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Analysis of Induced Seismicity at Pohang Geothermal Power Plant and Examination of Public Perception following the Incident – A Perspective

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Abstract

Alternative sources of energy are the need of the hour and numerous technological innovations have been explored in recent years to facilitate the demand for sustainable energy sources. However, premature deployment without completing a comprehensive risk assessment and formulating mitigative measures can lead to catastrophes that could, in addition to financial losses and human fatalities, tarnish the public perception of an alternative energy source and hinder its proliferation. The Pohang Earthquake aptly demonstrates this phenomenon where Enhanced Geothermal System (EGS), a relatively new technology, led to a large scale induced seismic event. This paper explores the risk posed by fluid injection in the EGS process considering the induced seismic event at Pohang and includes a Bow-tie analysis that proposes preventive and recovery controls to keep the impact of such events to a minimum. The paper also examines the change in Korean public perception to geothermal energy following the induced earthquake.

Keywords*: Sustainable Energy; Premature deployment; Risk assessment; EGS; Induced seismicity; Bow- tie; Public perception.*

1. Introduction

Energy sources have gone through numerous transformations over the years. From wood and coal to petroleum and natural gas, these transitions were instigated based on certain factors such as availability, accessibility, energy density, efficiency, cost of extraction and industrial as well as domestic demand [1-2]. At the turn of the century, a new facet has been included into this evolving chain – sustainability [3]. Sustainable energy extraction and generation featuring alternative fuels sources have become the crux of most environmental policies and receive substantial attention from the public. The perception of these alternative or renewable sources is generally favorable, however, the status quo can change immediately following an adverse incident or the discovery of a high-impact potential risk. Nuclear Energy and the Chernobyl disaster depicts this phenomenon quite vividly.

Geothermal Energy has been at the forefront of sustainable development projects and policies and the attention it receives is substantiated by the numerous benefits that this source possesses. The advantages of geothermal energy include small carbon footprint, natural replenishment, increased stability, and reliability [4]. Both government and private sectors are keen to tap into this plentiful alternative source with projections indicating a 28% growth in renewable energy extraction and helmed by Asia for the most part [5]. Despite the appealing nature of these benefits, a closer look will reveal that the extraction process comes with its own set of caveats. The most concerning among these is the potential for induced seismicity. Geothermal energy extraction has been known to trigger microseismic activity and the repercussions have often been sidelined due to the dearth of significant incidents. The dynamic changed following the aftermath of the 2017 Pohang Earthquake in South Korea. The event was measured to be of magnitude 5.5 on the Richter Scale and caused substantial economic damage. Further investigation and analysis revealed that the Pohang Enhanced Geothermal

System (EGS) project was the root cause of the incident and acted as the trigger for the earthquake [5]. There is much that is not known regarding EGS technology, primarily because the technology is relatively new. Risk Assessment and Environmental Impact studies for the most part have been superficial and sufficient base data is not presently available to perform comprehensive analysis.

The Pohang event is an acute example of oversight by the decision makers and serves as the perfect backdrop to motivate change [6]. Government policy makers who sanctioned the EGS project should have delayed the approval until 3-tier geographical analysis was completed [7]. Moreover, a small-scale pilot plant should have been set up first to understand the long-term repercussions of EGS prior to industrial-scale deployment. The Pohang incident serves as a wake-up call for decision makers in the government focused on sustainability projects involving nascent technology. A committee consisting of discipline experts as well as engineering professionals need to perform extensive site surveys prior to giving the nod to the decision makers [7]. This is definitely a time-intensive process, however, the potential damage incurred by a significant induced seismic event is considerable which justifies the time delay.

This paper explores the risk of induced seismicity brought about by Enhanced Geothermal Systems and the changes in public perception following the event. The paper will further discuss the risks posed by EGS in context of the Pohang project and suggest mitigation strategies to minimize the risk.

2. Induced seismicity

Seismicity is defined as the measure of the frequency and distribution of earthquakes in a particular geographical location in relation to its strength or magnitude. It is calculated using the following formula:

$$Seismicity = \frac{\sum_i E_{soi}}{\delta\phi_o \delta\lambda_0 \delta h_0 \delta t_o} \quad (1)$$

where: E_{s0i}: energy of a single seismic event; $\delta\phi_0$: latitude interval; $\delta\lambda_0$: longitude interval; δh_0: hypocenter interval; δt_0: seismic event time interval.

Induced seismicity refers to the seismic events or activities that are caused because of human activity or interference. Induced seismicity can also be defined by the equation above [8].

2.1. Mechanism

For induced seismic activity to occur, three conditions must be met at the extraction zone where the rock blocks are situated [9]. These include,

- The presence of a pre-existing fault at the site of origin.
- The fault is critically stressed and susceptible to slip
- The inducing well should be capable of inciting the slip

The operation that leads to fault failure is often fluid injection. There are two primary mechanisms that govern this mode of failure, pore pressure diffusion and increment of rock stress. Among the two, the former has a more pronounced effect. Pore structures in the rocks lead to stress transmission owing to the injection of fluid and the time lag between filling and inception of seismic activity can be used to confirm induced seismicity [9,11]. This time lag as well as the pressure diffusion can be described using Darcy's Law & the Seepage Equation in 2-D described below.

$$v_x = k\frac{\partial_p}{\partial_x};\ v_y = k\frac{\partial_p}{\partial_y} \quad (2)$$

where: k: permeability constant; p: pore pressure.

$$\frac{\partial p}{\partial t} = c\frac{\partial^2 p}{\partial^2 z} \quad (3)$$

where: t: time; c: coefficient of consolidation.

The pressure diffusion ultimately leads to fracture growth which in turn results in a slip, thereby triggering a microseismic event or earthquake. Therefore, determining the rate of growth fracture with respect to the fluid injection time will help in assessing the likelihood and creating a timeline for the seismic activity [12]. The fracture growth can be assessed using the following equation:

$$r_f(t) = \frac{g_1 t}{2h_f w + 4h_f C_L \sqrt{2t}} \quad (4)$$

where: r_f: fracture half-length as a fraction of injection time; t: injection time; q_1: injected fluid rate (average); C_L: fluid-loss coefficient.

The three equations mentioned above (eqn. 2–4) illustrate the mechanism of induced seismicity and can be used to prove the same with respect to pore size and pore pressure changes.

2.2. Enhanced geothermal system

One of the major contributors to induced seismicity during geothermal energy extraction is EGS. As the name suggests, EGS involves an artificially created reservoir. It is employed when the hot rocks in the chosen extraction site offer minimal permeability as well as fluid saturation. This scenario poses a host of challenges as fluid, permeability and heat are critical for the success of a geothermal operation. Therefore, EGS involves the injection of a fluid into a section of the rock structure with a pre-existing fracture. The stress derived from fluid injection causes these fractures to open and subsequently enhances permeability [13]. This makes the reservoir more potent in terms of both yield and ROI potential.

EGS is a relatively young technology system and is most popular in Iceland, Australia, United States of America, and Germany [13]. In addition to minimal greenhouse emissions, EGS has the potential to bridge the geographical limitations that tend to hold back the proliferation of geothermal energy. However, being a nascent technology, the risks associated with EGS are not fully understood and new evidence suggests that the process could very well disrupt fault lines leading to seismic events with drastic consequences [14]. This discussion on induced seismicity reached its crescendo following the Pohang earthquake, the largest recorded man-made earthquake!

3. Incident analysis

3.1 Overview

On 15th of November 2017, the city of Pohang in the North Gyeongsang province of South Korea was rocked by an earthquake measuring 5.4 on the Richter scale. The mainshock epicenter of the earthquake was found to originate from the EGS site of the Pohang Basin. Foreshocks and aftershocks were detected in the radius of 0.6 - 2.5 km from the epicenter [15]. In terms of scale, the Pohang earthquake was the second largest seismic activity in the recorded history of South Korea. A total of 90 injuries were reported following the earthquake and the property damage was estimated by various sources to be in excess of USD 52 million [16].

3.2 Seismic history of South Korea

South Korea is not geographically located on any major tectonic plate line and is classified by geologists to be a Stable Continental Region (SCR) [17]. The Korean peninsula is primarily influenced by the Eurasian and Indo-Australian plates. However, it is located more than eight hundred kilometers away from the closest plate boundary and is consequently not prone to any major seismic activity exceeding magnitude of 5 [15].

From the evaluation of the tectonic map depicting Subduction Zones of Northeast Asia utilized by Kim et al. in their study of the Pohang earthquake, it can be deduced that the likelihood of natural earthquakes is minimal and South Korea should be safe from catastrophic seismic events [15]. A comprehensive list of large-scale seismic events that occurred in South Korea is summarized in the Table 1.

From the Table 1, it can be surmised that the Pohang earthquake was an anomaly and that the frequency of earthquakes of magnitude of 5 greater have increased in the past decade.

Table 1. List of major seismic events in South Korea since 1976 [18]

Name	Date	Time (Kst)	Magnitude (M_l)	Location
Sangju earthquake	09/16/1978	17:07:06	5.2	Sangju, North Gyeongsang
Hongseong earthquake	10/07/1978	09:19:52	5.0	Hongseong County, South Chungcheong
Ongjin earthquake	03/30/2003	11:10:53	5.0	Ongjin County, Incheon
Uljin earthquake	05/29/2004	10:14:24	5.2	Uljin County, North Gyeongsang
Taean earthquake	04/01/2014	19:48:35	5.1	Taean County, South Chungcheong
Ulsan earthquake	07/05/2016	11:33:03	5.0	Dong District, Ulsan
Gyeongju earthquake	09/12/2016	11:32:54	5.8	Gyeongju, North Gyeongsang
Pohang earthquake	**11/15/2017**	**05:29:32**	**5.4**	**Buk-gu, Pohang, North Gyeongsang**

3.3. Human-induced event

From the previous section and the proximity of the earthquake's epicenter to the EGS site, it can be concluded that the earthquake was not caused due to plate tectonics. During the EGS process, Hydraulic Stimulation via fluid injection was carried out in four separate phases. A study conducted by Kwang-Hee Kim et al., revealed that seismic activity in the region peaked following a few days after each injection and subsequently died down [15]. Moreover, the study was able to establish a correlation between the quantity of fluid injected and the magnitude of the micro-seismic activity. All the evidence points to a slip occurring in a pre-existing fault line. Therefore, it can be conclusively stated that the Pohang earthquake was a human-induced event.

3.4. Results of analysis

The Pohang incident acutely depicts a disaster that was the result of unchecked accelerated innovation. The technology used was robust, however, the repercussions following its application were not fully understood and deployed prematurely. This shows the need for comprehensive risk assessment and preliminary studies prior to sanctioning projects, particularly in the field of energy extraction.

4. Risk management

The Pohang earthquake highlights the threat of induced seismicity and shows the importance of hazard identification and risk management. There are numerous methods to perform risk management with each of them having their own set of advantages and disadvantages. A Bow-tie analysis is carried out in this paper. Bow-tie analysis is a powerful risk evaluation tool that can be used to visually represent all possible combinations of risk, threats and consequences of an identified hazard along with the respective preventive as well as recovery controls. The Bow-tie method is perfect to gain an overview of the associated risks in a process and can significantly help the risk management team in establishing mitigating protocols [19].

4.1 Assumptions

Prior to executing the analysis, certain assumptions need to be made to ensure the integrity of the process and lend precision to the exercise. The assumption for conducting the risk analysis are as follows:

- The EGS site is considered as the epicenter of the earthquake and the plant will be assumed to be a single collective unit.
- The presence of a pre-existing faultline prior to the earthquake serves as the base for all analysis.
- The influence of plate tectonics is negligible.

- Seismic activity occurring in the past are not included in the scope of the analysis.
- Only fluid injection is assumed to induce seismic activity and the influence of other processes are not considered.
- A closed system is assumed to identify the conjectural solution free from external influence.

4.2. Bow-tie analysis

With the Pohang earthquake as the basis, a Bow-tie analysis of EGS via fluid injection is performed below (Figure 1) with top event being induced seismic activity. The threats and preventive controls are indicated on the left of the Bow-tie while the right side displays the consequences along with the recovery controls. The detailed description of each segment is provided in Table 2.

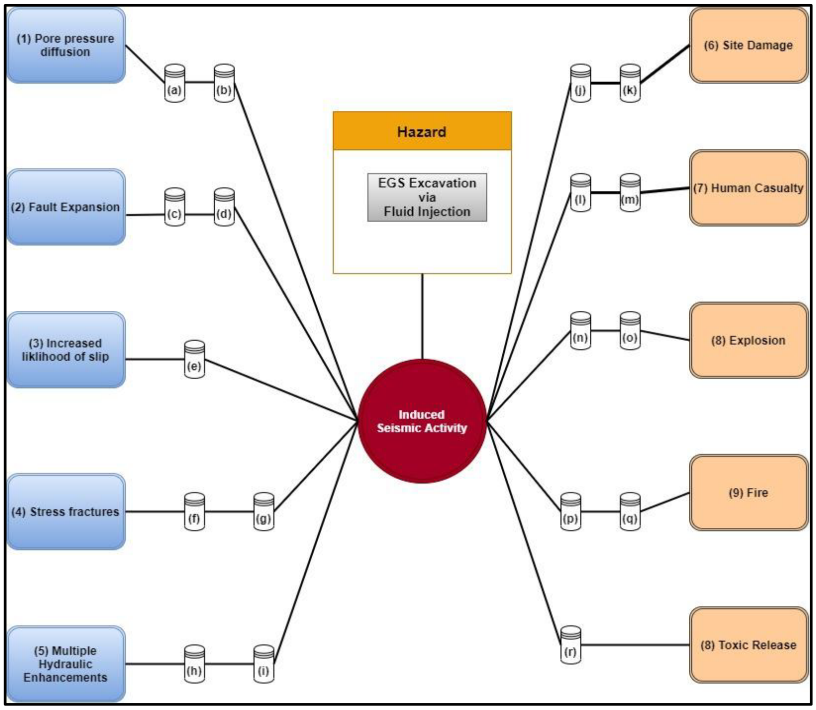

Figure 1. Bow-tie for induced seismic activity

Table 2. Description of preventive and recovery controls [7,12,17,20-22]

#	Preventive Control	Description	#	Recovery Control	Description
a.	Nucleation Model Forecasting	Use hydrologic and fluid injection data to forecast induced seismicity by estimating the intensity of pore pressure diffusion. This will help to determine the rate of progress thereby allowing for mitigation via modification of injection timelines.	j.	Moment Resisting Framework	Structural design of buildings on-site is resistant to bending moment and reduce likelihood of caving in during seismic activity.
b.	Numerical Simulation	Employ a 3D model for fluid flow by incorporating the hydraulic properties of the injection fluid and subsequently estimate the epicenter for a seismic event. Injection zones will be relocated farther away from the probable epicenter.	k.	Reinforced Modular Design	Structures are made of modules that can be easily modified or reinforced. Structural collapse does not upend modular integrity and can be easily reassembled.

#	Preventive Control	Description	#	Recovery Control	Description
c.	3D in-situ stress modelling	Estimate the stress field around the extraction site to determine the critical points at which fault expansion will occur. Extraction parameters are modified accordingly to minimize expansion rates.	l.	Robust Evacuation Plan	A comprehensive plan can increase the efficiency and pace of personnel evacuation from the danger zone during a seismic event.
d.	Geological Survey	Understanding the geological nuances of the site allows for detailed mapping of the faultlines. This information could be used to mitigate fault expansions by identifying injection sites that result in minimal expansion.	m.	Disaster Response Protocol	On-site personnel trained in emergency protocols can react more efficiently during an incident and, thereby, reduce casualties.
e.	Field Mapping	Geospatial data can be used to generate models that predict the likelihood for slip. The results will help in outlining restorative protocols.	n.	Control / Isolate Ignition Sources	Control ignition sources such as static electricity (earthing) and store flammable gases and liquids away from central locations on site with adequate clearance space.
f.	Monitoring Causative Stress	Monitoring zones of the geological formation with stress deformities over extended periods will aid in the isolation of regions where stress caused by injection becomes greater than the rock's strength.	o.	Pressure Release Valves	Automated pressure release valves will help to prevent anomalies such as pressure build-up caused by seismic activity.
g.	Use Low Damage Drilling Fluid	The composition and properties of the fluid can play a crucial role in exacerbating stress fractures. Switching to a more compatible fluid can lessen the stress.	p.	Fire Retardants	Employ automated dispersion of foam-based fire retardants and sprinklers to deter propagation of a fire.
h.	Increase delay times between enhancements	Multiple hydraulic enhancements are a necessity. Extending the downtime between each injection phase will prevent the regional accumulation of stress.	q.	Central Fire Handling	Central monitoring station to handle fire related events during an incident and coordinate fire quenching efforts to minimize spread.
i.	Reduce Intensity of Enhancement	Flow rate of fluid during injection is maintained below the stress failure threshold.	r.	Failure Release System	Controlled venting of toxic gases using washers to enable automated release during seismic activity.

4.3. Results

The Bow-tie analysis indicates the dire consequences of an induced seismic event and reveals the importance of 3D mapping prior to fluid injection. Mitigative measures in this scenario revolve around selecting the most conducive injection site for enhancements and the intensity of the enhancement with the type of injection fluid playing a supplementary role. Recent research has indicated that supercritical carbon dioxide can be used in place of wastewater, the typical injection fluid [23]. The physical and chemical interactions of carbon dioxide with rocks in the reservoir is not as pronounced as water and limits pore pressure diffusion and stress factors. Injecting carbon dioxide in zones that are not directly passing through fault lines will help to prevent causative shear and stress, thereby effectively reducing the likelihood of slip [23].

The potential of EGS is not yet fully realized and the fledgling technology is ripe for innovation. However, the execution of the concept requires detailed geological study to ensure that the enhancements do not accumulate towards a large-scale seismic event as observed in Pohang.

5. Public perception of geothermal energy

Climate change is an imminent threat that has already begun to spell disaster in certain parts of the world. Naturally, the interest in alternative energy capable of supporting a sustainable future has exponentially increased of late. Geothermal energy falls under this spectrum and is viewed as a viable energy source in many parts of the world. Unfortunately, the Pohang earthquake had a marked effect on the public perception of geothermal energy. This is synonymous to the public opinion of nuclear energy following the Chernobyl disaster. This section examines the public perception of geothermal energy in South Korea considering the induced seismic event at Pohang.

5.1 South Korean energy policy

Much of the Korean public's opinion of geothermal energy stems from the country's energy policy. As per the latest long-term plan, Korea seeks to transition to renewable energy by sourcing 35% of its energy supply from alternative sources by 2040. This is a Herculean task given that in 2018, 85% of the country's energy requirement was sourced via fossil fuels [24]. The influence of the policy extended to numerous primary and secondary sectors which ultimately spurred on a renewable revolution in the minds of the public. With EGS based geothermal energy being touted as the game-changing innovation spurring the paradigm shift, the technology was welcomed with open arms by Koreans. However, the major caveat is that risk perception was lacking amongst the public leading to creation of premature point of views.

Energy policies take into consideration both economic and technological factors, however, their execution involves various other limiting factors as well. They are highly influenced by external influences such as the political climate, international commitments, and logistical constraints. A study conducted by Woo et al. was able to establish a causal link between the Pohang earthquake and EGS project [25]. Therefore, it can be inferred that the technology was deployed prior to establishing adequate parameters for mitigating seismic activity caused by the fuel injection process. The South Korean energy policy is formulated around the 2040 deadline which results in energy projects being sanctioned at a greater pace and, as is the case with the Pohang incident, without due diligence [24].

5.2. Induced seismicity – EGS and the Pohang earthquake

As described in section 3 earlier, it can be conclusively established that the Pohang Earthquake was not a natural occurrence and was a human-induced event. Woo et al. were able to conclusively establish the causal link between EGS and the Pohang Earthquake [25]. They performed a parameter analysis involving hypocenter determination, initial and relative locations, magnitude determination, earthquake size distribution, focal mechanism solution, and hierarchical clustering analysis. The results were compared with hydraulic experiments and spatial distribution data to establish the relation between hydraulic stimulations at the EGS site and earthquake sequences [25].

5.3. Social consequences

The investigation shown in section 5 was able to conclusively establish that the Pohang Earthquake was caused by the activities of the EGS plant. The Geothermal Energy consortium overseeing the plant faced severe backlash from the Pohang community once the report went public [26]. Social media and online bulletin boards buoyed up the issue while support groups were formed for those who suffered physical, emotional, and financial losses due to the incident. The media broadcasted the aftermath of the earthquake in tandem with the induced seismicity report and the fall in grace of the EGS Geothermal plant was imminent.

The social consequences of EGS based geothermal energy extraction and the drastic shift in public perception can be attributed to the psychosocial cognitive effect known as anchoring [26]. Often considered a bias, anchoring refers to the decision-making that is concentrically elaborated from the initial piece of information [26]. This serves as the basis or anchor for all subsequent decisions with judgements being tailored to align with the anchor. For the Pohang incident, establishing the causation between EGS process and induced seismicity let down the anchor that led to a dip in the favorability of geothermal energy where the public perception was disproportionately skewed against geothermal energy [27]. A study conducted by Dong-Hyeon Im *et al.* to evaluate the favorability of various energy sources among Pohang residents following the induced seismic event revealed certain interesting points pertaining to the social consequences [26].

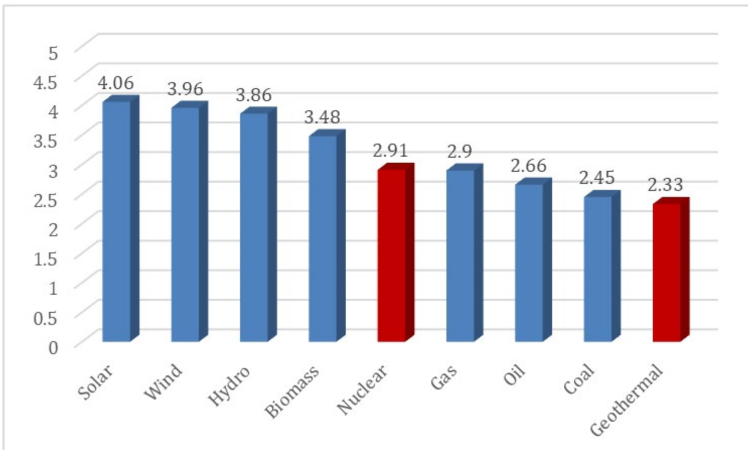

Figure 2. Favorability of energy sources ranked by Pohang residents following the earthquake with 1 being the least favorable and 5 being the most [26]

From Figure 2, it is apparent that Pohang Residents were extremely averse to the use of geothermal energy following the Pohang earthquake. It should be noted that geothermal energy was ranked below nuclear and coal, the energy sources typically vilified by media houses and green policy makers. Moreover, Pohang residents are well-versed with the concept of EGS which makes the change in perception more than a knee jerk reaction. The final nail in the coffin for the EGS plant in Pohang was the financial losses left in the wake of the disaster. An estimated $52 million worth of property and infrastructure damage was initially reported [16]. This figure does not include the privately owned losses and the harm caused to mental health as a result. Majority of the losses were due to structural collapses and could have been avoided if the recovery control shown in the Bow-tie analysis, particularly reinforced modular design and moment resisting framework, were employed to construct these structures [28].

5.4. Aftershock of perception shift

The polar shift in perception following a disaster has far-reaching implications. Once the EGS plant was confirmed to be the trigger for the earthquake in 2018, public outcry put an immediate stop to its operations. Risk mitigation teams were deployed to assess strategies to ensure safer operations while EGS expansion plans across the region were put on hold. Operations at the Pohang plant has been put on hold indefinitely. The energy policy had to be reviewed and priority lists were created based on risk assessments [27]. The perception change led to a ripple effect which ultimately had a marked impact on all stakeholders involved in the endeavor. As shown in the earlier section, once the public were made aware of the causal link between EGS and induced seismicity, they began to associate the technology with the damages incurred leading to its lowest position on the favorability chart [26]. Moreover, South Korean regulators have instigated high-level changes as indicated in the bow-tie analysis such as a focus on building materials as well as advanced geological surveys have been initiated with standard operating protocols being laid out for each of them [27-28]. Another significant change motivated by the incident is the development of disaster insurance industry with demand for the same surging following the government investigation mentioned earlier [28]. This shows that the public have become more cognizant of the induced seismicity risk following the Pohang earthquake.

6. Conclusion

The Pohang earthquake is an insightful case study that acutely details the dangers of premature deployment of a relatively nascent technology. The demand for sustainable alternative fuel sources is at an all-time high and this pressure is often devolved to technocrats and policy makers. Owing to South Korea's focused Energy Policy, regulators are required to expedite all proceedings pertaining to the same and this led to the oversight, as described in the earlier sections, which ultimately caused the induced seismic activity. Such instances force a scenario where risk identification and analysis are done for a limited scope. Thus, overarching risk factors and long-term repercussions are not integrated in operational design. Induced seismicity is a major issue that is often overlooked during geothermal extraction as past induced events often fell under the microseismic category. The Pohang earthquake measured significantly higher on the Richter scale and forced all responsible parties to reevaluate EGS. This served as the motivation for regulatory changes outlined in section 5.4. As depicted in the bowtie analysis in section 4, due deliberation at the preliminary stages could very well mitigate the impact of induced seismicity with onus being on comprehensive geological survey and fault identification. Optimizing operational parameters such as injection fluid composition, frequency and flow rates could also serve to minimize the impact of EGS. The major technical intervention required to ensure safe operations during EGS operations in the future are dynamic simulations and modelling as evidenced by the Pohang incident and described in the Bow-tie analysis. A combination of these technical and regulatory interventions holds the key to safe deployment of EGS technology.

The Pohang earthquake is also an important study of how improper risk management can distort public perception of a viable and sound technology leading to its shelving. In addition to financial losses and legislative bottlenecks, the sudden pause to a piece of critical innovation could significantly hamper progress in the particular discipline and very well eliminate it from the arsenal of sustainable development. The risk posed by induced seismicity has overshadowed the benefits of geothermal energy and resulted in the indefinite suspension of the EGS plant. The Pohang incident highlights the importance of thorough and detailed risk management practices to ensure safe operations as well as the necessity to remain in the good books of the public, a vital parameter for the adoption of alternative energy.

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