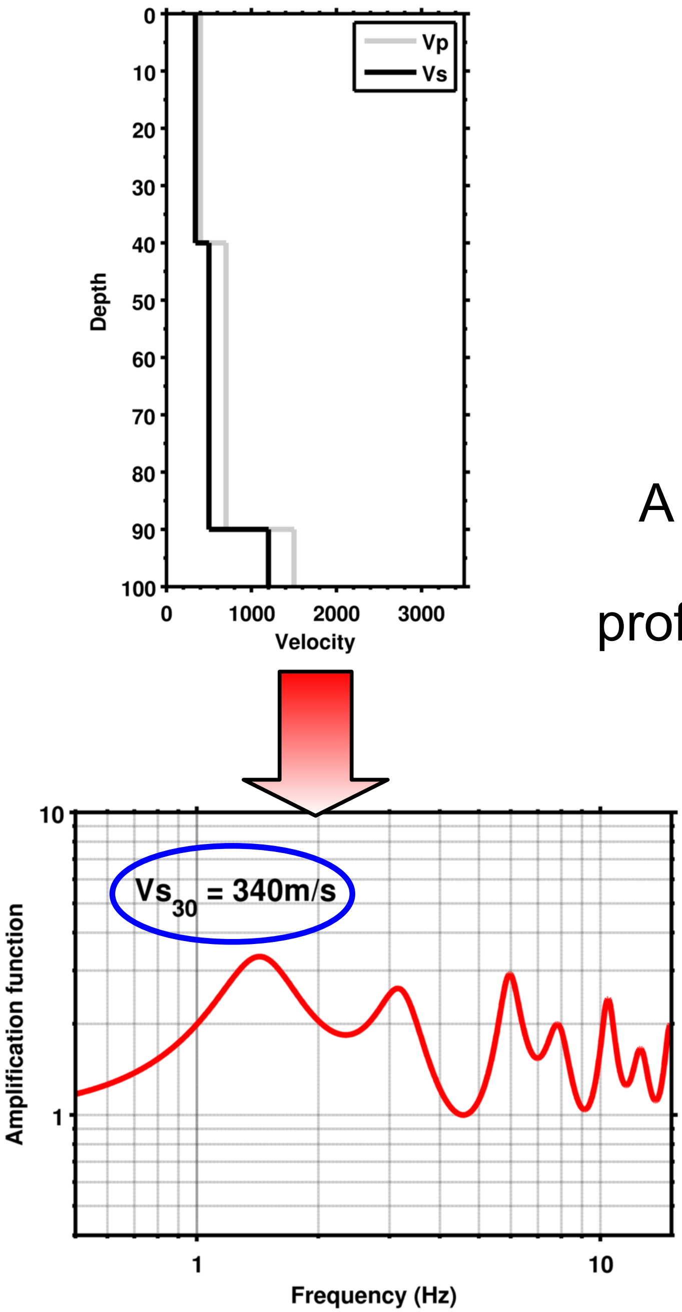
- However, Vs_{30} cannot explain those complex phenomena developing *"within"* the profile...

Works nicely with rock sites

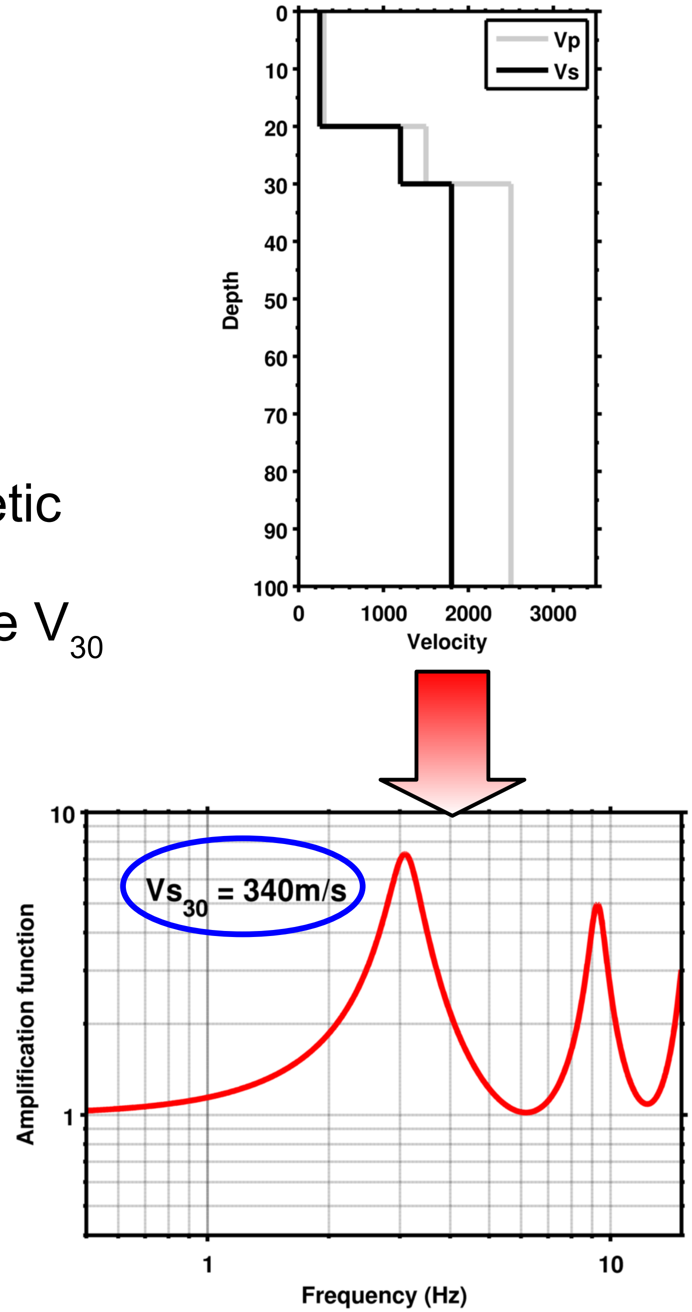


Resonance amplification not represented





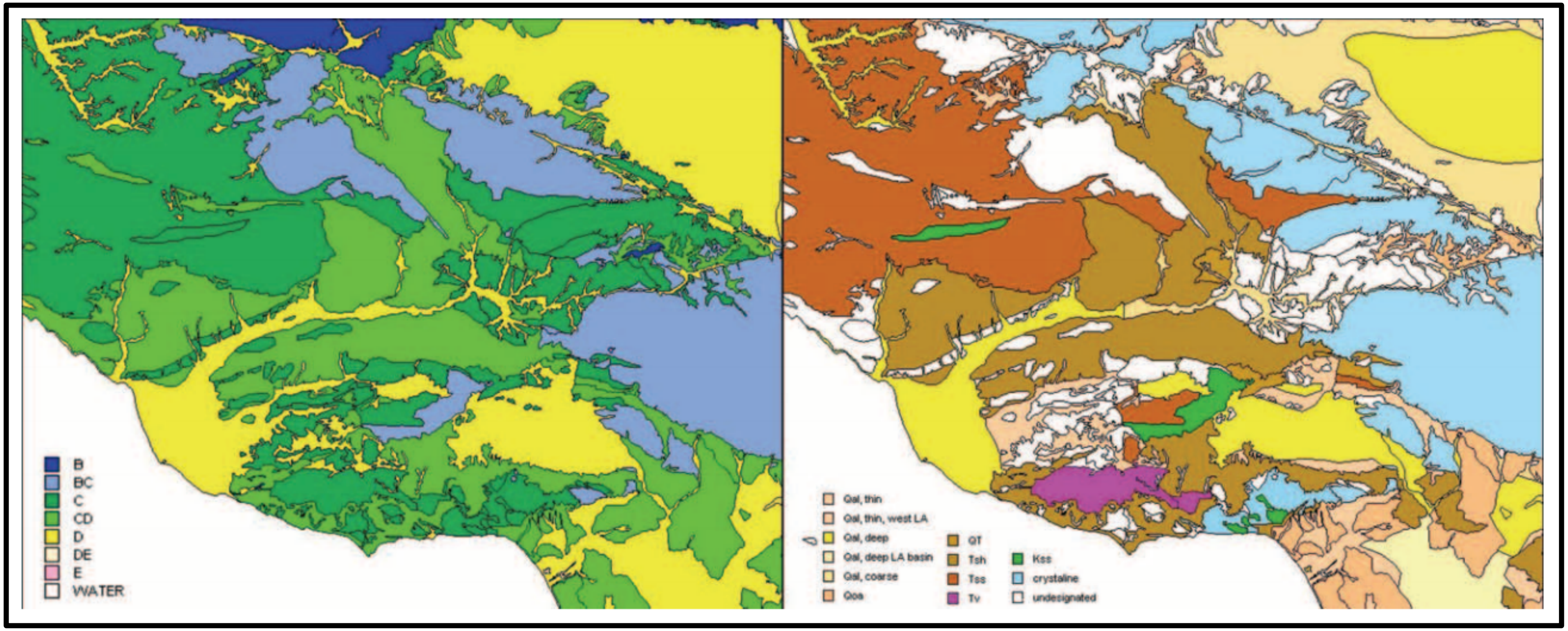
A simple synthetic example:
profiles with same V_{30}



Additional Source of Uncertainty

- Vs_{30} can also be biased by the way it is obtained, often not from direct measurement but **extrapolated** from other surface proxies (geology, geotechnical classification, CPT tests….)
- The conversion introduces an additional contribution to the uncertainty, which sum to the final error in the prediction

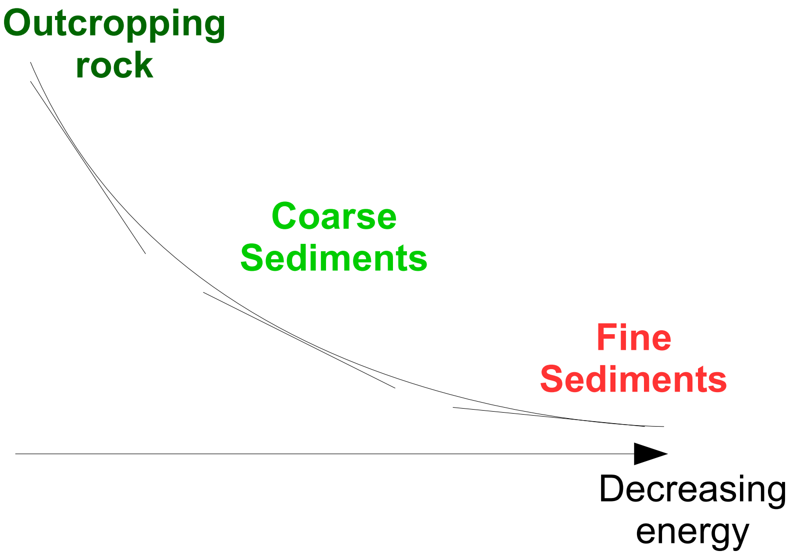
Geology **Vs30**

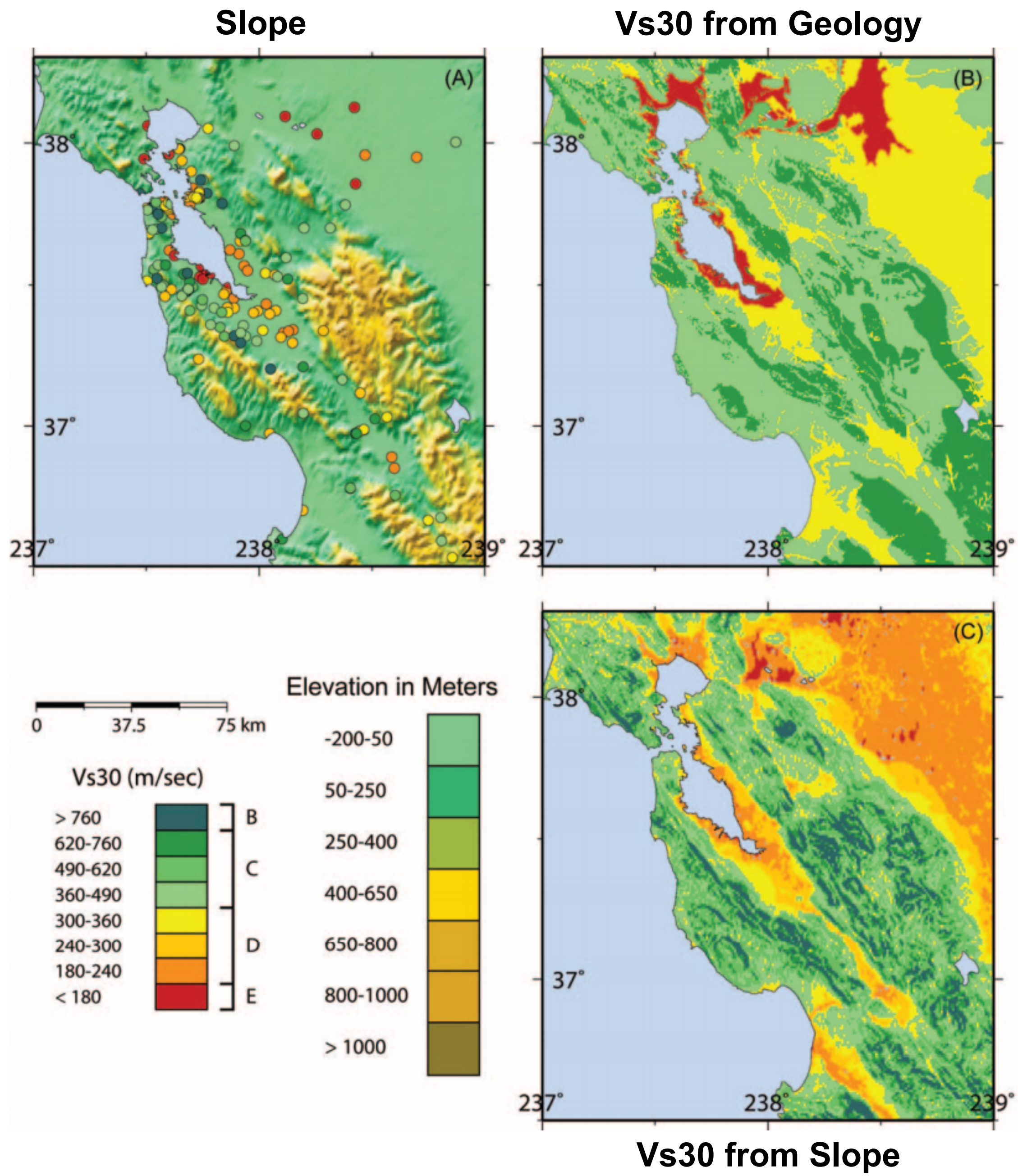


Willis and Clahan (2006)

Vs_{30} from Topography

- Nowadays, a popular way to map Vs_{30} over large areas is the use of **topographic slope** from geodetic observations (Wald and Allen, 2007, 2009)
- The relation is based on the concept of **“depositional energy”** of the sediments





Vs_{30} from Topography

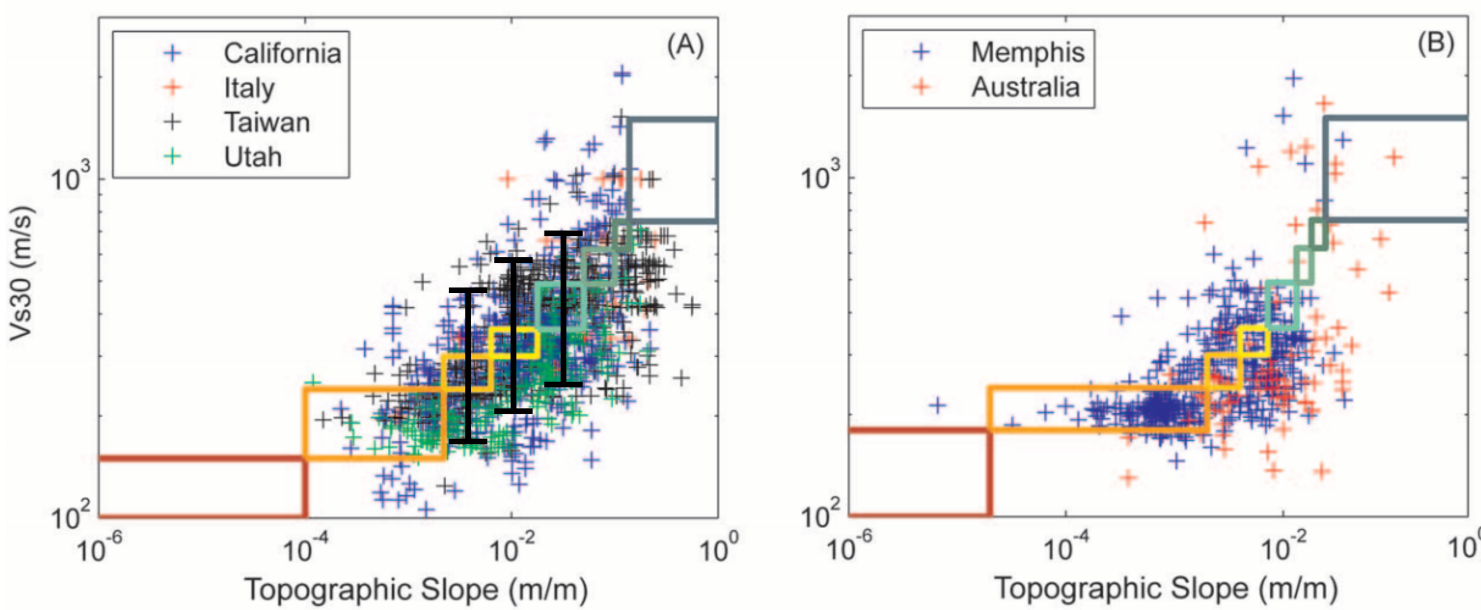
The slope-Vs_{30} relationship is based on the **National Earthquake Hazard Reduction Program** (**NERHP**) Vs_{30} boundaries (arbitrary?)

Summary of Slope Ranges for NEHRP V_S^{30} Categories

Class	V_S^{30} Range (m/sec)	Slope Range (m/m) Active Tectonic	Stable Continent
E	<180	<1.0E − 4	<2.0E − 5
	180–240	1.0E − 4–2.2E − 3	2.0E − 5–2.0E − 3
D	240–300	2.2E − 3–6.3E − 3	2.0E − 3–4.0E − 3
	300–360	6.3E − 3–0.018	4.0E − 3–7.2E − 3
	360–490	0.018–0.050	7.2E − 3–0.013
C	490–620	0.050–0.10	0.013–0.018
	620–760	0.10–0.138	0.018–0.025
B	>760	>0.138	>0.025

Calibration databases from different regions:

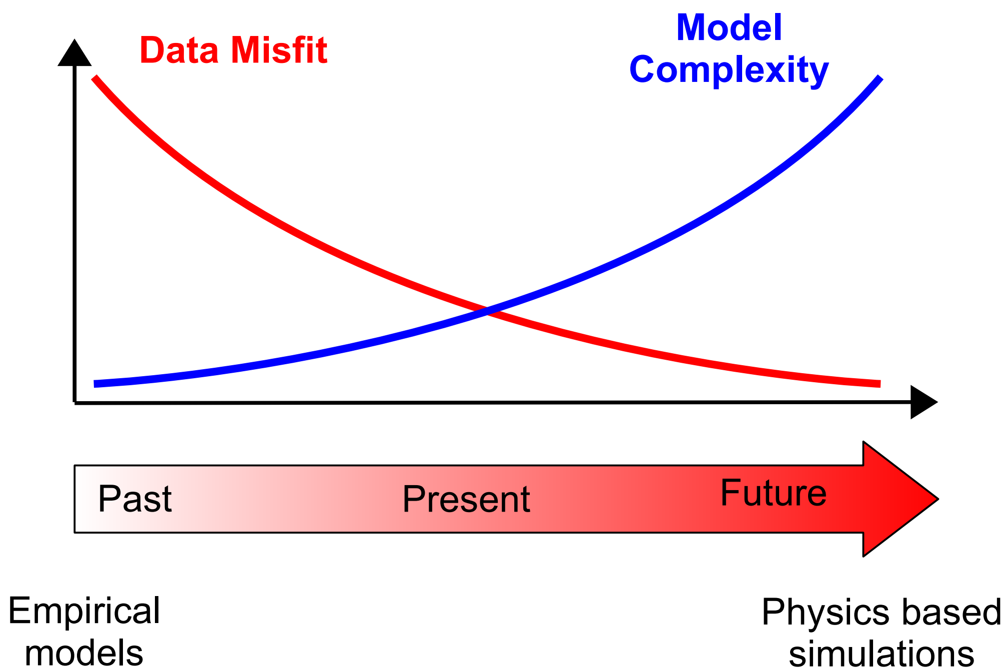
- California
- Utah
- Central U.S.
- Taiwan
- Italy
- Australia



...and the question is finally:

Is Vs_{30} really so adequate as proxy for site amplification?

Vs_{30} is probably not sufficient for future engineering products, as it introduces too large uncertainties



Epistemic uncertainty can be reduced at the expenses of increasing model complexity, by introducing **physics-based concepts**

Modeling Site-Response Into GMPEs

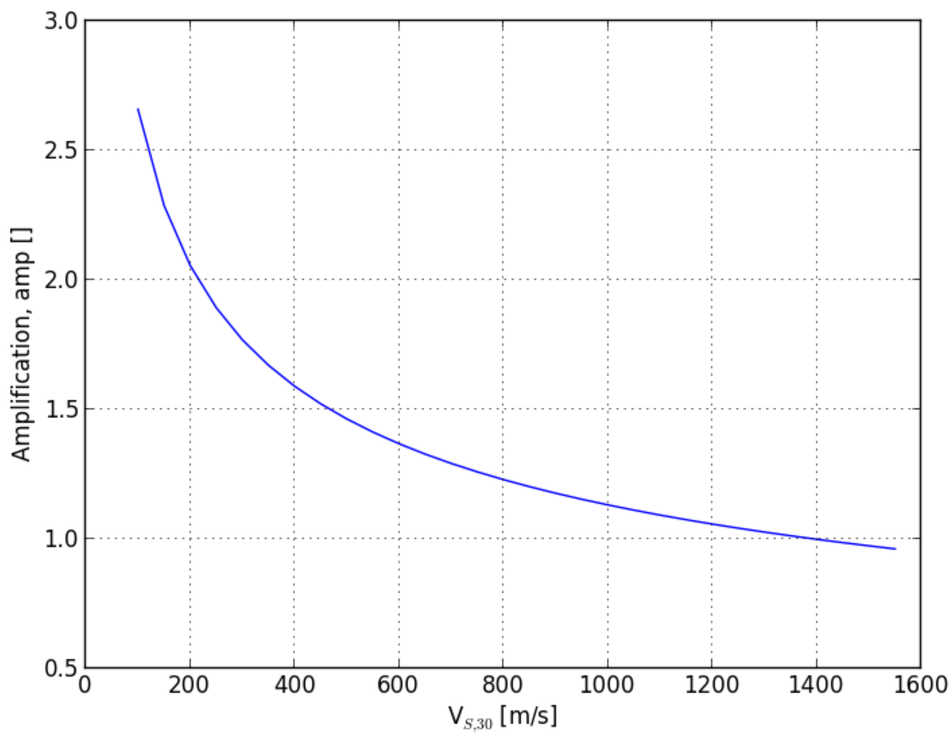
Boore et al. (1997)

Assuming a linear amplification of motion Boore et al. (1997) proposed the following formula to model site amplification using a site-specific $V_{S,30}$ value:

$$\ln(Amp) = a \ln\left(\frac{V_{S,30}}{V_{\mathrm{Ref}}}\right)$$

For PGA the coefficients are:

- $a = -0.371$
- $V_{ref} = 1396$ [m/s]



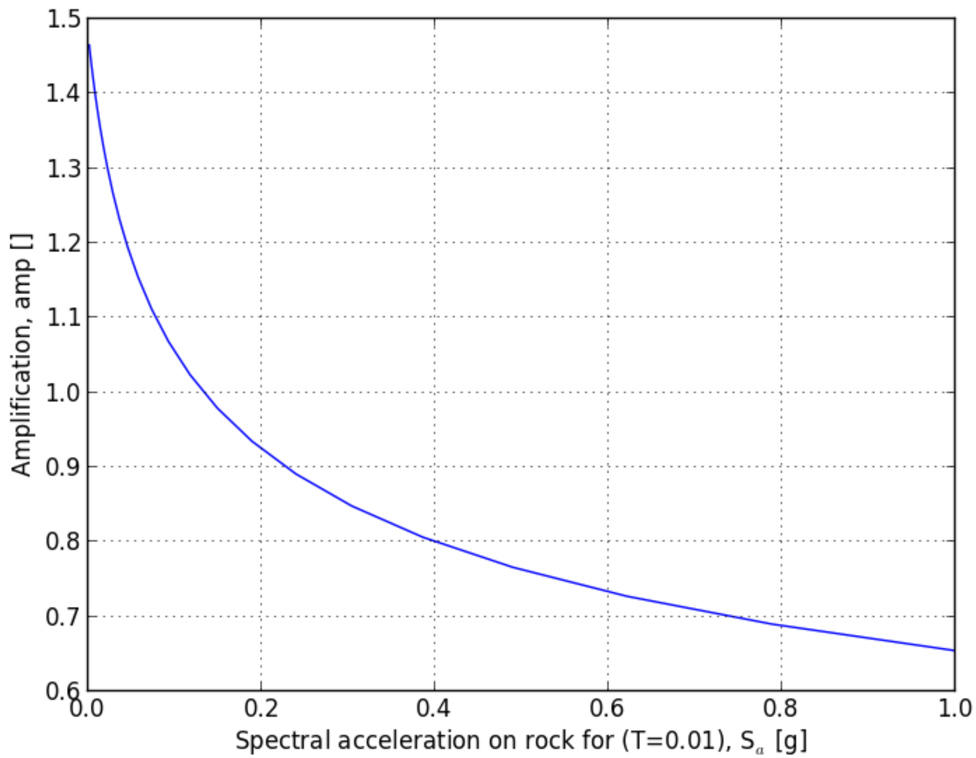
Ambrahamson and Silva (1997)

Ambrahamson and Silva (1997) using a generalized soil category developed a model for site response accounting for the non-linear behaviour of materials

$$\ln(Amp) = a + b\ln\left(P\hat{G}A_{rock} + c\right)$$

For PGA the coefficients are:

- a = - 0.417
- b = -0.230
- c = 0.03



Choi and Stewart (2005)

Choi and Stewart (2005) proposed and empirical model for assessing the nonlinear amplification factor for spectral acceleration as a function of $V_{S,30}$. The results can be used as *Vs-30-based* site factors with attenuation relationships

$$\ln(F_{ij}) = c\ln\left(\frac{V_{s\text{-}30_{ij}}}{V_{ref}}\right) + b\ln\left(\frac{PHA_{r_{ij}}}{0.1}\right) + \eta_i + \varepsilon_{ij},$$

where:

- PHA_r peak horizontal acceleration for reference [rock] site condition [g]
- V_{ref} and c are regression parameters
- h_i is a random effect term for earthquake event i (should have zero median across all events, standard deviation is denoted as t); and e_{ij} represents the intra-event model residual for motion j in event i (should have median near zero for well-recorded events, standard deviation is denoted s).