

GUIDELINES FOR MONITORING SEISMICITY, GROUND DEFORMATION AND PORE PRESSURE IN SUBSURFACE INDUSTRIAL ACTIVITIES

1. INTRODUCTION	2
2. MOTIVATIONS AND GOALS	4
3. TIPOLOGIES OF CONSIDERED ACTIVITIES AND APPLICATION RULES	7
4. GEOLOGICAL, STRUCTURAL AND SEISMOTECTONIC CHARACTERIZATION	8
5. SEISMIC MONITORING FEATURES	9
5.1 Definition of volumes involved in seismic monitoring	9
5.2 Purpose of seismic monitoring	9
5.3 Technical features of the seismic monitoring network	10
5.4 Data processing and analysis	11
6. GROUND DEFORMATIONS MONITORING FEATURES	14
6.1 General information	14
6.2 Technical features of the ground deformations monitoring	14
7. PORE PRESSURES MONITORING FEATURES	17
8. PUBLICATION OF MONITORING DATA AND INFORMATION DISCLOSURE	18
8.1 Information on license	18
8.2 Introduction to the monitoring activities (seismicity, ground deformation, pore pressure)	18
8.3 General data on monitoring	18
8.4 Seismic monitoring data	18
8.5 Monitoring data of ground deformations	19
8.6 Monitoring data of pore pressure	19
8.7 Documents	19
8.8 Training and access to the site	19
8.9 Useful Links	20
9. INDICATIONS ON THE MANAGEMENT, CONTROL AND INTERVENTION STRUCTURE	21
9.1 Design, realization and maintenance of monitoring networks	21
9.2 Activation system of the actions to be undertaken	22
9.3 Activities management phases	23
9.4 Experimental <i>traffic light</i> system	26
10. CONCLUSION AND RECOMMENDATIONS	28
GLOSSARY	30
BIBLIOGRAPHY	34

1. INTRODUCTION

The present document reports the results of the Working Group established at the Ministry of Economic Development (MiSE), in order to define indications and guidelines for monitoring mining subsurface activities. In particular, they refer to hydrocarbons exploitation, re-injection and storage activities. These Guidelines represent the first action promoted by MiSE aimed at keeping the safety standards for such activities at the highest level of knowledge, mostly in correspondence to seismic zones and areas where such activities can produce ground deformations.

The ICHESE Commission (International Commission on Hydrocarbon Exploration and Seismicity in the Emilia Region, Annex A) highlighted the opportunity that hydrocarbons exploitation and geothermal energy production, both ongoing and upcoming, will be constantly monitored through high technology networks, with the purpose to follow the space-time evolution of microseismic activities, of ground deformations as well as of pore pressure. The Commission stated that these networks should be put into operation before new activities start, to verify and measure the background seismicity and the ground deformation behavior in non-perturbed conditions. The Commission also hoped for the improvement of databases on monitored parameters.

In the Recommendations, the Commission already gave a first indication about minimum networks requirements: capability to detect all the earthquakes characterized by a magnitude value of at least MI 0.5, use of satellite methods to detect ground deformations with interferometric technologies - InSAR and GNSS/GPS (hereafter GPS) - with a resolution of some millimeters/year, daily bottom-well measurements of fluid pore pressure.

Furthermore, in the Recommendations, the Commission hoped also for the launch of a “traffic light” operating system, and for the definition of threshold values associated to different attention levels for the monitored parameters.

Waiting for the definition of a complete regulation framework on this subject by all the competent authorities, at both national and regional levels, MiSE believed to promptly proceed with the tuning of guidelines for an advanced and integrated monitoring system, given what is in its own competencies that are on the one hand the release of permissions, licenses and authorizations, and on the other hand the surveillance on hydrocarbons exploration and exploitation and natural gas and CO₂ storage.

This document represents, therefore, a draft version of the technical Guidelines for the development of monitoring systems and their management and control, and for the intervention procedures related to different scenarios of variation of the monitored parameters. MiSE will test these technical Guidelines on some pilot sites and, subsequently, the results of such tests will be published and shared with the Ministry of Environment, Land and Sea (MATTM) and the involved Regions.

These Guidelines were drafted by the Working Group established by MiSE with this purpose on February 27th, 2014, within the Commission on Hydrocarbon and Mining Resources (CIRM). The Working Group, coordinated by MiSE, is made by national specialists in seismicity, ground deformation and geology, working at Universities and Research Institutes with competences in these fields; furthermore, a representative of the National Department of Civil Protection is also present.

The Members of the Working Group are:

- Eng. Gilberto Dialuce (MiSE - coordinator),
- Dr. Claudio Chiarabba (INGV – Earthquakes Structure),
- Dr. Daniela Di Bucci (National Department of Civil Protection),
- Prof. Carlo Doglioni (Earth Science Department, Sapienza University of Rome),

Prof. Paolo Gasparini (University of Naples “Federico II”; Environmental Risk Analysis and Monitoring - AMRA),
Eng. Riccardo Lanari (CNR – Institute for the Electromagnetic Sensing of the Environment- IREA),
Dr. Enrico Priolo (OGS – Scientific Section Seismological Research Center),
Prof. Aldo Zollo (University of Naples “Federico II” - Physics Department).

The Working Group faced, for the first time in Italy, the issue of monitoring the hydrocarbon production, re-injection and storage related to seismicity, ground deformation and pore pressures, delivering a first version that includes the most advanced technical features. MiSE will evaluate, for each individual case, their first application, taking into account the variability of the geological and structural conditions, as well as the natural seismicity of each considered area. It is recommended that this first edition of this document will be reviewed after 2 years, based on:

- the experience gained in a first experimental phase on pilot sites that can be representative of different possible conditions encompassing - among the others - reservoirs in carbonate rocks where re-injection activities are carried out (in Italy, reinjection activities are already subjected to micro-seismic monitoring, usually managed by Operators);
- a feasibility study, including production and management (at operating speed) costs, for all the production fields where reinjection is present and for other cases that, as we will see in the following, we suggest to consider as a start (i.e. licenses for production with reinjection, and natural gas storage licenses).

Because of the wide experience already gained in monitoring subsurface natural gas storage, it is moreover suggested to include some of these storage fields among the pilot sites. In fact, seismic and ground deformation monitoring networks are already present in the majority of the gas fields operating in Italy.

2. MOTIVATIONS AND GOALS

The present Guidelines aim at defining early observation standards for monitoring the effects of human activities, such as underground fluids reinjection¹ (wastewaters) and hydrocarbons production/storage and, particularly, at establishing monitoring procedures and protocols, including methods to analyze the space-time evolution of some parameters representing seismicity, ground deformation and pore pressure. Such standards must be updated and improved by means of an experimental phase on pilot sites that are representative of different cases, before their widespread application.

Guidelines present indications and general criteria for the formulation, by competent Authorities (see Glossary), of further regulations or specifications to be applied to each license, depending on the site characteristics and on the reinjection, production or storage project. The Working Group took into account the monitoring provisions previously issued by MATTM, including the Report concerning criticalities related to the definition of the normative framework (MATTM, 2013).

Before the human activities start, the monitoring allows to quantify the background values, both natural and/or induced by pre-existing human activities, of the above-mentioned parameters. During the whole operating period, the monitoring allows to distinguish and measure in continuous the possible seismicity and the variations of all the monitored parameters, compared to the background values previously acquired and estimated.

In particular, **seismic monitoring** is intended to identify and localize the seismicity in a volume surrounding the area where human activities take place, also with the purpose to distinguish natural seismicity from the one possibly due to such activities. The monitoring must allow the space-time-magnitude evolution of the seismicity to be followed with the aim, if needed, to re-modulate or interrupt (in the foreseen cases) such activities.

Ground deformation monitoring is intended to identify possible surface deformation phenomena linked to the considered activities, to measure and analyze their space-time variations compared to the background conditions.

By **pore pressure** (or reservoir) **monitoring**, we consider to measure the bottom hole pressure and to carry out possible interference tests with near wells, aimed at verifying the fluid-dynamic model of that part of subsurface interested by human activities, and at evaluating the space-time evolution of the pressures.

These Guidelines were realized with particular reference to reinjection activities carried out onshore, to which the foreseen standards will be firstly applied; in any case, with proper technical adjustments, these standards can be also applied to the offshore activities, particularly near shore. Furthermore, they represent a reference for all mining activities of underground natural gas storage and hydrocarbons production, and they can be extended to other underground activities, with proper adjustments.

The experimental application is recommended, with priority: (a) to human activities, coming and ongoing, which foresee the underground reinjection of wastewaters separated from the produced hydrocarbons; (b) to underground natural gas storage.

For what concerns the pore pressure monitoring, it is suggested to start from upcoming activities and, for the ongoing ones, from those cases where the wells can be technically equipped with tools able to

¹ In this text, this term refers to the re-injection of incompressible fluids (deep groundwater), either into the reservoir from which they were withdrawn, or into a different one. This term does not refer, instead, to the natural gas storage, that is considered separately

carry out such measurements. For interference tests, it is suggested to start from the cases where suitable wells are present near the monitored well.

We believe that, in general, the indications contained in these Guidelines have not to be applied in cases of negligible production of anhydrous gas and oil at a depth shallower than 2 km, because activities carried out in such conditions are not sufficient to determine significant variations in the monitored parameters. With negligible productions we intend those coming from fields with original reserves lower than 300 000 000 Sm³ for gas, and lower than 30 000 000 barrels for oil. For such productions, in any case ground deformation monitoring has to be carried out.

More in general, Guidelines could be adopted -after proper adjustments- also in the case of:

1. dams and related basins,
2. conventional geothermal systems,
3. closed loop geothermal binary cycles,
4. unconventional geothermal systems (activity currently not developed in Italy),
5. CO₂ storage (activity currently not developed in Italy),
6. Mining activities (mines and quarries),
7. tunnels digging.

From a general point of view, we think that the implementation of these Guidelines will contribute to create an integrated monitoring system, aimed at better safeguarding the areas where activities of subsurface exploitation in Italy are foreseen. Through time, this will help also to develop further activities that will take advantage from increasing databases and knowledge, as well as from a more complete instrumental covering of the national territory. The Working Group wishes, hence, the strengthening of the existing synergies among the different bodies involved, both public (Public Research Institutes, Universities, Institutions) and private, and the promotion of new partnerships. This is aimed at ensuring the full sharing of the data and of the analysis and modeling methodologies, also through the specific use of available infrastructures.

Moreover, the Guidelines identify the way to ensure the highest transparency and objectiveness of monitoring, the publication of the acquired data and the information disclosure. They also sketch criteria and procedures to be adopted to identify the subjects that, based on their competences, will manage the monitoring networks, analyze the collected data and make them available to Operator and to competent authorities.

The purpose is to detect variations in the monitored parameters, highlighting their possible correlation with the human activity carried out in the subsurface and undertaking mitigation actions, needed to bring the measured parameters to expected background values, and also to launch proper actions for the safety of plant, people and involved environment.

For what concerns actions to undertake on the basis of variations of monitored parameters, a general scheme was defined that operates for consecutive activation levels. Furthermore, also based on the experience and regulation of foreign countries, we suggest to introduce, on an experimental basis and only for reinjection activities, a decision model, called “traffic light system”, based on exceeding pre-defined threshold values. To do this, criteria were defined to establish, for each case, thresholds of different activation levels for some monitored parameters. The way to control the parameters themselves and the human activities was also defined, as well as the actions to be carried out in case of passing from one activation level to another, or if exceeding the threshold values in case of traffic light system.

A crucial point concerns the procedures of analysis and, consequently, the actions to be adopted based on the monitoring. After an in-depth analysis, the Working Group concluded that sound and common methodologies about statistics or physical analyses, able to allow a correlation between observed

seismicity and human activities within a maximum time lapse of two days, that are needed to make a decision by means of directly applicable procedures, are nowadays missing in Italy. Waiting for a knowledge improvement in this field, a traffic light approach was chosen, based on parameters measured only within a defined underground volume surrounding the reinjection well, and on specific surface measurements of ground motion.

To better guarantee the independence of the subject responsible for the monitoring with respect to the Owner of the production or storage license, it is suggested to consider, if needed also by appropriate normative instruments, the establishment at the MiSE of a proper fund, which could be fostered by the Operators and by which MiSE would be able to rule the monitoring commitment by public procedures. Nevertheless, during the transient phase preceding the wished establishment of such a management procedure, and in order not to postpone *sine die* the fulfillment of the licenses monitoring for the sake of the general public interest, in Paragraph 9.2 a possible way is indicated to guarantee the maximum separation between the Operator and the subject that carries out the monitoring.

MiSE will ensure to check and verify that the monitoring carried out will respect the indications contained in the present document.

3. TIPOLOGIES OF ACTIVITIES AND MODALITY OF APPLICATION

The Guidelines, although applicable to all subsurface activities, were mainly developed for monitoring seismic, ground deformation and pore pressure variations related to hydrocarbons production, wastewaters reinjection and underground natural gas storage activities.

A first experimental application is recommended on pilot cases among already ongoing activities, supported by a feasibility study that includes realization and management costs, the latter at operating speed, for all the exploitation fields with reinjection, as well as for storage fields (see Chapter 1). It is recommended to pass, then, to the application to other ongoing and new activities, based on the acquired experience.

During application of these Guidelines, it is recommended that new monitoring infrastructures are designed also taking into account the principle to “enhance what already exists” and, then, to foresee the possible adjustments of already operating infrastructures, after a proper evaluation, to obtain the required performances.

4. GEOLOGICAL, STRUCTURAL AND SEISMOTECTONIC CHARACTERIZATION

A detailed geological and seismotectonic framework of the area of activities is required. This will also be useful for planning the monitoring network. Applicant Companies and -if foreseen- Operators prepare and make available the following data and information:

- at least 3 geological cross-sections: 2 perpendicular (along dip) and 1 parallel (along strike) to the geological structure forming the reservoir, with a length not shorter than 15 times the depth of wells. Sections must cover a depth at least 3 times greater than the one of the deeper wells. A geological map at the same scale of the sections, containing the sections themselves, must also cover the area. Both the map and sections should be provided preferentially at the scale 1:5,000 or at a scale not greater than 1:25,000;
- multi-channel seismic reflection profiles of the area defined by the criteria of the previous point and, if possible, 3D seismic acquisition of the extended survey domain;
- structural-stratigraphic 3D model, with a depth equal to at least 3 times the one of the deeper production or injection well, drilled or planned, and the sides equal to at least 2 times the size of the mineralized area (reservoir). Moreover, the subsurface reconstruction must include the potential seismogenic structures within the range of 15-20 km;
- direct or indirect evaluation, also through core analysis, of the primary and secondary porosity in the stratigraphy of the well, and in the hemispheric volume at the well bottom, with a radius of 2 times the depth of the same well (e.g., by well logs, geoelectrical or magneto-telluric measurements and lateral projection of stratigraphy);
- evaluation of the present compaction degree in the stratigraphy and the expected subsidence, as a function of fluids withdrawal/reinjection from primary porosity;
- based on the petrophysical characteristics, simulation of fluids migration in the reservoir and in the surrounding inner survey domain (as defined in Chapter 5);
- recognition of possible active faults adjacent (within 3 km) or near (within 15 km) the reservoir;
- kinematic tectonic framework of the area as supported by regional geology, space geodesy and seismological data, as explained in the following chapters;
- computation of the predicted lithostatic load variations, based on forecasted withdrawal or reinjection of fluids, i.e., positive or negative changes associated to mining activities;
- estimation of the volume around the well through which wastewaters could migrate, and planning of the related monitoring. To this aim, geochemical monitoring with tracers (e.g. oxygen isotopes) can be used to verify permeability and fluids migration velocity among wells;
- development of a geomechanical model that includes all the aforementioned information, which will be periodically updated with the data progressively available from monitoring and production.

Furthermore, it is suggested to care:

- the installation, in shallow pilot piezometric wells, of piezometers and tools continuously monitoring aquifer variations (depth, temperature, chemical composition) to highlight possible changes unrelated to the natural hydrogeological cycle. It is also recommended that at least one of the piezometers will be coupled with an assestimeter in order to measure the consolidation of surface layers through the sticking of a metal plank out of the ground; the plank is fixed at the bottom well, at a depth that reaches the deeper level of the aquifers;
- the acquisition of repeated geoelectrical or magneto-telluric surveys in the “inner domain” (see Chapter 5), in order to evaluate resistivity anomalies and their possible changes in time.

5. SEISMIC MONITORING FEATURES

5.1 Definition of volumes involved in seismic monitoring

Inner survey domain (DI) - It defines the volume within which induced seismicity and ground deformation could be potentially caused by anthropic activities. It represents the reference volume within which seismicity and ground deformation will be monitored, analyzed and, when possible, identified with maximum sensitivity.

- a) For activities of **oil/gas production from the oilfield** without reinjection, DI is the volume that includes the mineralized zone (oilfield), as defined by geological study, extending up to the surface. It stretches to a 3 km wide neighborhood around the oilfield and the mineralized zone at depth. If fluid reinjection occurs within the oilfield, the neighborhood should extend to 5 km from the re-injection well.
- b) For **storage** activities, ID is the volume that includes the mineralized area (reservoir used for storage), as defined by geological study, and extends to a 2-3 km wide neighborhood around the reservoir, depending on the reservoir size.
- c) In case of **fluids reinjection outside an oilfield**, ID is the volume, extending up to the surface, defined by the envelope built by drawing spheres centered at the reinjection wells' bottom, with radius equal to the depth of the well and in any case not smaller than 8 km.

Extended survey domain (DE) - It is a wider volume surrounding the DI, which is used to better constrain monitoring and to help the interpretation of the measured quantities (i.e.: seismicity, deformation, and pore pressure) within the existing structural and geological background. For all the activities, it is suggested that it stretches beyond the DI to a neighborhood of 5-10 km, taking into account both oilfield dimensions and type of activities.

The above definitions come from the evidence that, according to the current literature, the majority of induced seismicity can be generated mostly within the volume surrounding the oilfield and reinjection wells. For fluids reinjection outside the oilfield, the reference is the depth of the layers reached by the well where wastewater is re-injected. For production and storage, the reference is the outer boundary of the oilfield/reservoir, being production and storage wells always included within the oilfield.

A **possible extension** of the survey domains can be decided for each single license either at the design of the monitoring network on the basis of specific observations, or during the monitoring period on the basis of the monitoring data. In the case of **activation of new reinjection wells**, either inside or outside the oilfield, the survey domains volumes must be redefined in accordance with above specified rules.

5.2 Purpose of seismic monitoring

The aim of seismic monitoring is:

1. to detect, localize and determine the main parameters of the earthquakes occurring within survey domains;
2. to improve the magnitude completeness of seismicity at the local scale of the survey domains;
3. to measure with high accuracy the ground accelerations produced at the surface by earthquakes.

Moreover, the collected data should help to build a database of seismic events that can be used to monitor the seismicity evolution within the survey domains in the space-time-magnitude domain, as well as to assess the hazard due to induced seismicity, also as function of time.

5.3 Technical features of the seismic monitoring network

The seismic monitoring network must satisfy the following requirements:

1. within the inner survey domain DI, detection and location of earthquakes possibly down to M_L (local magnitude) between 0 and 1 ($0 \leq M_L \leq 1$), with uncertainty of some hundreds of meters in the hypocenter location;
2. within the extended survey domain DE, improvement of the magnitude completeness of about 1 unit with respect to national or regional bulletins released by the seismic monitoring service and carried out for civil protection purposes at national and regional level, and uncertainty in hypocenter location not exceeding 1 km;
3. evaluation of ground motion acceleration and velocity due to (weak or strong) earthquakes at recording sites;
4. integration with existing monitoring networks (i.e., either national or regional networks, as well as further possible local networks), with the aim to improve both accuracy and completeness of seismic monitoring.

The suitability of the realized monitoring infrastructure will be evaluated on the basis of its performance, i.e. of its capability to fulfill the above points from 1 to 4. Nevertheless, the present Guidelines aim also at suggesting some technical features for design purposes. With this respect, a number of recommendations are explicitly stated below.

- a) The inter-distance among the stations should be roughly 3-5 km within the DI, and it should gradually increase in the DE.
- b) Each station must be equipped with 2 tri-axial sensors, i.e. a high-sensitivity seismometer and a high-dynamics accelerometer, respectively. Short period seismometers ($T \leq 1$ s) are allowed, but with natural period not lower than $T = 0.5$ s. It is recommended that at least one of the stations be equipped with a broadband sensor (natural period $T \geq 20-40$ s and maximum survey frequency not lower than 80 Hz).
- c) Signal must be recorded continuously, with data sampling frequency not lower than 200 Hz for seismometers, 100 Hz for accelerometers located at ground surface, and 250 Hz for sensors (either seismometers or accelerometers) located in deep wells. Signal must be sent in “quasi real-time” at the acquisition center of the Structure in charge of Monitoring (hereafter called SPM, see Chapter 9). Here, data will be archived and managed with suitable protocols in order to ensure integrity, completeness and security. The acquisition units must be equipped with a high precision clock system, preferably based on GPS technology.
- d) It is recommended to install a permanent geodetic (GPS) station with high sampling rate (i.e. 10 Hz) near the broadband seismic station. Such GPS station will be part of the ground deformation monitoring system, which will be described in Chapter 6.
- e) Suitable precautions should be adopted when installing seismometers, in order to reduce the environmental seismic noise. In the case of high seismic noise level, it is recommended to deploy seismometers in borehole, at a depth which depends on the lithology and sensor features; in the case of poorly consolidated soils, as those of the plains, a depth of about 100-200 m is recommended.
- f) It is recommended to implement a management strategy to minimize interruptions in data transmission and processing. In particular, data completeness should be achieved for at least 95% of the time for each station; possible stops or malfunctioning of stations should be fixed in short time, i.e. approximately within 7-10 days. In this respect, it is recommended to be equipped with a suitable set of spare parts, i.e., all parts needed to build a complete station (e.g., seismological, electronic, electrical, etc. components) every 4 stations of the network.
- g) It is recommended to set up a number of basic procedures for the correct management of the network, such as procedures to: determine the instrumental response of the stations, including the response of both sensors and digital acquisition units; evaluate the orientation of borehole seismometers; verify the instrumental response periodically; perform all needed updates after any change or substitution of some devices.

Should the required performances not be fulfilled, it is recommended to deploy seismometers into boreholes, even at a greater depth, in order to reduce the distance from the target as much as possible (e.g. in the case of already existing wells, equip them with instruments for passive seismic). In those cases, it is suggested to deploy arrays, each of them consisting of at least 4 seismometers, equipped with short or very short period sensors and with sampling frequency higher than the one indicated at aforementioned letter c).

Generally speaking, the seismic network geometry should be designed in order to improve the resolution capability in terms of both magnitude and localization (e.g., by increasing the stations density) as a function of both the expected induced seismicity hazard and the injected volumes.

As already emphasized in Chapter 3, the design as well as the setting of the technical features of the microseismic network should be carried out having in mind the principle of the “exploitation of the existing”; therefore, in the case of already existing networks or stations, it is recommended to evaluate the opportunity of updating/upgrading the existing instrumentation and sites in order to obtain the requested performances.

Concerning the schedule the following procedures are recommended:

1. seismic monitoring should start at least 1 year before the beginning of production or storage activities, in order to measure and assess the natural background seismicity in unperturbed conditions;
2. seismic monitoring should go on for the whole period of production or storage activity, and it should continue for at least 1 year after the conclusion of the activities.

After two consecutive years of activity, the SPM will evaluate the performances of the monitoring network and the possible weakness points of the analysis and processing system. Should the performance not be fulfilled for technical reasons, suitable actions should be undertaken to improve the system. Possible objective obstacles to the attainment of the required performance should be documented by Operators to MiSE within the SPM reports.

5.4 Data processing and analysis

Data processing and analysis procedures will be implemented for the monitoring goals described in paragraphs 5.2 and 5.3. In addition, suitable practices for safe data archiving and distribution/diffusion have to be adopted, using consolidated procedures and standard formats currently in use by the seismological scientific community.

Concerning location and magnitude calculations, it is recommended to adopt parameter configurations that provide the highest accuracy within the inner survey domain DI, and improve them progressively with time, according to the following scheme:

Configuration 0 - it has to match with the procedures of absolute location and magnitude evaluation, implemented by National Seismic Network or Regional Seismic Networks possibly existing in the area, adopted for national or regional civil protection purposes. Local or moment magnitude has to be assessed, at this level, using procedures that match with those adopted at national or regional scale. More accurate estimations can be implemented through calibration of amplitude attenuation laws and site-specific correction factors.

To be adopted at the start of seismic monitoring operations.

Configuration 1 - one has to implement: a) a 1D *ad hoc* velocity model for the survey domains, which relies on specific studies and is consistent with stratigraphy and data obtained from the monitoring network; b) possible absolute location methods that can be considered more accurate or complete; c) calibration of the whole procedure (e.g., by minimizing station residuals), with the aim of further improving the overall accuracy of the system. At this level, both local and moment magnitude will be determined.

To evaluate moment magnitude, suitable correction for the anelastic attenuation will be applied.

To be adopted by the end of the third year of monitoring.

Configuration 2 – one has to implement: high-precision relative location methods, and/or methods based on waveform coherency (e.g., cross-correlation). At this level, both local and moment magnitude will be re-determined, focal mechanism will be calculated and stress drop will be assessed.

To be adopted by the end of the fourth year of monitoring, in case of existing local event, sufficiently clustered in space.

Configuration 3 – one has to implement: a specific 3D velocity model for the survey domains and the adoption of (absolute or relative) location methods able to exploit such model. At this level, both local and moment magnitude will be re-determined, as well as focal mechanism and static stress release (stress drop) will be calculated.

Optional, but recommended, without time limit.

The monitoring results will be delivered at least as a parametric catalogue of located events, for each of the adopted configurations. The whole seismicity dataset should be processed and delivered for each configuration level.

On the basis of the technical specifications, network density and data analysis methodologies recommended in these Guidelines, the dedicated networks should allow to attain more accurate locations and local/moment magnitude estimations for the seismic events that occur in the survey domains, compared with those estimated by the national/regional networks. For this reason, it is recommended that the decision protocol (see next Chapter 9) be based on the local or moment magnitude assessed by the dedicated network.

Seismicity recognition system should implement the following functionalities:

- a) an automatic recognition system in quasi real-time mode, which will be used by SPM to check the values of the adopted parameters and exceedance of threshold levels (see Chapter 9). Seismic activity possibly occurring outside the ordinary framework should be promptly notified and analyzed with times and modes described in Chapter 9,
- b) an off-line processing system for enhanced recognition and detailed review of data, with schedule defined in Chapter 9. The SPM should continuously update the seismicity data detected in the survey domains for a pre-defined, current time lapse (moving temporal window) of some days; the time lapse length will depend on the kind of activities carried out (see Table 1) as well as on the values adopted for parameters and threshold levels, especially if the latter have been exceeded by some events in the past (see Chapter 9).

Type of activity	ΔT_s
Oil&Gas extraction	30 dd
Fluids re-injection	1-2 dd
Gas storage in depleted reservoirs	10-20 dd

Table 1 – Length of the moving temporal window (ΔT_s) for which the off-line seismological data analysis must be carried out, depending on type of activities.

In general, these Guidelines do not require SPM to set up a H24 seismological service. Instead, it is recommended to set up an on-call seismological service.

The monitoring results should be documented and analyzed in periodical reports, roughly each 3-12 months (suggested: 6 months). Such reports should describe, for the reported period: the network state of operation, with the indication of its possible anomalies, including diagrams of the daily on/off station status and background signal/noise ratio; the recorded seismicity, including a complete and

updated parametric catalogue; a global analysis of the network performance, which should account for the detected seismicity (e. g., assessment of the magnitude completeness); possible space-time change of seismicity within the survey domains as well as the exceedance of threshold levels. In such cases, specific reports will be delivered according to the schedule indicated in Chapter 9.

6. GROUND DEFORMATION MONITORING FEATURES

6.1 General information

The activities for hydrocarbon extraction/storage and fluid re-injection in the subsurface can induce significant surface deformation phenomena. Such ground deformation effects give important information on the subsurface causative phenomena from which they are generated and on their evolution with time. They typically have a rather slow dynamics and they are spatially extended. Therefore the use of enhanced InSAR technologies seems to be appropriate for their measurements. Advanced InSAR technologies are based on the processing of large sequences of temporally separated SAR images (Sansosti et al., 2010). The results of InSAR processing (hereinafter: InSAR measurements) are represented by the temporal series of ground deformation, whose values are referred to a reference area (generally represented by a pixel of InSAR images, often defined as the “coupling” or “reference” pixel), which is typically selected in a non-deforming area. The achieved deformation time series is relevant to the component projected along the radar Line Of Sight (LOS) of detected surface deformation during the considered time interval.

These measurements need to be properly integrated with those provided by a continuous GPS station network, which allow to obtain information on the three components of the motion detected at the receiver station.

Such a monitoring system aims at providing information both on the temporal trend of ground deformations (more precisely of the upper ground layer) during the observed period, and on their spatial distribution over the analyzed area, highlighting possible variations with respect to the background deformation scenario.

As concerning the ground deformation monitoring system, it is recommended what reported in Chapter 3, i.e., the system has to be realized or updated considering the characteristics described in the following, but according to the general principle of improving the already existing instrumentation network (and related database).

6.2 Technical features of the ground deformation monitoring

It is recommended that the monitoring involves the upper layer of the (inner and extended) survey domains and that it has the following features:

- for the considered survey area, a description of surface deformations detected by using InSAR measurements carried out on archive data should be provided. The latter should be possibly collected during the last 15-20 years (or at least during the last 10 years), with accuracies of 5-10 mm (for what attains the single InSAR measurement in LOS) and of about 1-2 mm/year for the mean deformation velocity values. Such activities can possibly benefit from the databases of interferometric measurements already available, such as those obtained thanks to Special Plan of Environmental Remote Sensing or to regional financial support. In any case, the accuracies of the available interferometric measurements has to be consistent with the above specifications;
- the monitoring of the ground deformation phenomena has to be updated every 3 to 12 months through new InSAR measurements (suggested: every 6 months, but this has to be evaluated depending on the availability of SAR data, as well as on the geological, structural and seismotectonic characterization of the considered site) and for at least 3 year after the end of production, storage or underground reinjection activities. The above-mentioned frequency needs to be properly increased in case of observed changes with respect to the background deformation framework, in agreement with what stated in Chapter 9. The InSAR measurements update can be carried out by using recent data acquired by the currently available SAR sensors, such as RADARSAT-2, COSMO-SkyMed and TerraSAR-X, characterized by an *on demand* acquisition policy. In this case, in addition to InSAR measurements, raw SAR data (the so called Level 0) or SAR images (generated at full spatial

resolution and often defined SLC -Single Look Complex- Images) used for InSAR measurements must be also available. Starting from 2015 it is recommended the use of SAR data collected by the European SAR systems Sentinel-1, which allows to acquire in a short time interval and with a “*free and open-access*” scenario a wide SAR data archive relevant to the whole Italian territory;

- the updated InSAR measurements have to foresee the use of SAR data acquired from both ascending and descending orbits, in order to reconstruct the vertical and horizontal (E-W) components of the detected ground deformations. If only SAR data collected from one acquisition orbit are available, the deformation component projected into the radar LOS has to be considered. The InSAR measurements must be delivered with standard formats and through well established methodologies within the scientific community, for which the estimated accuracies (depending on the temporal span of the analyzed SAR image sequences and on their characteristics) have to be indicated; furthermore, the InSAR measurements have to be generated with a spatial sampling ranging between 30 and 100 m, obtained by proper spatial average operations;
- the ground deformation values inferred by InSAR measurements have to be integrated/complemented with the ones provided by a continuous GPS network, already existing or newly implemented, whose features have to be adjusted or defined after the ground deformation monitoring network project supervised by SPM (see Chapter 9). The information obtained by the local GPS network, properly set in the international reference system (currently ITRF2008), has to allow to:
 - make the InSAR measurements independent from the “reference zone” selected for their analysis and representation,
 - detect (and correct) possible artifacts that can be present in InSAR measurements,
 - perform 3D modeling of the detected deformation field.

It is therefore recommended that the local GPS network foresees the placement of precision permanent stations (geodetic type), properly located depending on the size and on the characteristics of the area to be monitored. The stations have to be installed with a siting suitable for geophysical aims (e.g. UNAVCO). In particular, it is requested that the inter-station distance will be less than 10-15 km with respect to the station co-located with the broad-band seismic station of the monitoring network (Chapter 5); furthermore, it is suggested to evaluate the possibility to install bi-axial inclinometers at the stations, to discriminate possible localized phenomena from the ground deformation under study. Finally, it is important to verify the availability of data acquired from at least 5 continuous GPS stations, operating since at least 2 years and located at less than 200-300 km far from the inner survey domain.

- the data collected from the GPS stations have to be made available as RINEX format, besides a format compatible with the results of softwares widely used by the scientific community (e.g. BERNESE software). For each GPS station, deformation time series have to be provided, relevant to the three daily N-S (latitude), E-W (longitude) and vertical displacement components, and their corresponding velocity values;
- the SPM (see Chapter 9) has to consider the opportunity to integrate information on ground deformation, achieved through InSAR and GPS measurements, with measurements of precision spirit levelling. In this case, the levelling network, based on a number of properly spaced benchmarks (typically located on building, bridges, etc.), has to be linked to already existing networks (if possible the IGM one) and its exploitation assumes a good knowledge of the spatial extension of the surface deformation field. The levelling measurements must be carried out every 2-3 years at maximum;
- the overall results of the ground deformation surveys have to be analyzed and published every 3 to 12 months (suggested: 6 months) in periodic reports. For the considered period, such reports have to:

- describe the operational progress of the monitoring system,
- provide information on both temporal evolution and spatial distribution of ground deformations,
- highlight possible variations, compared with the background deformation scenario; in this case, the above-mentioned reports must be delivered with the specifications indicated in Chapter 9.

7. PORE PRESSURE MONITORING FEATURES

The static pore pressure value in the survey domain is useful to update and verify reservoir models for storages and reinjections.

The choice of the wells to be monitored will be based on the geological setting of the area and on reservoir engineering criteria.

For new storage and reinjection wells (exception made for the production wells), the pore (or reservoir) pressure will be measured in continuous at bottom well level through dedicated tools fixed at the bottom ("*surface read-out*"), installed at the completion of the same well, and that will provide a real time measurement.

For some of the existing wells, memory gauges, temporarily placed at the bottom well, will be used for remote recording of pressure at pre-defined intervals. Moreover, campaigns for measuring static pressure of the field will be periodically carried out.

A further way to acquire pressure values is to use non productive wells, also located outside the reservoir in its proximity,.

The pressure values in the volume surrounding the wells, although rather difficult to be measured and somehow doubtful, can be evaluated carrying out correlations with other monitoring wells, also benefitting from the use of some models.

Reports on measured or estimated pressure rates has to be produced every 6 months at least.

More details on such aspects will be defined after the experimental phase.

8. PUBLICATION OF MONITORING DATA AND INFORMATION DISCLOSURE

In order to guarantee the effectiveness and the transparency of the developed activities, the realization of a dedicated area on the website of the Ministry of Economic Development - DGRME is foreseen, with specific sections for each license, aimed at disseminating information on ongoing activities and data acquired during the monitoring phase.

The template for such sections will be the same for all the monitored reservoirs. Operator will provide the reservoir data, while the monitoring data will be provided directly by the SPM (see Chapter 9). The same subjects, then, can prepare educational products, also printed, and to organize public meetings to show industrial activities as well as control activities on induced seismicity and deformation through monitoring surveys.

In the website section relevant to each license, the following information should be provided.

8.1 Information on license

1. history
2. characteristics of the reservoir/storage field
3. brief description of the geomechanical model
4. monthly production data from the beginning of the activities
5. FAQ

8.2 Introduction to the monitoring activities (seismicity, ground deformation, pore pressures)

1. **seismic monitoring:** introduction to seismicity; measurement techniques; setting of natural seismicity at regional scale; focus on near site seismicity
2. **ground deformation monitoring:** introduction to ground deformation, measurement techniques; setting of regional natural deformations; focus on near site deformations
3. **pore pressure monitoring:** introduction to pore pressures; measurement techniques and evaluation through modeling analysis

8.3 General data on monitoring

1. subject who planned the networks, who made them and looks after their maintenance, who collects and analyzes data
2. features of the networks (general map of the stations, number and features of detectors)
3. inner and extended survey domains (identification criterion, map)

8.4 Seismic monitoring data

1. General information:
 - a) introduction to seismicity
 - b) measurement techniques
 - c) setting of the regional natural seismicity and focus on seismicity in the proximity of the extended domain DE
2. General data on the developed monitoring:
 - a) subject who planned the networks, who realized them and who looks after their maintenance, who collects and analyzes data
 - b) features of the networks (general map of the stations, number and features of detectors)
3. Seismic monitoring data:

- a) location of recorded events on the map of the stations belonging to the national and local network, both in the license and its proximity; in the same map, the location of the installations (wells, treatment station, etc.) has to be included
- b) waveforms data in continuous and with standard seismological formats (e.g., miniSeed and/or SAC), including the needed information for making instrumental correction (e.g., dataless files)
- c) updated information on stations (operational or temporarily not operational)
- d) complete list of seismic events localized from the starting of the operational phase of the network, with updates based on timing reported in Table 1

8.5 Monitoring data of ground deformation

- 1. General information:
 - a) introduction to ground deformation
 - b) measurement techniques
 - c) setting of regional natural deformations and focus on deformations near the site
- 2. General data on developed monitoring:
 - a) subject who planned the networks, who realized them and who looks after their maintenance, who collects and analyzes data
 - b) features of the networks (general map of the stations, number and features of detectors)
- 3. Monitoring data on ground deformation:
 - a) InSAR: publication of the measurements according to the surveys frequency
 - b) in continuous GPS survey: publication (at least weekly) of the processed data
 - c) geodetic spirit levelling (if available)
 - d) publication of previously available data

8.6 Monitoring data of pore pressure

- 1. General information:
 - a) introduction to reservoir pressures
 - b) measurement and evaluation techniques through modeling
- 2. General data on developed monitoring:
 - a) subject who planned the networks, who built them and looks after their maintenance, who collects and analyses data
 - b) features of the networks (location of monitored wells, number and features of detectors)
- 3. Monitoring data of reservoir pressures:
 - a) bottom well measurements
 - b) pore pressures in the proximity of the reservoir, estimated through a modeling approach, starting from well measurements

8.7 Documents

- 1. reports on the management of the license (yearly)
- 2. periodic reports on monitoring results, possible related scientific papers
- 3. document for the operational management of monitoring (DGOM; see Chapter 9)

8.8 Training and access to the site

- 1. workshops
- 2. news and events

3. set-up of tours at the plants (including modules of request)
4. movies and photos of the plant

8.9 Useful Links

1. Links to the reference institutional sites
2. email addresses for possible contacts (info@...)

9. INDICATIONS ON THE MANAGEMENT, CONTROL AND INTERVENTION STRUCTURE

1 Design, realization and maintenance of the monitoring networks

At present, the Italian national framework does not encompass a structure with specific competences, suitable for the control of the monitoring activities, aimed at identifying possible effects of human-induced seismicity. In this transient phase, a highly skilled, technical/scientific subject has been defined to support MiSE (in particular the UNMIG technical offices - National Mining Office for Hydrocarbons and Geo-resources) and, more in general, the competent Authority, in the management, analysis and use of monitoring data. Therefore, waiting for the institution of a fund that would allow MiSE to directly commit the monitoring (see Chapter 2), we suggest to follow the present indications to identify such a structure, here defined as Structure in charge for Monitoring (SPM, Struttura Preposta al Monitoraggio), which is a technical body of MiSE. The SPM is composed of one or more Universities or Research Institutions with proved skills in the considered fields, if needed joined in a consortium, also with private Companies.

For each license, one SPM will be identified. It will play with exclusive rights the role of technical body supervising the projects, collection, process and transmission of the data to the MiSE and to the Operator. The procedures to appoint the SPM will be established by MiSE.

For what concerns the realization and the management of monitoring - “monitoring” stands for the collection of the three considered monitoring activities, i.e., seismic, ground deformation and pore pressure monitoring -, the Operator and SPM tasks are organized as explained in the following.

In agreement with the appointed SPM, the Operator is in charge of arranging the monitoring project and it is responsible for the networks fulfillment (that is, the purchase, the installation or the adjustment of the instrumentation, if needed), as well as for their maintenance and management.

The SPM examines and evaluates the monitoring project in order to support MiSE approval, and carries out the data processing, analysis and interpretation. The SPM can also be charged by the Operator with the networks installation and maintenance, being the responsibility and the cost coverage in charge of the Operator. To allow the complete efficiency of the SPM, this must receive directly the continuous data flow.

Neighboring licenses can be equipped with a shared monitoring system and, with this aim, dedicated agreements can be drawn up.

While the monitoring infrastructure is under completion (networks, data collection center, etc.), the SPM, the Operator, the UNMIG, the Region and, if required, the MATTM meet together to define the operational procedures for the monitoring management and the interaction among the different subjects involved, including the procedure according to which the Operator provides daily the production/injection/storage data to the SPM. They write a Document for the Operational Management of Monitoring (DGOM, Documento di Gestione Operativa del Monitoraggio). The DGOM has to be published according to what defined in Chapter 8, anyway safeguarding the industrial privacy of the production data. Within this document, the decisions agreed among the parts will be indicated and the more relevant issues for the development of monitoring will be illustrated. Moreover, in connection with competent Authorities, procedures will be described about the communication and information to the public on possible variations of activation levels and the related actions to be undertaken (see Paragraph 9.2). In particular, the following information will be made clear:

- the boundaries of the survey domains;
- the parameter values for the reference framework and for the traffic light thresholds to be adopted within the specific decisional model for each license (See Paragraphs 9.2 and 9.4);
- the procedure according to which the gradual reduction or the stop of production/reinjection/storage activities will be made up in case the Activation Levels 2 and 3, corresponding to orange and red colors, respectively, are reached;
- the procedure according to which the activity is restored, in case the monitored parameters will move back down to the values corresponding to the Activation Levels 1 and 0;
- any further element useful for interpreting the monitored data.

In the transient phase already mentioned in Chapter 2, it is suggested to establish a Worktable coordinated by MiSE, where the subjects playing the role of SPM, together with delegates of MATTM and of Operators, at least every six months will:

- discuss about how to fulfill the present Guidelines;
- analyze the methodologies applied in different cases and the quality of the obtained results;
- find operational procedures shared as much as possible;
- provide suggestions to solve possible criticalities that could ever appear during the activities and the implementation of the present Guidelines.

9.2 Activation system of the actions to be undertaken

For what concerns the Guidelines for the monitoring management, we suggest to experimentally adopt a decision system defined through four activation levels, established on the evaluation of the geodynamic model of the area and on the overall frame of a series of parameters monitored within the survey domains, like:

1. variation of number and frequency of seismic events, their related magnitudes and spatial distribution,
2. peak ground acceleration and velocity values,
3. change of ground deformation rates,
4. variation of pore pressures.

The four activation levels are defined in the Table 2.

Activation Level	Corresponding Status
0	Ordinary conditions
1	Attention
2	Reduction of activities
3	Stop of activities

Table 2 – Activation Levels, established through the evaluation of the overall frame of the monitored parameters.

The *traffic light* decisional system considers some procedures aimed at undertaking actions related to different activation levels, defined on the basis of threshold values of the monitored parameters. Taking into account the current scientific knowledge, the Working Group does not consider appropriate to adopt a decisional model which encompasses *traffic light* automatisms, linked to precise threshold values, for all the activities treated in the present Guidelines. Given the variability of geological frameworks, of the depths and of the ways hydrocarbon exploitation and production activities are carried out, as well as of the background natural seismicity and of its depth, it is not

possible to univocally establish threshold values for all the above mentioned parameters, but only for some of them. In particular, the variations of the deformations and of their velocity rates have been evaluated for case by case, depending on their spatial distribution and with reference to the background deformation.

Hence, the suggested decisional model considers that the switch from one to another level occurs on the basis of evaluations carried out by SPM, UNMIG, Region and Operator, in joint agreement, in the framework of their specific competences. These evaluations are carried out contextually with the occurrence of a frame of parameters values that are out of the ordinary conditions, and with the identification of a possible correlation between the variations of the monitored parameters and the ongoing production/storage activities.

It is proposed, instead, the experimental adoption of a *traffic light* decisional system, with automatisms linked to precise threshold values, exclusively for underground fluids reinjection activities. This part is discussed in detail in Paragraph 9.4.

The reference (or threshold, for foreseen cases) values of parameters adopted in the DGOM will be defined by SPM for each single license, depending on the seismotectonic setting of the area of activity. These values can be further refined, if needed, and specified in the DGOM in the light of the data progressively acquired during the activities. We highlight the importance, during the first years of application of these Guidelines, to promote studies and research, as well as occasions of scientific debate, with the purpose to attain, hopefully, the identification of markers that allow to distinguish natural seismicity from that induced by human activities.

9.3 Activities management phases

For what concerns the actions to be undertaken on the basis of the monitoring results, three different management phases are identified, which have to be faced as described in the following.

Phase 1 - Ordinary management of monitoring

This phase deals with the case in which the parameters monitored in the inner survey domain DI are similar to the background values, or below the reference values adopted in the DGOM, or below the threshold values in case of traffic light system (an example of reference values is reported in Paragraph 9.4). Such parameters refer to the variation of the number of events and/or of the seismicity magnitude, as well as to the peak ground acceleration and velocity, to the ground deformation and pore pressures rates. These conditions correspond to the Activation Level 0 (ordinary conditions, green color).

The SPM provides the Operator, the UNMIG and the Region with the acquired data and the processing results carried out in ordinary conditions, in accordance with the time intervals described in Chapters 5, 6 and 7; moreover, it publishes the data on internet as described in Chapter 8. Furthermore, the SPM releases to the UNMIG and the Region a periodic report on the activities carried out (see Chapters 5, 6, 7 and 8).

Phase 2 - Ordinary management of variations in the monitored parameters

In the case variations of the monitored parameters are observed, exceeding the range of background variations, and/or in case Level 0 threshold values of traffic light are exceeding, in accordance with what defined in the DGOM for each license, the Activation Level 1 (attention, yellow color) is reached.

In this case, the actions to be undertaken are the following:

1. the SPM immediately informs the Operator, the UNMIG and the Region;
2. the SPM daily analyses monitoring signals and gives advise to the Operator and the above mentioned authorities;
3. the Operator provides production/injection/storage data, possibly hourly, or daily in any case, as foreseen in the DGOM, along with any new possibly available information, to allow the SPM to study the observed variations in comparison with the ongoing production, reinjection or storage activities, as well as to verify the occurrence of possible correlations, if data allow to do it. It is desirable that the used processing methodologies allow, among the others, to highlight variations with respect to the typical background seismicity rates, like time interval variations among the events, b-value variations in the magnitude distribution, spatial and/or temporal *clustering*, non-poissonian behaviors. In the meanwhile, the production, reinjection and/or storage go on, unless UNMIG and Operator decide differently;
4. If conditions exist to carry out in short time correlation analyses among variations of monitored parameters and exploitation/storage activities, and the corresponding outcome is negative, meaning that no correlations are observed, it is possible to come back to the Activation Level 0 (ordinary conditions, green color). If the result is positive, however, then the UNMIG, the Region and the Operator, each of them for its own authority and on the basis of the SPM analyses, decide whether progressively reduce (Activation Level 2, orange color) or definitely stop (Activation Level 3, red color) the ongoing production/reinjection/storage activities.

If conditions do not exist to carry out in short time correlation analyses between variations of the monitored parameters and ongoing exploitation/storage activities, the UNMIG, the Region and the Operator, on the basis of the SPM analyses, jointly evaluate the framework obtained from the monitored data and establish, each of them for its own responsibility, if staying in an attention status (Activation Level 1, yellow color) or, in case, progressively reduce the ongoing production/reinjection/storage activities (Activation Level 2, orange color). If the decision is taken to pass to the Activation Level 2 (orange color), then the Operator gives prompt formal communication on undertaken actions to the competent UNMIG section (that in turn informs MiSE-DGRME), to the Region and, in the pertinent cases, to the MATTM - Directorate General for environmental evaluations and to the Province. The MiSE-DGRME informs the National Department of Civil Protection.

If the actions undertaken in the Activation Level 2 are considered not sufficient, the UNMIG, the Region and the Operator, on the basis of the SPM analyses, each one for its own responsibility, evaluate the opportunity to pass to the highest Activation Level (Level 3, red color), thus stopping the ongoing production/reinjection/storage activities. The Operator gives prompt formal communication on undertaken actions to the competent UNMIG section (that in turn informs the MiSE-DGRME), to the Region and, in the pertinent cases, to MATTM - Directorate General for environmental evaluations and to the Province. The MiSE-DGRME informs the National Department of Civil Protection.

In all cases, the SPM continues to analyze daily the monitoring signals and to provide advice to the Operator and the above-mentioned bodies.

Within ten days from the reduction or the stop of the activities, the SPM verifies if a variation of parameters occurred, allowing to come back to a lower level or, more in general, to the restoration of background conditions, or if a trend inversion in the observed variations occurred. In case one of the first two outcomes occurs, the Operator informs the above mentioned bodies that the frame of parameters is compatible with a lower attention level and complies with them if re-start or progressively increase the activities, verifying daily the trend of the monitored parameters values with

respect to the considered level. In case the frame of parameters shows an inversion in the variation rates that is not sufficient to come back to lower levels, one still remains in the Activation Level that has been reached for a further period of observation, jointly established by SPM, UNMIG and Region, once the Operator has been listened. In all cases, the MiSE informs the National Department of Civil Protection.

If such conditions are not verified, and so the anomaly in the measured parameters continues over the above defined period, one has to pass to Phase 3.

Phase 3 - Extraordinary Management of variations in the monitored parameters

It concerns the case in which neither the procedures implemented in the above mentioned Phase 2 determine a parameters variation corresponding to a lower level return, nor they cause, more in general, the reactivation of the background conditions or a trend inversion in the observed variations within the above indicated time intervals.

Such a case corresponds to what envisaged by the article 5 of Law 225/1992 and following modifications (imminence of natural hazards or disasters related to human activities that, due to their intensity and extension, must be, with immediate actions, faced with extraordinary means and powers to be used within limited and pre-defined time periods).

The Operator, therefore, in collaboration with SPM, promptly warns UNMIG and the Region. The MiSE, after having received prompt communication by UNMIG, informs the National Department of Civil Protection, which activates its own scientific and operational bodies to undertake the appropriate actions, in agreement with Law 225/1992.

Table 3 summarizes, in a synthetic although not exhaustive way, the actions to be undertaken in accordance with the different Activation Levels.

Activation Level	Actions For the complete frame of the actions to be undertaken, see Paragraph 9.3
0	The SPM provides Operator, UNMIG and Region with the acquired data and the processing results.
1	<p>a) The SPM carries out an analysis of the variations of monitored parameters verifying, where possible, if there is a correlation with the production/reinjection/storage data.</p> <p>b) The SPM immediately informs Operator, UNMIG and the Region.</p> <p>c) The Operator provides further data on production, reinjection or storage, if existing.</p> <p>d) In case a correlation is excluded between the variations of monitored parameters and the data of production/reinjection/storage, it is possible to come back to Level 0. If a correlation is found, on the basis of the SPM analyses, UNMIG, Region and Operator carry out an overall evaluation of the available information and establish whether to progressively reduce (Activation Level 2) or stop (Level 3) the ongoing activities.</p> <p>In case it is not possible to conduct an analysis on the possible correlation, UNMIG, Region and Operator, considering their own responsibility and on the basis of the SPM analyses, establish whether to remain at Level 1 or pass to Level 2.</p>
2	<p>Previous letters a-c) remain. Moreover:</p> <p>d) The Operator progressively reduces the activity.</p> <p>e) UNMIG, Region and Operator, on the basis of the SPM analyses, establish whether to stop (Level 3) or not the ongoing activities.</p>

	f) Within 10 days from the activity reduction, the SPM verifies if there are the conditions to come back to the ordinary Level 0, or to Level 1.
3	Previous letters a-c) remain. Moreover: d) The Operator stops the activity. e) Within 10 days from the activity stop, the SPM verifies if there are the conditions to come back to the ordinary Level 0, or to the Levels 1 or 2.

9.4 Experimental *traffic light* system

As a first application, it is suggested to test the adoption of a traffic light system in the survey domain for the reinjection wells.

For activities of underground fluids reinjection, the traffic light system will be applied to the parameters monitored within the Inner survey Domain (DI), related to reinjection wells, as defined in Chapter 5.

The monitored parameters are those already listed in Paragraph 9.1. As said, the variability of the geological settings, of the depths and ways the activities are carried out, of the natural background seismicity and its depth, does not allow to univocally set the threshold values for all the parameters, but only for some of them. In particular, the variations of ground deformations and of their velocity rates have to be evaluated case by case, depending on their spatial distribution and taking into account the background deformation frame.

Thresholds are set for the following parameters: magnitude (Max), peak ground acceleration (PGA) and peak ground velocity (PGV). For the activation of the traffic light system, only the values reached by the parameters within the Inner survey Domain (DI) have to be considered. Table 3 displays ranges or reference values that can be adopted for the definition of the related thresholds. We highlight that what reported in the table is just an indication, and that the threshold values have to be defined and made clear in the DGOM, case by case and for each license, also taking into account the seismotectonic setting of the area and, in any case, after the monitoring period carried out in not disturbed conditions (see Paragraph 5.3), in which background seismicity is detected.

It is suggested to consider a time period for the calibration of the different threshold values, taking into account the data progressively acquired, in order to avoid the activation of not adequate action levels. The threshold values for the adopted parameters could be re-calibrated, and specified in the DGOM, in the light of the data collected during the activities.

For what concerns the magnitude, Table 4 suggests the intervals including the maximum values (Mmax) that have to be adopted for the definition of each traffic light level. The PGA and PGV values, which describe the seismic shake, are instead univocal and have been chosen in accordance with those adopted by INGV for the shakemaps, within the national seismic monitoring system (*shake maps*; Michelini et al., 2008; <http://shakemap.rm.ingv.it/shake/index.html>). Such values are useful to activate the proper actions with respect to the shake measured at surface, felt and/or potentially able to cause damage to buildings. The final threshold values, both for magnitude and for seismic shake, will be chosen by the UNMIG and the Region, in collaboration with the Operator, each one for its own competence and taking into account the SPM analyses, also considering vulnerability and exposure conditions of the area where activities are ongoing.

Activation Level	Traffic light	M_{max}	PGA (% g)	PGV (cm/s ²)
0	Green	$M_{max} \leq 1.5$	-	-
1	Yellow	$M_{green} \leq M_{max} \leq 2.2$	0.5	0.4
2	Orange	$M_{yellow} \leq M_{max} \leq 3.0$	2.4	1.9
3	Red	$M_{orange} < M_{max}$	6.7	5.8

Table 4 – Ranges or indicative values for the parameters monitored in the inner survey domain (DI), which have to be used as a reference for the thresholds definition. The following parameters are defined: maximum magnitude (M_{max}), peak ground acceleration (PGA) and peak ground velocity (PGV).

In order to pass from one to another level of the traffic light it is sufficient that one of the parameters listed in Table 4 (measured in the inner survey domain DI) exceeds the specified thresholds. Nevertheless, as said before, it is possible to pass from one to another Activation Level also on the basis of an overall evaluation of the variations observed in the survey domains (e.g., number of events and increase of their frequency).

In case it is not possible to establish the correlation mentioned before, as well as in the lack of any correlation, although the values of the monitoring parameters remain above the thresholds, the SPM informs the Operator, the UNMIG and the Region, which evaluate the possibility to stop/continue the activity and to undertake additional measurements to monitor the phenomenon evolution.

We remark again the need to carry out studies and research to identify markers that can contribute to distinguish between the natural seismicity and that one possibly induced from human activities, and to define reliable threshold values with respect to the different activities carried out.

The management phases described in Paragraph 9.3 can clearly integrate the indications coming from the traffic light system, associating the Activation levels to corresponding colors of the traffic light and considering that the thresholds exceeding of such a traffic light system causes the immediate adoption of the actions foreseen for the different levels in the different phases.

In case the third threshold value of the traffic light (red traffic light) is directly overcome, the Operator reduces the ongoing production/reinjection/storage activities and gives prompt formal communication of the actions undertaken to the competent UNMIG section (that in turn informs the MiSE-DGRME), the Region and, in the pertinent cases, to MATTM - Directorate General for environmental evaluations and to the Province. The UNMIG, the Region and the Operator, each of them for its own responsibility and on the basis of SPM analyses, can stop the ongoing production/reinjection/storage activities. The MiSE-DGRME informs the National Department of Civil Protection about the decisions taken and the ongoing actions.

10. CONCLUSIONS AND RECOMMENDATIONS

These “Recommendations and Guidelines” derive from the need to improve the safety standards of activities of extraction/injection of fluids below the Earth’s surface, taking into account that the Italian territory is affected by natural earthquakes. They represent the first national document where technical specifications for the monitoring networks are provided systematically. The document includes indications useful for decision making and for developing procedures needed to transform the results of the monitoring activities into actions. The document includes some issues for which operational experience is quite poor. For this reason the recommendations have to be re-evaluated about 2 years after their first test application at pilot sites on the base of the direct experience and practice.

One of the issues on which an immediate and unanimous agreement was reached by the Working Group was related to the potential impact of production activities implying fluids reinjection. In order to minimize it, it is recommended to:

1. preserve the natural original load, maintaining the balance between produced and reinjected fluids as near as possible to zero;
2. keep the reinjection pressure as near as possible to the original natural one. Evaluate the reinjection pressure by means of injectivity tests.

The Working Group faced some relevant problems, basically due to:

- the peculiarity of Italian territory compared to other countries. In fact, Italy is probably one of the few countries with large part of its territory characterized a medium/high exposure to earthquakes;
- the limited scientific knowledge allowing to separate induced from triggered or natural seismicity in a clear and unambiguous way;
- the lack of well-assessed and accepted methodologies of statistical or physical analyses that allow to quickly correlate the detected seismicity with production/injection activities in a time range useful to take decisions (1 or 2 days at maximum).

One of the issues analyzed more in depth has been the general organizational structure. We considered crucial:

to assign to highly qualified public bodies the task to design the monitoring networks, and to analyze and interpret the collected data;

to prevent the direct link between the Operator and the subject in charge of monitoring, in order to guarantee the independence of scientific evaluations;

and to establish a criterion of verification and control of the monitoring activities in course.

As explained in Chapter 2, we reiterate our suggestion to foresee the establishment of a dedicate fund at the MiSE, fed by Operators. This fund should be used by MiSE to assign directly the monitoring activities through public procedures. Indications given in Chapter 9 have to be considered the best possible solution, in the Working Group’s opinion, considering the current normative framework.

The boundaries of the areas to be monitored and the way in which efficient decisional procedures can be implemented are other important issues dealt with. The experience (mostly related to seismic monitoring) coming from different cases of production activity was reviewed and synthesized in a formal system simple and applicable. At the end, the unifying principle was found in the definition of two volumes, respectively called “inner survey domain” and “extended survey domain”, on the basis on wells location and on hydrocarbons or storage reservoir width. The inner survey domain for seismic monitoring contains all the points (wells) or the source zone (reservoir) of activities and it is limited, but large enough to include induced seismicity. The seismic monitoring network within the

inner survey domain has to be of the highest sensitivity, in order to permit the application of refined techniques of earthquake localization and the reconstruction of changes in velocity models and, in case that data will allow this,, even to track the possible migration of the seismicity.

A criterion for the quantification of the minimum volume (that can however be widened, if needed) of the extended survey domain is also given. This volume accounts also for the possible occurrence of natural seismicity and of the possible occurrence of triggered seismicity in a volume surrounding that one where activities take place. Although with a lower sensitivity and precision, the observation quality in the external volume permits to map seismicity and ground deformation with the needed accuracy.

The last issue addressed concerns the indications on the decisions to be adopted on the basis of the values of the monitored parameters. A four levels of activation approach was chosen, where the levels are used as international standards. The levels were established on the basis of the overall framework of the monitored parameters. Procedures on how to come back to ordinary conditions are also foreseen.

Activation Level 2, the yellow one, represents an attention level that is very important as, when it is reached, it allows SPM to prepare timely a scientific overview coming from the monitoring, to support the possible implementation of actions for reducing or stopping human activities.

Moreover, we suggested the preliminary experimental adoption of a traffic light system, only for activities involving fluids reinjection into the underground. The thresholds between different levels of the traffic lights are defined on the basis of the earthquakes magnitude and ground motion detected within the survey domains.

The possibility was also evaluated that decisions could be taken following analyses aimed at retrieving in a short time a possible correlation between detected seismicity and ongoing activities. Considering the intrinsic problem of its implementation, this possibility has been foreseen, but we consider it as an option that will be more applicable in the future, when knowledge will increase and scientific methodologies will be stronger and well-assessed, and thus able to provide immediate and reliable answers to the Italian situation. The Working Group recommends that a strong research activity will be developed, aimed at quickly giving the instruments needed for their application within the traffic light system. More generally, it is suggested that Ministers or by other competent Institutions promote some specific research items, among which:

- recognition and characterization of induced, triggered and natural seismicity;
- development of quick and reliable methodologies to establish the correlation among the different monitored parameters and the exploitation activities;
- analysis of the meaning of the observed values in comparison with production/reinjection/storage parameters;
- procedures for integrating induced seismicity in *time dependent* seismic hazard evaluations.

Rome, November 24th, 2014

Eng. Gilberto Dialuce

Dr. Claudio Chiarabba

Dr. Daniela Di Bucci

Prof. Carlo Doglioni

Prof. Paolo Gasparini

Eng. Riccardo Lanari

Dr. Enrico Priolo

Prof. Aldo Zollo

GLOSSARY

1. **Competent Authority:** the definition of a Competent Authority has to be introduced by a proper legislative definition. Nowadays, in the lack of references in the national normative framework concerning the field of underground exploitation, as Competent Authorities we intend, each for their own competences: UNMIG for safety and surveillance of mining activities with specific reference to hydrocarbon exploration and production, and to storages; MATTM for issues concerning environmental impact evaluation; Regions for authorizing reinjection and for agreement in licenses release, and even as exclusive authority in the field geothermal activities; Provinces for mines and quarries, and for solid minerals.
2. **Lithostatic load:** lithostatic load (including fluids) corresponds, in extensional tectonic settings, to the direction of the main axis of the maximum stress tensor. The increase of lithostatic load causes the differential stress growth, that can induce the activation or the triggering of active faults. Conversely, the lithostatic load in compressional settings corresponds to the minimum stress tensor and its decrease lets the differential stress grow, facilitating the activation or the triggering of active faults. In transcurrent tectonic settings, the lithostatic load corresponds to the medium stress tensor. Hence such modifications of stress field must be carefully monitored and evaluated in the crustal volume involved in mining activity, aiming at preserving its equilibrium.
3. **Operator:** the owner of a license of mining resources and, in particular, of hydrocarbon and of underground natural gas storage. The Operator is, for the Italian law following the EU regulation on safety (D. Lgs. 624/1996 of transposition of Directives 92/91/CEE and 92/104/CEE), the owner responsible for activities safety, for drafting and carrying out the safety and emergency plan, and for the coordinated document about safety and health set at the surveillance authority, in which frame all the measurements on risk prevention, monitoring and intervention on safety field must be planned.
4. **Ground deformation:** shape, volume and/or position changes of one or more parts of the surface layer that covers the earth crust.
5. **Active fault:** fault showing evidence of displacement between the two rock/soil volumes at its sides occurred in the past 40,000 years, reason why it is assumed, therefore, that motion can occur again.
6. **Seismogenic fault:** fault able to generate earthquakes. In order to estimate the seismic hazard, the adjective seismogenic is assigned to faults located in that part of lithosphere, above the brittle-ductile transition, which is characterized by a prevalent elastic-brittle and/or elastic-frictional behavior of rocks.
7. **Reservoir:** geological structure whose characteristics allowed, during time, the hydrocarbons store and conservation. The presence of particular geological/structural settings in the underground (traps) determined potentially suitable conditions to hydrocarbons storage, avoiding their migration and, hence, leakage. Once depleted, after evaluation of its total volume capacity (stock) and petrophysical characteristics (porosity, permeability, gas/water saturation), the reservoir can be sometimes used as storage site. The reservoir is a rock system, porous and permeable, with a complex structural setting, showing heterogeneous geo-mining properties that affect the considered volumes and fluids motion.
8. **Differential Interferometry SAR (DInSAR or InSAR):** technique for estimating ground deformation with accuracy in the order of fractions of the wavelength of the radar signal transmitted in the microwave band of the electromagnetic spectrum.

9. **Local magnitude:** local (ML) or Richter magnitude was introduced by Richter (1935). The original definition is based on the amplitude measure of a seismogram recorded by a standard seismograph called Wood-Anderson:

$$ML = \log_{10}A - 1.67 + 2.56 \log \Delta \quad (1)$$

where A is the maximum amplitude of the ground motion, adjusted for instrumental response, measured in μm and Δ is the distance in km ($\Delta < 600$ km). The Local magnitude (ML) is nowadays rarely used in its original formulation because Wood-Anderson torsion seismometers are not available anymore and because, obviously, the majority of earthquakes doesn't occur in California. For this reason, coefficients of equation (1) have to be properly re-calibrated by specific preliminary analyses on seismograms acquired in the investigated area. With the occurrence of the digital recording of seismic events, today is common to calculate local magnitude from the conversion of seismograms in simulated recording at a Wood-Anderson seismometer.

10. **Momentum Magnitude (M_w):** the moment-magnitude (M_w) was introduced by Kanamori (1977) and Hanks & Kanamori (1979) to measure the magnitude of an earthquake in terms of energy release. It is based on a source parameter, the scalar seismic moment (M_0) that represents the moment of one of the 2 force couples that generate the dislocation at the origin of the earthquake, and that results equal to the factor between the rocks stiffness (μ) in the source region, the mean final dislocation on fracture surface (D) and the size of the fault area (Σ):

$$M_0 = \mu D \Sigma$$

The scale of the moment-magnitude is therefore defined in terms of magnitude M_w obtained from seismic moment by the relation:

$$M_w = \frac{2}{3} \log M_0 - 6.1$$

Where M_0 is expressed in Nm. This scale of magnitude, even if calibrated on M_S (magnitude of surface waves), has the relevant property that it does not saturate when magnitude increases.

11. **Focal mechanism:** the focal mechanism of an earthquake describes the deformation of the source region from whom seismic waves radiate. In case of a seismic event produced by the fracture along a fault surface, the focal mechanism provides information on the spatial orientation of the fault plane, and on the dislocation vector. It is also known as "the fault plane solution". To describe the orientation of such a plane in a geographic coordinates system, 2 angles are needed: the strike and the dip. The dislocation direction is instead specified by one or two possible quantities that describe the medium direction of the dislocation (rake or plunge).
12. **Memory Gauge:** type of detector/electronic pressure gauge that samples and records the pressure at bottom hole, collecting data and making them suitable for the download on devices for acquisition when the gauge is brought back at the surface. Memory gauges are generally used to measure the pressure and the temperature at bottom well in response to variations in production flows during productivity verification tests at the well, and during reservoir performance tests.

13. **Pore pressure:** it is the water pressure within the pores of a saturated medium, and it is indicated with the letter (P). When fluid is present within rocks, the effective stress σ_n is reduced of an amount equal to the pore pressure, and the shear stress (τ) requested to induce a shear strain is reduced according with the following law:

$$(1) \tau_{\text{crit}} = \mu (\sigma_n - P)$$

This reduction of the effective stress on the crustal fault is the basic mechanism of the induced seismicity. If the tectonic stress is constant, the effective stress on the crustal fault can be reduced below the critical threshold by an increase of fluid pressure within rocks, bringing a sudden motion and thus the occurrence of an earthquake.

14. **Data acquisition/transmission system in quasi-real time:** it is the kind of acquisition and transmission by which the data, once gathered by an acquiring device (seismological station), is immediately sent to the processing and archiving system through data packages of preset size. In the quasi-real time, the system releases the information with a certain frequency not rigorously defined and followed as it occur for real time systems. In quasi-real time systems the delay by which the information is released is generally in the range of fractions of seconds for the acquisition system, and in the range of some tents of seconds up to few minutes for the processing, localizing and possible warning system.
15. **Induced seismicity:** seismicity generated by variations in the stress field ascribable to human activities (McGarr et al., 2002) or to natural phenomena not linked to the tectonic deformation of the earth crust (e.g. rainfall).
16. **Triggered seismicity:** it is a natural activity whose generation was hastened by human activities and in particular by induced seismicity. Human activities are responsible of just a minimum fraction of the stress field variations that generate seismicity. The primary role is played by the pre-existing, tectonic stress field.
17. **Natural seismicity:** seismicity caused by stress field variations due to tectonic deformation of the earth crust.
18. **Synthetic Aperture Radar (SAR):** way of acquisition through coherent radar systems able to allow the generation of microwaves images with high spatial resolutions (meters/tens of meters), thanks to proper processing of acquired data.
19. **Stress -drop:** it is the difference between the initial and final stress along the fault plane, after the occurrence of a fracturing event that generates an earthquake. It is a physical parameter generally variable along the fault plane, but its average value is usually indicated and measured. The stress-drop can be static (*static stress drop*), i.e., the difference between the initial stress and the static friction level after the fracture occurred, or dynamic (*dynamic stress drop*), i.e., the difference between the initial stress and the dynamic friction level during the evolution of the fracture.
20. **UNMIG:** National Mining Office for Hydrocarbons and Geo-resources, of the General Directorate for Mining and Energy Sources (DGRME) - Ministry of Economic Development - Technical office distributed on the territory with tasks of technical-administrative management of hydrocarbon prospection, research, production and storage activities, surveillance and control on plants, accident prevention, safety and health of workers both onshore and offshore.

21. **Surface Readout (SRO):** general term to indicate a surface reading carried out by sending an information in a readable format /read out). In the specific case, it indicates the surface reading out of bottom well data at the surface by means of an electric line.
22. **SPM - Structure in charge for Monitoring:** technical-scientific body (of MiSE), composed by one or more Universities or Research Institutes with proved skills in the considered fields. If needed, they can be joined in a consortium, also with private Companies expert in design and management of monitoring networks, data acquisition and analysis. The Competent Authority charges the SPM with tasks of acquisition and analysis of the monitored data, and of technical support to the Authority in the following evaluations. The SPM can also carry out the networks design and realization.

ANNEX A

Recommendations of ICHESE Report (page 187):

“Existing and new hydrocarbon/geothermal activities must be accompanied by high technology monitoring networks aimed at following the time evolution of the three fundamental aspects: microseismic activity, ground deformation and pore pressure. These should be put into operation as soon as practicable when licensing is being considered, so that as long as possible periods of prior environmental seismicity can be gathered. Microseismic monitoring can give indications of fault activity and source mechanisms, which are useful in characterizing seismogenic zones.

Seismic monitoring should be carried out with a dedicated local network able of detecting, locating and characterizing all earthquakes with magnitudes of at least 0.5 ML.

Ground deformation, mostly with Earth observation satellite: interferometric (InSAR) and GPS technologies, should be carried out, allowing to get resolution of some mm/year with the aim of identifying subsidence rates.

Fluid pore pressure must be measured directly at the bottom of the wells and in the surrounding rocks on a daily basis.

On the basis of the experience gained from other areas in the world and the geological and seismotectonic characteristics of the area under study, an operational traffic light system should eventually be generated with a relative threshold system.

It is advised that all the seismic data should be continuously statistically analyzed for deviations from typical background seismicity with discrimination techniques such as, changes in inter-event time, changes in b-value of magnitude distribution, temporal and spatial clustering, non-Poissonian behavior, ETAS methodologies and incorporation of new developing techniques should be encouraged as they become available.

It is needed that all the relevant data provided by operators are made available to the authorities responsible for the control.

It is critically important to implement an Outreach and Communication Program to local residents/administrative authorities so that they can gain confidence that operations are being managed optimally.

BIBLIOGRAPHY

1. Hanks, T.C. and H. Kanamori (1979). Moment magnitude scale, *Journal of Geophysical Research* 84 (B5): 2348–50).
2. H. Kanamori (1977). The energy release in great earthquakes. *J. Geophys. Res.* 82, 2981-2987).
3. International Commission on Hydrocarbon Exploration and Seismicity in the Emilia Region Report (2014).
4. ISPRA, Rapporto sullo stato delle conoscenze riguardo alle possibili relazioni tra attività antropiche e sismicità indotta/innescata in Italia (2014).
5. Legge 24 Febbraio 1992, n.225, Istituzione del Servizio Nazionale della Protezione Civile. (GU n.64 del 17-3-1992. Suppl. Ordinario n.53).
6. MATTM, – Commissione VIA – VAS (2013). Relazione del gruppo di lavoro per la formulazione di prescrizioni inerenti il monitoraggio microsismico, geodetico e termodinamico negli stoccaggi di gas.
7. McGarr, A., D. Simpson, and L. Seeber (2002), 40. Case histories of induced and triggered seismicity, *International Geophysics*, 81A, 647-661
Michellini, A., Faenza, L., V., Lauciani, and L. Malgini, 2008. ShakeMap implementation in Italy. *Res. Lett.* 79, 688-697.
8. Michellini, A., Faenza, L., V., Lauciani, and L. Malgini, 2008. ShakeMap implementation in Italy. *Res. Lett.* 79, 688-697.
9. Richter, C.F. (1935). An instrumental earthquake magnitude scale". *Bulletin of the Seismological Society of America* 25 (1-2): 1–32).
10. Sansosti, E., Casu, F., Manzo, M., Lanari, R., 2010, Space-borne radar interferometry techniques for the generation of deformation time series: An advanced tool for Earth's surface displacement analysis, *Geophysical Research Letters*, 37, DOI: 10.1029/2010GL044379.
11. Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in The Netherlands - Torild van Eck*, Femke Goutbeek, Hein Haak, Bernard Dost

Seismology Division, Royal Netherlands Meteorological Institute (KNMI) - Engineering Geology - Volume 87, 105-121, 2006.
12. TNO – 2008-U-R1071/B – Berghermeer seismicity study.
13. Zollo A. e Emolo A., *Terremoti e onde: Metodi e pratica della sismologia moderna*, 2011, Liguori ed., Napoli.