From rock concerts and soccer matches to in-situ, non-linear experiments: a numerical study of extreme, man-induced ground vibrations

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BACKGROUND

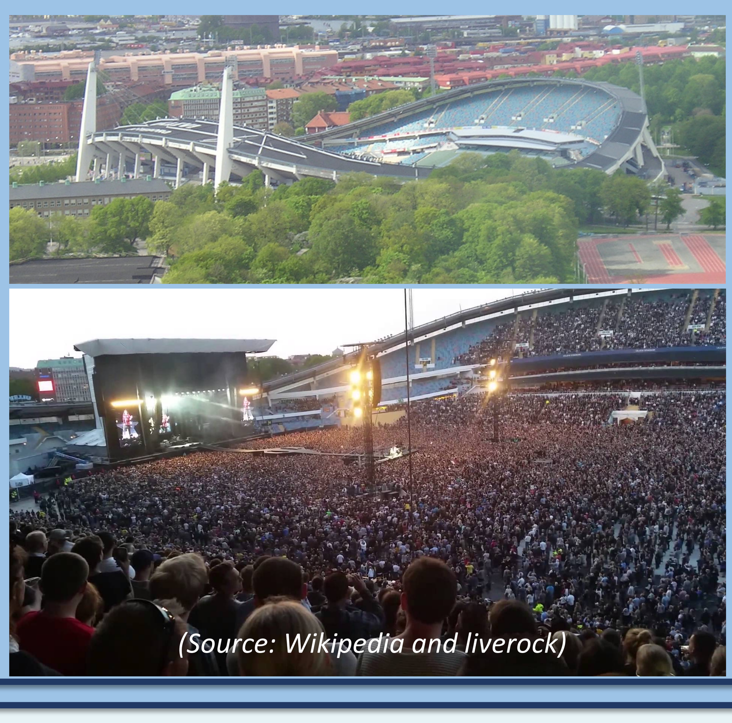
Examples of large ground) vibrations in the near field of large crowd gatherings

1. **Rock concert in Ullevi stadium (Gotheborg, Sweden)**

- Damaged during a B. Springsteen concert on 8 June 1985 (Repair cost : 4-5 M€)
- tens of thousands of people rythmically jumping on the stadium, frequency coincidence between clayey soil, jumping frequency, and structural modes
- Estimated displacements and velocities (H and V : up to 2.0-2.5 mm, and beyond 2 cm/s, respectively

2. **World Cup 2018, Mexico 1 – Germany 0**

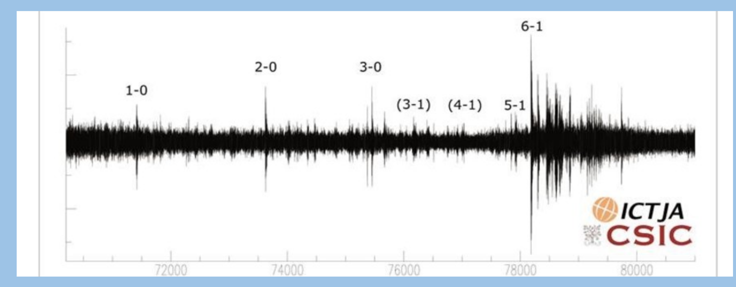
- Triggering of a fake earthquake warning in Mexico City (ABC News, 17/06/2018) due to exulting Mexican fans

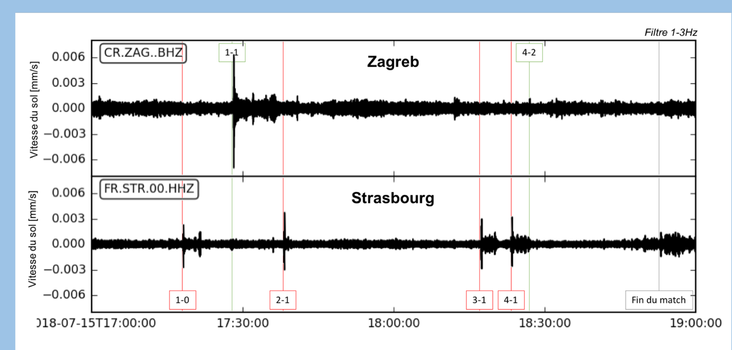


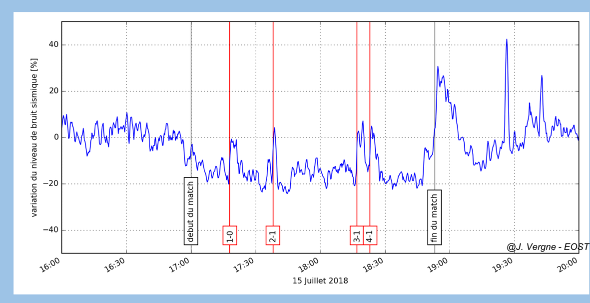
(Source: Wikipedia and liverock)

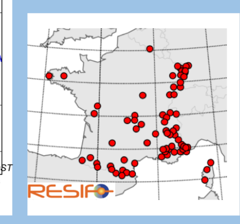
Examples of detectable long distance seismological signals

1. **Barça – PSG "remontada", Champion's league, 2017**
   Camp Neu recordings
2. **World Cup 2018 Final, France 4 – Croatia 1**
   Goals detected throughout France and Croatia









Average seismic energy on 74 stations of the French RESIF network in the 2-3 Hz band

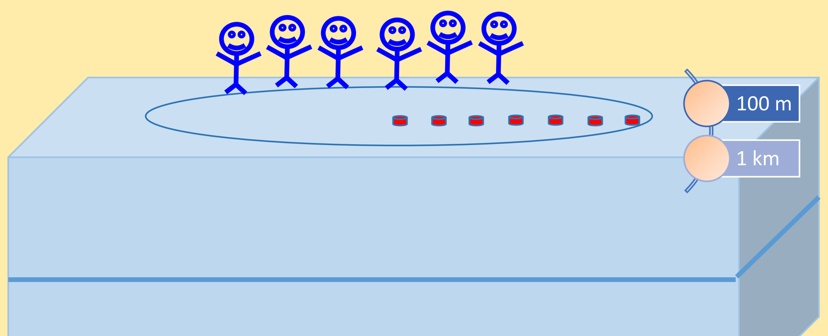
Courtesy J. Vergne, EOST Strasbourg

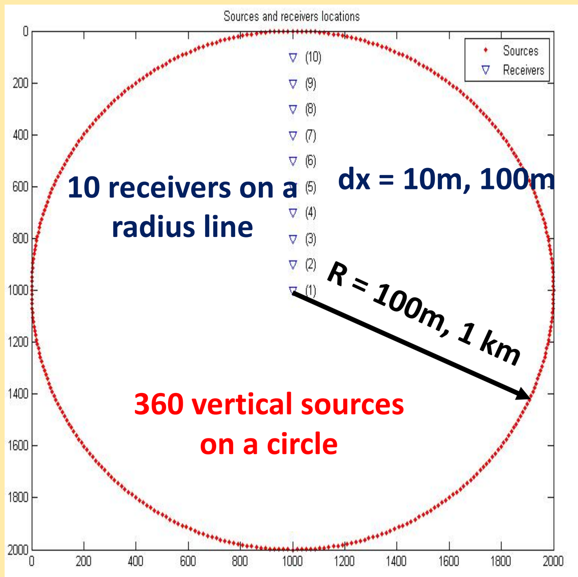
OBJECTIVES : HOW EXTREME + APPLICATIONS ?

Methodology: numerical simulation

Looking for an upper bound with extremely unfavorable conditions

- Source geometry
- Underground structure
- Source waveform / frequency content





A - Source / receiver geometrical configuration: 2 cases

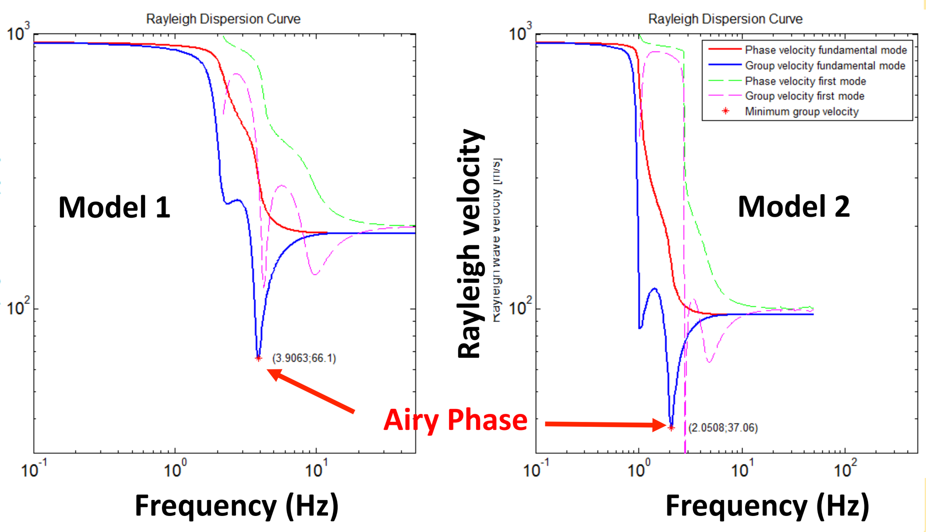
- Focusing from a circle of 360 vertical source
  - 2 radius R: 100 m, 1000m
- Line of equidistant receivers from center to sources
  - Spacing dx: 10 m, 100 m (respectively)

B – Underground structure: 2 models

- Single layer (h=25 m) with large impedance contrast
  - 2 velocities : B_1 = (200 m/s (2 Hz), 100 m/s (1 Hz)
  - Qs = 25 (ς=2%)

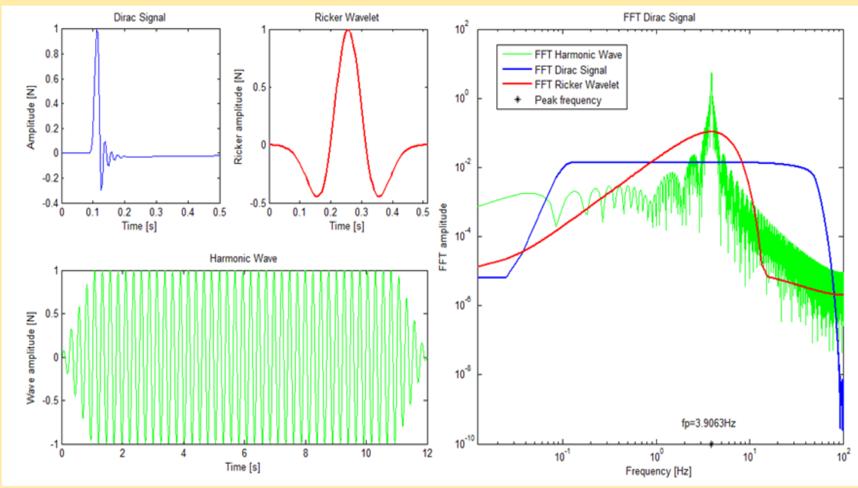
Model	1	2
Thickness h	25 m	
ρ_1	1900 kg/m³	
ρ_2	2500 kg/m³	
B_1 (m/s)	200	100
β_2 (m/s)	1000	
Q_{S1} / ς_1 *(%)*	25 *(2%)*	25 *(2%)*
f_0 (Hz)	2	1
Airy phase (Hz)	3.9	2.1

Rayleigh wave dispersion curves : phase and group velocities (solid red: phase; solid blue, fundamental mode)



C – Source : waveforms and amplitude

- 3 types: (quasi)Dirac, Ricker (tuned frequency), quasi-harmonic (20 cycles, tuned frequency)
- 2 amplitudes : F_1 = 1N, $F_{2,R}$ = 3 kPa * 2πR / 360
  - ***Erlingsson (1996):*** external surface load for people jumping around a stage estimated at 3 kPa
  - ***Linthorne (2001)*** : vertical force from a jumper: around 1 to 1.5 kN ➔ realistic density of 2-3 people / m²
    R = 100 m ➔ $F_{2,100}$ = 5.24 kN
    R = 1000 m ➔ $F_{2,1000}$ = 52.4 kN

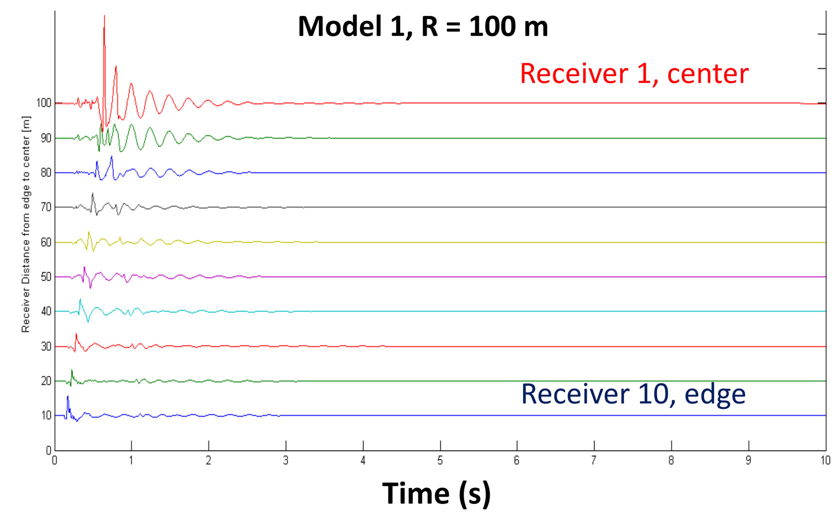


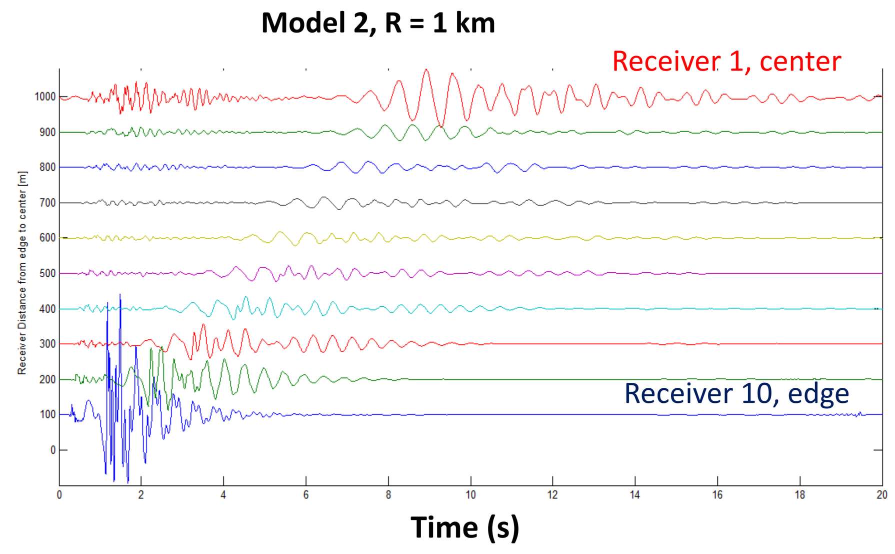
Source functions in the time (left) and frequency (right) domains: blue = quasi Dirac, red = Ricker, green = harmonic

D. Computation: Discrete wavenumber (Bouchon, 1981; Hisada, 1994, 1995)

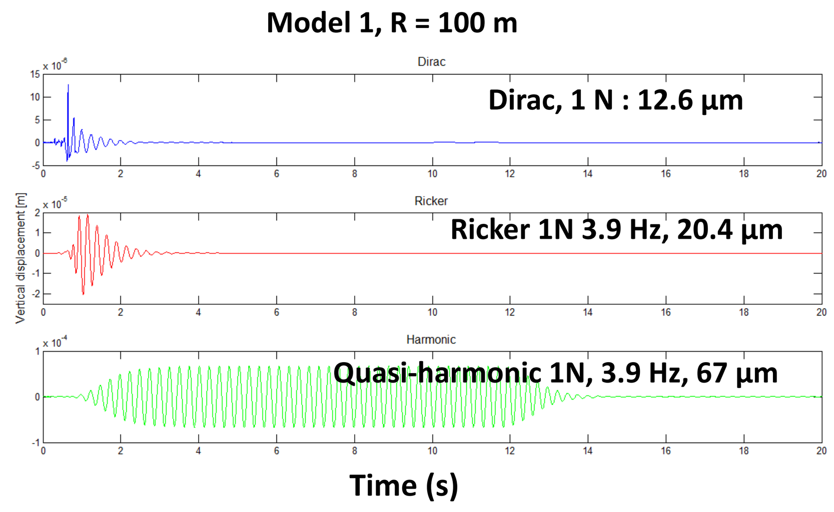
Results

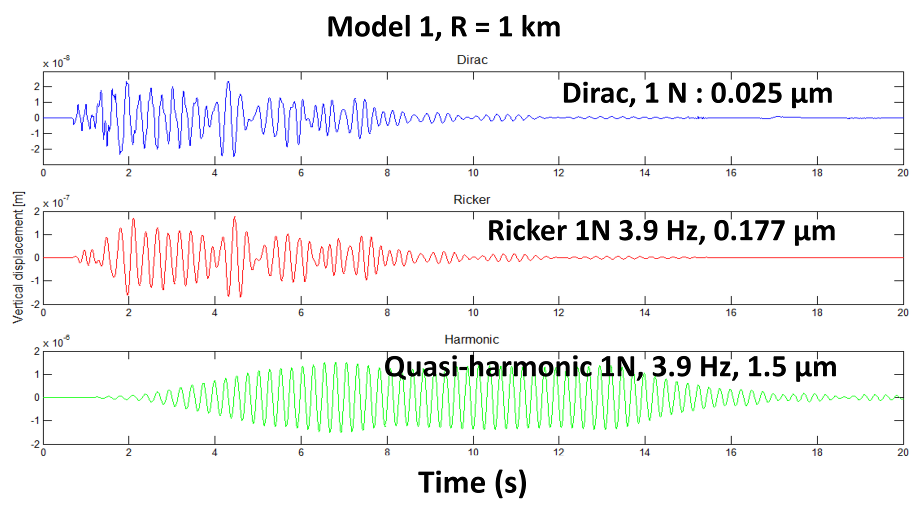
Predicted waveforms along the receiver line (quasi-Dirac impulse)





Impact of source waveform (central receiver)





Summary of results : peak displacement and velocity values at central receiver

Radius	Model	Dirac 1N		Ricker 1N		Harmonic 1N		Harmonic 3kPa	
		PGD (µm)	PGV (mm/s)	PGD (µm)	PGV (mm/s)	PGD (mm)	PGV (mm/s)	PGD (cm)	PGV (m/s)
100 m	1	12.6	1.25	20.37	0.63	0.0675	1.7	35.3	8.9
	2	26.3	1.5	70.21	1.1	0.208	2.7	109.1	14.1
1 km	1	0.025	$0.86\ 10^{-3}$	0.177	$3.66\ 10^{-3}$	$1.51\ 10^{-3}$	0.037	8.47	1.96
	2	0.043	$1.04\ 10^{-3}$	0.515	$5.09\ 10^{-3}$	$0.51\ 10^{-3}$	$7.3\ 10^{-3}$	2.85	0.38

Conclusion / discussion

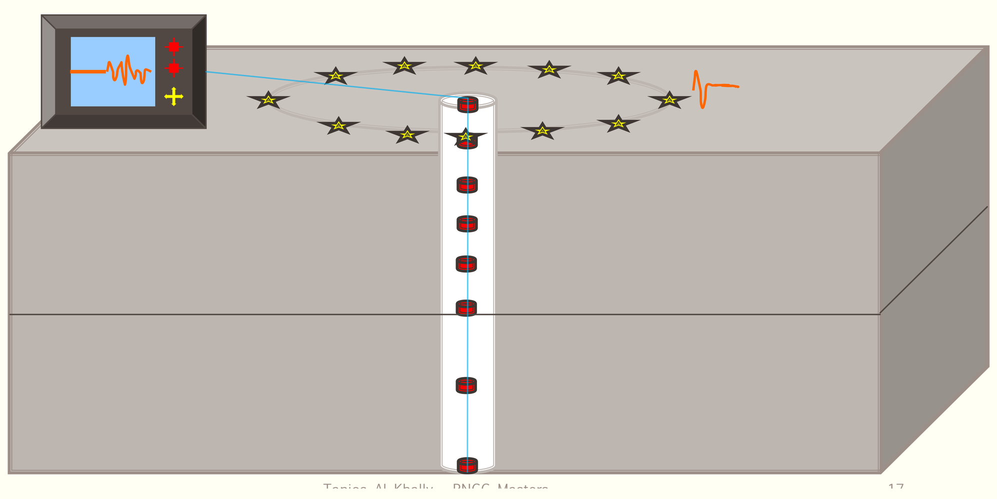
Jumping crowds arranged along a circle can therefore generate very large motion in the very center (displacement and velocities beyond several cm and several tens of cm/s, respectively). The motion at the next receiver (10 or 100 m distant for models 1 and 2, respectively), not shown here) is between 3 and 6 times smaller, which remains important and well beyond the acceptable comfort limits. This is due

a) the efficient excitation of Rayleigh waves by surface sources,
b) their high energy due to the coincidence of jumping frequencies with Airy phase,
c) their focusing in the central part.

The reached values indicate nevertheless that the linear (visco-)elasticity assumption will not hold at least in the central part, and that the actual values should be lower because of increased damping,

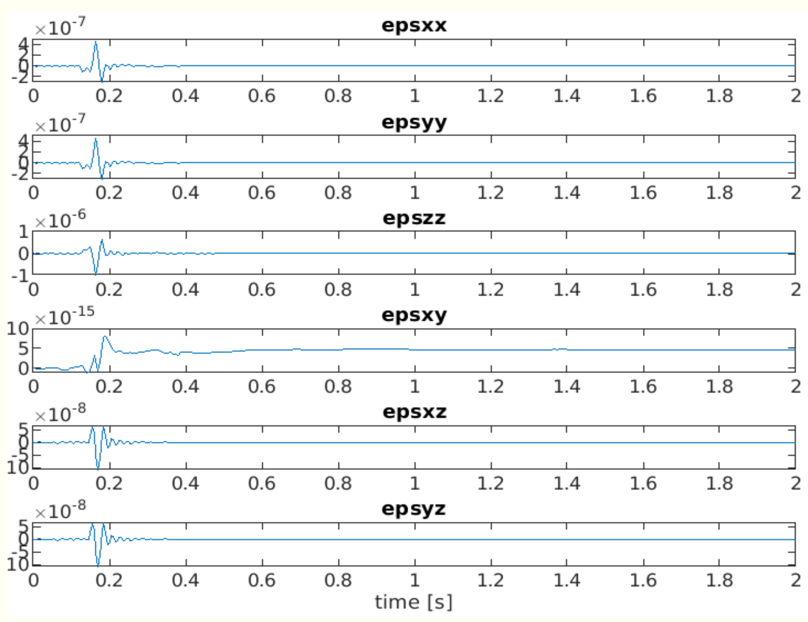
APPLICATIONS : IN-SITU NON-LINEAR TESTING

These numerical tests thus open the way for investigating the feasability of an instrumental device to perform in-situ non-liner tests. The basic idea is to use a set of active sources installed on a small-aperture circle around the considered site, and to try to focus the energy in order to generate large enough strains at a target depth within a borehole at the center of the circle (sketch below).



Preliminary computations (AlKhally, 2018)

Example computations for a set of 12 vertical sources along a 10 or 20 m radius for model 1 above.



$$\varepsilon = \begin{bmatrix} 4.49\times10^{-7} & 7.9\times10^{-15} & -1.07\times10^{-7} \\ 7.9\times10^{-15} & 4.49\times10^{-7} & -1.07\times10^{-7} \\ -1.07\times10^{-7} & -1.07\times10^{-7} & -9.68\times10^{-7} \end{bmatrix}$$

Strains waveforms and values obtained at 5m depth for a set of 12 1N quasi-Dirac vertical forces along a 10 m radius circle

Time focusing with time reversal techniques

In addition to the spatial focusing, the use of time reversal techniques could result in a time domain focusing of the strain at a given depth in the borehole, potentially allowing to reach at least the onset on non-linearities with only limited energy for the active sources. The Table below lists the force levels F_{NL} that are needed to reach a 10^{-4} strain level at shallow depth (1-25 m) for a set of 12 vertical, radial and tangential sources along a 10 m radius circle, without and with time reversal techniques

Force direction	Strain level	Source time function	Sensor depth (m)					
			0	5	10	15	20	25
Vertical	$\varepsilon_{zz}=10^{-4}$	Quasi-Dirac source	236	103	152	316	525	1150
		With time reversal	30	19	72	126	107	156
	$\varepsilon_{xz}=10^{-4}$	Quasi-Dirac source	734	932	4012	9999	16405	26946
		With time reversal	127	248	419	1687	4620	12146
Radial	$\varepsilon_{zz}=10^{-4}$	Quasi-Dirac source	174	197	217	240	322	689
		With time reversal	91	29	21	70	183	349
	$\varepsilon_{xz}=10^{-4}$	Quasi-Dirac source	5778	2632	6034	6831	7327	11622
		With time reversal	66	922	413	388	1453	4433
Tangential	$\varepsilon_{xz}=10^{-4}$	Quasi-Dirac source	4973	1462	1823	3062	4429	8185
		With time reversal	111	275	87	215	1015	4375

Force levels (in Newtons) required to reach a 10^{-4} strain level for a set of 12 excitators installed along a 10 m radius circle (From AlKhally, 2018)

Main references

Al Khally, T. (2018) Time reversal and soil non-linearity, Master Internship report, Lebanese University / ISTerre, 51 pages

Bouchon M. (1981) A simple method to calculate green's functions for elastic layered media *Bulletin of the Seismological Society of America, Vol 71, No 4, pp 959-971, August 1981*

Denton, P., Fishwick, S., Lane, V., & Daly, D. (2018). Football Quakes as a Tool for Student Engagement. *SRL 89-5, 1902-1907*

Erlingsson & Bodare (1996) Live load induced vibrations in Ullevi Stadium dynamic soil analysis *SDEE 15 (1996) 171-188*

Erlingsson S. (1999) Three-dimensional dynamic soil analysis of a live load in Ullevi Stadium *SDEE 18 (1999) 373–386*

Hisada Y. (1994, 1995) An Efficient Method for Computing Green's Functions for a Layered Half-Space with Sources and Receivers at Close Depths *BSSA: Part 1 Vol. 84 No.5, pp. 1456-1472;* (Part 2) *Vol. 85, No. 4, pp. 1080-1093, August 1995*

Linthorne, N.P., 2001. Analysis of standing vertical jumps using a force platform. Am. J. Phys., Vol. 69, No. 11, November 2001, p. 1198-1204. doi: 10.1119/1.1397460

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