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A FORTRAN Code for the Sensitivity Estimate of a Seismic Network: An Application to Campi Flegrei

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Abstract

The resolution power of a seismic network is a crucial point both for scientific and legal reasons. Firstly it allow to understand whether an area is not affected by seismicity or we are just not able to detect it; consequently it is an important parameter when the possible seismicity is eventually associated with human activities. When subsoil exploitation is planned a certain minimum level of sensitivity to earthquake location is indeed usually required for the monitoring network to be installed. The sensitivity of a seismic network is its ability to detect or locate earthquakes. Here we present free downloadable and friendly software to define the sensitivity of a seismic network. Input to the program are the station positions, the seismic noise level of the area and the mean elastic properties of the area and the output is a grid with the minimum magnitude of earthquakes which are localizable or detectable at a certain depth.

Keywords: Seismic network; Sensitivity; Seismic network optimization

Introduction

Heat and power production is an attractive field that often collides with environmental aspect. Energy production is anyway so important that people are willing to accept even the pollution and drawbacks associated with it. The environmental impact monitoring is therefore fundamental to reduce the risks. In particular, the ground water quality and level, the eventual ground deformation and seismicity are the most important parameters to monitor. Usually, the States legislation provides instruction on the characteristic of the monitoring systems, especially for mining and geothermal exploitation. As the subsoil exploitation is often associated to micro-seismicity, the installation of a seismic network is an important tool and a cost to benefit analysis is usually required to deploy a network that meets certain specifications. The seismicity monitoring is useful both to understand the fluid movement in the underground and to plan the injection or pumping rate as a function of the seismicity occurrence. The sensitivity of a network to location or detection of earthquakes is a parameter that is always considered in the mandatory guidelines. The sensitivity of a seismic network is defined as the location performance of the network, i.e. the minimum magnitude of an earthquake that can be located using the records of the network itself. The detection performance of a network is, instead, the minimum magnitude for an earthquake to be detected by the network, i.e. the minimum magnitude of an earthquake that is visible at least on one seismogram of the recording network. This minimum magnitude depends on the seismic noise of the station site and on the earthquake-station distance, increasing moving away from the station.

Location and detection performances are also very important for the interpretation of seismic data set. It is a matter of fact that when the seismicity of an area is considered, the seismic network capability to detect earthquakes is often not taken into account. This behavior brings to possible bugs in the geophysical interpretations, because the lack of resolution of the seismic network in a certain area cannot be interpreted as the lack of seismicity in the same area. The preventive analysis of the network capability would certainly help the data interpretation.

The program we present here allows a fast computation of the resolution performance of a seismic network and will help to compile the mandatory roles for underground exploitation. This program provides a map of the areas where earthquakes of certain magnitude can be located with a defined network and can be used to plan an enhancement of a seismic network itself.

Methods

The basic concept of the seismic location is that at least 4 pickings are needed to locate an earthquake and the SENSI program takes advantage of this concept. Consequently, for each magnitude the program investigates if the seismic wave emitted by an earthquake in a given grid is visible at the stations of the network, that is, the seismic wave amplitude is greater than a certain multiple of the seismic noise at the site. The amplitude of the seismic signal at the recording station is calculated as P impulse amplitude using the Brune's approximation [1] for a point source with assigned magnitude, stress drop and medium elastic parameters [2]. For each grid point, the program searches which are the minimum earthquake magnitude needed for the seismic signal to be readable at the station. Stress drop and medium elastic parameters are constant and input from the user. The Brune's approximation of the source representation leads to a slightly overestimation of the amplitude attenuation. The theoretical amplitude signal is simulated with a single corner frequency spectral model [3] as a triangle with an area proportional to the seismic moment and base depending on the stress drop.

The theoretical amplitude of the first P pulse velocity is evaluated in a subroutine as: $A = \Omega / T_r^2$

Where Ω is low frequency spectral level of the earthquake and T_r is

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the rupture time. Ω is calculated by:

$$\Omega = \frac{R_\theta M_0}{2\pi R \rho \alpha^3}$$

Where M_0 is the moment magnitude; R the source-station distance; α the mean P wave velocity; ρ the medium density and R_θ the radiation pattern. R_θ is fixed to 0.52 for the P-waves and α is taken as 1.73*β, the S-wave velocity.

Tr is the time needed for the fault to break and is calculated as the source ray divided by the rupture velocity that is taken equals to 0.9*β. The source ray, A, is estimated as: $A = \sqrt[3]{\frac{7}{16}\frac{M_0}{\sigma}}$ using the Madariaga formula [4] for the circular fault model, where σ is the stress drop of the earthquake. σ is the shear stress released by the earthquake and its values usually falls between 10 and 100 bars [5]. This parameter depends on the characteristics of the medium involved by the fracture. Its value is usually low for fractured media and high for compact ones.

The P-wave pulse is then corrected for the attenuation, using the Carpenter operator [6], and for a factor that takes into account the mean radiation pattern for the P-waves that, as said before, is chosen equal to 0.52. The attenuation is quantified by the non-dimensional seismic quality factor, Q. Q is a rock property defined by the fractional energy loss per cycle experienced by a propagating seismic wave [7]. High Q values (500–1000) are expected for non-attenuative materials such as massive crystalline rocks, and low Q values (10–100) are typical for attenuative materials such as porous and/or fractured rocks.

Input to the program

To analyze the resolution power of the network the program needs an ASCII file describing the seismic network. Each line of the station file must contain 5 rows (Figure 1): station name, latitude and longitude in degrees, station height in km (positive when above the sea level) and the mean seismic noise level at the site in cm/s. This value is estimated mediating the seismic noise at a site for a characteristic time and is compared with P-wave amplitude to decide whether the seismic event is detectable at the seismic station.

```
Name Latitude      Longitude    Height(km)    Noise(cm/s)
STA1  -23.782312 -67.780571         1.0           0.0001
STA2  -23.818025 -67.725335         1.0           0.0001
STA3  -23.831656 -67.758410         2.5           0.0001
STA4  -23.813464 -67.784515         2.5           0.0001
STA5  -23.737307 -67.731029         0.5           0.0001
STA6  -23.758909 -67.696129         0.5           0.0001
```

Figure 1: Example of seismic network description file.

The program requires some parameters (Table 1) from the user that can be both manually input at the startup of the program or written to a file that can be sending to the standard input of the program. When using an input file, this must contain 12 lines, with a single parameter per line. An example of such a file can be found in Figure 2. The first two lines must contain the name of the seismic network description file (Figure 1) and the name of the output file.

The following four lines must contain the earthquake and medium characteristics described in the previous section as earthquake stress drop and hypo central depth, medium density and attenuation and S-waves velocity around the source.

The minimum number of detecting stations is the following input to the program. This number can be changed from 1, to define the detection limit of the network, to a number greater than 3 to define the location limit of the network. The knowledge of the detection limit of a network allows understanding the network capability and its ability to solve a certain area.

The minimum signal to noise ratio, SNR, necessary for an impulse to be detectable is then input to the program. This value is often assumed equal to 2.

The other inputs concern the search steps and, two of them, modify the running time: magnitude step, map extension and grid point number. The magnitude step is the minimum magnitude variation that is tested. The program search from M=-2 to M=5: for moderate to high magnitude the fault geometry and source directivity became important and cannot be neglected as we do in the program. Anyway SENSI program is useful to define the lower magnitude of earthquakes which can be detected or located with a certain network, consequently high magnitude can be neglected. The map extension and grid point numbers are the parameters that regard the geometry of the output. The first one is expressed as percentage of the maximum station distance, if 0 the output map will cover just the network area, if 1 the output map will cover four times the area (twice in x and twice in y). The grid point number is the number for which this area will be divided along x and y.

Examples

We applied the SENSI program to three seismic networks to describe their performance. With these examples we list the inputs for the program. The first example describe the simple case of a 4-stations network arranged almost radially (triangles in Figure 3). The inner-station distance is around 1-2 km. After editing the station file we run the program 2 times, one with the input described in Figure 2 and the other changing just the minimum number of detecting stations from 4 to 1 to show the detection limit of the network.

Parameter	Short explanation
Stress drop	is associated to the difference between the stress across a fault before and after an earthquake and it is usually included between 10 bar and 100 bar
Medium density	density of the rocks around the source; generally between 1.5 g/cm^3 and 2.8 g/cm^3
S-waves average velocity	Vs around the seismic source
Earthquakes depth	depth for which the sensitivity is calculated
Minimum number of detecting stations	1 for detection threshold, >3 for location threshold
Signal to noise ratio for detection limit	limit for an impulse to be visible on the seismogram
Magnitude steps	increments in the minimum detectable magnitude research
Map extension (Percent of the station distances,>0)	the map extension of the grid is defined as the maximum distance between the stations times a percent of the same distance for X and Y separately
Grid point number	numbers of the grid points along X and Y. The program running time increases as the square of this number.

Table 1: Synthetic explanation of the input parameters of the SENSI program.

```
Stations          # Name of the seismic network file
output.dat        # Name of the output file
20                # Stress drop (bar)
2                 # Medium density (g/cm3)
1.5               # S-Waves average velocity (km/s)
100               # Anaelastic attenuation factor
-2                # Earthquakes depth (km a.s.l.)
4                 # Minimum number of detecting stations
2                 # Signal to noise ratio for detection limit
0.1               # Magnitude steps
1                 # Map extension (% of the station distances)
50                # Grid point number along X and Y
```

Figure 2: Example of input file for the SENSI program. The parts after the hashes (#) are comments.

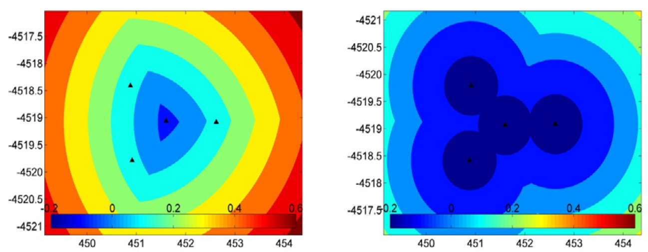

Figure 3: Sensitivity to location (left) and detection (right) power of a test network, which seismic stations are represented by black triangles) for earthquakes located at 2 km b.s.l. The color represents the value of the minimum magnitude needed for an earthquake in that position to be located/detected by the network.

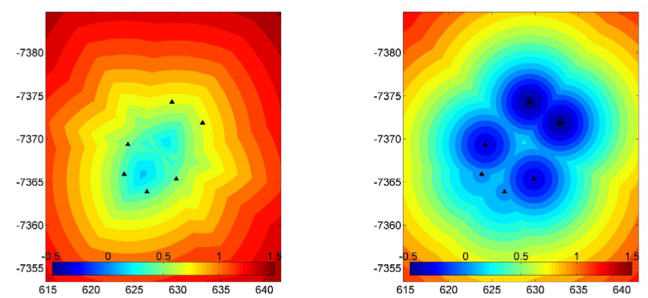

Figure 4: The same as in Figure 3 but for a different seismic network (black triangles).

The output of the program provides the value of the minimum magnitude recordable/localizable by the network for earthquakes located at a certain depth for each map point. The output is organized as x coordinate in km, y coordinate in km (UTM) and magnitude.

Figure 2 shows the images of the output obtained for the sensitivity to the location (left) and detection (right) for the test seismic network represented by the black triangles. The four stations are all located at the sea level and each of them has a mean noise of 10-4 cm/s. The synthetic network is capable to detect events with magnitude higher than -0.2 below each station and higher than 0.3 in all the analyzed area.

The second example illustrates the case of the network described in Figure 4 and plotted in Figure 5 (black triangles). We used the following input: stress drop of 30 bar, medium density of 3 g/cm^3, S-waves velocity of 2 km/s, Q equals to 500, earthquakes depth of -2 km, SNR of 2, magnitude steps of 0.1, 1 for map extension and 1000 grid points. Also in this case we run the program twice to obtain the sensitivity to the location (left) and detection (right) for the seismic network.

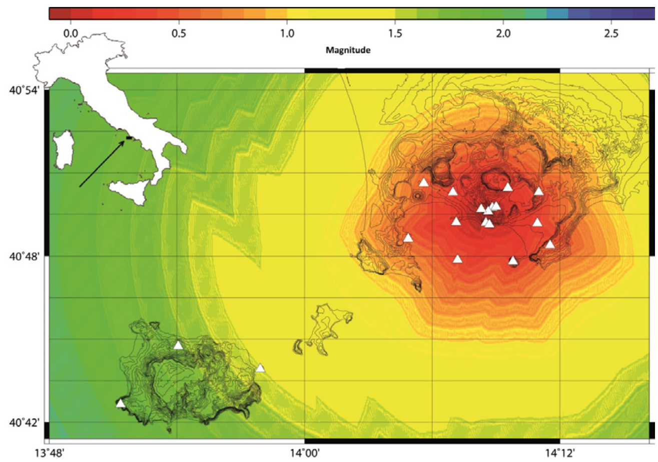

Figure 5: Sensitivity to location of the actual seismic network of Campi Flegrei/ Ischia (Italy) for earthquakes at a depth of 2 km.

The results show that with this particular station configuration the center of the network is less covered and in this part the network is able to detect earthquake with magnitude higher than 0.2 while it detect M>-0.4 in the NE part where the seismic stations are located at a lower elevation. Also the map of the sensitivity to the location shows a maximum (~0) in the area central to the four stations in the SW part of the network, while the two stations in the NE part are not enough to locate seismic events with the same magnitude located close to them.

The last example is performed using the actual seismic network of Campi Flegrei/Ischia (Italy) deployed by Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Vesuviano (INGV-OV). The network is composed by 19 stations (white triangles in Figure 5). The input parameters used by the programs are: stress drop=20 bars; medium density=2 gr/cm^3; Vs=1.5 km/s; Q=100; earthquakes depth=-2 km; minimum number of detecting stations=4; SNR=2; M steps=0.1; map extension=1; grid size=1000. Figure 5 shows that the resolution of the actual seismic network is around 0 in the very central part of the Campi Flegrei caldera and around 0.5 within the caldera as confirmed by the dataset analysis performed by D'Auria [8]. The magnitude of completeness of locating earthquakes increases moving away from the caldera till values of 2.

Conclusions

The program presented here could form part of a wider cost-benefit analysis that seeks to find the optimum number of instruments to install in an area interested by human operations that could induce seismicity. This is an handy program that could be used by operators to meet the mandatory requirements for the seismic monitoring associated to oil or geothermal exploitation. The program provides the minimum magnitude of an earthquake that can be detected or localized by a certain seismic network. Here we do not take into account the location errors that depend on picking accuracy and velocity model quality, but we just check if the seismic signal is readable on the seismic trace recorded by the station; in this way the program is faster.

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