Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)

Rock concerts and soccer matches: How extreme could be ground motion generated by jubilant crowds?

P.Y. Bard, T. Alkhally*, M. Wathelet, B. Guillier, C. Cornou & E. Chaljub
ISTerre (Institut desSciences de la Terre), Université Grenoble-Alpes, Université Savoie Mont-Blanc, CNRS, IRD, IFSTTAR, Grenoble, France

ABSTRACT: There have been over last decades several examples of large ground vibrations caused by masses of people gathered for special events: a rock concert in Ullevi stadium (Gothenburg, Sweden) in 1985 generated strongly felt tribune vibrations, while there are repeated examples of seismological recordings corresponding to goals in high stake soccer matches (for instance, the famous Barça "remontada" against PSG in 2016-17 Champion's league, and the Mexico victory over Germany during World Cup 2018). Such man-induced vibrations can therefore be a concern for the design of stadium facilities, in order to avoid coincidence between structural frequencies and man-made beating frequencies (generally around 2 Hz). The present work reports a numerical investigation about how extreme could be such vibrations at ground level. We use the discrete wavenumber approach to model the wave field generated by surface sources (corresponding mainly to vertical forces) with an amplitude corresponding to the surface load estimated for jumping crowds (around 3 KPa, Erlingsson and Bodare 1999). We consider a ground layering leading to resonant frequencies close to 2 Hz, and compute the ground motion at various distances (from a few tens of meters to several kilometers). The largest ground motion is found to correspond to the center of sets of sources arranged in circles having a radius of several hundred meters, and a beating frequency tuned to the Airy phase of Rayleigh waves, and an underground structure with significant velocity contrast and low damping. In such cases, as long as the soil behaves linearly, the ground displacement is found to possibly exceed several cm, while the velocity can reach several tens of cm/s at the very center of the circle. The conditions for large vibrations are thus: efficient wave trapping in shallow soil layers (i.e., large velocity contrast), rather low damping, energetic surface waves and specific geometrical configurations (underground structure combined with source geometry). This series of results also pave the way to investigations on the use of concentric, active surface sources that could be combined to perform in-situ measurements of soil non-linear characteristics.

1 INTRODUCTION

Over last decades, a particular issue has drawn the attention of the geotechnical and structural engineering communities: the ground (and possibly structural) vibrations generated by large crowd gatherings. Several examples of these special events have been reported, such as rock concerts (Erlingsson and Bodare, 1996; Erlingsson1999), or people jubilating on goals in high stake soccer matches. In many occasions, seismic detectors were able to register non-natural vibrations. For instance, during the 2018 World cup, the victory of Mexico over Germany made the sensors in the city trigger a fake earthquake warning (ABC News, 11/07/2018). These recorded vibrations were due to the massive jumps of the exuberant soccer fans. Many similar cases occurred during which people reported high ground vibrations, feeling the earth moving under their feet. It is also more and more common to obtain seismological recordings of soccer goals:

* Also at Lebanese University, Faculty of Engineering

recent examples are the famous Barça "remontada" against PSG in 2016-17 Champion's league, the qualification of Peru for its first World Cup since 1982 after defeating New Zealand 2-0 in the Peruvian capital, Lima, or the respective vibration levels recorded by broad band networks in Croatia and France during the 2018 World Cup final (Vergne, 2018- on twitter).

One of the impetus of this study was to address a case history of two rock concerts, leading to vibration levels strong enough to be largely felt. This occurred in the Ullevi stadium in the city of Gothenburg, Sweden, during two rock concerts in the 1985 summer, with high vibrations in the soil and in the structure. The motion of the stadium and the ground was due to a large harmonic load mobilized by the crowd jumping in time to the music. The spectators succeeded to create repeated rhythmic wave, resulting in large enough displacement in the clay deposit material under the stadium, to result in significant to violent shaking in the tribunes. The external surface load due to the crowd was estimated to be around 3.0 KPa (Erlingsson, 1996; Erlingsson and Bodare, 1999) with a jumping frequency of 2.4 Hz. This event showed that man-made vibrations are thus able to excite the sediment layers under the stadium as well as some structural elements, due to close resonant frequencies. According to Erlingsson & Bodare study, vertical and horizontal displacements were calculated and found to be up to 2.0-2.5 mm, with velocities exceeding 2 cm/s: these values are well beyond the accepted thresholds for anthropic explosions and vibrations.

2 METHODOLOGY

2.1 *Overall approach*

In our study, we aim to estimate the upper limit of ground displacements and velocities due to a large number of people modeled as vertical surface sources. We will thus consider "extremely unfavorable" conditions combining specific underground structure and source geometry, and coinciding excitation and soil frequencies.

2.2 *Source/receiver geometrical configurations*

The sources are thus placed along a circle, so as to focus energy and to reach maximum vibrations in the center. We thus consider a total of 360 vertical forces standing every 1° around a circle, corresponding to people standing in a stadium or a university course. We have here consider two values for the circle radius, to investigate two different scales: 100 m and 1 km.

The receivers consist of an equispaced linear array inside the circle perimeter, with an inter-receiver distance of 10 and 100 m for the cases, respectively. The geometrical source/receiver configuration is presented in Figure 1.

2.3 *Underground model*

The soil model used for this exploratory study is the M2.1 model from SESAME study. It consists of a single layer of thickness 25 m over half space, exhibiting a large velocity contrast (5) with the underlying bedrock, and a fundamental frequency of 2 Hz. Then, in order to investigate

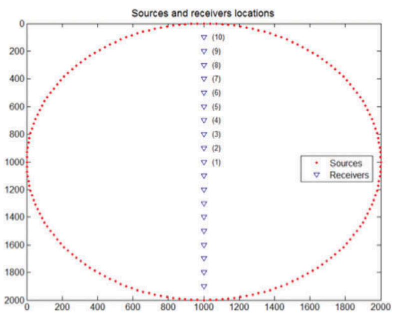

Figure 1. Sources and receivers location for a 1 km radius.

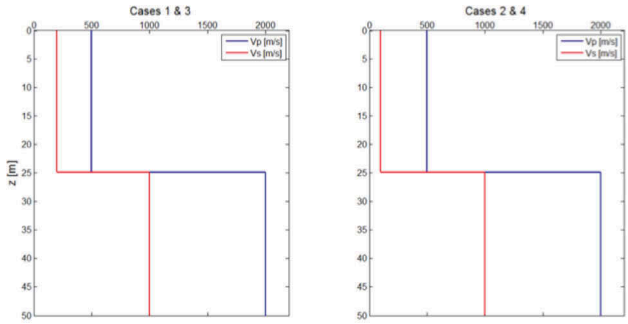

Figure 2. Velocity profiles for P and S waves for the soil models

the sensitivity to the underground structure for rather extreme cases, a total of four soil models have been analyzed, with a geometry similar to the initial model but with variation in the S wave velocity and attenuation factor as listed below (see Figure 2 for the velocity profiles)

1. $V_s = 200\ m/sQ_s = 25$ (M2.1 model)
2. $V_s = 100\ m/sQ_s = 25$ (increased wave trapping, site frequency reduced to 1 Hz)
3. $V_s = 200\ m/sQ_s = 100$ (lower damping compared to case 1)
4. $V_s = 100\ m/sQ_s = 100$ (lower damping and increased velocity contrast

The wave field is expected to be dominated by surface waves whenever the source-to-site distance is relatively long compared to soil thickness, which is always the case for the 1 km radius circle, and most often the case for the other case (100 m radius). It is therefore meaningful to analyze the dispersion curves for Rayleigh waves plotted in Figure 3: the minima in group velocity correspond to the Airy phase of Rayleigh waves, and the corresponding frequencies are thus likely to correspond to the largest energy in the induced vibrations. The minimum velocity for the fundamental Rayleigh mode is 66 m/s and the corresponding frequency f_p=3.9 Hz for cases 1 and 3, while the values for cases 2 and 4 are 37 m/s and 2.1 Hz, respectively.

2.4 *Computational method*

In order to calculate surface displacements induced by surface sources, we used the calculation code proposed by Hisada (1994, 1995) corresponding to an improved version of the discrete wavenumber method (DWM) proposed by Bouchon (1981). Bouchon and Aki (1977) proposed two discretization scheme to model the wave field generated by surface sources, for Cartesian coordinate system and for cylindrical system. By generalizing R/T (reflection and transmission) coefficient method of Luco et al. (1983) with a specific integration scheme in the wavenumber domain, the computational method proposed by Hisada allows to calculate the static and dynamic Green's Functions for viscoelastic, horizontally layered half-spaces even when the sources and receiver are located at the same depth. Figures 4 and 5 display the impulsive response

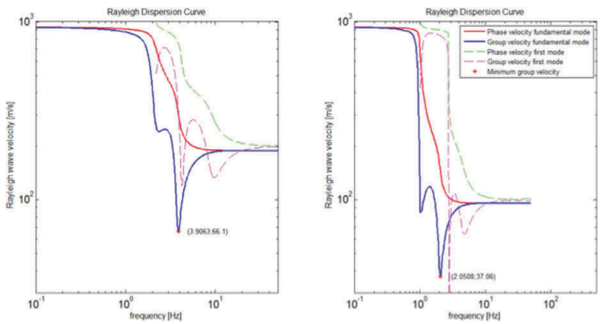

Figure 3. Rayleigh dispersion curves for cases 1-3 (left) and 2-4 (right)

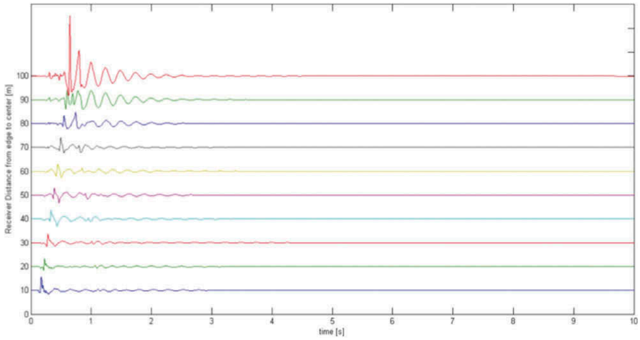

Figure 4. Time domain impulsive response along the profiles of ten receivers (from edge to center) for the L2.1 soil model and the 100 m radius case

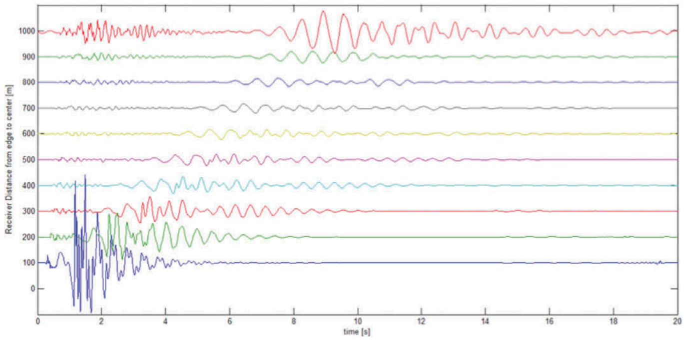

Figure 5. The same as Figure 4 but for case 2 (low velocity), and for the 1 km radius case

along the ten receivers profile for the M2.1 soil model (case 1) for Figure 4 and case 2 soil model for Figure 5, in the two source configurations (circles with radii 100 and 1000 m, respectively). These waveforms illustrate both the importance of surface waves at the central receiver (especially in the 1 km radius case), and the importance of focusing at the central receiver.

2.5 *Considered sources*

As illustrated in Figure 6 for the particular case of soil models 1 and 3, a total of three different wavelets with unit amplitude (1N) were used for the time dependence of circular sources,

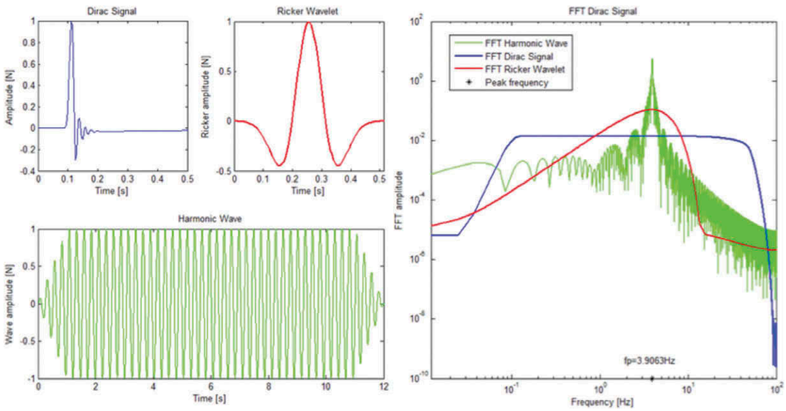

Figure 6. Time dependence and Fourier spectral contents (log-log scale) of the different source signals used for soil models 1 and 3

considering that the corresponding ground motion at all receivers may be obtained by a simple convolution as long as a linear behavior is assumed:

1. Quasi-Dirac impulse
2. Ricker wavelet, with a central frequency tuned to the Airy phase of Rayleigh waves
3. Quasi-Harmonic wavelet, representing jumping human beings, with a frequency tuned to the minimum group velocity (i.e., different for cases [1, 3] and [2, 4]).

3 RESULTS

3.1 *Impulsive sources*

The impulsive responses displayed in Figures 4 and 5 indicate that the largest ground motion corresponds to the central receiver. For a 100 m radius the peak displacement at the very center equal to 12.6 μm for the case 1 (Figure 7), with a peak velocity of 1.25 mm/s. For a larger velocity contrast (case 2), the ground motion increases at all receivers, especially in case of low damping. Peak displacements at the center reach values of 26.3 μm, 34.7 μm, and 95 μm for cases 2, 3 and 4, respectively. In the latter case, the peak velocity reaches 9.7 mm/s, i.e., approximately 8 times greater than for case 1.

Similarly, for the set of sources on a 1km circle (Figure 8), the peak values at the center of the circle increase from 0.025 µm and 0.90 µm/s for case 1 to 0.8315 µm and 41.4 µm/s for case 4.

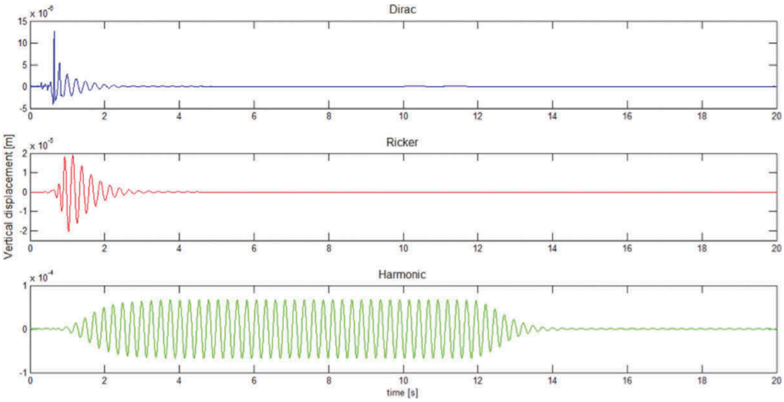

Figure 7. Time domain responses at the central receiver for the Dirac, Ricker, and harmonic sources for the case 1 and 100 m radius.

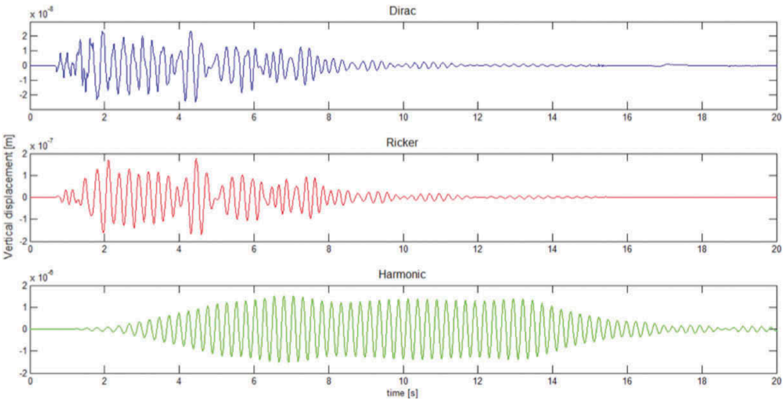

Figure 8. The same as Figure 7 for the 1 km radius case

3.2 *Ricker*

One of the very particular characteristic of the Ricker Wavelet, is that, in the frequency domain, its amplitude spectrum is peaked on a particular frequency. This frequency has been chosen to correspond to the Airy phase of Rayleigh waves, and thus to the most efficient trapping in the layer. Compared to the impulsive sources, displacements as well as velocities among the receivers are found to be greater. Tables 1 and 2 list the peak values, in term of displacement and velocity at the central receiver, for the different cases, sources and radii.

The maximum displacement at the center of the 100 m radius circle increases from 12.61 μm for an impulsive source to 20.37 μm. On the other hand, for the sources located at 1 km, the peak displacement increases from 25.0 nm to 177 nm. The increase is thus significantly larger for the larger radius, as the development of Airy phase Rayleigh waves is more effective over long distances.

3.3 *Harmonic source*

The harmonic wave corresponds to people jumping with a frequency corresponding to the minimum velocity of the group phase. As mentioned before, the frequency is 3.9 Hz for cases 1 and 3, and 2.1 Hz for cases 2 and 4. The latter is the most realistic jumping frequency for crowds gathered for musical concerts, while the former one is too high.

It is clear that displacement at the very center of the circle is significantly amplified with respect to the Ricker and/or impulsive wavelets as illustrated in Figures 7, 8 and 9. For case 1, the registered maximum displacement for sources at 1 km is 1.52 μm (i.e., 60 times greater than the same scenario for a quasi-Dirac signal). Similarly, for case 4, the recorded peak displacement is 28.3 μm instead of 0.83 μm, i.e an amplification by a factor of 35.

3.4 *Jumping crowds, 3kPa*

According to Erlingsson's study (1996), the external surface load for people jumping around a stage is approximately 3 KPa, which is consistent with the force of 1 kN for one single jumping person (Linthorne, 2001), and a density of 3 persons/m^2. For sake of simplicity, we will

Table 1. Peak amplitudes (displacement and velocity) in the four cases at the central of the concentric circles, at 100 m.

	Displacement			Velocity		
	Dirac μm	Ricker μm	Harmonic mm	Dirac mm/s	Ricker mm/s	Harmonic mm/s
Case 1	12.61	20.37	0.067	1.25	0.63	1.7
Case 2	26.3	70.21	0.21	1.5	1.1	2.7
Case 3	34.7	27.15	0.104	4.2	0.85	2.6
Case 4	95.01	98.06	0.33	9.7	1.6	4.4

Table 2. Peak amplitudes (displacement and velocity) in the two cases at the central of the concentric circles, at 100 m.

	Displacement			Velocity		
	Dirac nm	Ricker μm	Harmonic μm	Dirac $\mu m/s$	Ricker $\mu m/s$	Harmonic $\mu m/s$
Case 1	24.98	0.17	1.52	0.86	3.66	37.45
Case 2	43.23	0.52	0.51	1.04	5.09	7.26

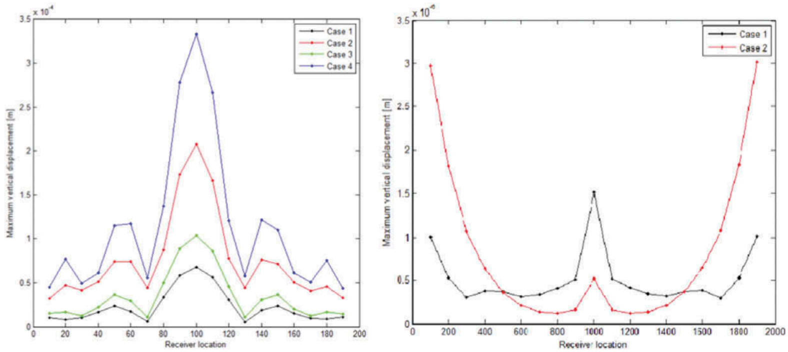

Figure 9. Variations of the peak displacement values along the profile, for the 100 m and 1km radius cases (left and right, respectively) and for the worst case of harmonic sources

consider here that the case of a continuous, circular ring of jumping people can be simulated, at least in the central part of the ring, by the set of 360 point circular sources displayed in Figure 1, with an appropriate amplitude scaling as described below.

We thus assume that the crowd is organized along a 1 m wide disc, and that their rhythmic jumping applies a 3kPa pressure. producing a pressure of 3 KPa. The total disc surface is thus $= 2\pi R \times 1m = 2\pi \times 100 \times 1 = 628.3m^2$ for the 100 m radius case, and the total force generated by jumping crowd is:

$$F = \sigma \times S = 3000 \times 628.3 = 1.885 \times 10^6 N$$

In order to reproduce such a force, the individual force to be associated to each one of the 360 sources of our simple circle model is thus: $F = 1.885 \times 10^6/360 = 5236N$. A harmonic jumping crowd would thus generate signals 5236 times larger than those listed in Table 1. Similarly for a distance of 1 km, as the radius is ten times larger, each of the 360 harmonic point sources should have a ten times larger amplitude of 52360 N to mimic the effects of a jumping crowd. Note that with a density of 3 people/m^2, these estimates correspond to gatherings of about 2000 and 20000 people for the 100 m and 1km radius cases, respectively, which look rather realistic.

The resulting motions at the central receiver, as listed in Table 3, indicate huge displacement and velocity values. For case 1, the displacement is found to be 35 cm for 100 m radius and 8 cm for 1 km radius, with velocities largely exceeding 1 m/s. These values become much more important when the medium is characterized by a greater velocity contrast and/or a lower damping. They are very probably unrealistic, since for such high values, the soft layer would behave non-linearly, with in particular an increased damping (that is why we have not listed in Table 3 the jumping crowd estimates for the low damping cases 3 and 4). However, such values indicate that extremely unfavorable conditions such as those considered here could lead to very large, potentially destructive crowd-induced vibrations. One must note however that given the source geometry, this very high motion is limited to the central part of the circle, as shown in Figure 9.

Table 3. Peak amplitudes (displacement and velocity) for cases 1 and 2 at the central of the concentric circles, at 100 m and 1 km radius, for a harmonic load of 3 KPa.

	Sources at 100 m		Sources at 1 km	
	Displacement m	Velocity m/s	Displacement m	Velocity m/s
Case 1	0.35	8.9	0.08	1.96
Case 2	1.1	14.13	0.027	0.38

4 CONCLUSION AND DISCUSSION

We reported a numerical investigation about how extreme could be vibrations at ground level caused by jubilant crowd in case of unfavorable conditions. 360 surface sources were arranged around a circle every 1°, with 100 m and 1 km radius. Ground vibrations were calculated for receivers aligned on a diameter and for different sources: impulsive, Ricker and Harmonic wave. Different cases of the underground structure were considered, in order to investigate the effects of damping and velocity contrast. The ground displacements is found to possibly exceed several cm, especially for a medium characterized by a low damping and a high velocity contrast. When the harmonic sources are tuned to correspond to the estimated crowd pressure of 3 KPa, the peak displacement and velocity values at the very center of the circle are found to reach up to 1 m and several m/s. These values are thus interpreted as non-realistic, since the soil would then enter the non-linear domain, and the increasing damping would effectively reduce these values. The next step should thus be to complement this numerical simulation experiment with a more realistic one, taking into account the non-linear behavior of the soil, once the strains exceed the threshold linear limit. Also, a more realistic distribution for sources and wider surface rings could be used to better represent jubilant crowds in stadiums. However, the present numerical investigation may open the way to new kinds of in-situ measurements to detect and measure soil non-linear behavior, using sets of circular, active sources, which would be a useful alternative or complement to laboratory experiments on small size soil samples.

REFERENCES

Apsel R. J. and Luco J. E. (1983) On the Green's functions for a layered half-space, part 2 Bulletin of the Seismological Society of America, Vol. 73,931-951

BardP.-Y.Bonnefoy-ClaudetS.CornouC.FähD.KristekJ. & MoczoP., (2004) Simulation of seismic noise: report on parameter studies *SESAME report D12.09, last downloaded from http://sesame.geopsy.org on November 2018, Tech. rep.*

Bouchon M. and Aki K. (1977) Discrete Wave number Representation of Seismic Source Wave Fields *Bull. Seismol. Soc. Am. 67259–277*

Bouchon M. (1979) Discrete Wavenumber Representation of Elastic Wave Fields in Three-space Dimensions *J. Geophys. Res. 843609–3614*

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*

Bouchon M. (2003) A Review of the Discrete Wavenumber Method *Pure appl. geophys. 160 (2003) 445–465 0033–4553/03/040445–21*

Erlingsson & Bodare (1996) Live load induced vibrations in Ul!evi Stadium dynamic soil analysis *Soil Dynamics and Earthquake Engineering 15 (1996) 171-188*

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

Erlingsson S. (1999) Three-dimensional dynamic soil analysis of a live load in Ullevi Stadium [Soil Dynamics and Earthquake Engineering 1999; 18:373–386] *Soil Dynamics and Earthquake Engineering 18 (1999) 531*

Greenfield R. (1995) Comment on "An Efficient Method for Computing Green's Functions for a Layered Half-Space with Sources and Receivers at Close Depths" by Y. Hisada *Bulletin of the Seismological Society of America, Vol. 85, No. 5, pp. 1523-1524, October 1995*

Hisada Y. (1994) An Efficient Method for Computing Green's Functions for a Layered Half-Space with Sources and Receivers at Close Depths *Bulletin of the Seismological Society of America, Vol. 84, No. 5, pp. 1456-1472, October 1994*

Hisada Y. (1995) An Efficient Method for Computing Green's Functions for a Layered Half-Space with Sources and Receivers at Close Depths (Part 2) *Bulletin of the Seismological Society of America, Vol. 85, No. 4, pp. 1080-1093, August 1995*

Hisada Y. (1995) Reply to Comment on "An Efficient Method for Computing Green" s Functions for a Layered Half-Space with Sources and Receivers at Close Depths" by Roy J. Greenfield *Bulletin of the Seismological Society of America, Vol. 85, No. 5, pp. 1525-1526, October 1995*

Luco J. E. and Apsel R. J. (1983) On the Green's functions for a layered half-space, part 1 *Bulletin of the Seismological Society of America, Vol. 73,909-929*

Wang Y. (2015) Frequencies of the Ricker wavelet *Geophysics Vol. 80 NO. 2 (MARCH-APRIL 2015); P. A31-A37*