A Brief Introduction to Nanoseismic Monitoring

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Abstract

Major terrestrial hazards are associated with the generation of fractures that evolve with time and finely lead to total structural collapse. Fracture singles emitted in response to stress accumulation and subsequent its release, if properly understood, provide sound background for the development of Early Warning Systems (EWSs). Different attempts have been made in the past for the proper understanding of such signals, but in this study Nanoseismic Monitoring (NM) is being discussed, in term of its sensors employment and signal processing methods. NM is a method dedicated to the detection and location of very low seismic energies (ML < 1) at short distances (< 10 km). Data are acquired by small aperture (max 200m) seismic arrays are easy to install and consists of one central three component (3C) sensor surrounded by three vertical one component (1C) sensors in a tripartite layout and which are suited for beam processing. Detection and location of weak events (ML < 1) are done by dedicated software: the NanoseismicSuite, was developed at Stuttgart University Germany. Seismograms are processed in the form of sonograms (i.e. spectrograms with a frequency-dependent noise adaptation). Sonograms enhance the display of weak signal energy down to the noise threshold and allow for supervised pattern recognition of weak target events in the frequency domain. Locations of weak events are supported by a graphical jackknifing approach. Case studies on dynamics of unstable material in Europe have shown that NM successfully detects various weak fracture signals induced by the LS dynamic and structural health, hydraulic fracturing, erosional features and stress relief mechanism associated with material deformation.

Introduction

Materials under stress emit specific signals before their final collapse. These fracture signals/ stress relief mechanism having low energy (Ml<0) (Walter et al., 2011) emitted by the material, in response to applied stresses. Micro earthquakes in response to material instabilities cause micro fractures usually referred to as quakes (Gomberg et al., 1995) that grow with time and leads to complete failure. These emitted signals vary in frequency, time and their spectra (Wust-Bloch and Tsesarsky, 2013) and are attenuated at shorter slant distances especially, in unconsolidated materials like clays. These signals are associated with major global hazards like soil erosion, structural heath, landsliding and sinkhole collapses. Each one has its own share in the total annual global hazards (Planes et al. 2015). The effects of these hazardous phenomena can be mitigated by strengthening Early Warning Systems (EWS) based on these fracture signals detection. The complete understanding of these singles will help to develop more reliable EWS.

Many geoscientists has contributed to the development of seismology by providing new and advanced methodologies in the field of both data acquisitions and processing. The challenge that has been continuously disturbing the scientists and engineers of all ages is the low resolution of seismology that limits its use for the detection of fracture generation and its propagation through the material. The problem of low resolution in seismology hinders the accurate identification of seismic signal associated with the deformation as the fracture signals have magnitude (ML=0) than the background ambient noise. The other problems of seismology associated with its survey in the urban populated areas were the use of active source of seismic energy like dynamite. These shorting comings in the traditional seismology gave rise to new techniques with their own merits and demerits.

Different techniques are used for the detection of these fracture signals like acoustic, passive, and Microseismic, but all have their own limitations. An important contribution to seismology was the concept of Microseismic; it is the study of signals associated with material deformation like hydraulic fracturing, active faults, structural health monitoring and landslide etc. Microseismic monitoring is based on single station, where events are located by Geiger approach; the correct event localization is based on correct onset. The details of these techniques lie beyond the scope of this study.

Nanoseismic Monitoring (NM) that took the seismic monitoring to new highs by increasing its sensitivity down to noise levels was introduced by Joswig, 2008 which has revolutionized the seismology. The new demands for the sensitivity in fracture signal detection, was achieved by the specialized deployment of sensors and with the concepts of Hypolines, respectively. This sensitivity achieved by NM is because of up gradation in recording instruments and their deployment in the form mini arrays called as Seismic Navigation System (SNS).

This concept of NM has been applied to many studies until now. NM was first applied to identify sinkholes before their collapse in Israel (Wust-Bloch and Joswig, 2006). A similar technique was applied to Heumoes landslide in Austria (Walter et al., 2011). This slope is creeping in nature, which has been resolved into discrete rupture episodes on the basis of seismic rupture signal. Same technique was applied for small noisy or impact signals to Super-Sauze mudslide in the southern French Alps, where waveform and sonogram analysis were applied to discriminate the event types and on the basis of the spatial distributions of their epicenters, the authors notified a mechanical phenomenon associated with each type of signal. From that study, it was concluded that the slide obviously relieves stress continuously, but extensive rainfall can trigger stronger material failure processes (Walter and Joswig, 2009). Another study was conducted at the Super-Sauze in which NM was benefited from Unnamed Arial Vehicle (UAV or drones). In the Austria and Alps cases, processes were constrained by the uppermost meter where mudslide material dries out in summer to consolidate with sufficient shear resistance. In Israel, a study was conducted that demonstrated the potential of Nanoseismic Monitoring in rapidly detecting, locating and analyzing brittle failure generated within unconsolidated material before total collapse occurs (Wust-Bloch, 2009). Countrywide, adaptability of NM makes it an attractive choice for expert from various fields, oil industry to structural health monitoring to hazard assessment. Germany and Israel have played a leading roles in the development and application of NM for various purposes. However some other countries like Italy, Iran and Brazil has also contributed to the evolution of NM.

The present study is an attempt to provide, a brief methodological introduction to Nanoseismic Monitoring and introduction of dedicated NanoseismicSuite software package.

Method

A field of passive seismic which has achieved the sensitivity of event detection 2 to 3 magnitude lower than zero at slant distances of 10 m to 10 km, through its acquisition and processing endures is referred to as Nanoseismic monitoring. The robustness against noise level and autonomy in event detection are the two important aspects of this concept that took it to new highs of unprecedented sensitivity. The essence of autonomy lies in the application of SNS because it can be achieved on the principle that event of weak magnitude can be detected at nearest station only. And the second pillar of NM i.e. robustness against noise is achieved in signal processing where a detected software 'Hypoline' reduces the signal detection below 0 db signal to noise ratio.

Mini-array

The importance of seismic arrays in the detection of events cannot be neglected from local to telemeismic scales. Their operation is similar to phased arrays used in acquisition Radar and applied first time to seismic problem in 1960s. The maximum phase coherence among all stations is achieved by utilization of the concept that plane waves travel along the array aperture. Then the SNR is improved by utilizing the sum and delay concepts commonly referred to as Beamforming, where SNR is proportional to the square root of number of stations used. In turn array give only one location by using many stations. The three-component stations provide the backazimuths from station to event and constraints in direction of S-P time provide distance, in this way the events are localized.

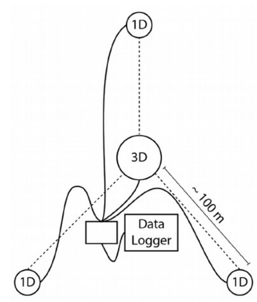

Figure 1-Data acquisition with SNS and data acquisition equipment (Naomi et al. 2016)

Data Processing

In the field data is acquired by deploying mini-arrays. Mini-arrays are very fast to install and easy to carry. Only two persons are required to acquire the field data. Mini-array has a very long history. These mini-arrays were first applied to onsite inspections (OSI) of Nuclear Test Ban treaty (NTBT). Data acquisition by mini-arrays is best suited to determine azimuth of incoming signals. Mini-arrays are called Seismic Navigation System (SNS) because it leads or navigates through the source. Each mini array, consists of one three-component and three vertical one components short-period seismometers installed at appropriator angle (120^0). The aperture size is a function of slant distance (source-receiver distance) which is usually kept in the range of 50-200m (Joswig, 2008).

In the absence of a priori velocity model the signal processing in NM is of constant loop type which rests on trial and error approach. To meet this challenge a dual analysis approach based on both array and network was introduced to find the influence of single trace onto location space to display signal energy in time–frequency and in slowness space and to access error bars by jackknifing and trough hundreds of options in parameter space in a virtual reality manner. In NM the nano events having ML -2.0 are obtained from cross correlation of captured earth quake events of ML 0.0 (Joswig & Schulte-Thesis, 1993).

Data processing in NM has following important steps and all these steps can be carried out in a dedicated software package referred as NanoseismicSuite.

Sonograms

Sonogram is the most important step of processing Nanoseismic. These are logarithmic scaled power spectral density matrix with capabilities of noise adaptation and are pre-whitened that reduces the detection threshold to 0db signal-to-noise ratio (Joswig, 1990, 1995; Sick et al., 2012). Four processing steps are required to achieve this distinction of sonogram over others as 1) Power Spectral Density Matrix (PDM), 2) the energy binned at 13 half octave wide bandpass and the results are being transformed to a logarithmic scale. 3) In this step a noise adaptive filter is applied, the advantage of applying this filter is that it rates the fracrturaction of energy which differentiate it from background noise. 4) The last step is the pre-whitening, the objective to mute the analogues noise spike in order to avoid disturbance in signal visualization. The spectral whitening equalizes the spectrum of the signal by enhancing low level spectral components and attenuating high level ones, making it similar to the white noise spectrum (spectral amplitude equal to one). Its aim is to remove the influence of signals which manifest in amplitude spectra such as frequency-localized noise sources. (D'HOUR, 2015).

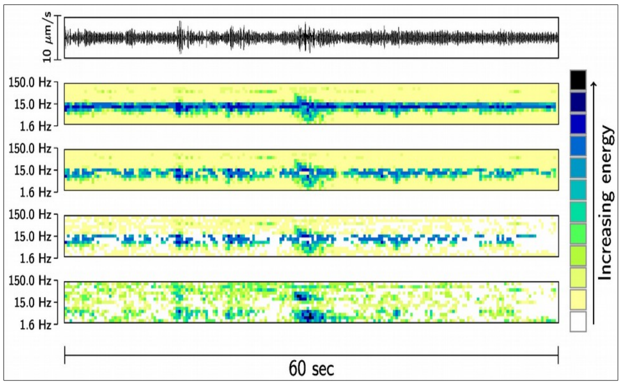

Figure 2-Steps of Sonogram calculation (Sick et al., 2014).

Hypolines

Each station contributes in event location through making hypolines, which are constraining curves (hyperbola of tp at any two station or circle of ts-tp of any single station it can be a array beam if possible) in event location. The highest concentration of these hypolines in solution space is the best event location. These hyperbolas are best suited for half space solution models and with zero depth. Increase in depth will leave a cut on the surface (hyperboloid), which become hyperbola when this cut (hyperboloid) become parallel to axis of symmetry. The ability of Hypoline in event location depends on its handling and displaying uncertainty. Like other classical approaches it also consider area of hypolines crossing like classical approach (matrix inversion), but unlike classical approaches its values are determined by jackknifing and not by fuzzy logic. Jackknifing or one leave out is a method of breaking down the equations into permutation sets.

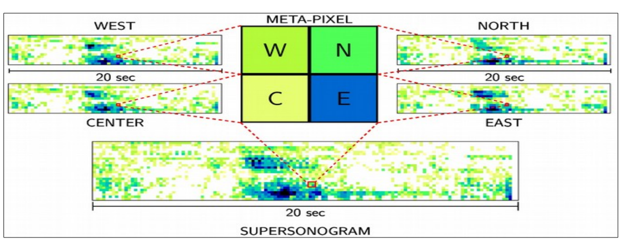

Figure 3–Supersonogram calculated at each sensor of SNS

Jackknifing

Event localization is done by determining the contribution of single stations in erroneous averaged space, this technique of outlier resistant statistics is usually referred to as Jackknifing. As the technique goes all the hypocenter related information is broken down into small location constraints in the case where they all meet at a single point is considered as ideal solution. Hypocentre in this technique is an outer parameters selected by user and not determined by inversion as done by the previous researches. At any single point in the solution space the time difference ts-tp gives us semi-spherical circles, the radius of which remains constant and is the constraint on event location in the 3D solution space. The advantage of taking depth as external constraint is that it reduces the ts-tp semi-sphere to circle on intersecting and reduces tp-tp of two different stations semi-hyperboloid to hyperbola. Pairwise permutation of station tp will form a jackknife assembly of hyperbolae that constraints the epicenter, whose depth is determined by reducing the curves size graphically (Joswig, 2008).

NanoseismicSuite

It's a java based user interface which provide the environment for carrying out all the processing steps of the Nanoseismic Monitoring. SonoseimicSuit (software) package was developed at Institute of Geophysics, University of Stuttgart, Germany. This software uses a graphical approach. Phases are determined interactively and the results are updated in real time in the solution space. Locations are computed with a combination of array and network processing with the following information: P arrival times, ts–tp time differences from the two central 3c's as well as array beams from the two mini arrays. P and S onsets are determined interactively. Event detection is carried out with sonograms that enhance the display of signal energy close to the noise threshold by auto-adaptive, non-linear filtering. This software consists of multiple modules (Figure 4).

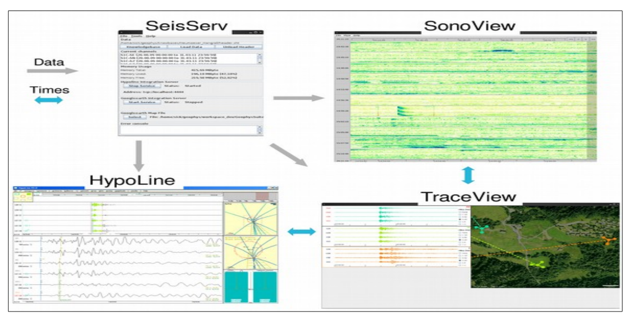

Figure 4-Different processing windows of NanoseismicSuit Application

Applications of NM comprise aftershock surveys for natural and man-made seismic sources, active fault mapping, sinkhole activity (the first application of NM), monitoring of volcanic and induced seismicity (Joswig & Wust-Bloch, 2002; Wust-Bloch & Joswig, 2003).

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