Seismic risk could have been evaluated months before the November 2017 earthquake near Pohang, South Korea.

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POLICY FORUM

INDUCED SEISMICITY

# Managing injection-induced seismic risks

## The Pohang quake shows the need for new methods to assess and manage evolving risk

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Heat transported from deep within Earth's crust can be used to generate electricity or provide direct heating by circulating fluid through permeable fracture networks in hot rock. Because naturally permeable systems are rare, enhanced geothermal system (EGS) technology stimulates the creation of permeable pathways in otherwise impermeable rock by means of the injection of water under high pressure, creating new fractures and causing preexisting fractures to open. But several EGS projects have encountered problems of induced seismicity, particularly the moment magnitude ($M_w$) 5.5 earthquake in 2017 that occurred near an EGS drill site in Pohang, Republic of Korea (South Korea). Here we explore the implications of, and derive lessons from, the Pohang experience. The Pohang earthquake provides unequivocal evidence that EGS stimulation can trigger large earthquakes that rupture beyond the stimulated volume and disproves the hypothesis that the maximum earthquake magnitude is governed by the volume of injected fluids. Because that hypothesis tacitly underpins hazard-based methods used for managing induced seismicity, those methods must be revised and based on considerations of risk.

EGS is a promising source of clean energy for a decarbonizing world and an important source of energy in natural resource–poor countries. The Pohang EGS project was intended to create an artificial geothermal reservoir within low-permeability crystalline basement by hydraulically stimulating the rock to form a connected network of fractures between two wells, PX-1 and PX-2 [(*1*); see the figure]. If successful, about 1.2 MW of electricity would have been generated.

On the afternoon of 15 November 2017, the half-million residents of Pohang experienced violent shaking in a $M_w$ 5.5 earthquake (U.S. Geological Survey). The earthquake injured 135 residents, displaced more than 1700 people into emergency housing, and caused

more than $75 million (USD) in direct damage to more than 57,000 structures and more than $300 million of total economic impact, as estimated by the Bank of Korea.

Questions soon arose about the possible involvement in the earthquake of the Pohang EGS project, because the preliminary epicenter of the quake reported by the Korean Meteorological Administration was located a few kilometers from the project's drill site (*2*, *3*). The EGS project was suspended, and, on behalf of the South Korean government, the Geological Society of Korea (GSK) conducted an investigation whose findings have recently been released (*4*). The GSK's analysis of the tectonic stress conditions, local geology, well-drilling data, hydraulic characteristics of the five high-pressure well stimulations undertaken to create the EGS reservoir, and seismicity associated with stimulation produced definitive evidence that small earthquakes induced by high-pressure injection into the PX-2 well activated the fault that ultimately ruptured in the $M_w$ 5.5 earthquake (see the figure). Injection into PX-1 also induced seismicity, but in a spatially and hydraulically distinct volume of rock, and is not believed to have played a role in the earthquake.

The Pohang EGS project is not the only geoenergy project to have encountered problems of induced seismicity. In recent years, small earthquakes induced during the drilling or stimulation phases of EGS projects in Europe exceeded predefined safety thresholds, leading to the termination of those projects. Although none of the quakes in those cases were as large as in Pohang, they caused alarm among the local communities and minor damage (*5*, *6*). Earthquakes induced during the development of hydrocarbon resources by hydraulic fracturing and by the disposal of wastewater have also led to the scaling back or termination of projects in several jurisdictions and led to regulatory changes (*7*).

## STIMULATION AND SEISMICITY

It is useful to segment the analysis of the Pohang event into three sequential phases of the project: site assessment, drilling of the injection boreholes, and stimulation through the high-pressure injection of water.

The selection of the EGS site near a major city, port, and industrial center inherently posed an issue of seismic risk. Predrilling site investigations did not identify any large faults in the vicinity of the EGS project but did indicate that the faults in the region capable of generating moderate or large earthquakes were critically stressed, as shown by stress-state investigations. Even before the start of the drilling, it should have been clear that if the EGS project intersected a large fault susceptible to slip, it would pose a specific hazard that needed to be factored into the risk assessment and mitigation strategy.

During drilling of PX-2, the borehole intersected a fault at about 3.8-km depth, as noted in drilling records of the on-site geologists, resulting in loss of more than 160 $m^3$ of drilling fluid that transferred an additional pressure of >20 MPa to the formation, triggering microearthquakes (*4*). Triggering of earthquakes in this manner is unusual and points again to the critical stress condition of the fault crossed by the borehole. This microseismicity, however, was noted only after the $M_w$ 5.5 earthquake (*2*), and the importance of the previously unknown fault was not appreciated at the time and did not lead to changes being made to the operational plan.

The EGS project monitored seismicity induced during each well stimulation to determine each earthquake's magnitude and approximate location. It was only learned during the GSK investigation that injection into PX-2 had activated a fault (see the figure). The affected part of the fault grew to more than 1 km in length during the second stimulation of PX-2 in April 2017 when a $M_w$ 3.2 earthquake occurred. The induced earthquakes delineate a planar structure that projects to the fault zone encountered at 3.8-km depth in PX-2, which subsequent seismological and geodetic observations indicated was the mainshock fault. The abrupt resurgence of seismicity releasing tectonic strain during each stimulation phase indicates that this fault was very sensitive to perturbations (*4*).

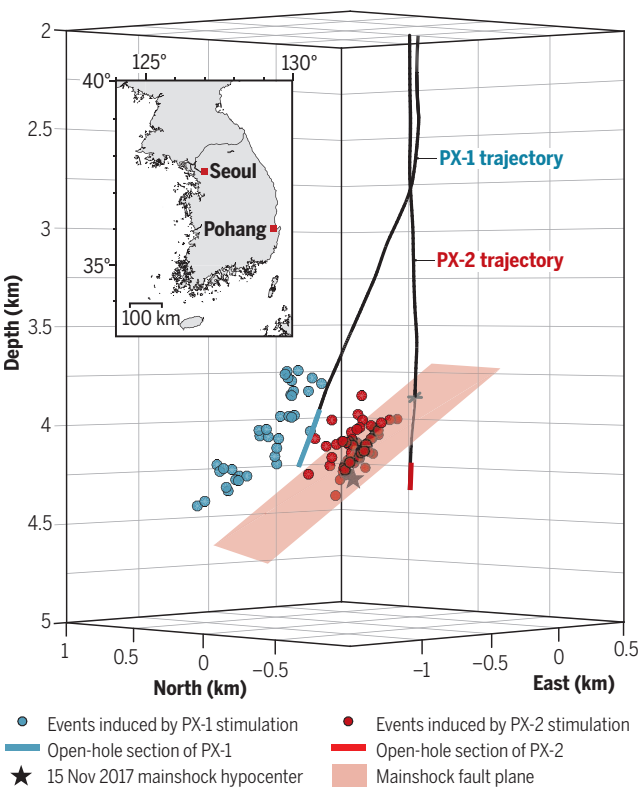
The focal mechanisms (which describe the geometry of the faults that slipped and the corresponding directions of slip) of the largest earthquakes that occurred during stimulation, of the foreshocks, and of the mainshock all display the same geometry. This again shows that this fault was critically stressed, meaning that it was susceptible to slip with only a small stress perturbation. Destabilization of the fault continued after the final PX-2 stimulation in September 2017, with foreshock activity initiating on 14 November and the $M_w$ 5.5 mainshock occurring the next day and rupturing more than 10 km of the fault (*4*).

Had the presence of the fault and its susceptibility to slip in the prevailing stress regime been recognized at the time, it would have been clear that injection into PX-2 posed a substantial hazard and greatly increased the risk because of the proximity to Pohang.

To manage the potential for inducing unwanted earthquakes, the Pohang EGS project team monitored seismicity during

### Seismicity activated by injections near Pohang

The direction of view is toward the northeast, obliquely along the plane of the previously undetected fault activated by injection into PX-2. The intersection of this plane with the PX-2 borehole is indicated by "X." The inset shows the location of Pohang, South Korea.




GRAPHIC: BASED ON (*4*) BY N. CARY/SCIENCE

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injection and adjusted operations when specific magnitude thresholds were exceeded (*8*). Such an approach is often referred to as a "traffic light system" (TLS), with green, amber, and red states representing seismicity at background, anomalous, and increased levels, respectively. At Pohang, this approach focused on keeping induced seismicity below a threshold magnitude of 2 (later raised to 2.5) and did not address the potential for a larger earthquake triggered by injection, as ultimately occurred.

## NEITHER TOO LATE NOR TOO LARGE

Shortly after the $M_w$ 5.5 earthquake, comments reported by the Korean media suggested that the earthquake was unrelated to EGS activities because it occurred almost 2 months after the final stimulation had ended and was disproportionately large, given the volumes of fluid injected. But it has been well known since the 1960s that induced earthquake hazard does not end when injection stops. The induced $M_w$ 4.8 earthquake that shook Denver, Colorado, in 1967 occurred more than a year after injection in a deep well nearby had ended (*9*). At Basel, Switzerland, seismic activity including multiple $M_w$ 3 earthquakes continued for several months after pressure was bled off (*5*).

It has been argued that the size of earthquakes induced by stimulation can be managed by controlling the volume, pressure, rate, and location at which fluid enters the rock mass and by allowing time for pressure to diffuse when seismicity rates escalate (*10*). The threshold magnitudes for TLSs have often been set to avoid earthquakes that pose a shaking nuisance and/or risk of damage.

Part of the rationale for selecting the magnitude thresholds comes from an empirical hypothesis that the largest magnitude of induced earthquakes is bounded by a function of the injected volume (*11*, *12*). If correct, this "volume hypothesis" would enable the hazard to be managed prescriptively by simply maintaining the net injection volume below a certain value (the concept underlying magnitude-based TLSs). However, an alternative analysis of the same data found that the largest event in an induced seismicity sequence is not related to the injection volume, but rather to preexisting tectonic conditions and the number of earthquakes induced. The greater the number of earthquakes, the higher the odds of one of them being large (*13*).

The Pohang earthquake violated the volume hypothesis, as the injected volume was less than 1/500th of the amount expected to produce an earthquake of $M_w$ 5.5. Once initiated, the Pohang earthquake grew through the release of tectonic strain rather than being limited by the pressure perturbation induced by the injected fluids or confined to the perturbed volume of rock. The earthquake was almost two magnitude units larger than the $M_w$ 3.7 predicted by one model (*11*); by rupturing beyond the volume affected by stimulation, it exceeded the maximum "arrested" earthquake size predicted by the other (*12*) and constituted a "runaway" earthquake in their terminology.

## HOW TO PROCEED

The Pohang EGS project was located close to a major city, port, and industrial center. This proximity raises clear issues of seismic risk, governance, and mitigation. It is crucial that strategies and tools for monitoring, mitigating, and communicating the risk of induced seismicity are established together with responsible authorities. Seismic risk scenarios should be developed to evaluate possible consequences and to identify risk mitigation measures. Best practice involves a formal process of risk assessment, with input from competent authorities, and the updating of this assessment as knowledge of the potential hazard evolves. Implementation of a comprehensive risk framework should incorporate scenarios of a triggered large earthquake.

The analyses and investigations carried out as part of the GSK investigation (*4*) were done only after the Pohang earthquake, but they would have been possible during the sequence of stimulations, which lasted almost 2 years before the earthquake. All the data required for this analysis were collected during that 2-year period, and the most important evidence was available in April 2017 after the second stimulation in PX-2. Evaluations of seismic risk of possible relevance to the different stakeholders in the area could have been performed and communicated months before the mainshock.

In future EGS projects, the project team and the scientific institutions involved should engage in comprehensive and ongoing efforts to monitor, analyze, and understand the evolving seismic hazard. They should prioritize an open-access policy and clear channels of communication to maximize their contribution to the mitigation of seismic risk and to update information to the public authorities on the changing seismic risk conditions.

The Pohang earthquake had a complex origin. Seismicity induced by stimulation activated portions of a previously unknown fault that ultimately triggered the mainshock. The Pohang earthquake reinforces the conclusion that induced earthquake magnitudes are not limited by injected volume, and runaway earthquakes do occur (*13*). Models of earthquake nucleation do not adequately forecast the pre-mainshock evolution of a fault or the possibility of pressure perturbations triggering runaway slip. Further work is required to develop physical and statistical models of induced and triggered seismicity to provide appropriate bases for risk assessment.

As in many projects involving injection of water to stimulate permeability, the emphasis of the monitoring program in the Pohang EGS project was on the avoidance of earthquake magnitudes that would breach TLS thresholds, rather than on obtaining accurate hypocenters and documenting the evolution of the seismicity sequence. This narrow focus meant that the evolving risk was neither recognized nor communicated. It is essential that EGS and related stimulation activities use a risk-based TLS that adapts to evolving hazards such as fault activation from multiple stimulations.

Earthquakes are heavy-tailed phenomena, with the hazard concentrated in the large-magnitude, low-probability events (*14*). However, the risk that this hazard poses depends on exposure and vulnerability. The siting of the Pohang EGS project close to a major population and industrial center should have emphasized the need to consider risk rather than simply hazard. Such considerations are likely to be increasingly problematic if EGS activities are to be located near the population centers they are intended to power. The Pohang experience emphasizes the critical importance of formal processes of risk assessment and ongoing review that involve responsible authorities and appropriate independent oversight and scrutiny (*15*). ■

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