Case study – Seismic Effects:

Effects of soil-structure interaction on the excitation and response of an RC building subjected to near- and far-field strong-motion

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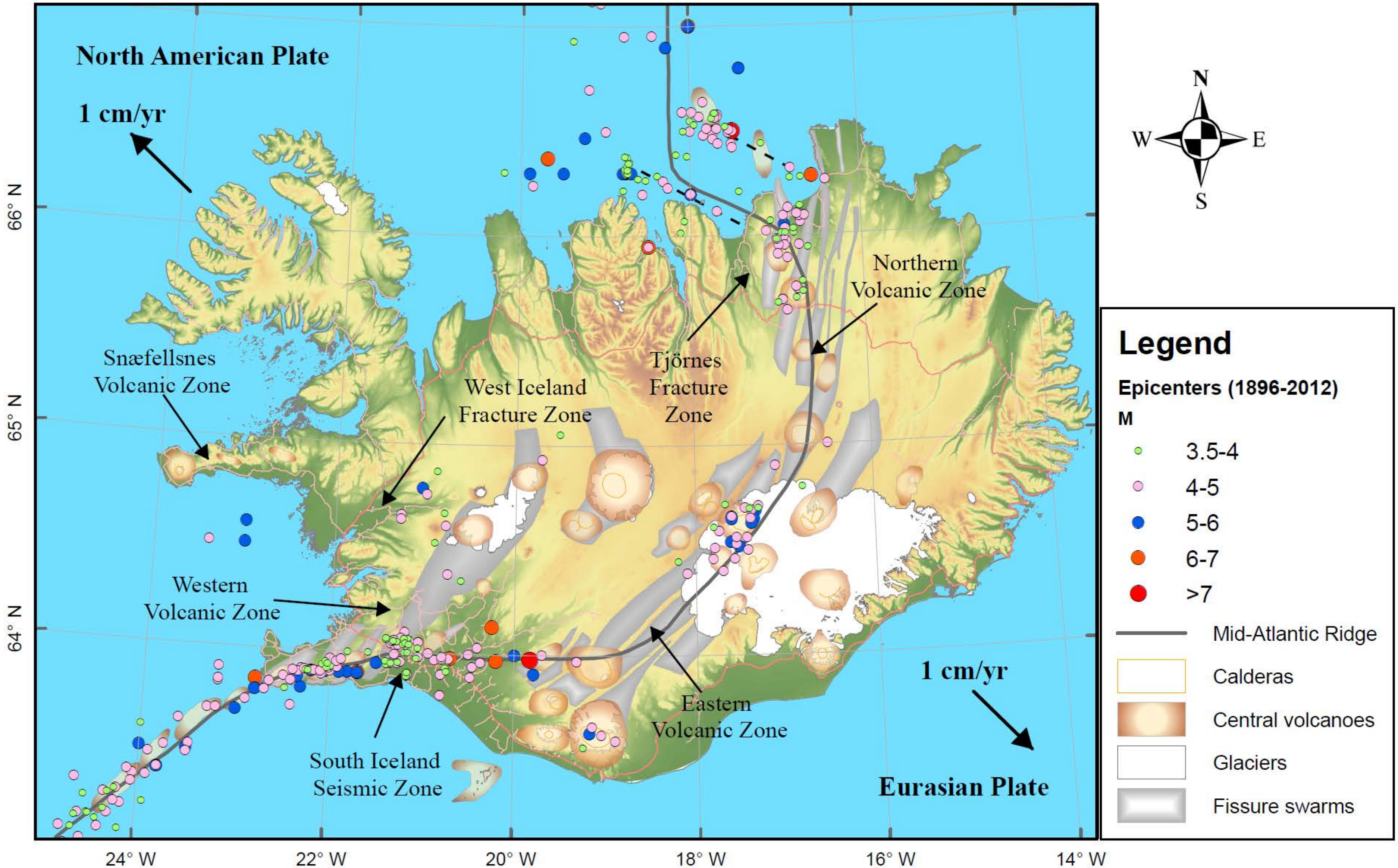
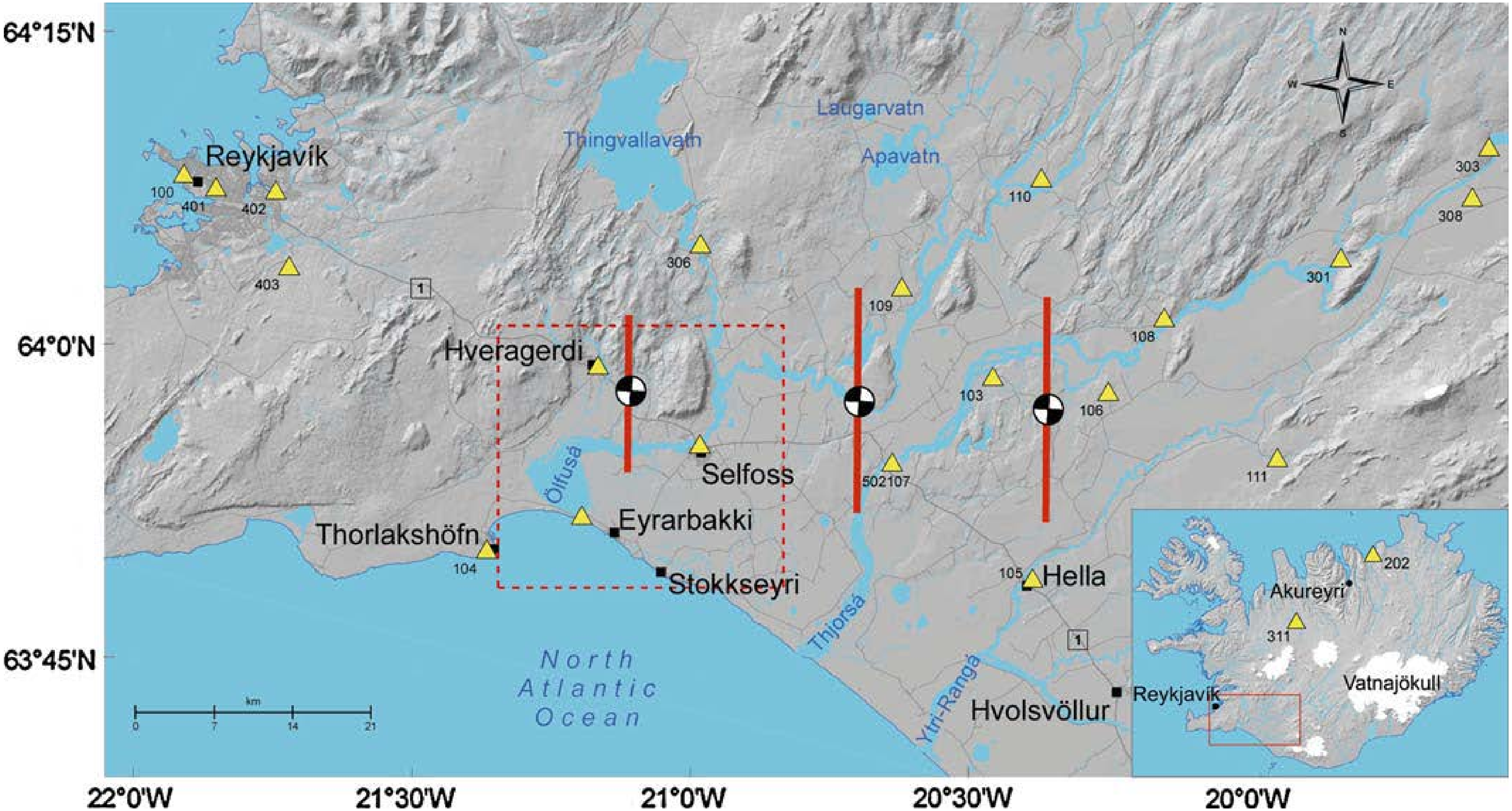
INTRODUCTION

- A study of response characteristics of a specific buildings located in Selfoss, a rural town in South-Iceland, within the SISZ.
- Available data
  - Earthquake induced acceleration – ground motion and response
  - Ambient seismometer data
  - Structural analysis and finite element modelling.
- Acceleration data and structural analysis have revealed an interesting and somewhat unexpected site response phenomenon strongly influencing the structural response.
- The relevance of the geological settings for earthquake resistance of similar buildings needs to be adressed.

Plate tectonics and seismicity in Iceland

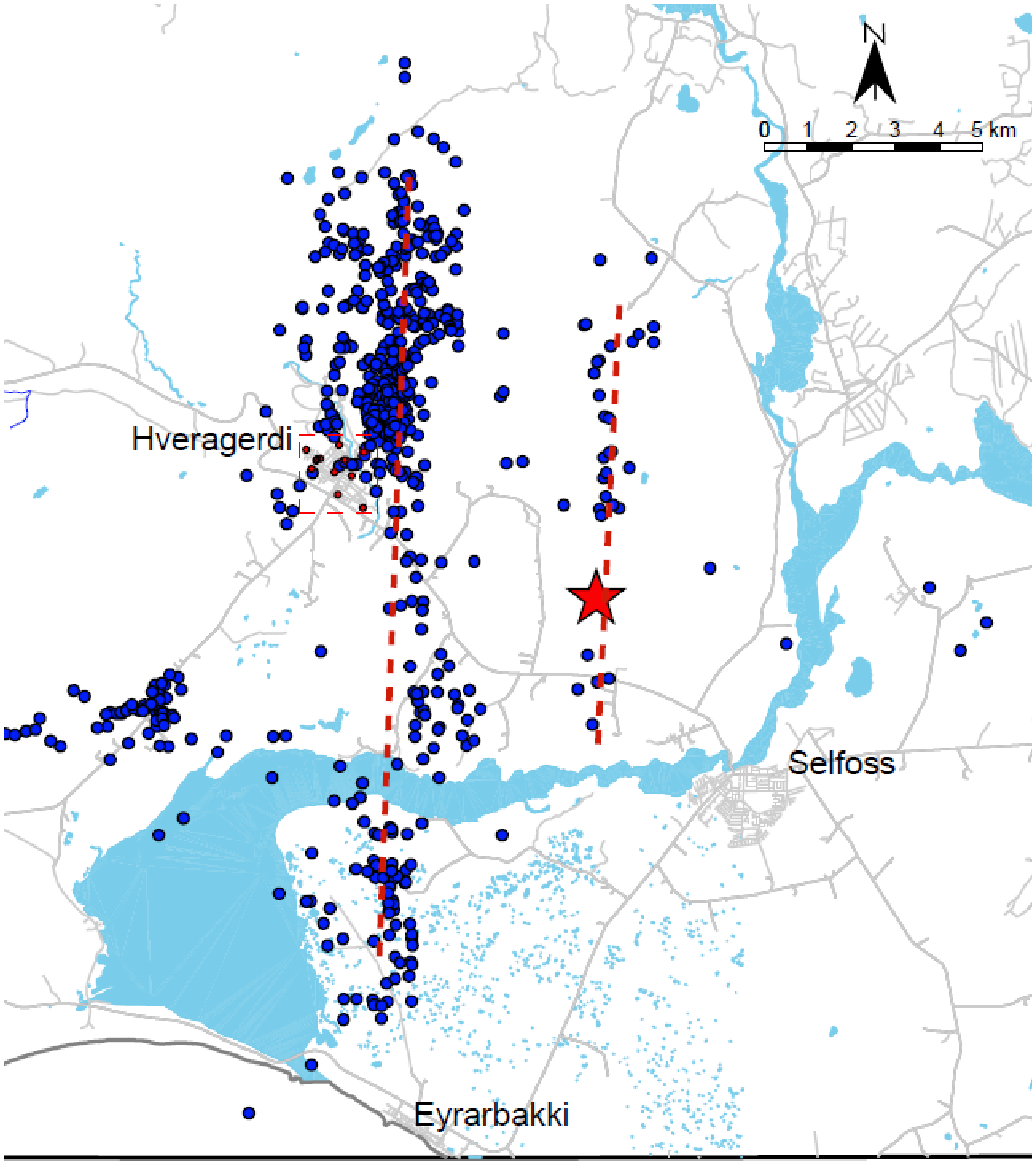


EARTHQUAKES IN THE SISZ IN THE LAST 16 YEARS



SELFOSS Town Hall Date of event	Magnitude	Distance from site (km)	Peak ground acceleration (%g)			Peak response acceleration (%g)		
			Vert	N-S	E-W	W: N-S	C: W-E	E: S-N
June 17, 2000	6.5	32	2.9	7.6	5.5	14.6	12.1	15.8
June 21, 2000	6.4	15	6.8	12.7	11.2	30.2	21.4	29.2
May 29, 2008	6.3	8	26.6	53.8	33.4	74.6	47.3	68.2

The 15:45 UTC 29 May 2008 Ölfus earthquake



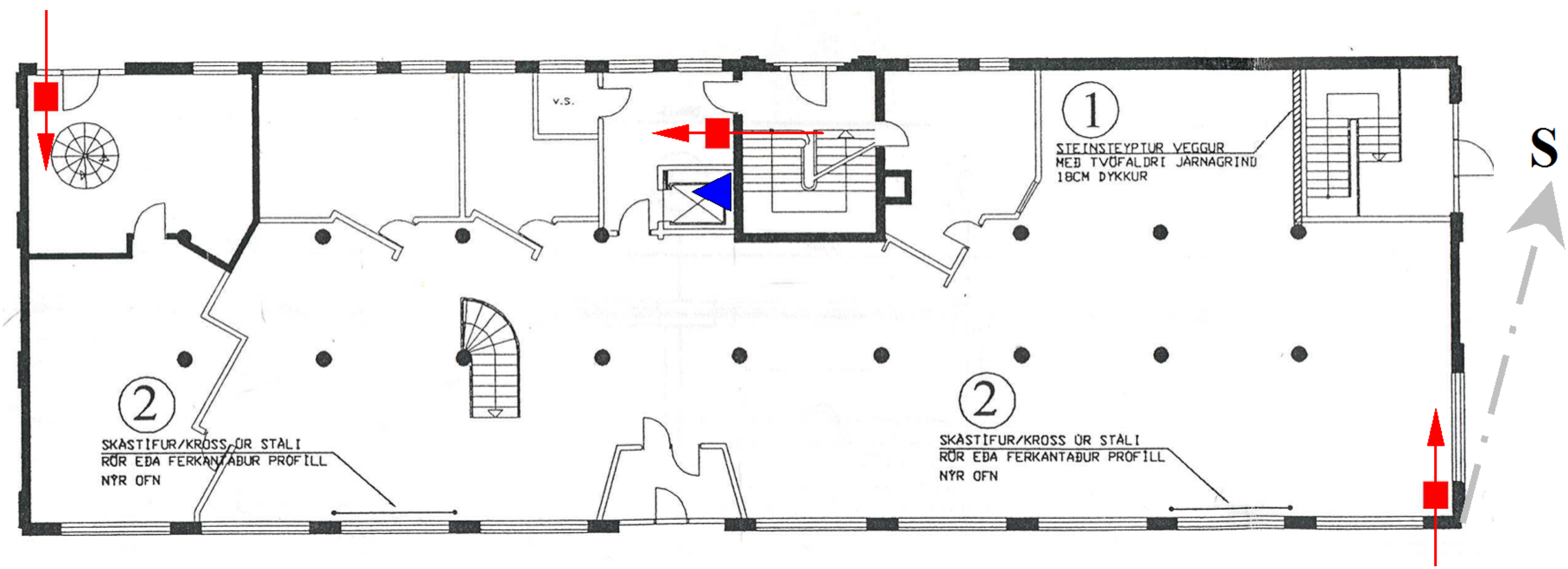
The N-S trending alignments of the seismicity distribution of aftershocks (blue circles) indicate the location of the causative faults (dashed lines).

The red pentagram shows the epicenter of the first shock.

The Town Hall at Selfoss (built in the 1940's)

< View from Northwest

v Plan view of the ground floor. Location of uni-axial & tri-axial accelerometers is shown. The location of retrofitting elements: (1) RC wall & (2) steel cross-braces installed in spring 2000

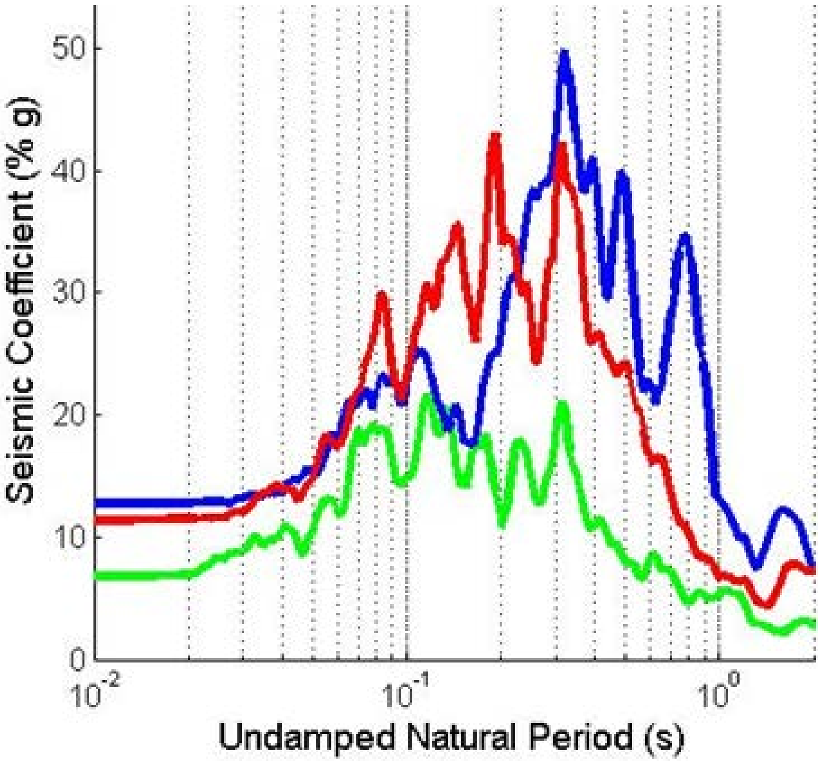


THE CASE STUDIED

- Three story reinforced office building, built in the 1940's, located within the South-Iceland-Seismic-Zone (SISZ)
- Instrumented in 1999, accelerations recorded at the basement level and on the third floor
- The focus of the study:
  - M6.4 earthquake on June 21, 2000, epicentral distance 15 km
  - M6.3 earthquake on May 29, 2008 , epicentral distance 5-8 km
- Strong dissimilarities are observed in the structural response characteristics for these two events
- It is believed that the differences can be explained by soil-structure-interaction between the building and the different soil and rock layers underneath the building

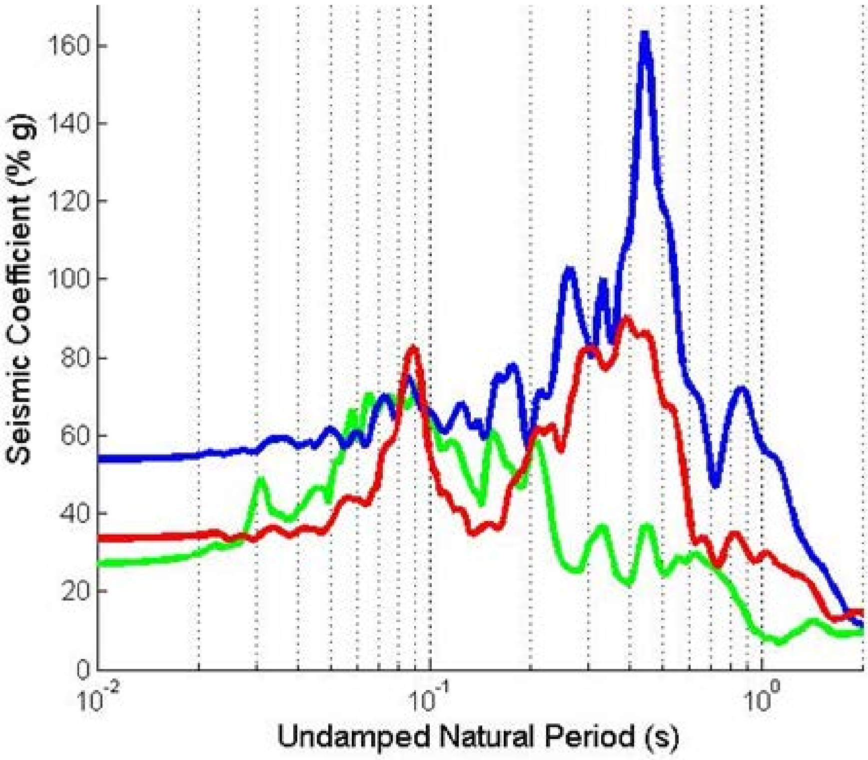
Response spectra evaluated from the Town Hall basement records

Epicentral distance ~ 15 km
PGA = 13, 11 & 7%g



(a) The event on June 21, 2000

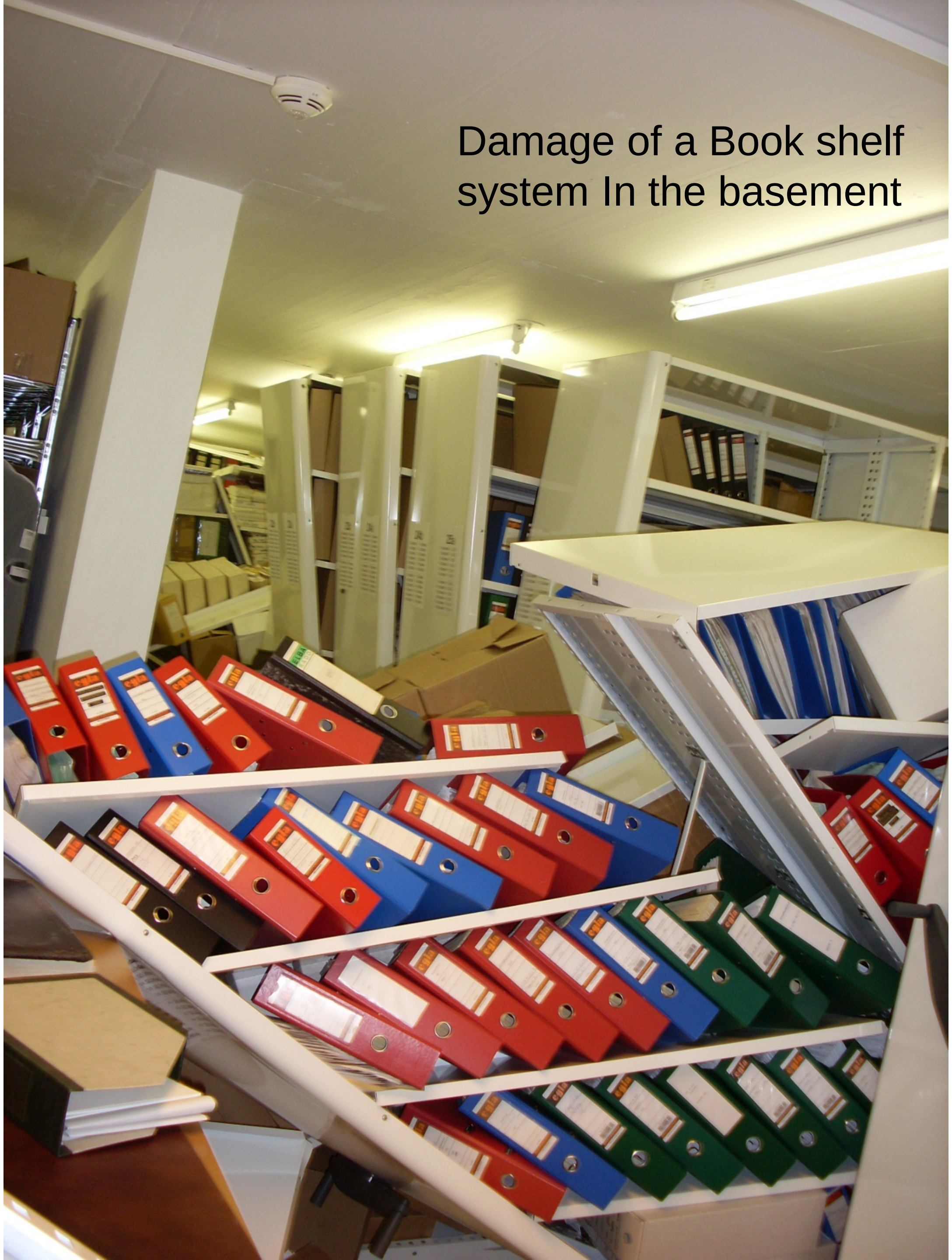
Epicentral distance ~ 8 km
PGA = 54, 33 & 27%g



(b) The event on May 29, 2008

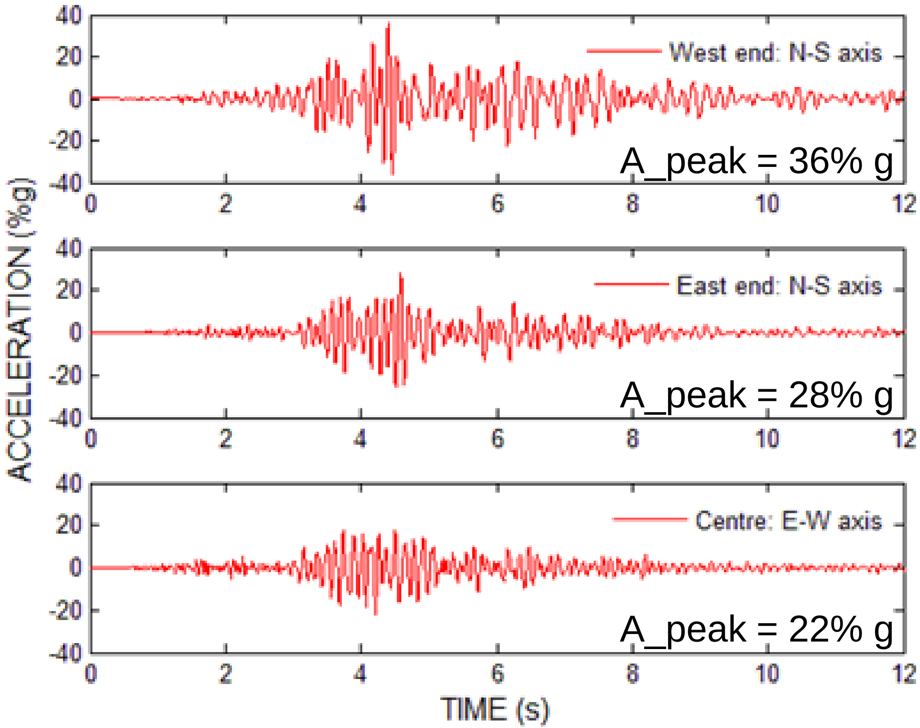
- blue line is the N-S component, - red line is the E-W component,
- green line is the vertical direction. The damping is 5% of critical.

Fracturing of the stairwell shear core walls


Damage of a Book shelf
system In the basement

Time-series of relative acceleration response on the 3ed floor

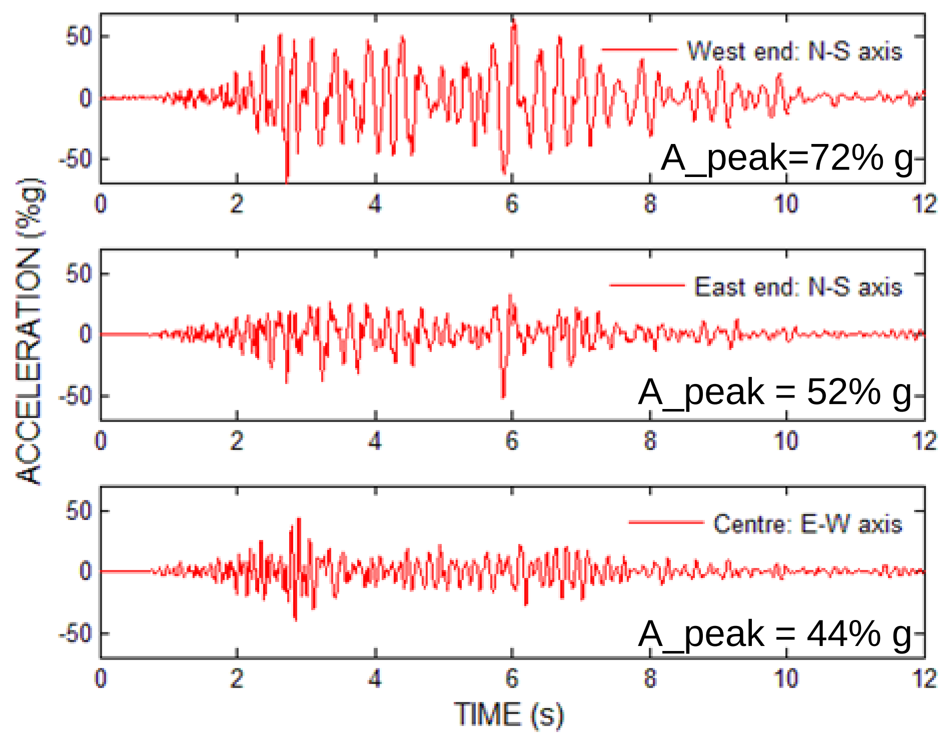
Horizontal PGA = 13 & 11%g



(a) The event on June 21. 2000

Peak values on 3ed floor ~3 times larger than in the basement

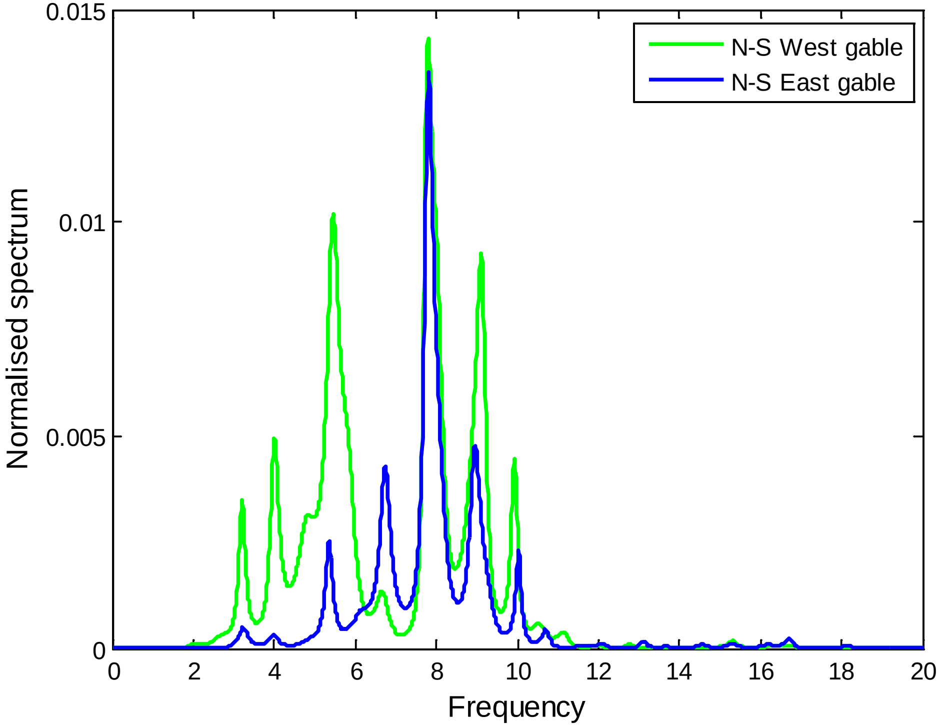
Horizontal PGA = 54 & 33%g



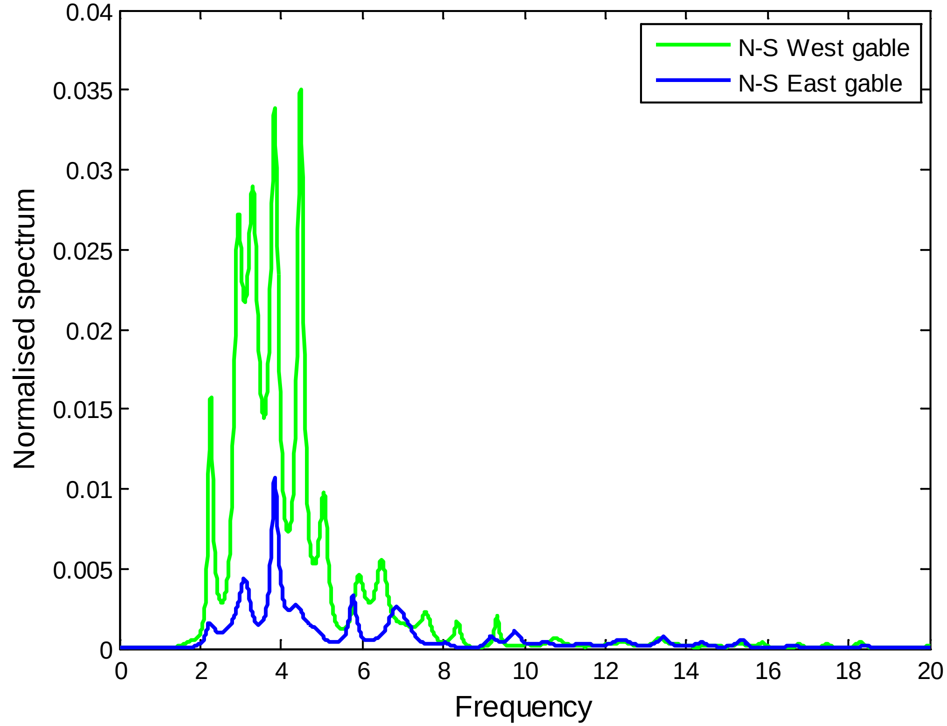
(b) The event on May 29. 2008

Peak values on 3ed floor ~1.4 times larger than in the basement

Power spectral densities of relative acceleration response on the third floor



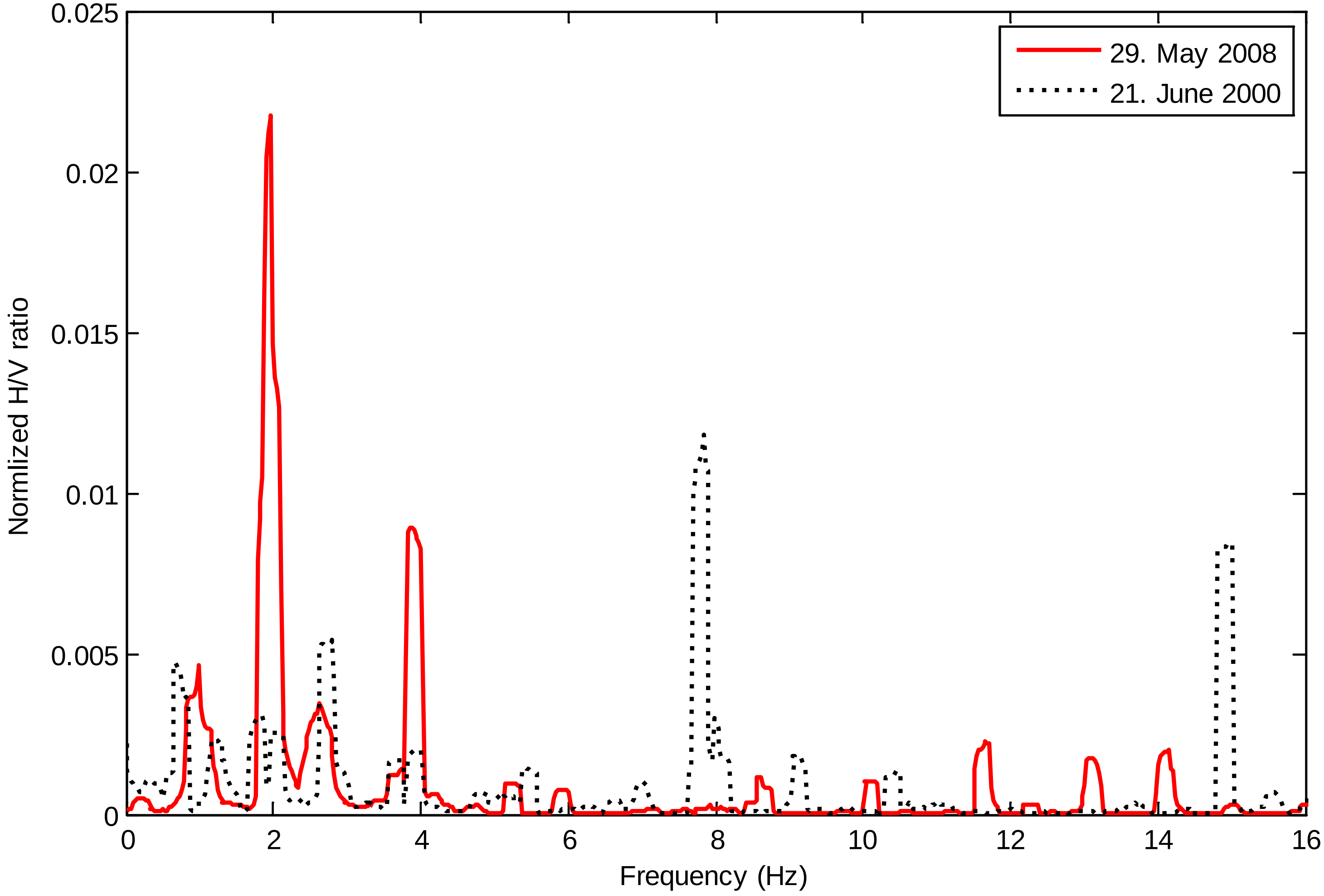
(a) The event on June 21. 2000



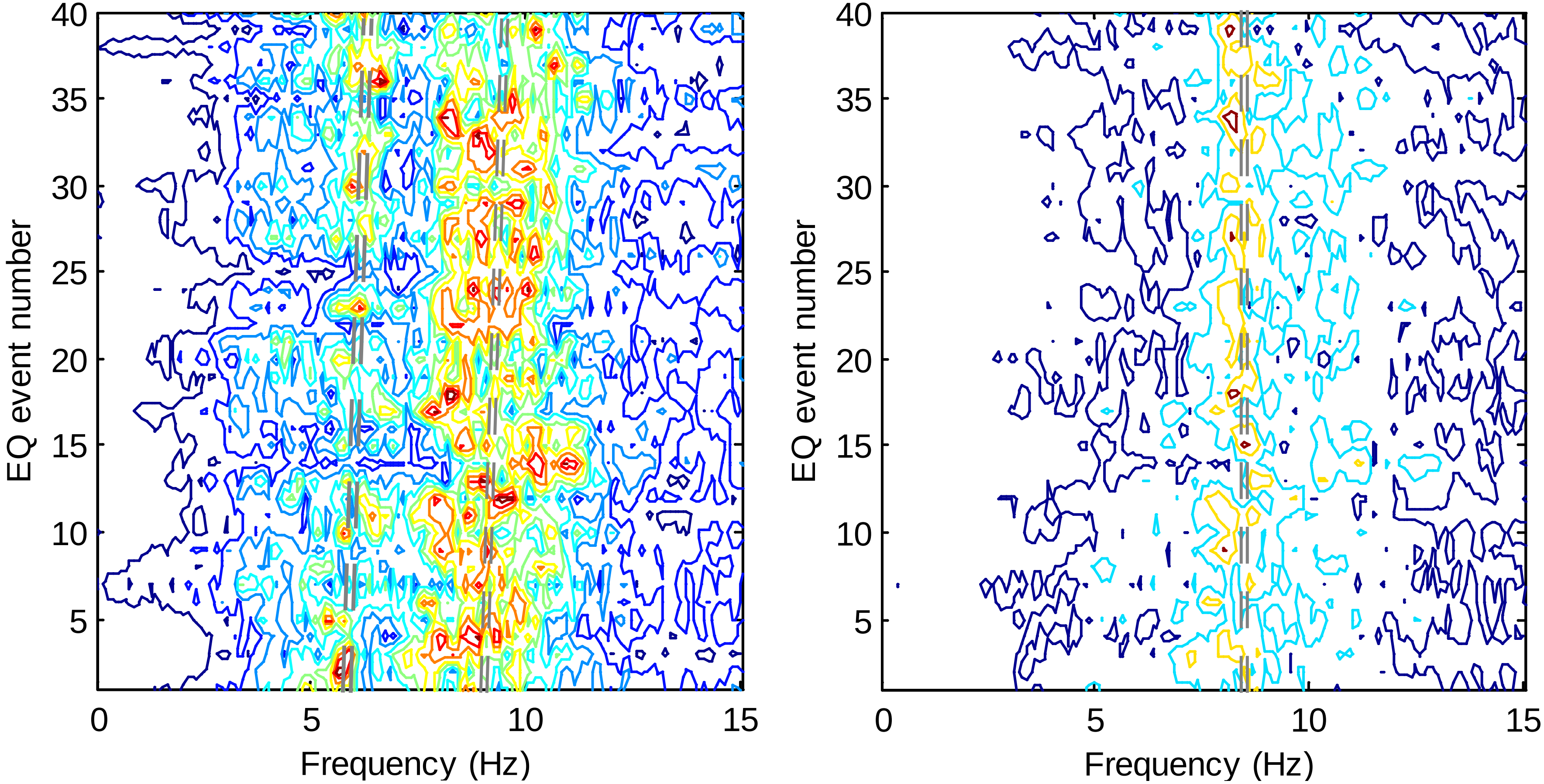
(b) The event on May 29. 2008

Selfoss Town Hall

Normalised H/V spectral ratio as a function of frequency for the two earthquakes in 2000 and 2008

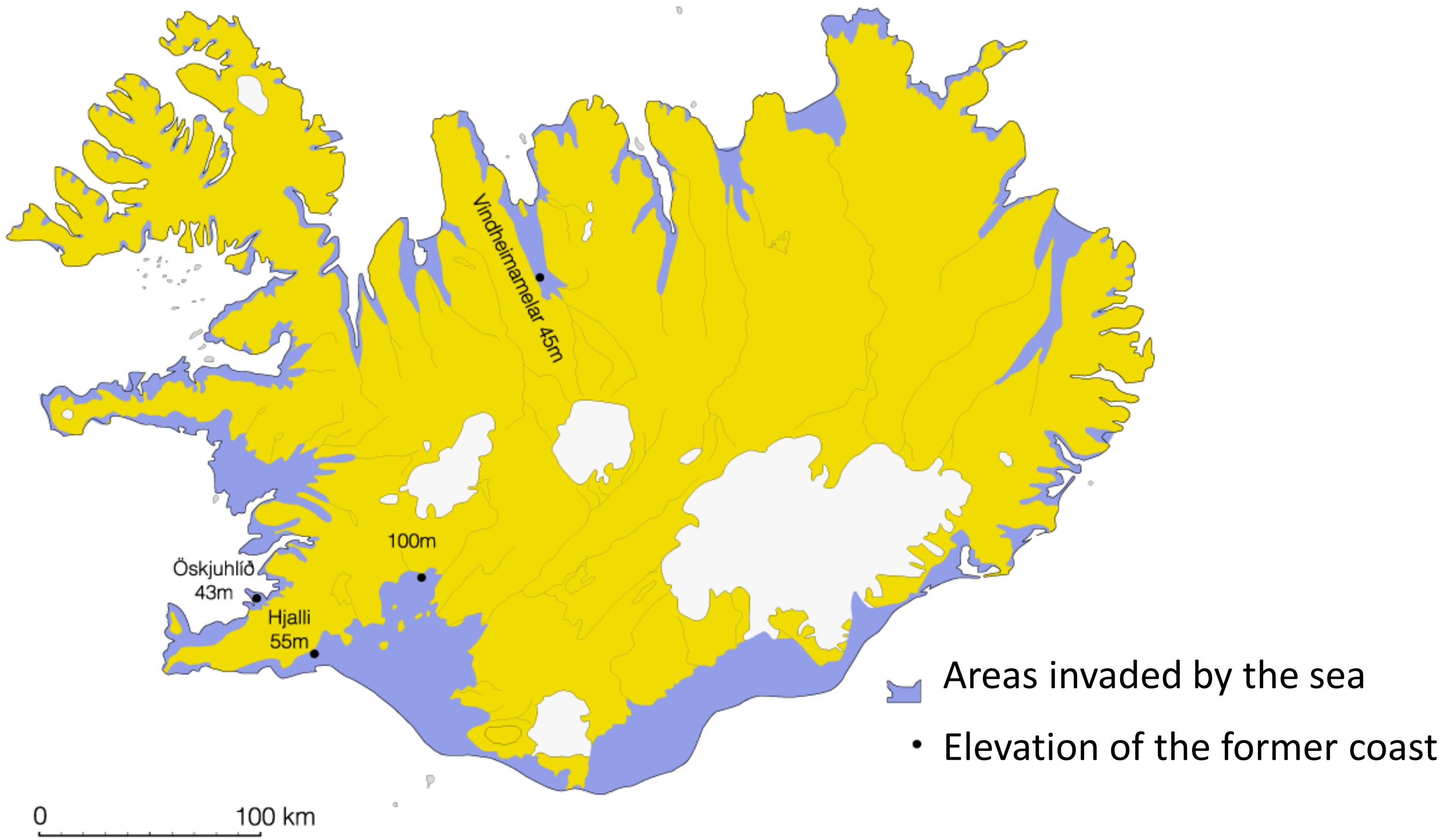


The Town Hall in Selfoss, data from 1999-2001

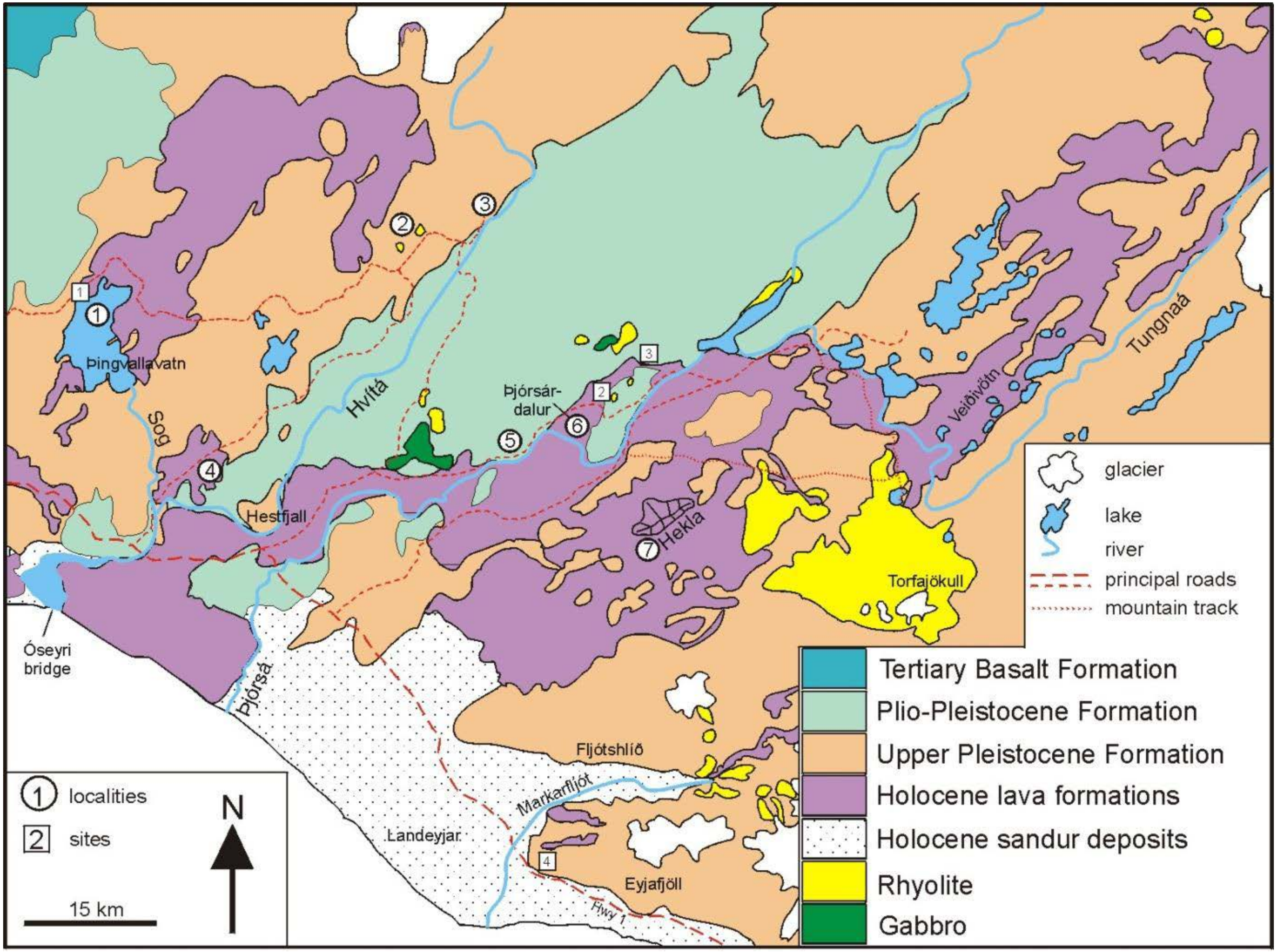


Contour graphs of the Fourier spectrum for the 40 events analysed. (a) Vibration in the NNE-SSW dir. & (b) Vibration in the ESE-WNW direction. Double dotted lines point out the slight drift in natural frequency of each mode of vibration throughout the observation period.

During the Ice Age several interglacial periods occurred,
causing the sea level to rise up to 100 m above the present coastline.



The Great Thjórsá Holocene lava flow (8500 years old) covers the area between the Thjórsá and Hvítá-Ölfusá River



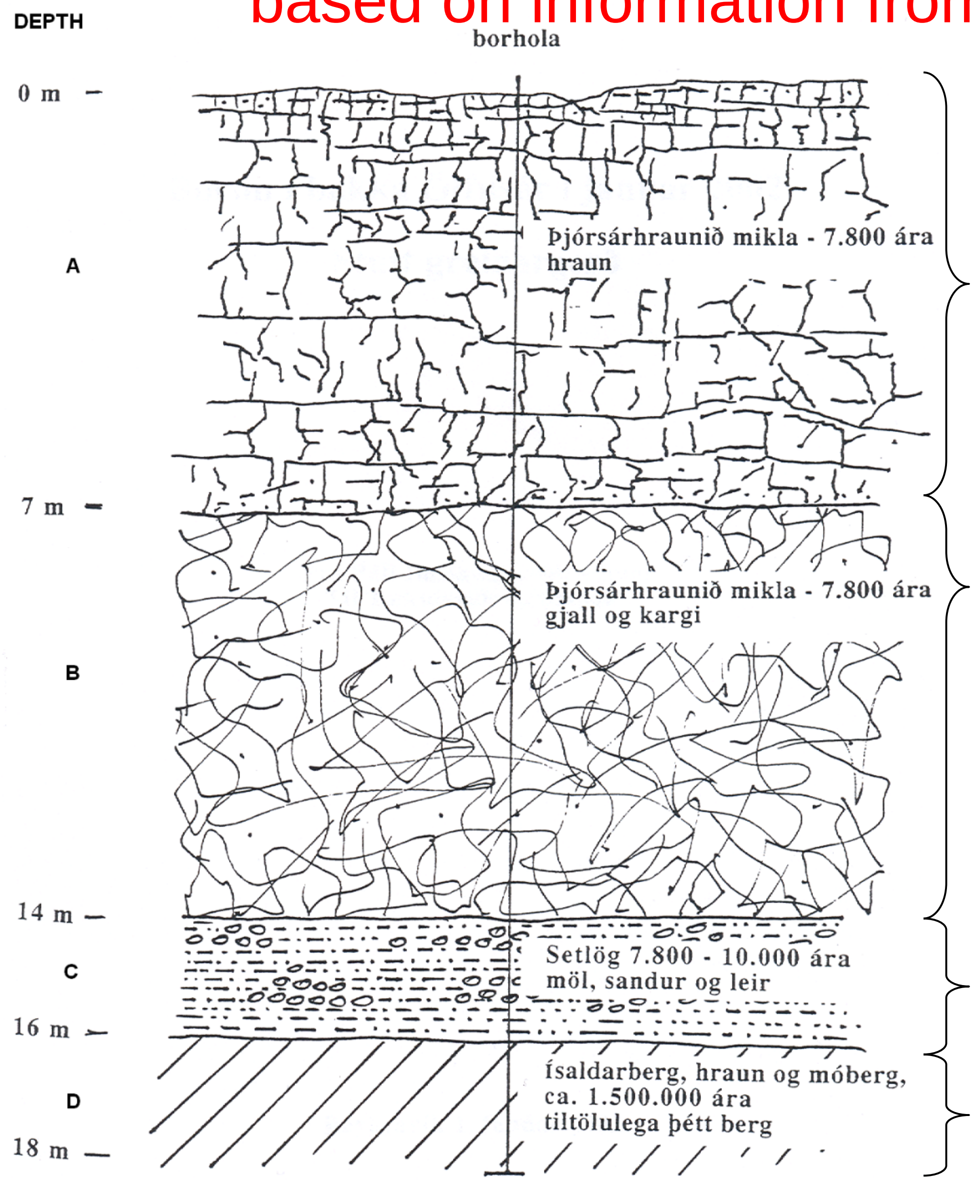
Igneous rock in Iceland, basalt and andesite

- Basaltic tuff/hyaloclastite (subglacial eruption)
- Basaltic lava flows (eruption on land) appearing mainly as two types:

Scoria lava has a crumbly, rough surface made of loosely stacked scoria lumps. Scoria lava

Ca 10 meters thick lava pile, composed of numerous, thin flow units, each varying from 10 cm to 2 m.

A hypothetical rock-soil profile,
based on information from a Borehole near Ölfusá river



The Great Thjórsá river lava flow
8500 years old Compound lava

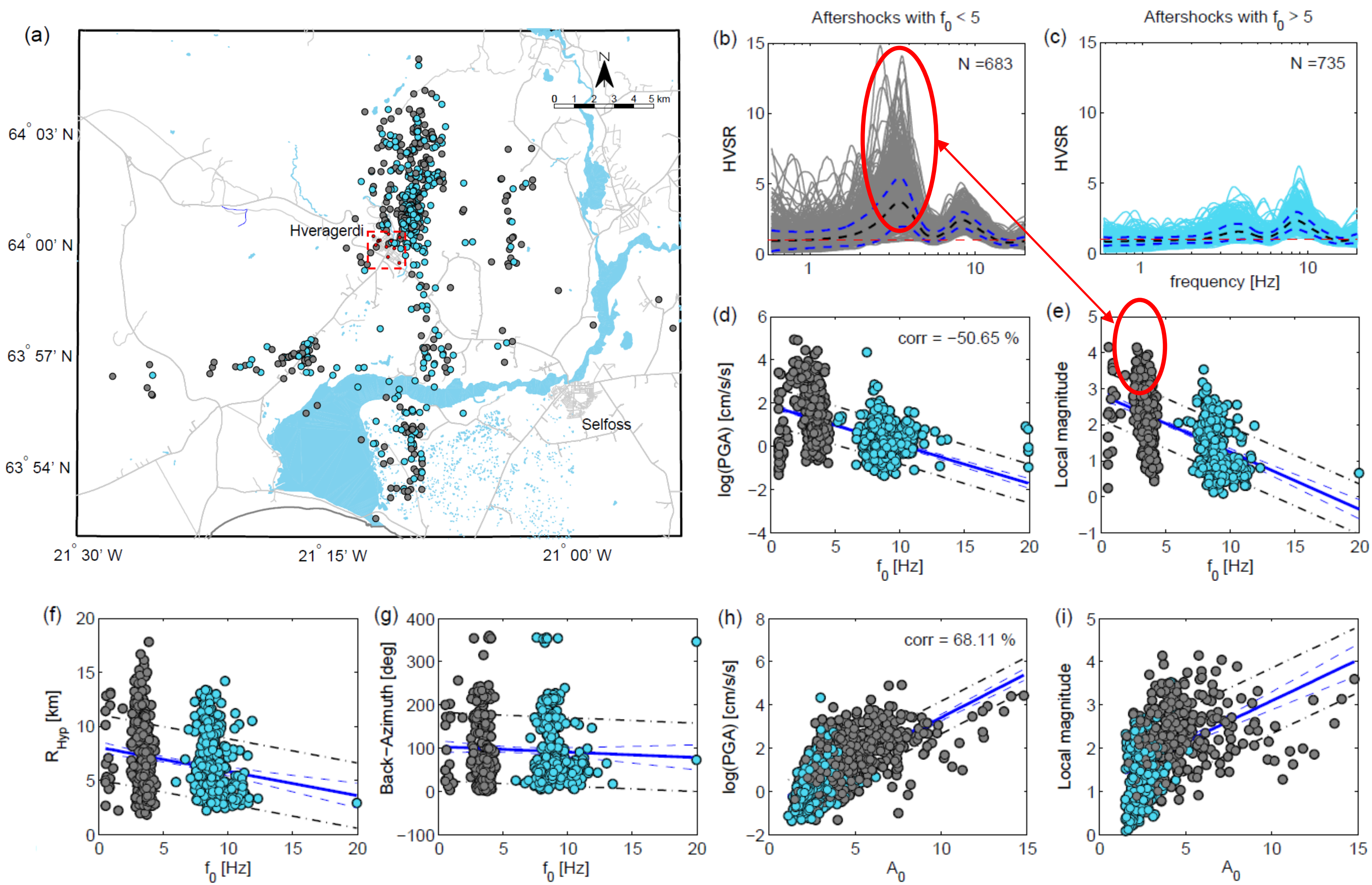
The Great Thjórsá river lava flow
8500 years old scoria lava

Sediments 8500 – 10.000 year
old, gravel, sand and clay

Tertiary basalt formation ca. 1.500.000
years old, relatively dense rock

Figure: Páll Imsland

Hveragerdi - Earthquake parameters vs. HVSR characteristics

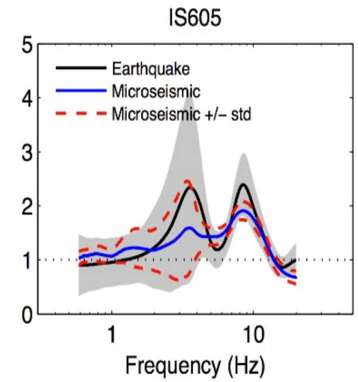


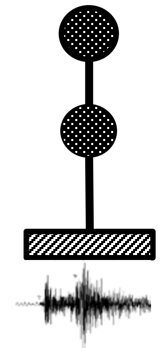
Rahpeyma, S., Halldorsson, B., Olivera, C., Green, R. A., & Jonsson, S. (**2016**). Detailed site effect estimation in the presence of strong velocity reversals within a small-aperture strong-motion array in Iceland. *Soil Dynamics and Earthquake Engineering*, *89*, 136-151.

Hveragerdi - Dynamic response of soil structure as a damped linear oscillator

- **Step1:** For the bimodal amplification curve at station IS605, a two-degree of freedom (2DOF) linear oscillator can be used. The nodal displacement vector $\boldsymbol{u}(t)$ of the system can be expressed in terms of modal coordinates by using the expansion theorem for multi-degree-of-freedom (MDOF) systems (modal superposition):

$$\boldsymbol{u}(t) = \sum_{n=1}^{N} \boldsymbol{u}_n(t) = \sum_{n=1}^{N} \boldsymbol{\Phi}_n q_n(t), \qquad N = 2$$





- **Step 2:** The undamped modal frequencies ω_n and modes ϕ_n can be obtained by solving the eigenvalue problem

$$(\boldsymbol{K} - \omega_n^2 \boldsymbol{M})\boldsymbol{\Phi}_n = 0$$

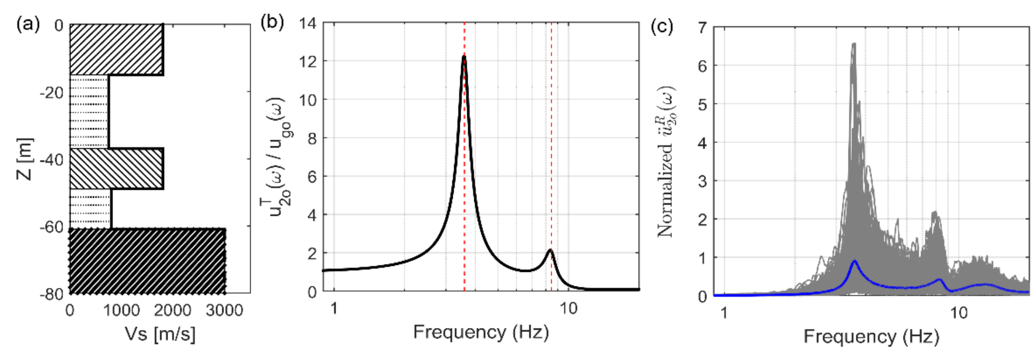
- **Step 3**: Calculating the relative displacement

$$\boldsymbol{M}_n \ddot{\boldsymbol{q}}_n(\boldsymbol{t}) + \boldsymbol{C}_n \dot{\boldsymbol{q}}_n(\boldsymbol{t}) + \boldsymbol{K}_n \boldsymbol{q}_n(\boldsymbol{t}) = -\boldsymbol{m}\iota \ddot{u}_g(t)$$

$$u_{2o}^{R}(\omega) = -\left(\frac{\phi_{21}\Gamma_1}{\omega^2\left[\left(\left(\frac{\omega_1}{\omega}\right)^2 - 1\right) + i2\xi_1\left(\frac{\omega_1}{\omega}\right)\right]} + \frac{\phi_{22}\Gamma_2}{\omega^2\left[\left(\left(\frac{\omega_2}{\omega}\right)^2 - 1\right) + i2\xi_2\left(\frac{\omega_2}{\omega}\right)\right]}\right)\ddot{u}_{go}(\omega)$$

Soil and 2DOF model properties.

Layers	Soil Properties				2DOF system	
Lava	H (m)	ρ (g/cm³)	Vs (m/s)	Gs (N/m²)	K (N/m)	m (kg)
Sediment	15	2.2	1800	7.13×10^9		51.7×10^3
Lava	22	1.7	750	0.95×10^9	43.5×10^6	
Sediment	12	2.2	1800	7.12×10^9		55.9×10^3
Lava	12	1.8	800	1.15×10^9	96.0×10^6	



(a) Vs profile (b) The ratio of absolute displacement frequency response at the surface to the ground displacement at the bottom. (c) Relative acceleration frequency response of horizontal motion at the free-surface for the 2DOF system .

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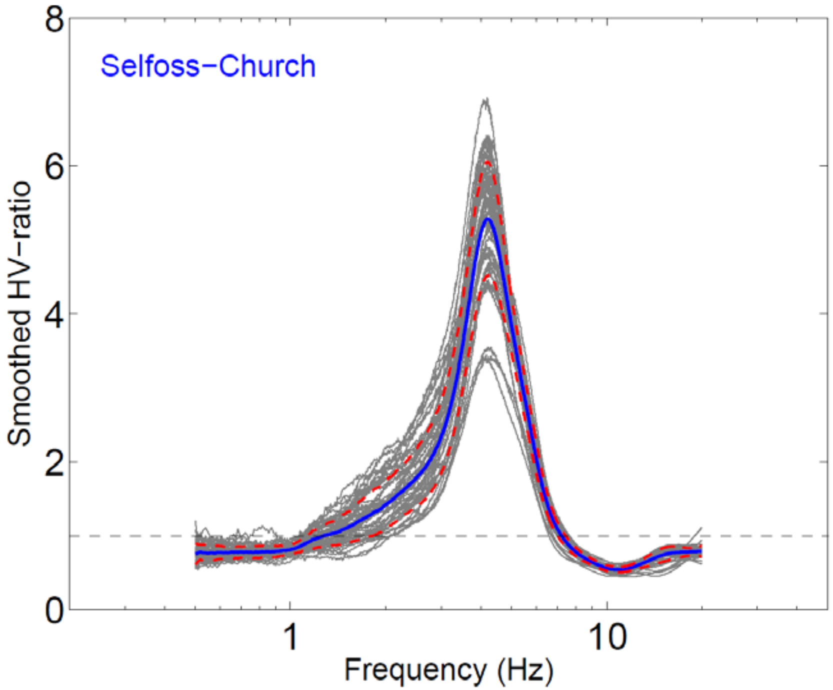
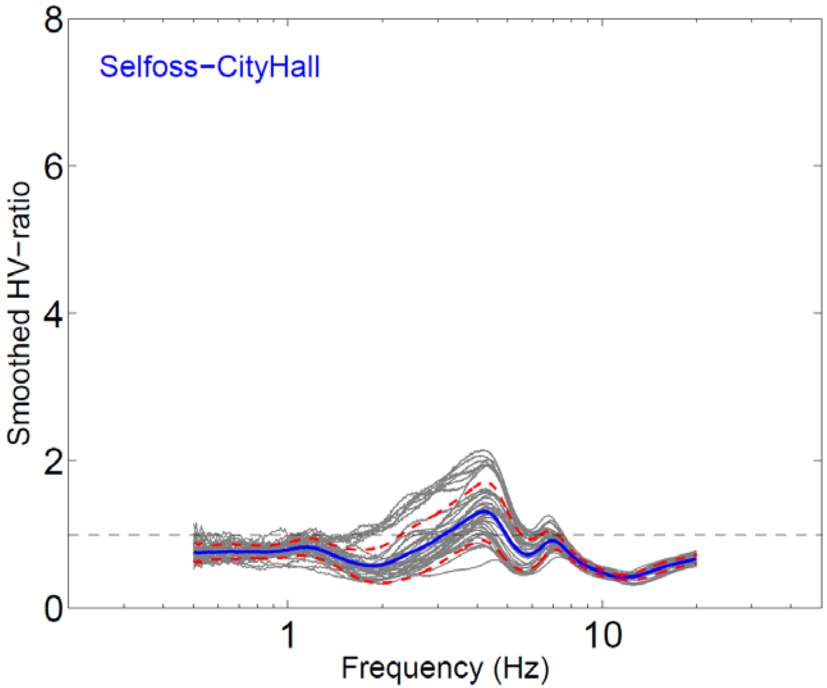
Site response estimated using Spectral analysis of microseismic (ambient) vibrations via the HVSR method

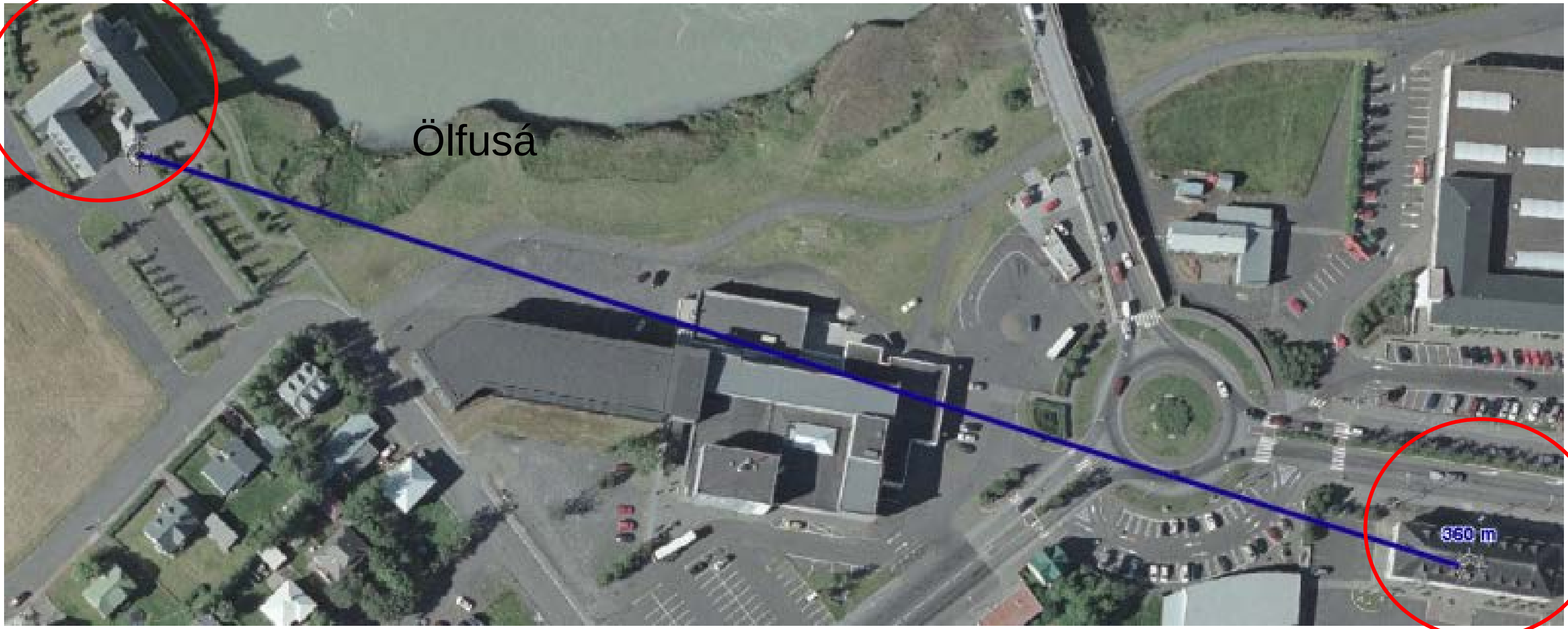




Mean Horizontal to Vertical Spectral Ratio (HVSR) +/- one standard deviation from ambient noise measurements. The grey lines show 20-min ambient noise windows used to derive the mean HVSR (blue line) and standard deviation (red dashed line). The instruments used were a Lennartz LE-3D/5s seismometer and a REF TEK 130-01 Broadband Seismic Recorder.

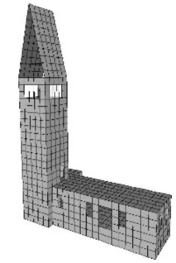
Magnification at frequency between 4 and 5 Hz at both sites & at 7 Hz the Town-Hall.

Location of the Town Hall and the Church of Selfoss



The distance between the two buildings is indicated with the blue line ~ 360 m.

The Church of Selfoss at the east bank of Ölfusá



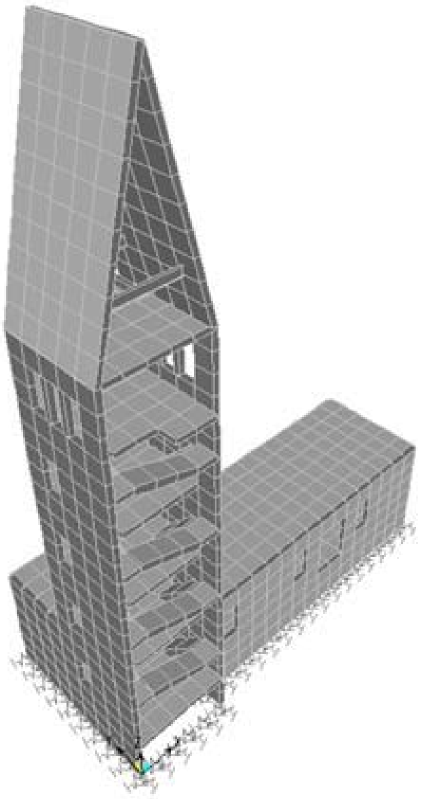
The Church Tower:

- 4x4 m cross section, reinforced concrete tower, built in 1985
- 5 levels, each ~3m, giving a 15 m tall concrete tower.
- Timber roof with cooper cladding, the top of the roof is 23 m above ground.
- Three curch bells 75, 67, & 56 cm in diameter, weighing 240, 170 & 100kg, respectively

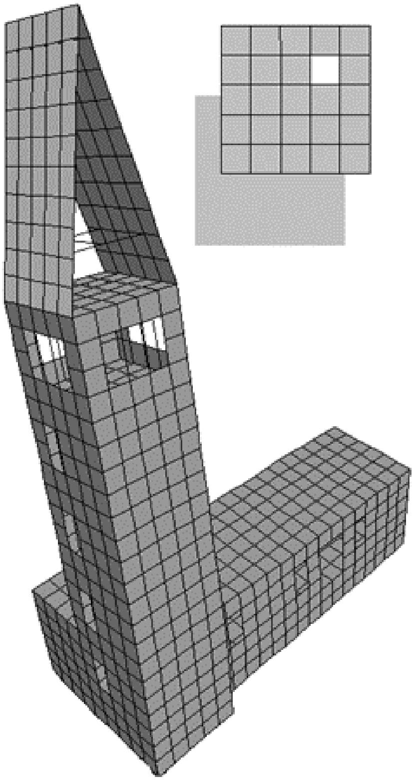
Earthquake induced damage of the Bell Tower

Earthquake induced fracture indicated by yellow lines

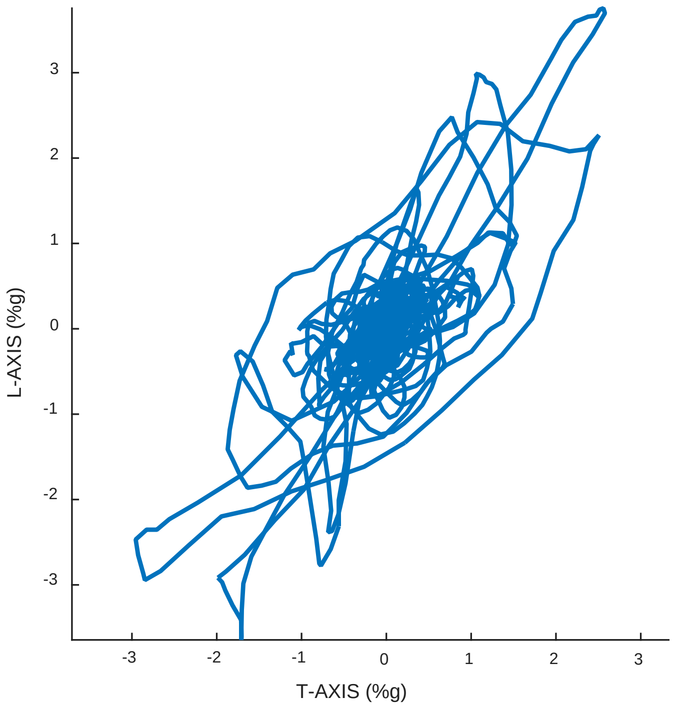
Monitoring and FE analysis of the Bell Tower



The Finite element model with spring supports

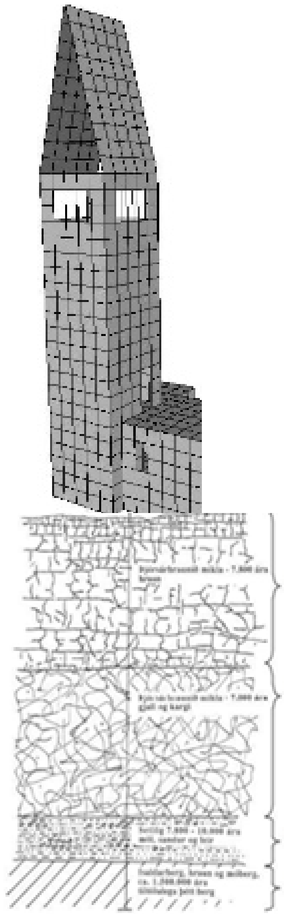


The first mode of vibration has a frequency of 5 Hz

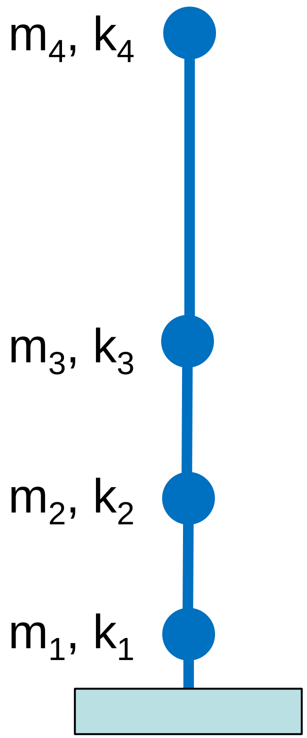


A plot of the two horizontal acceleration components recorded in an aftershock

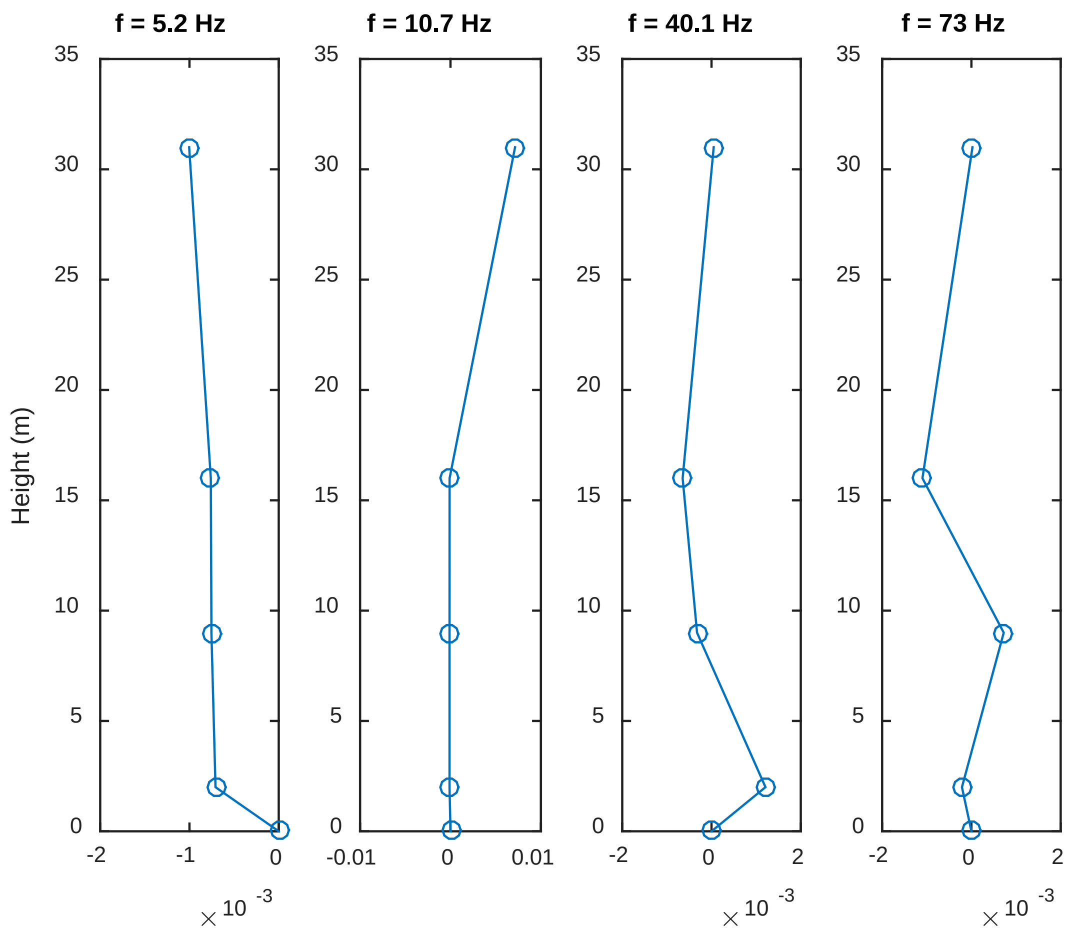
A simple dynamic soil-structure model



The tower & the propsed soil structure



A simple dynamic model, combining the soil-structure and the tower.



The modes of vibration of a simple dynamic soil-structure model.

DISCUSSION

- Analysis confirm the influence of the soil-rock layers beneath the buildings on the building response.
  - Earthquake motion of different intensity will result in a non-linear change in material properties such as shear strength and damping.
  - The amount of strains in the sedimentary layer will, to a large degree control the frequencies of response.
  - The damping effects created by the soft layers may reduce the amplitude of the ground accelerations in strong earthquakes
- The site effects/soil-structure interaction observed in the earthquake in May 29, 2008, has most likely been beneficial for the buildings studied.
- For taller, more flexible buildings the frequency shift observed in the input motion might on the other hand magnify their response.
- The foundation layers can either act as equivalent seismic isolation for stiff low rise buildings ($f_1 > 5$ Hz) or induce additional magnification in the response of medium to high rise buildings ($f_1 < 5$ Hz)
- The foundation layers thereby affect Hazard and Risk analysis for the area, as well as structural safety.

OPEN QUESTIONS

- How to distinguish between the foundation frequencies and the structural frequencies?
- How to properly evaluate the natural frequency and damping of the structure?
- What properties of the seismic event determine or affect the response characteristics of the foundation (2Hz vs 8 Hz)?
- For which buildings will the foundation layers act as a seismic-isolator?
- For what type of buildings will the foundation layers act as magnifying substructure?
- What is the importance of the frequency content of the ground motion vs amplitude on the response of buildings?
- How will the observed behaviour of the subsurface layers affect the seismic hazard and Risk for the area?
    - Magnitude – acceleration – distance from source
- Approach for implementing formal Value of information analysis?

VOI SCHEME – INITIAL IDEA

- Consider simplified scenarios
  - Select Earthquake action levels (amplitude, distance)
  - Select foundation systems
    - Stiff, 8 Hz, 2 Hz,
  - Evaluate “hazard”
  - Different building types (low rise, medium rise, high rise)
  - Evaluate response
  - Evaluate “risk”
  - VoI – Information on difference in risk
    - Stiff foundation versus 8Hz & 2Hz

  - (Suggestions regarding further information required)