The evolution of induced seismicity sequences generated by long-term fluid injection

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The injection of fluids into the subsurface carries the risk of causing induced seismicity. Larger cases of induced seismic events have caused damage to nearby buildings and infrastructure. Where smaller induced seismic events are felt by nearby residents this can lead to significant disquiet and public opposition to the causative industry. Cases of induced seismicity have forced the closure of many different projects, such as natural gas storage sites and geothermal energy plants; and even entire industries, such as shale gas development in the UK. Given the planned volumes that will be injected into the subsurface by a commercial-scale CCS industry, there is a clear need to manage the hazards posed by the induced seismicity that could be generated.

For a given industrial project or activity, the level of seismicity that is to be avoided should be based on an assessment of risk. This should include an assessment of the likely ground motions that would be caused by a given magnitude event, and the impacts that such ground motions would have on nearby buildings and infrastructure. In addition, social and political considerations may be relevant in this assessment. For example, higher levels of seismic risk may be tolerated for an industry that brings significant social or economic value, or that is seen as significant for geo-political reasons.

To date, induced seismicity has typically been managed using Traffic Light Schemes (TLSs). TLSs impose magnitude thresholds: if the induced seismicity exceeds a given threshold then an operator must take certain pre-defined actions to mitigate seismicity. Typically, TLSs define a "green" level, where operations proceed as normal, a "yellow" level, where injection rates and/or pressures must be reduced, and a "red" level, where injection must stop. As such, TLSs work in a retroactive manner – actions are taken after induced seismicity reaches a certain level.

The effectiveness of a TLS is therefore predicated on two assumptions: (i) that induced seismicity sequences evolve gradually, from smaller to larger magnitudes, such that green, yellow and then red levels are reached in sequence, and (ii) that seismicity will cease (or decrease substantially) in response to a reduction or cessation of injection. However, induced seismicity magnitudes can "jump" substantially (i.e., an event occurs that is significantly larger than any previous event), and trailing events can see magnitudes continue to increase after injection has stopped. These effects mean that a suitable gap must be defined between the red threshold and the level of seismicity that the TLS aims to avoid. The size of this gap will be based on the extent to which magnitude jumps and trailing events might be expected to occur.

In this study, we compile induced seismicity data from a broad range of sites where large volumes of fluids have been injected over long timescales into large, porous sedimentary formations. Such sites provide the most suitable analogues for CCS with respect to injection rates, pressures and volumes. From this compiled dataset, we evaluate the degree to which magnitude "jumps" and trailing events occur, thereby providing the necessary scientific basis from which appropriate TLS yellow and red-light thresholds for CCS operations can be established.

We found that 75% of our cases have magnitude jumps of less than 1 magnitude unit, while only one sequence, in Pawnee, Oklahoma had a magnitude jump larger than 1.5 magnitude units. The distribution of magnitude jumps for long-term injection projects is smaller than that observed for hydraulic fracturing, implying a more gradual evolution of magnitudes during long-term injection. We found few examples of trailing events for WWD-induced seismicity, primarily because there were few cases where injection had been stopped in response to large events, and therefore by definition trailing events could not occur (since a trailing event is defined as occurring after injection has stopped).

Our results indicate that induced seismic event magnitudes do tend to increase systematically as the subsurface perturbations generated by low-pressure, long-term injection develop. This implies that the assumptions that underpin TLSs are reasonable, and so they could be used as a tool for mitigation of induced seismicity at future CCS sites. Based on our observed magnitude jumps, we suggest that for TLSs applied to CCS, a reasonable red-light threshold should be set at 1.5 magnitude units below the risk-based threshold that is to be avoided.