Definition

Induced seismicity refers to typically minor earthquakes and tremors that are caused by human activity that alters the stresses and strains on the Earth's crust. Most induced seismicity is of a low magnitude. The human activities may cause induced seismicity during quarrying, mining, dam reservoir impoundment, extraction of ground water, production of oil or gas, injection of wastewater or fluids underground, the injection of fluids to enhance oil or gas recovery, geothermal stimulation, or hydraulic fracturing.

Reservoir Induced Seismicity (RIS)

The column of water in a large and deep artificial lake or reservoir alters in-situ stress along an existing fault or fracture. In these reservoirs, the weight of the water column can significantly change the stress on an underlying fault or fracture by increasing the total stress through direct loading, or decreasing the effective stress through the increased pore water pressure. This significant change in stress can lead to sudden movement along the fault or fracture, resulting in an earthquake. Reservoir induced seismic events can be relatively large compared to other forms of induced seismicity. Though understanding of reservoir induced seismic activity is very limited, it has been noted that seismicity appears to occur on dams with heights larger than 330 feet (100 m). The extra water pressure created by large reservoirs is the most accepted explanation for the seismic activity. When the reservoirs are filled or drained, induced seismicity can occur immediately or with a small time lag.

The first case of reservoir-induced seismicity occurred in 1932 in Algeria's Oued Fodda Dam. The largest earthquake attributed to reservoir-induced seismicity occurred at Koyna Dam. The 6.3 magnitude 1967 Koynanagar earthquake occurred in Maharashtra, India with its epicenter, fore- and aftershocks all located near or under the Koyna Dam reservoir. 180 people died and 1,500 were left injured. The effects of the earthquake were felt 230 km away in Bombay with tremors and power outages. During the beginnings of the Vajont Dam in Italy, there were seismic shocks recorded during its initial filling. After a landslide almost filled the reservoir in 1963 triggered a massive flooding and around 2,000 deaths, it was drained and consequently seismic activity was almost non-existent.

On August 1, 1975, a magnitude 6.1 earthquake at Oroville, California, was attributed to seismicity from a large earth-fill dam. The filling of the Katse Dam in Lesotho, and the Nurek Dam in Tajikistan is an example. In Zambia, Kariba Lake may have provoked similar effects. The 2008 Sichuan earthquake, which caused approximately 68,000 deaths, is another possible example.

Mining

Mining affects the stress state of the surrounding rock mass, often causing observable deformation and seismic activity. A small portion of mining-induced events are associated with damage to mine workings and pose a risk to mine workers. These events are known as rock bursts in hard rock mining, or as bumps in underground coal mining. A mine's propensity to burst or bump depends primarily on depth, mining method, extraction sequence and geometry, and the material properties of the surrounding rock. Many underground hard rock mines operate seismic monitoring networks in order to manage bursting risks, and guide mining practices.

Seismic networks have recorded a variety of mining-related seismic sources including:

- Shear slip events (similar to tectonic earthquakes) which are thought to have been triggered by mining activity. Notable examples include the 1980 Belchatow earthquake, and the 2014 Orkney earthquake.
- Implosion events associated with mine collapses. The 2007 Crandall Canyon mine collapse and the Solvay Mine Collapse are examples of these.
- Explosions associated with routine mining practices, such as drilling and blasting, and unintended explosions such as the Sago mine Disaster. Explosions are generally not considered "induced" events since they are caused entirely by chemical payloads. Most earthquake monitoring agencies take careful measures to identify explosions and exclude them from earthquake catalogs.
- Fracture formation near the surface of excavations, which are usually small magnitude events only detected by dense in-mine networks.
- Slope failures, the largest example being the Bingham Canyon Landslide.

Waste disposal wells

Cumulative number of earthquakes in the central U.S. The area in and around Oklahoma experienced the largest seismic activity since 2009. The 2011 Oklahoma earthquake near Prague, of magnitude 5.8, occurred after 20 years of injecting waste water into porous deep formations at increasing pressures and saturation. On April 21, 2015, the Oklahoma Geological Survey released a statement reversing its stance on induced earthquakes in Oklahoma: "The OGS considers it very likely that the majority of recent earthquakes, particularly those in central and north-central Oklahoma, are triggered by the injection of produced water in disposal wells." On September 3, 2016, an even stronger earthquake with a magnitude of 5.8 occurred near Pawnee, Oklahoma, followed by nine aftershocks between magnitudes 2.6 and 3.6 within 3 and 1/2 hours. Tremors were felt as far away as Memphis, Tennessee, and Gilbert, Arizona. Mary Fallin, the Oklahoma governor, declared a local emergency and shutdown orders for local disposal wells were ordered by the Oklahoma Corporation Commission.

Injecting liquids into waste disposal wells, most commonly in disposing of produced water from oil and natural gas wells, has been known to cause earthquakes. This high-saline water is usually pumped into salt water disposal wells. The resulting increase in subsurface pore pressure can trigger movement along faults, resulting in earthquakes. One of the first known examples was from the Rocky Mountain Arsenal, northeast of Denver. In 1961, waste water was injected into deep strata, and this was later found to have caused a series of earthquakes.

Hydrocarbon Extraction and Storage

Large-scale fossil fuel extraction can generate earthquakes. Induced seismicity can be also related to underground gas storage operations. The 2013 September–October seismic sequence occurred 21 km off the coast of the Valencia Gulf (Spain) is probably the most known case of induced seismicity related to Underground Gas Storage operations. In September 2013, after the injection operations started, the Spanish seismic network recorded a sudden increase of seismicity. More than 1,000 events with magnitudes (M_L) between 0.7 and 4.3 and located close the injection platform were recorded in about 40 days. Due to the significant population concern the Spanish Government halted the operations.

Groundwater extraction

The changes in crustal stress patterns caused by the large scale extraction of groundwater has been shown to trigger earthquakes, as in the case of the 2011 Lorca earthquake.

Geothermal energy

Enhanced geothermal systems (EGS), a new type of geothermal power technologies that do not require natural convective hydrothermal resources, are known to be associated with induced seismicity. EGS involves pumping fluids at pressure to enhance or create permeability through the use of hydraulic fracturing techniques. Hot dry rock (HDR) EGS actively creates geothermal resources through hydraulic stimulation. Depending on the rock properties, and on injection pressures and fluid volume, the reservoir rock may respond with tensile failure, as is common in the oil and gas industry, or with shear failure of the rock's existing joint set, as is thought to be the main mechanism of reservoir growth in EGS efforts.

HDR and EGS systems are currently being developed and tested in France, USA, Germany, and Australia. Induced seismicity at the Geysers geothermal field in California has been strongly correlated with injection data. The test site at Basel, Switzerland, has been shut down due to induced seismic events. On November 2017 a Mw 5.5 struck the city of Pohang (South Korea) injuring several people and causing extensive damage, the proximity of the seismic sequence with an EGS site, where stimulation operations has taken place few months prior the earthquake raised the possibility that raises the possibility that this earthquake was anthropogenic.

Hydraulic fracturing

Hydraulic fracturing is a technique in which high-pressure fluid is injected into the low-permeable reservoir rocks in order to induce fractures to increase hydrocarbon production. This process is generally associated with seismic events that are too small to be felt at the surface. Several cases of even larger magnitude events ($M > 4.0$) have been recorded in Canada in the unconventional resources of Alberta and British Columbia.

Carbon Capture and Storage (CCS)

Operation of technologies involving long-term geologic storage of waste fluids have been shown to induce seismic activity in nearby areas, and correlation of periods of seismic dormancy with minima in injection volumes and pressures has even been demonstrated for fracking wastewater injection in Youngstown, Ohio. Of particular concern to the viability of carbon dioxide storage from coal-fired power plants and similar endeavours is that the scale of intended CCS projects is much larger in both injection rate and total injection volume than any current or past operation that has already been shown to induce seismicity. As such, extensive modelling must be done of future injection sites in order to assess the risk potential of CCS operations, particularly in relation to the effect of long-term carbon dioxide storage on shale cap rock integrity, as the potential for fluid leaks to the surface might be quite high for moderate earthquakes. However, the potential of CCS to induce large earthquakes and CO_2 leakage remains a controversial issue.

Since geological sequestration of carbon dioxide has the potential to induce seismicity, researchers have developed methods to monitor and model the risk of injection-induced seismicity, in order to better manage the risks associated with this phenomenon. Monitoring can be conducted with measurements from an instrument like a geophone to measure the movement of the ground. Generally a network of instruments around the site of injection is used, though many current carbon dioxide injection sites do not utilize any monitoring devices. Modelling is an important technique for assessing the potential for induced seismicity, and there are two primary types of models used: physical and numerical. Physical models use measurements from the early stages of a project to forecast how the project will behave once more carbon dioxide is injected, and numerical models use numerical methods to simulate the physics of what is occurring inside the reservoir. Both modelling and monitoring are useful tools to quantify, and thus better understand and mitigate the risks associated with injection-induced seismicity.

Failure mechanisms due to fluid injection

To assess induced seismicity risks associated with carbon storage, one must understand the mechanisms behind rock failure. The Mohr-Coulomb failure criteria describe shear failure on a fault plane. Most generally, failure will happen on existing faults due to several mechanisms: an increase in shear stress, a decrease in normal stress or a pore pressure increase. The injection of supercritical CO_2 will change the stresses in the reservoir as it expands, causing potential failure on nearby faults. Injection of fluids also increases the pore pressures in the reservoir, triggering slip on existing rock weakness planes. The latter is the most common cause of induced seismicity due to fluid injection.

Comparison of risks due to CCS versus other injection methods

While there is risk of induced seismicity associated with carbon capture and storage underground on a large scale, it is currently a much less serious risk than other injections. Wastewater injection, hydraulic fracturing, and secondary recovery after oil extraction have all contributed significantly more to induced seismic events than carbon capture and storage in the last several years. There have actually not been any major seismic events associated with carbon injection at this point, whereas there have been recorded seismic occurrences caused by the other injection methods. One such example is massively increased induced seismicity in Oklahoma, USA caused by injection of huge volumes of wastewater into the Arbuckle Group sedimentary rock.