Results of the SUPRE project execution promising for development of a methodology for combined seismic-electromagnetic testing of the earthquake preparation zone

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Abstract
Results of the European collaborative project SUPRE (**S**tudy of the **U**LF electromagnetic **P**henomena **R**elated to **E**arthquakes) executed recently by Russian, Greek, Italian, Ukrainian and Georgian teams are presented and discussed in relation to development of methodology for seismic-electromagnetic testing of the earthquake preparation zone and seismic hazard assessment. Principal aspects of the following topics are introduced: measuring technique being useful in particular seismic active zones, methods of data processing promising for extraction of the earthquake precursory signatures, and modelling the earthquake preparation processes. On that basis, strategy of the newly proposed project SHARP (Study of Seismic Hazard Anomalies Recognition Possibilities) is reviewed as a next step in development of collaborative seismic-electromagnetic research. Its preliminary results are presented.

Introduction
It is now evident that the earthquake preparation dynamics involves both seismo-tectonic and electromagnetic processes. So the combined seismic-electromagnetic measurements in tectonically active areas are of great importance for seismic hazard assessment. Here we present the principal results of the collaborative project SUPRE (Study of the ULF electromagnetic Phenomena Related to Earthquakes), which is based on the joint seismic and electromagnetic observations in tectonically

active regions. The SUPRE project strategy has been particularly introduced in [1]. The main objective of SUPRE is directed toward understanding the physics of earthquake precursory phenomena especially of seismo-electromagnetic origin. To achieve that, an experimental, methodological and theoretical framework for identification of the earthquake precursory signatures has to be implemented. The corresponding research is jointly fulfilled by Greek, Italian, Russian, Ukrainian, and Georgian teams in the course of the SUPRE project. The following 5 tasks have been scheduled and executed: 1) Development of the advanced ULF measurement technique; 2) Actualization of the ULF electromagnetic field experiments at the selected test regions of Greece, Italy, and Georgia; 3) Development of mathematical methods for geophysical time series analysis with application to tracing precursory signatures of catastrophic events; 4) Development of geophysical tomography with application to seismo-electromagnetic experiments; 5) Modelling the earthquake preparation processes

1. Development of the advanced ULF measurement technique

Particular emphasis of SUPRE is put on the ultra-low frequency (f=0.001-10 Hz) range - so-called ULF seismo-electromagnetic precursors of earthquakes. Those signals are expected to be extremely sensitive to structural changes in earthquake hazard systems during the preparation phase of strong events [1,2,3]. The optimal ULF measurement technique has been developed for electromagnetic field recording in seismic active areas and for registration of the ULF electromagnetic earthquake precursors. This technique is based on the MVC-2DS and LEMI 009 instrumentation designed by Russian and Ukrainian teams and advanced in the course of the SUPRE project execution [2,4]. Both instruments have been certified at Nurmijarvi Calibration Stand in Finland, and installed for comparative measurements on Crete Island, Greece during campaign of 2001-2002. The ULF data obtained from LEMI-009 and MVC-2DS magnetometers have been compared. It is provided that the improved versions of MVC-2DS and LEMI 009 are eligible for ULF electromagnetic measurements in seismically active regions and adaptable for registration of the earthquakes precursors.

2. ULF electromagnetic field experiments at the selected seismically active test regions

Geophysical survey to identify the optimal test site (favorable geological and seismotectonic settings) for magnetic measurements has been carried out. Since March 2002, permanent measurements of ULF geomagnetic fields have been organized at the selected seismically active regions of Greece (Crete island, Keramia) and Georgia (Dusheti) using the developed versions of MVC-2DS and LEMI 009. For comperative analysis, the ULF electromagnetic measurements have been carried out also in Russia (Karelia) and Ukraine (Kiev region). The data received from ULF data acquisition systems have been preliminary processed and compared. Self-potential measurements have been carried out in Potenza (Italy). The special task-oriented servers for SUPRE data collection, processing and exchange have been created in Greece (TEICH) and in Russia (St.Petersburg University).

3. Development of mathematical methods for geophysical time series analysis

The advanced mathematical methods of geophysical time series analysis developing by SUPRE partners have been analyzed and compared. The set of methods, including Burlaga-Klein and Higuchi methods, Detrended Fluctuation Analysis, methods of nonlinear dynamics, have been tested on simulated and observational time series. The most promising methods have been developed and applied for investigation of stochastic, subcritical, critical and supercritical stages in evolution of the earthquake hazard systems. Hgh efficiency of the fractal and multifractal approaches for study of the earthquake preparation processes has been demonstrated. Application of those methods to regional seismicity distribution [5,6] and ULF geomagnetic variations in seismic active regions [7] allowed us to reveal definite regularities in the behaviour of scaling (fractal and multifractal) characteristics of the ULF time series and spatio-temporal distributions of seismicity on the preparation phase of strong seismic events. The most important regularities are clustering of seismicity and appearance of flicker-noise in the ULF frequency range. Opportunities of the multifactor analysis for study of the geophysical time series structure have been investigated. The objective techiques has been applied to discriminate anomalies from background noise, and estimate the probability of the extreme events.

4. Development of geophysical tomography

Comparison of different tomography methods (ray, diffraction, and probability tomographies) has been carried out. It has been argued, that the diffraction tomography method is the most promising for solution of the SUPRE tasks. This method has been advanced for application to ULF seismo-electromagnetic tomography experiments [8]. Numerical simulation of the solution of direct problem for seismic and electromagnetic waves and restoration of seismic parameters and electrical conductivity has been fulfilled. Estimation of validity of seismic diffraction tomography method with the use of the physical modeling has been accomplished. The algorithms of restoration of the parameters of medium (electrical conductivity, elastic parameters, mass density) have been constructed and tested using many examples of numerical simulation [9]. Estimation of accuracy of restoration of local inhomogeneities with the help of seismic and electromagnetic sounding signals is carried out. The observation schemes with a small number of the source-receiver pairs have been examined. As a result, theoretical and methodological basis for a combined seismo-electromagnetic tomography experiment has been created. As a field experiment, resistivity and self-potential tomographies have been carried out in Italy to investigate active faults in Irpino-Lucano Apennine.

5. Modelling the earthquake preparation processes based on SOC theory and crack mechanics

Essential attention is given to create physical models of the tectonic processes responsible for generation of electromagnetic precursors of strong seismic events. Simulation of the crack network development in elastic body under external stresses has been performed [10]. It is shown that the crack network evolve from the state with random (chaotic) distributions of cracks and seismicity to the state with fractal, clustered patterns. The results of simulations are supported by the results of case studies of regional seismicity dynamics before a set of strong worldwide earthquakes. It is shown that variations of the multifractal characteristics of the seismicity distribution manifest certain tendencies in the process of evolution of the hazard system towards the main rupture. Modeling of the physical processes in the earthquake focal zone has been implemented on the basis of the SOC (self-organized criticality) theory taking into account phenomenological model of the large-scale evolutionary processes between two violent earthquakes suggested in [11]. A possibility of using the non-Abelian sandpile model for studying coupling effects between seismic activity and the multiscale spatial structure of faults has been analyzed [12]. It is shown that conductivity fluctuations of the model exhibit long-range correlations carrying useful information on system's stability. The shape of the simulated conductivity signals in the vicinity of global critical point has been found to be reminiscent of real pre-seismic ULF electromagnetic emissions. This promising result is a good support for the subsequent development of the non-Abelian SOC model in the frame of the next collaborative project, which is planned to be SHARP (Study of Seismic Hazard Anomalies Recognition Possibilities). Here we present its strategy and preliminary results. As ones of them, we give the results of simulation of the crack network evolution and solution of 2D problem of elastic waves propagation in elastic media containing a number of cracks. It is shown that the fractal dimension of synthetic seismograms of scattered coda waves decreases as the crack network evolves to pre-rupture state. It is found also, that the spectrum of scattered waves develops from the multiscaling to almost monoscaling form. That manifests transition of the crack network from random distribution to fractal, ordered state with pronounced scaling dependencies.

Conclusions

So the SUPRE project findings outline the opportunity to use scaling (fractal) characteristics of ULF emissions, seismic coda waves and seismicity distribution in development of the earthquake forecast methods. Realization of the SUPRE project helps us to understand better the earthquake preparation dynamics and dip into physics of seismo-electromagnetic precursors of earthquakes. Also it gives a possibility to estimate perspectives of seismic-electromagnetic tomography experiments in tectonically active regions for creation of the optimal monitoring networks in the particular hazard zone. Thus, execution of the SUPRE project has provided certain technological, experimental, theoretical, and methodological advances in study of the ULF electromagnetic phenomena related to earthquakes. As perspectives, the new methods of data analysis: methods of neural networks, topological dynamics and Minkowski functionals [13,14] will be implemented in the next collaborative propjet SHARP.

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