Correction of downhole to EC8 reference rock outcrop ground motion for Kik-Net considering nonlinear soil behavior

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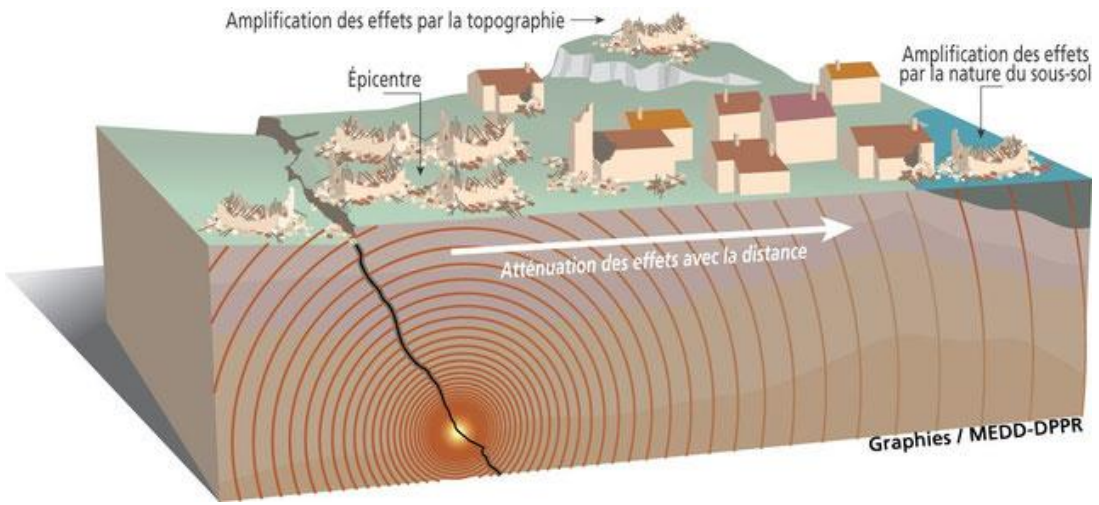
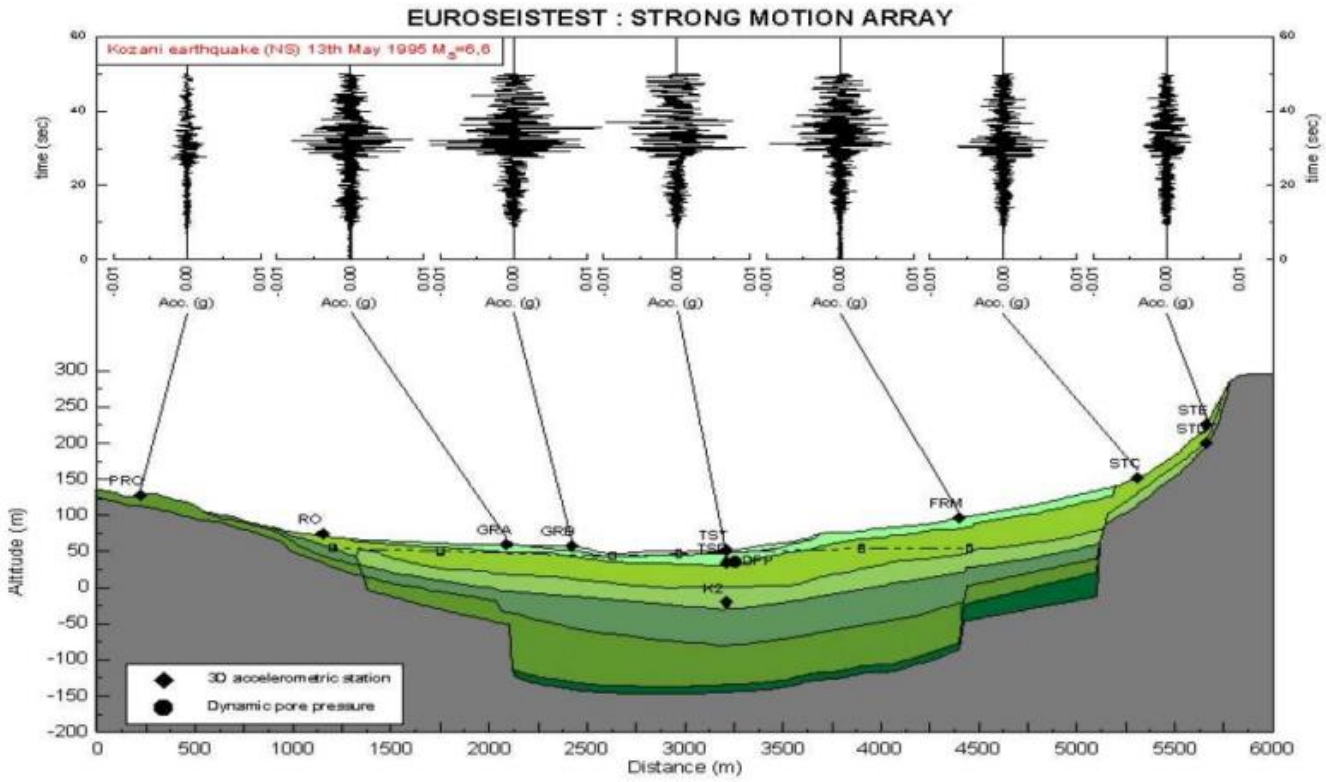
Introduction

Earthquakes are one of the most devastating natural disasters on Earth

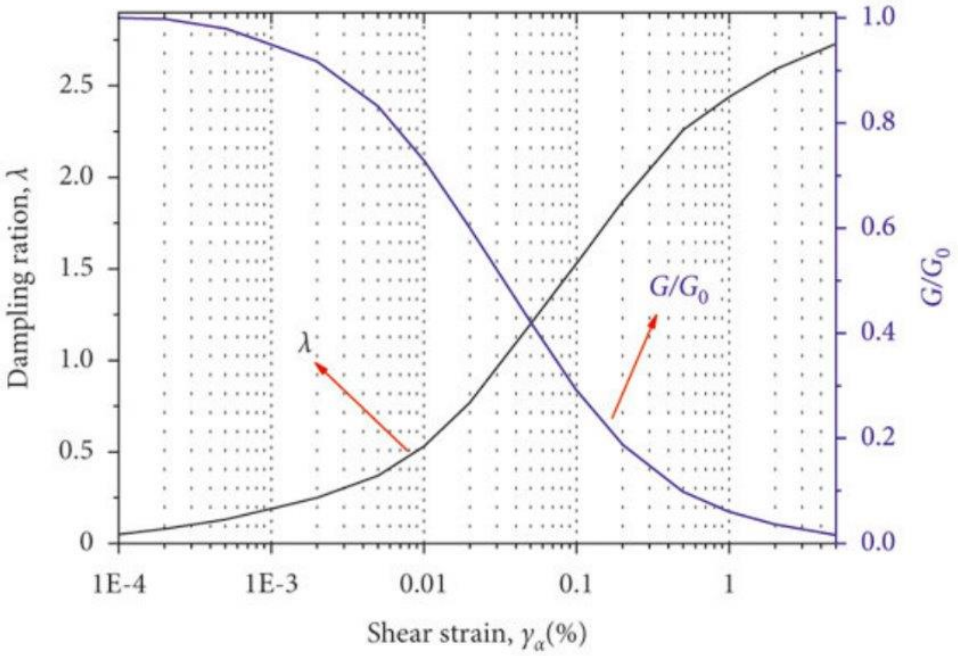


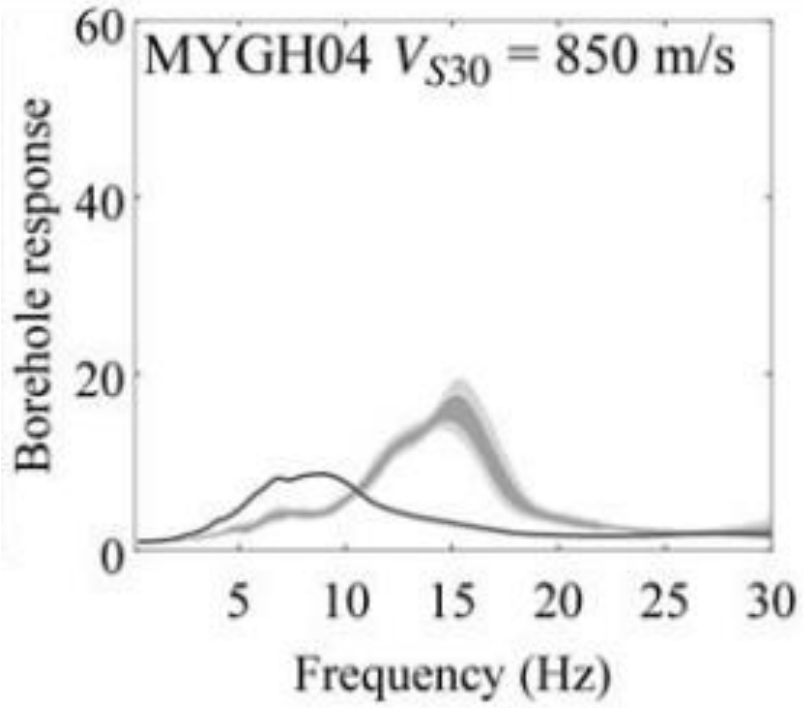
Site effects

Modification of seismic waves by the geological configuration of the site



Introduction





❖ Shear modulus reduction → Shift of resonance frequencies

❖ Damping augmentation → Attenuation of strong movements

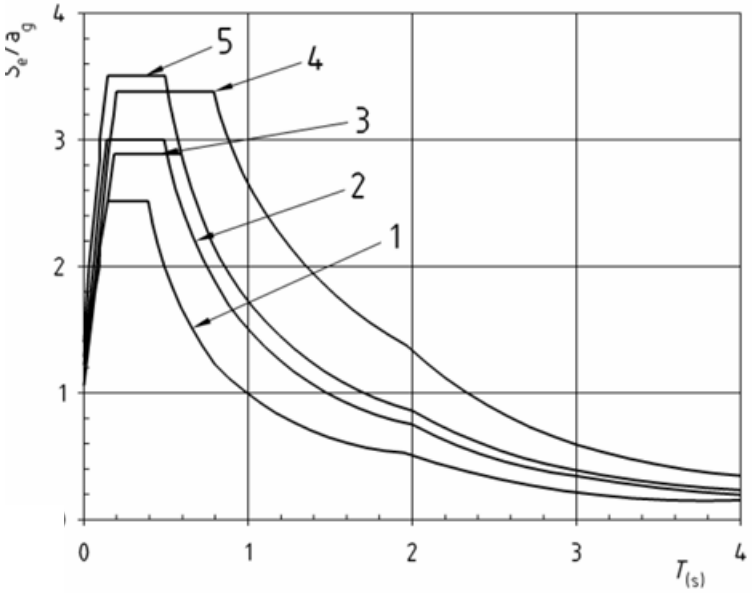
Introduction

Objective: How we can Introduce Empirical Nonlinear Effects in a Site Response Analysis?

- Response spectra in EC8 depend on Vs30 (for now)
- Nonlinearity is not taken into account

Tableau 3.1 — Classes de sol

Classe de sol	Description du profil stratigraphique	Paramètres		
		$v_{s,30}$ (m/s)	N_{SPT} (coups/30 cm)	c_u (kPa)
A	Rocher ou autre formation géologique de ce type comportant une couche superficielle d'au plus 5 m de matériau moins résistant	> 800	—	—
B	Dépôts raides de sable, de gravier ou d'argile sur-consolidée, d'au moins plusieurs dizaines de mètres d'épaisseur, caractérisés par une augmentation progressive des propriétés mécaniques avec la profondeur	360 – 800	> 50	> 250
C	Dépôts profonds de sable de densité moyenne, de gravier ou d'argile moyennement raide, ayant des épaisseurs de quelques dizaines à plusieurs centaines de mètres	180 – 360	15 – 50	70 – 250
D	Dépôts de sol sans cohésion de densité faible à moyenne (avec ou sans couches cohérentes molles) ou comprenant une majorité de sols cohérents mous à fermes	< 180	< 15	< 70
E	Profil de sol comprenant une couche superficielle d'alluvions avec des valeurs de v_s de classe C ou D et une épaisseur comprise entre 5 m environ et 20 m, reposant sur un matériau plus raide avec v_s > 800 m/s			
S_1	Dépôts composés, ou contenant, une couche d'au moins 10 m d'épaisseur d'argiles molles/vases avec un indice de plasticité élevé (PI > 40) et une teneur en eau importante.	< 100 (valeur indicative)	—	10 – 20
S_2	Dépôts de sols liquéfiables d'argiles sensibles ou tout autre profil de sol non compris dans les classes A à E ou S_1.			



Response spectra recommended by EC8 for soil classes from A to E

Objective: How we can Introduce Empirical Nonlinear Effects in a Site Response Analysis?

- Response spectra take into account nonlinearity using numerical models (in the future, 2027)

Old EC8	New EC8
PGA	$S_{\alpha,RP}$ $S_{\beta,RP}$

	Classe de sol	rigide	rigidité moyenne	souple
Classe de profondeur	Plage $v_{s,H}$ / Plage H_{800}	400 m/s ≤ $v_{s,H}$ < 800 m/s	250 m/s ≤ $v_{s,H}$ < 400 m/s	150 m/s ≤ $v_{s,H}$ < 250 m/s
très peu profond	H_{800} ≤ 5 m	A	A	E
peu profond	5 m < H_{800} ≤ 30 m	B	E	E
intermédiaire	30 m < H_{800} ≤ 100 m	B	C	D
profond	H_{800} > 100 m	B	F	F

Tableau 5.4 — Coefficients d'amplification de site F_α et F_β pour les catégories de sites standard du Tableau 5.1

Catégorie de sites	F_α		F_β	
	H_{800} et $v_{s,H}$ disponibles	Valeur par défaut	H_{800} et $v_{s,H}$ disponibles	Valeur par défaut
A	1,0	1,0	1,0	1,0
B	$\left(\frac{v_{s,H}}{800}\right)^{-0,4\,r_\alpha}$	$1,3\,(1-0,1\,S_{\alpha,RP}/g)$	$\left(\frac{v_{s,H}}{800}\right)^{-0,7\,r_\beta}$	$1,6\,(1-0,2\,S_{\beta,RP}/g)$
C		$1,6\,(1-0,2\,S_{\alpha,RP}/g)$		$2,3\,(1-0,3\,S_{\beta,RP}/g)$
D		$1,8\,(1-0,3\,S_{\alpha,RP}/g)$		$3,2\,(1-S_{\beta,RP}/g)$
E	$\left(\frac{v_{s,H}}{800}\right)^{-0,4\,r_\alpha \frac{H}{30}\left(4-\frac{H}{10}\right)}$	$2,2\,(1-0,5\,S_{\alpha,RP}/g)$	$\left(\frac{v_{s,H}}{800}\right)^{-0,7\,r_\beta \frac{H}{30}}$	$3,2\,(1-S_{\beta,RP}/g)$
F	$0,9\left(\frac{v_{s,H}}{800}\right)^{-0,4\,r_\alpha}$	$1,7\,(1-0,3\,S_{\alpha,RP}/g)$	$1,25\cdot\left(\frac{v_{s,H}}{800}\right)^{-0,7\,r_\beta}$	$4,0\,(1-S_{\beta,RP}/g)$
	avec $r_\alpha = 1-\frac{S_{\alpha,RP}/g}{v_{s,H}/150}$ et $r_\beta = 1-\frac{S_{\beta,RP}/g}{v_{s,H}/150}$ (H en m, $v_{s,H}$ dans m/s, g=9,81 m/s²)			

Objective: How we can Introduce Empirical Nonlinear Effects in a Site Response Analysis?

- Response spectra take into account nonlinearity using numerical models (in the future, 2027)

↓ Our objective

- Propose an amplification function to take into account **empirically** site effects and nonlinearity

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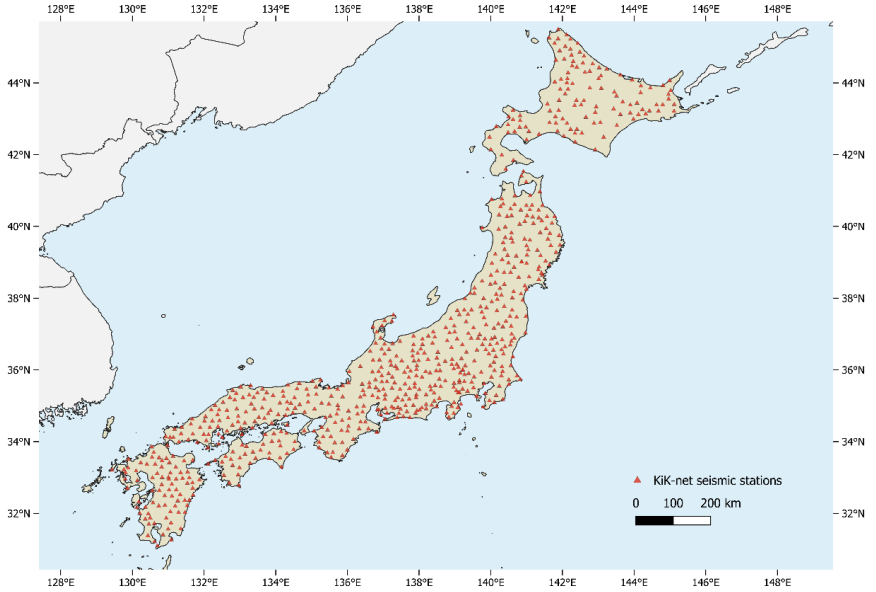
Introduction

Large database used

KiK-net (Kiban-Kyoshin network) database in Japan:

- 697 stations
- Description of the soil
- 2 sensors: one at the surface, one at the end of the borehole
- Recordings of seismic acceleration, the location of the epicenter, the depth of the hypocenter, and the magnitude of the earthquake



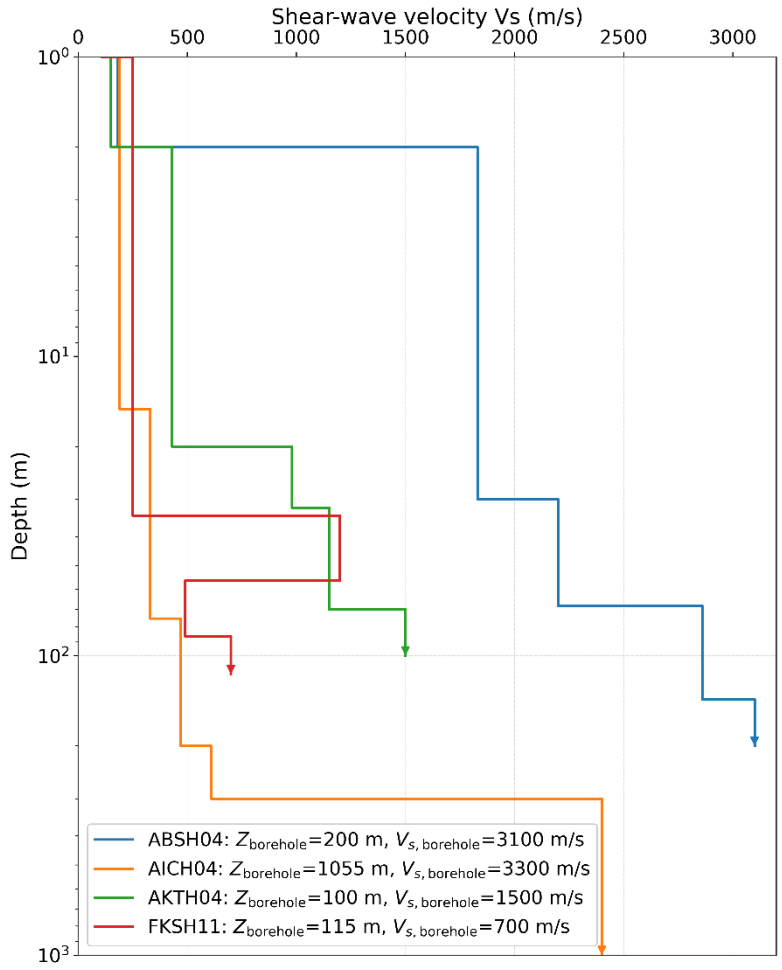
Introduction

KiK-net data are not directly comparable across stations because each downhole sensor has different reference condition

1. Downhole depth varies from site to site
2. Changes in the shear wave velocity at downhole

Goal

Transform downhole ground motions into a common outcrop rock reference used in EC8 (Vs30 = 800 m/s) to compare site amplification



Three transfer steps in the frequency domain

1 Correct the borehole spectral ratio

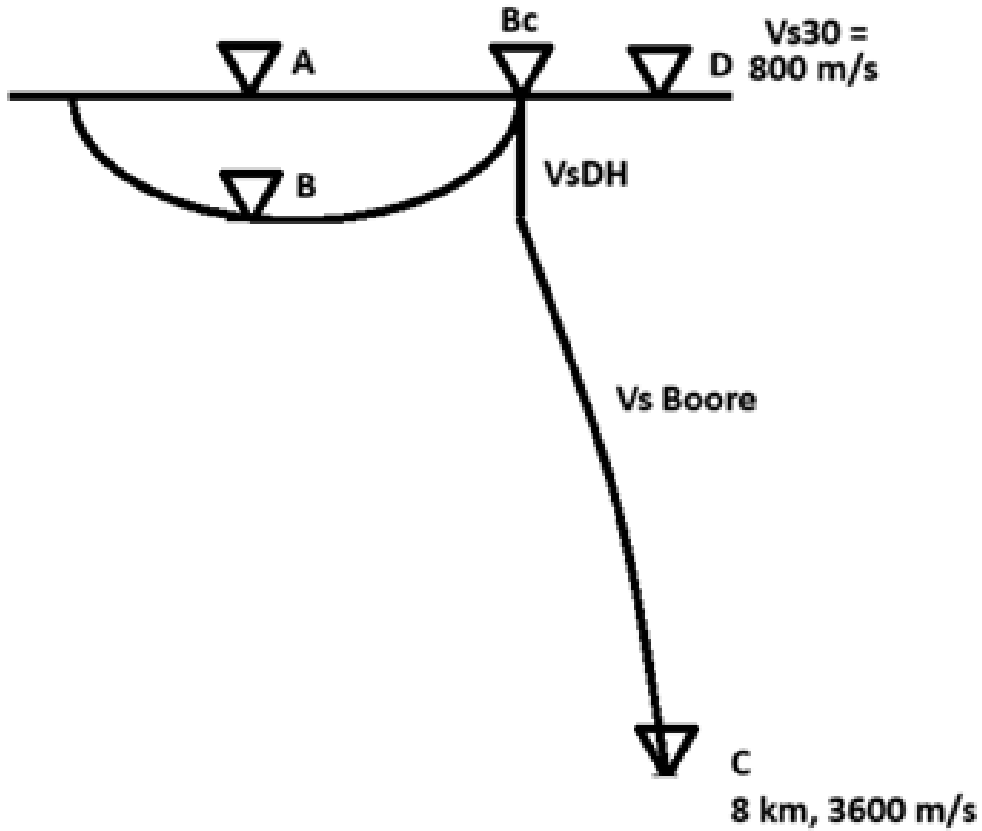
BSR(A/B) is corrected for free-surface and down-going-wave effects to obtain OSRc(A/Bc)

2 Deconvolve to a common deep virtual site

Bc → C transfer to a common deep virtual site of 8 km and 3600 m/s

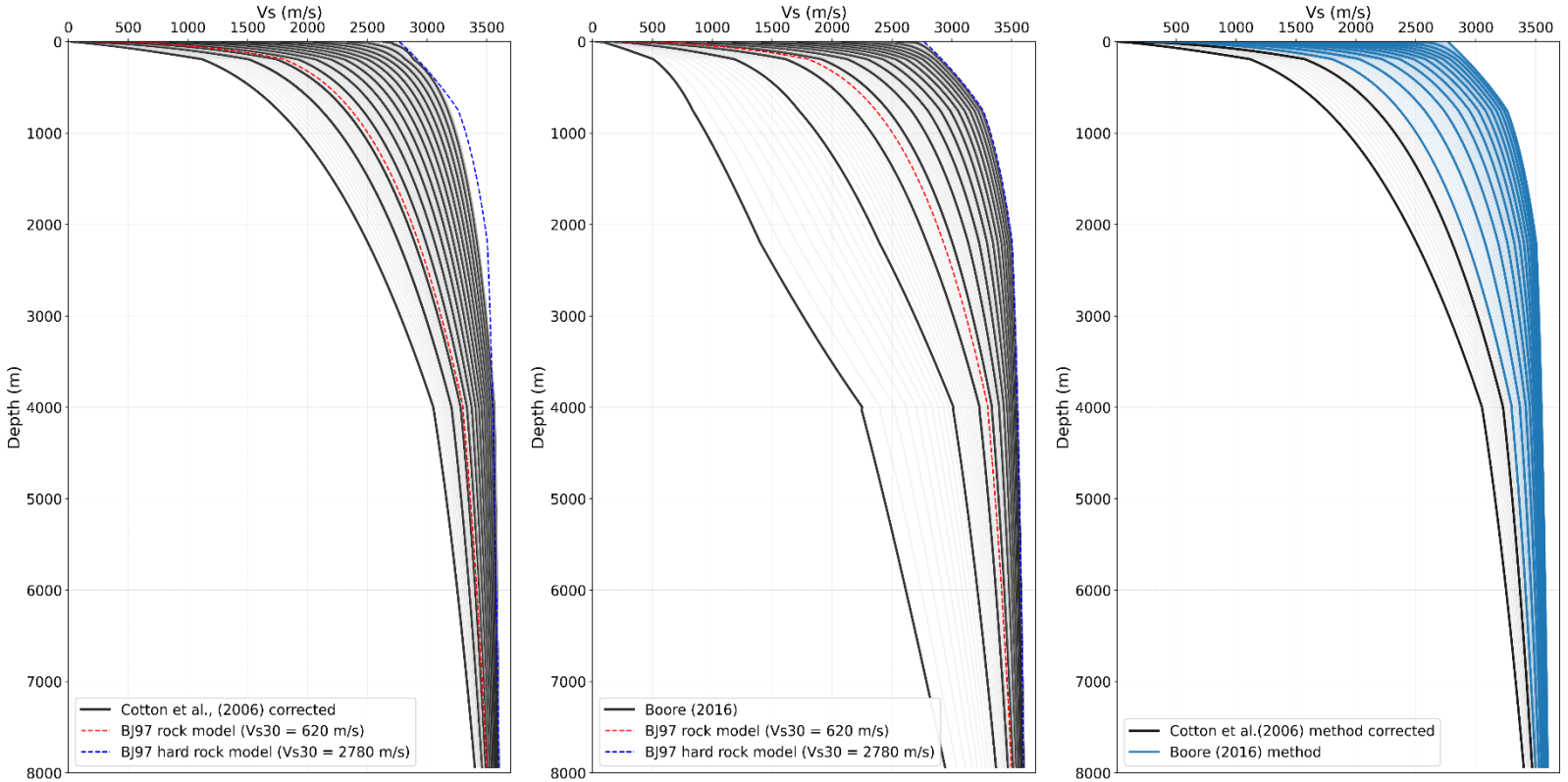
3 Reconvolve to a target outcrop rock

C → D transfer defines the desired EC8-compatible reference, VS_{30} = 800 m/s



Methodology

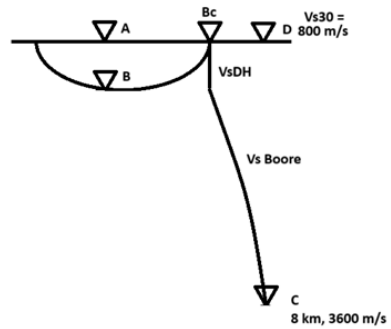
- Generic profiles are required to model wave propagation between sites B–C and C–D
- KiK-net Vs profiles are limited to borehole depth ⟶ deeper velocity structures must be assumed
- Rock-site models of Boore and Joyner (1997) are used as reference profiles (to 8 km depth)



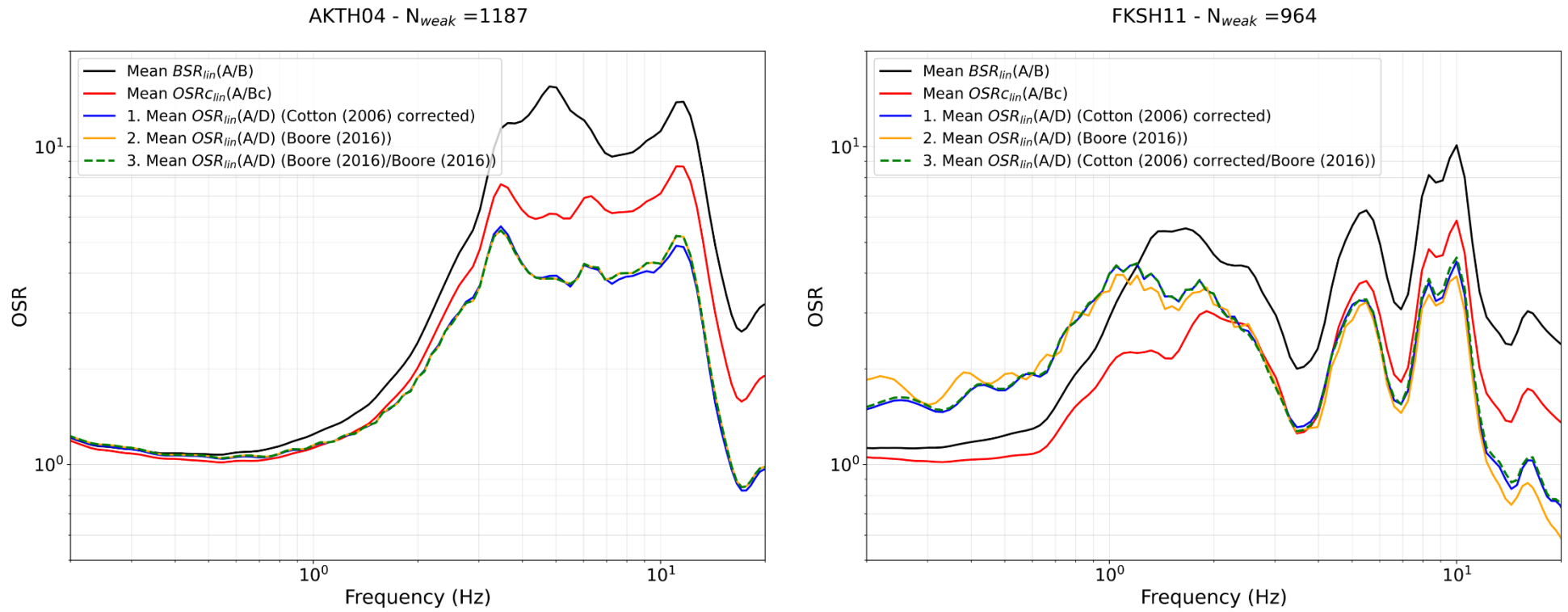
- **Method 1:** Corrected logarithmic interpolation after Cotton et al. (2006)
- **Method 2:** Slowness-based interpolation after Boore (2016)
- **Method 3:** Combined approach using both methods by Vs30 range

Weak motion response

- AKTH04: outcrop response is generally lower than BSR
- FKSH11: outcrop response is higher at low frequency because Vsborehole (700 m/s)



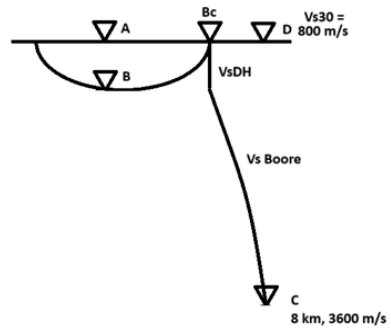
➢ Generic-profile sensitivity remains limited but increases for softer sites

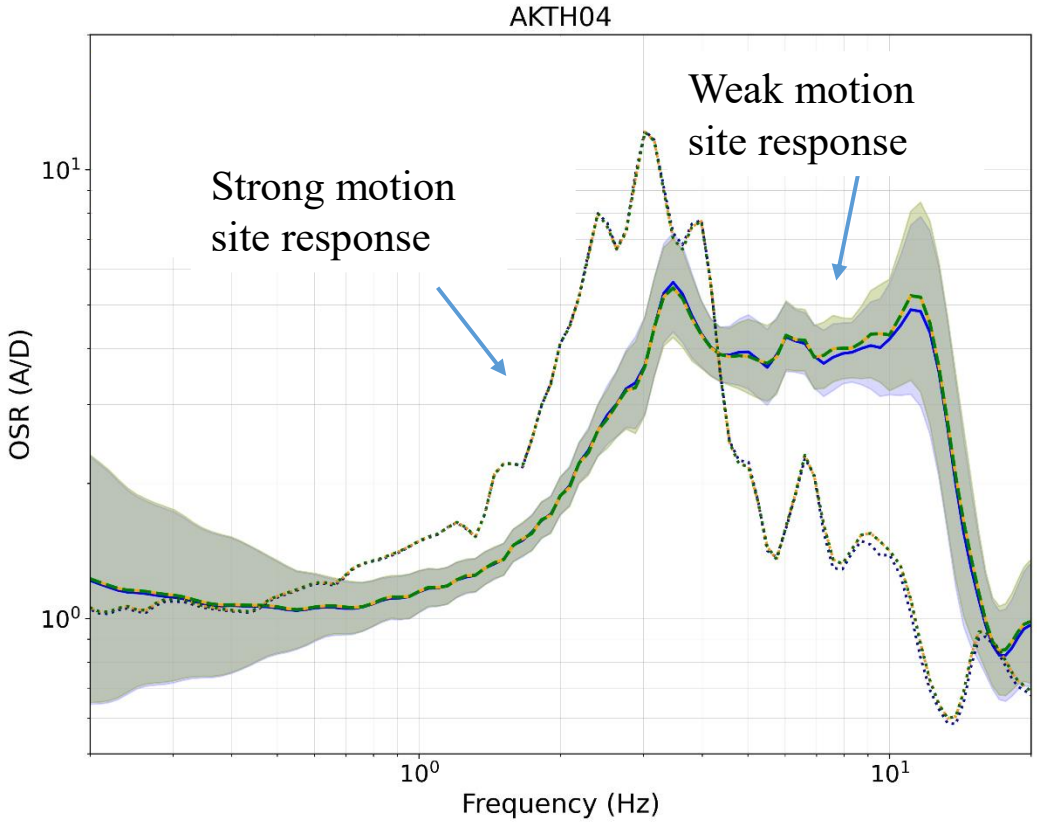


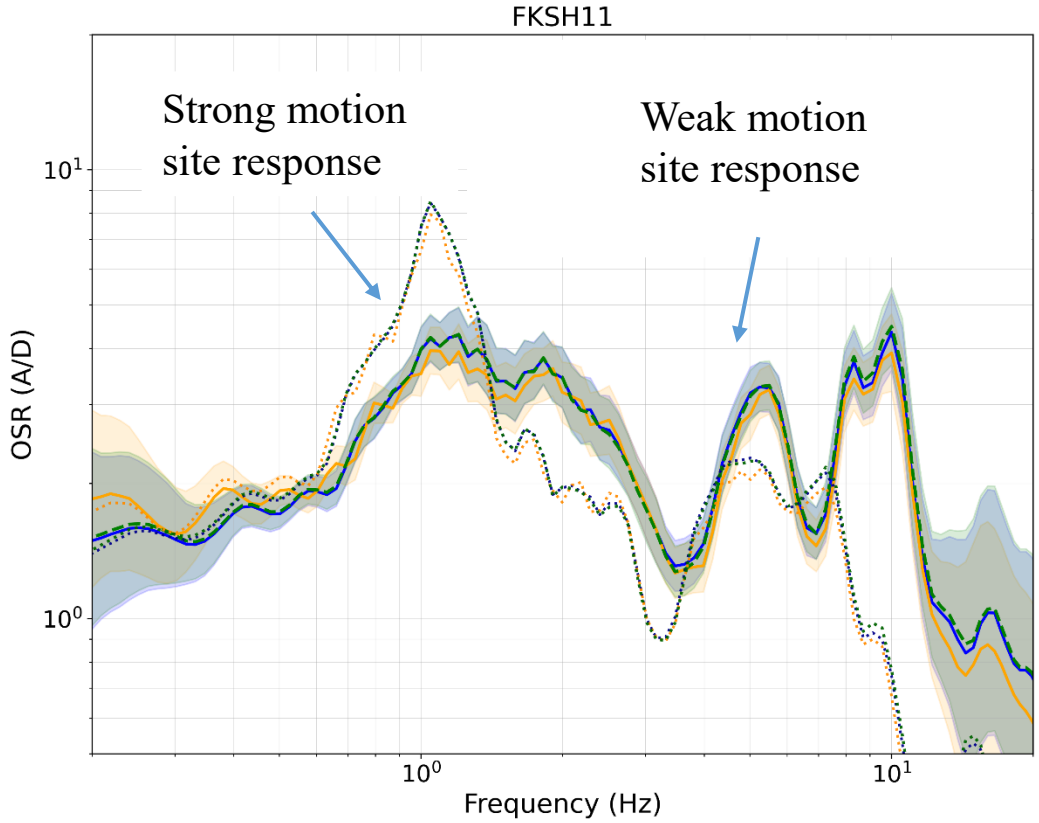
Strong motion response

Nonlinearity signature shown:
- Frequency shift toward lower frequencies
- Reduced amplification at high frequencies

➢ Three generic profile methods give very similar nonlinear OSR curves

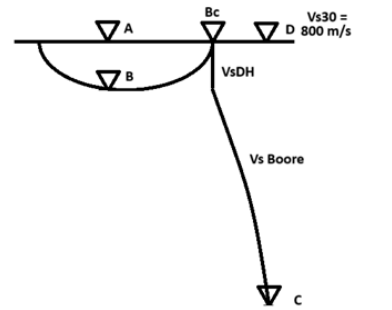


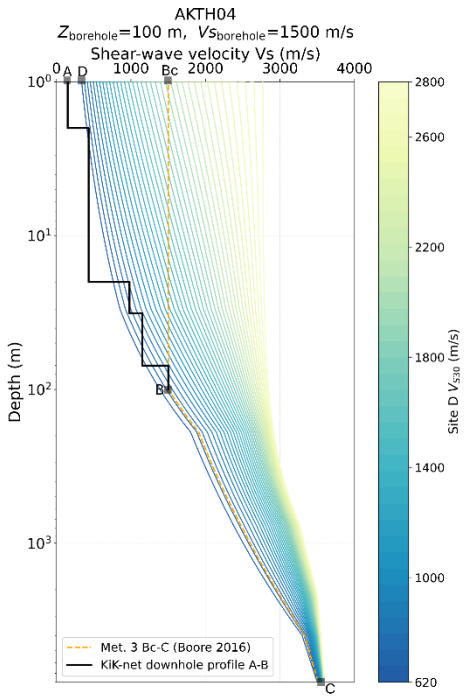


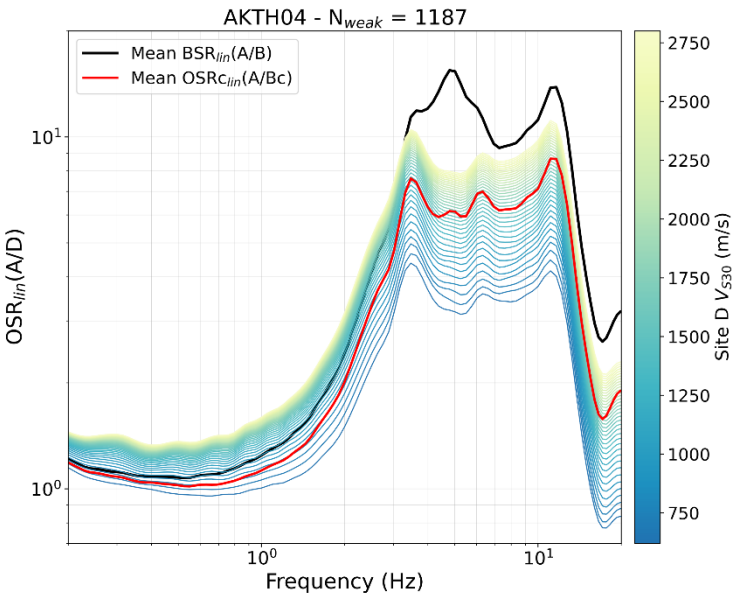


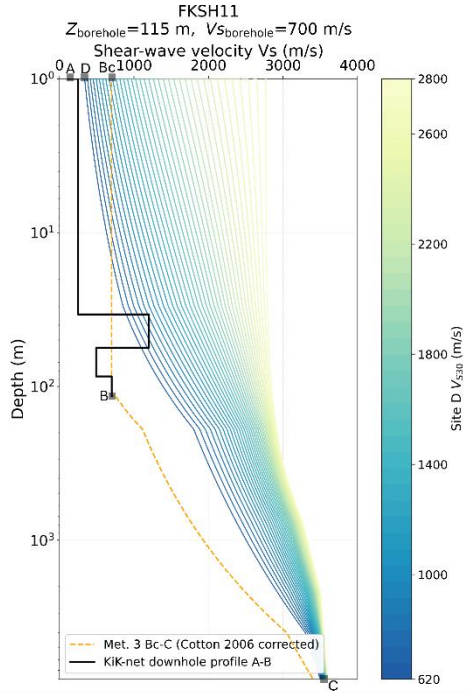
Discussion

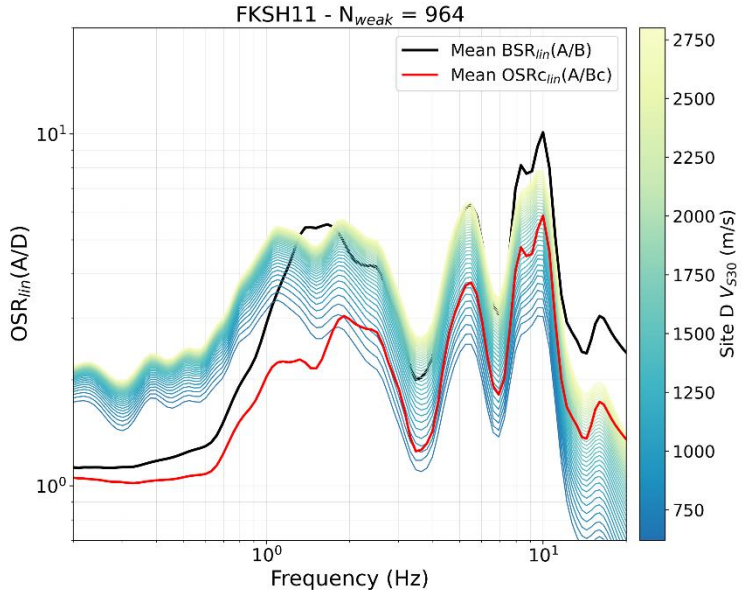
Reference Vs_{30} controls the corrected amplification





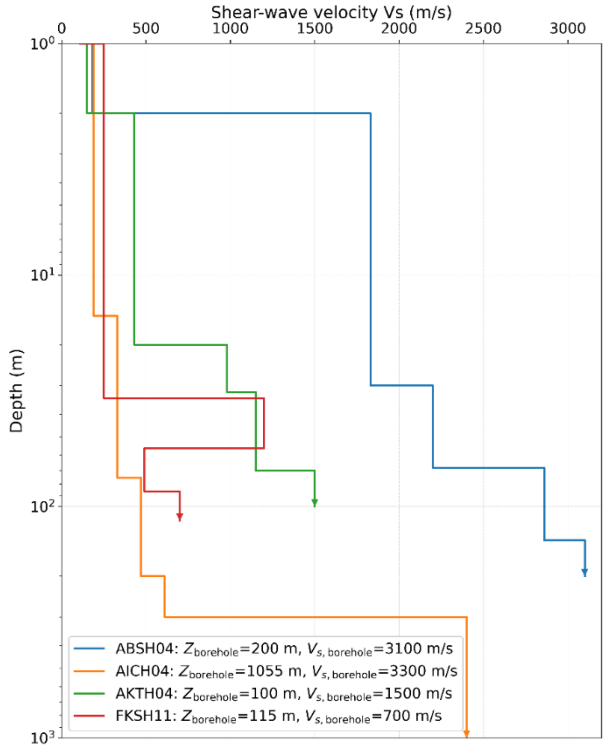


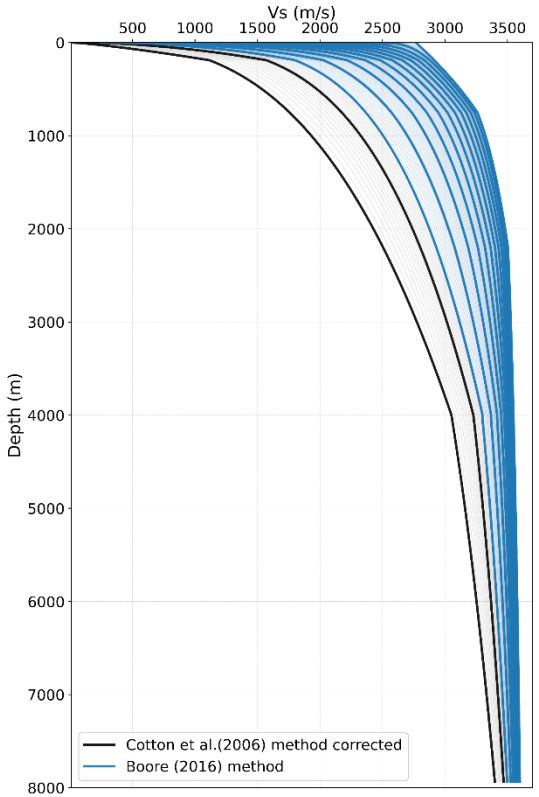


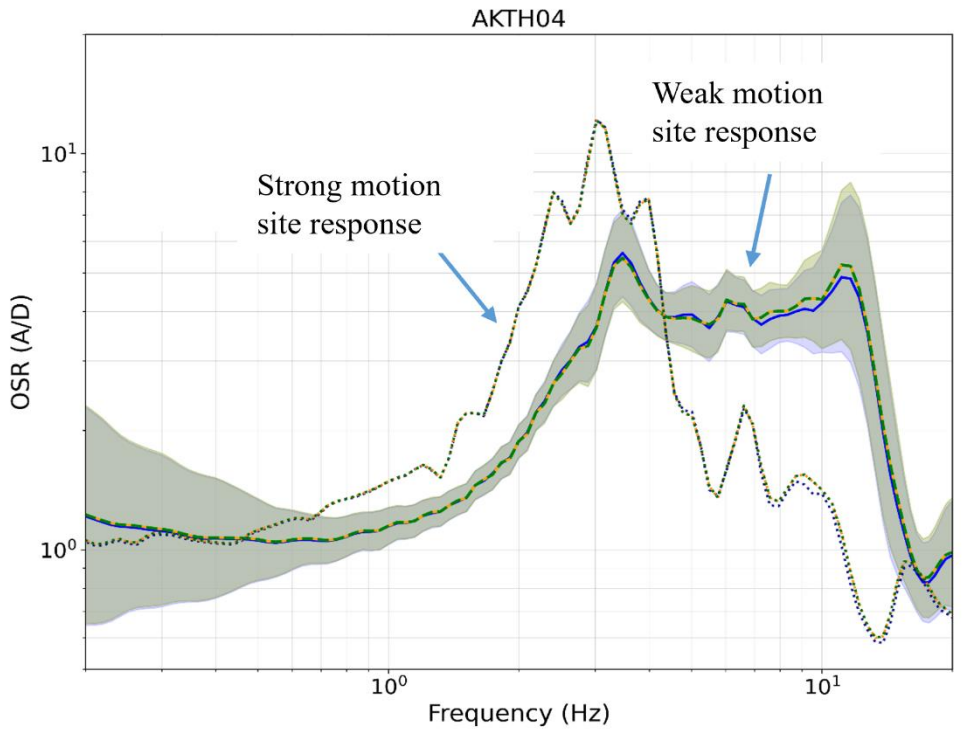


Reference Vs30 ↗ The outcrop reference site becomes stiffer → OSRlin (A/D) amplitudes ↗

Conclusion and perspectives







Perspectives

1. Calculation of outcrop ground motion from surface ground motion
2. Calculation of response spectra from the new outcrop ground motion
3. Proposition of an amplification function

Thank you!

Questions?