EPJ Web of Conferences **268**, 00015 (2022) https://doi.org/10.1051/epjconf/202226800015
LNES 2021

Exploitation of energy geo-resources and their impacts on the environment

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Summary. — The increase of the world population has led to a major demand for energy with a consequent huge exploitation of natural fossil resources. To build a sustainable future and reach the goals of the green economy, it is necessary to gradually use low-carbon energies taking into account the possible risks associated with each type of energy production. A much-debated incidental event is the anthropogenic or induced seismicity connected with the exploitation of energy geo-resources. It arises because of changes in the pore pressure of subsurface rocks that, in turn, create increased stress that can exceed the threshold value for fracture. This situation may verify from underground extraction or injection of fluids, geothermal energy production, storage of CO_2, natural gas, or hydrogen in underground cavities. The interest of the scientific community, politics and society towards this issue has grown in the last decade especially after the wide use of the fracking technique in the United States and the occurrence of the 2012 Emilia Romagna earthquake (Italy). Both conventional and unconventional geo-resources exploitation techniques can induce seismicity causing damage to the industrial plant itself and the surrounding buildings especially in highly urbanized areas and in extreme situations even generate loss of life. It is, therefore, necessary to carry out detailed studies of seismicity occurred in areas of geo-resources exploitation to expand knowledge of this phenomenon and develop safety protocols to prevent and mitigate the risks.

1. – Introduction

Today's greatest challenge facing science, technology, policymakers, and society is to make the world more sustainable. The increasing world population and the resulting growing demand for energy has led to a massive exploitation of fossil fuels (coal, oil, and gas). This trend has led the energy sector to be the major contributor to anthropogenic greenhouse gas emissions into the atmosphere [1]. Therefore, talking about sustainability inevitably means talking about energy transition and a change of approach regarding energy production and consumption to avoid the most serious impacts of climate change. The European Union's strategy for a sustainable future is via the Green Deal, which contemplates a 55% reduction in greenhouse gas emissions by 2030 up to net-zero emissions in 2050 [2]. To achieve this ambitious result, it is necessary to gradually abandon fossil sources in favor of low-carbon energy and plan the development of reliable technologies for carbon capture and storage. At the same time, in accordance with the objectives of the green economy it is necessary to consider the risks that each type of industrial exploitation of geo-resources is able to generate on the environment, society and economy. It is important to remember that the use of any energy source, whether fossil or renewable, inevitably involves risks. Reducing the impacts is possible through detailed risk analyses that take into account each phase of energy production: from raw material sourcing and plant construction to decommissioning. The accidents that produce the greatest consequences have a low frequency of occurrence and happen especially when the industrial and natural worlds collide. These incidental events can be classified into TechNa (Technological Hazard Triggering Natural Disaster) and NaTech (Natural Hazard Triggering Technological Disaster) events depending on whether the natural phenomenon is a consequence of anthropogenic industrial-type activity or acts as a hazard for an accidental industrial event. In the first case a technological activity can generate a natural disaster, such as the occurrence of an earthquake, the pollution of air, seas, or groundwater. Conversely, a NaTech event can be originated when a natural event (*e.g.*, earthquake, tsunami, extreme weather events, etc.) impacts on the industrial plant causing the release of toxic substances giving rise to a domino effect [3]. The study of NaTech and TechNa events is of particular importance to develop a deeper knowledge and elaborate strategies for risk prevention and mitigation in the perspective of sustainable development. In the following, an overview of a particular TechNa event, known as anthropogenic or induced seismicity is presented.

2. – Anthropogenic seismicity

Anthropogenic activities related to the exploitation of energy geo-resources can be risky for the surrounding environment. Although the best-known environmental consequence is air pollution with the emission of greenhouse gases, the attention of the scientific community but also of politics and society has in recent years also focused on induced seismicity due to the damage that this event can generate [4]. Technological activities such as extraction of fossil fuels (oil and gas), geothermal energy production, storage of CO_2, natural gas, or hydrogen in underground cavities are all potential causes of anthropogenic seismicity. Public interest in this topic has increased especially following specific seismic events, such as the 2011 Oklahoma earthquake that occurred after wastewater injection following a fracking operation and the much-debated 2012 Emilia-Romagna (Italy) seismic sequence [5]. Because of increasing numbers of induced seismicity cases, the Human-Induced Earthquake Database (HiQuake) was created in 2017 [6]. This freely accessible database was initially funded by Nederlandse Aardolie Maatschappij BV (NAM) to Durham University (UK) and Geoenergy Durham Ltd, containing to date the largest collection of anthropogenic projects worldwide that have reported induced seismicity (approximately 1231 cases) [7].

To understand why the technological activities mentioned above are potential causes of seismicity, it is necessary to remember that an earthquake occurs when an effort acting on a point of the Earth's lithosphere exceeds a threshold value, generating a fracture that propagates as long as the stress and friction conditions allow it. Through the extraction or injection of fluids in the underground these industrial activities are able to change the physical parameters of the rocks leading to breakage. The critical condition is quantified by the fracture criterion established by Coulomb in 1773. It is expressed by the following equation:

$$\tau_{\text{crit}} = \mu(\sigma_n - P) + \tau_0,$$

where τ_{crit} is the shear stress that generates the fracture, μ is the internal friction coefficient, $(\sigma_n - P)$ the difference between the normal stress and the pore pressure, called the effective normal stress. Finally, τ_0 is the cohesion or cohesive strength. A small variation of one of these parameters can perturb the system generating an earthquake.

The industrial activities that have attracted more attention than others on this topic are surely the extraction and injection of fluids in the subsoil, in particular to produce oil and gas. The extraction process can cause a contraction of the reservoir giving rise to changes in stress in the surrounding rocks and neighboring fault systems. To increase production, it is often necessary to inject fluids in the subsurface [8, 9]. The most common method is water flooding which involves a controlled injection of water to avoid exceeding the initial reservoir pore pressure [10]. Nevertheless, it may happen that the threshold value is exceeded and therefore the conditions of the stress field can vary. In addition, in the last decades, the well-known unconventional technique of fracking has come to the fore, raising new questions about induced seismicity in areas of low seismic risk [4]. This technique widely used in North America and Canada permits to extract oil and gas by hydro-fracturing rock formations with low permeability (*e.g.*, oil shales or black shales). Fluid pumped at high pressure fractures the rock creating pathways into which the hydrocarbon can pass. To prevent fracture closure, a solid substance (quartz sand or ceramic microspheres) called proppant is added to the injected water. The fracking process lasts from hours to days during which a network of horizontal fractures connected to the well bore are created [9]. In this way a microseismicity ($M_w < 1$) [4] that serves as a guide to understand the geometry of the fractured area is generated.

Upon completion of fracturing, the well is opened and the flowback phenomenon begins. Previously injected water or produced water extracted with hydrocarbons and other substances (*e.g.*, chemicals, debris) collected during the process return to the surface where they are cleaned and used for other purposes. In some cases, the wastewaters are re-injected into the subsurface at depths greater than those of the extraction wells and in nearby areas. The re-injection process takes years or decades in new wells without a balance between extracted and injected fluids, leading to an increase in the pore pressure and a subsequent variation of the stress field. Therefore, this technique has a high potential to generate seismicity.

Unfortunately, induced seismicity is not exclusive to industrial activities that exploit fossil resources but is also potentially caused by some of the technologies that will be widely used in a sustainable future. Among them is geothermal energy that exploits the internal heat of the Earth and is known to be a low-carbon green energy. The increasing adoption of unconventional methods such as Enhanced Geothermal Systems (EGS) challenges the scientific community and civil society about the possible consequences that such facilities may generate. The technique involves pumping cold fluids into hot, dry rocks to create artificial fractures or the opening of pre-existing faults to reduce reservoir permeability and form pathways in which water can circulate [5]. As fluids reach deep wells, they heat up in contact with hot rock and then rise to the surface. This process deliberately generates microseismicity that permits to understand the path of water in the subsurface, also indicating areas where an increase in permeability occurs. Seismic events induced with this technique are generally of low magnitude but especially in densely populated or already seismically active areas could be felt by the population and generate significant damages.

In addition to renewable forms of energy, to achieve net-zero emissions by 2050 it is necessary to develop advanced technologies to capture and store CO_2. The Carbon Capture and Storage (CCS) has the aim to capture the carbon dioxide produced by industries before it reaches the atmosphere and then storage it in underground geological formations suitable for this purpose [9]. This process is not immune to the risk of inducing seismicity since the injection of high rates of CO_2 at high pressure for long periods of time could lead to increases in pore pressure and changes in the stress field [11,12]. Since this technology will be increasingly important and more used in the future, it is necessary to carry out careful studies of induced seismicity related to this type of activity and risk analysis to mitigate the impacts and design facilities that can maximize the benefits.

3. – Main cases of induced seismicity in the world

There are numerous episodes of induced seismicity confirmed through detailed studies. Among the best documented cases of induced seismicity by gas extraction there is the Gazli gas field in Uzbekistan [9]. The gas production began in 1962. In the following years large quantities of water were injected into the reservoir to facilitate extraction, but, despite this, there was a consistent decrease in pressure (from 70 atm in the 1960s to about 30–35 atm since 1976 and to 15 atm since 1985). This situation caused three seismic events of magnitude 7 that occurred in 1976 and 1984 in the northern area of the production field that was previously seismically silent. Even the northern area of the Netherlands, naturally at low seismic risk, has had to deal with the increase in seismicity due to the extraction of gas using the conventional method. In the Groningen field, in operation since 1963, the first earthquake felt by the population occurred in 1991 with a local magnitude 2.4. In 2012, an earthquake with M_L 3.6 caused significant damage to homes in the neighborhood areas [13]. In conjunction with oil and gas production, wastewater is produced, often re-injected into the underground. The first documented and known earthquake caused by wastewater injection occurred in Denver, Colorado, in the 1960s in an area considered to be of low seismicity. The injection activity began in 1962 and lasted until 1966 despite the hundreds of tremors recorded in that period by the Bergen Park seismic station. The three strongest events of magnitude 5, however, occurred in 1967, more than a year after the end of the fluid pumping activities, causing extensive structural damage [9]. In 2011, seismic events induced by wastewater injection occurred in Trinidad, Colorado, and Prague, Oklahoma, with magnitudes 5.3 and 5.6, respectively [14]. It is precisely this re-injection following fracking operations that has led Oklahoma to an increase in seismicity in the last decade. Considering the geothermal energy production, a major unconventional project suspended due to the occurrence of seismicity was launched in Basel, Switzerland, in 2006. On December 2 of the same year high-pressure water was injected into the crystalline basement rock at a depth of about 5 km with the aim to create a geothermal reservoir and increase its permeability. Over the following days, increased injection and pressure rates of injected fluids resulted in a concomitant increase in seismicity that generated a seismic event of local magnitude 2.6, exceeding the expected safety threshold during well stimulation [15]. On December 8, the project was stopped but a few hours later another seismic event (M_L 3.4) was felt by the population.

4. – Conclusions

In order to achieve the green economy goals, it is necessary to reduce the impacts that human activities related to the exploitation of geo-resources produce on the environment. The development of innovative technologies and a careful risk assessment at each phase of the industrial process can help prevent and mitigate the impacts (environmental, economic, and social) associated with these industrial operations. This kind of studies are not simple because they require multidisciplinary knowledge. More specifically, to elaborate detailed studies of induced seismicity being able to discriminate between a natural or anthropogenic earthquake, seismological and industrial data (*e.g.*, rate and pressure of fluids extracted or injected) are needed. The last are often inaccessible to researchers because they are only available for energy companies. For this purpose, it is essential to overcome this barrier promoting the cooperation between scientists and energy leaders to carry out site-specific studies to analyze and understand in detail the mechanisms related to this type of seismicity especially in tectonically active areas. In addition, based on these analyses, it is very important to develop safety protocols and emergency plans to deal with the occurrence of these events and finally educating and informing in an appropriate way the population living in the surroundings of industrial plants.

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