PROTOCOL FOR INDUCED SEISMICITY ASSOCIATED WITH ENHANCED GEOTHERMAL SYSTEMS

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INTRODUCTION

As the global demand for energy increases, the contribution from geothermal energy could be extremely large, particularly if resources developed with Enhanced Geothermal Systems (EGS) technology are incorporated in the total energy picture. A recent study by MIT (2006) predicts that in the United States alone, 100,000 MW_e of cost-competitive capacity could be provided by EGS in the next 50 years with reasonable investment. The USGS estimates that in the U.S., which uses about 100 quads of energy per year, there are 300,000 quads in the >200˚C heat sources down to 6 km depth. Large countries in other continents, such as India and China, have similar heat resources, so the global potential of geothermal energy is enormous. Because implementation of EGS affects subsurface conditions, especially fractures, there exists the potential to cause induced seismicity.

Induced seismicity has occurred in the development and production of several conventional fractured geothermal resources (typically deeper than 1 km), as well as oil and gas resources, large water-impounding dams, and mining applications. In each of these instances, properly monitored and analyzed induced seismicity has provided valuable information in developing the particular resource, but has not prevented the development from proceeding. To help gain acceptance from the general public for geothermal generally and EGS specifically, it would be beneficial to clarify the problems with and beneficial applications of micro-seismicity (seismicity, micro-earthquakes, MEQ) during the development stages of an underground reservoir and the subsequent extraction of the geothermal energy.

This document is intended to serve as a general guide *that identifies steps a geothermal developer can take to address induced seismicity issues.* The proposed protocol includes simple planning steps that would apply to most developments, as well as more elaborate procedures that would apply under particular circumstances to a small number of geothermal developments. Therefore, this protocol is not intended to be a universal prescriptive approach to seismicity management. However, it may be used to build confidence in the manageability of seismicity at geothermal projects. It is directed at geothermal developers, public officials, regulators, and the public at large. This proposed protocol stems from a recently developed paper that reviewed the present state of knowledge of induced seismicity during the development of EGS reservoirs, and during production or injection of fluids in conventional geothermal reservoirs (Majer et al., 2007). The paper also identifies gaps in knowledge that should be addressed by ongoing research to improve understanding of induced seismicity, and, by improving the general state of knowledge regarding seismicity in general, better understand natural earthquakes.

To access both conventional and EGS geothermal resources, wells are drilled to depths where a temperature suitable for heat extraction is reached. In cases where economically viable temperatures are found in a conventional (naturally permeable) geothermal reservoir developed at depths shallower than one km, felt seismicity is very unlikely to be induced. In higher temperature conventional reservoirs at greater depths, both cooling due to injection and pressure perturbation due to production can trigger small MEQ's on local fractures. In the case of EGS, fluid injection is carried out to enhance rock permeability and recover heat from the rock, often at depths greater than 2 km. During the process of creating an underground heat exchanger by opening permeable space in the rock or during subsequent circulation of water to recover heat, stress patterns in the rock may change and produce microseismic events. In almost all cases, these events in the deep reservoir have been of such low magnitude that they are not felt at the surface by nearby inhabitants. The events usually have so little energy relative to natural earthquakes, with relatively short duration, high frequency and very low amplitude, that they pass unnoticed.

The difference between microseismic events created directly by fluid injection and a natural earthquake is significant: To the extent that they are sometimes felt, the former usually falls into the category of a nuisance, like a pneumatic hammer or the passing of a train or large truck, whereas the latter may cause extensive damage. For example, experience and scientific data indicate that the vibration at depth from an MEQ related to fluid injection is unlikely to cause any damage to modern buildings. In the case of Basel, Switzerland, however, a large number of damage claims were lodged for minor effects that probably occurred as a result of EGS pumping causing induced seismic events. These will be covered by the project developer's insurance, but the long term effect of the accumulated cost will probably be a rise in future insurance premiums.

The sound emitted by induced MEQ can be a nuisance, particularly at night or on a very calm day, when the ambient cultural noise is very low. On some occasions, observers have reported that the effect from a microseismic event sounds like a quarry explosion, a truck going by, or a thud from an object hitting a hard floor.

Induced seismicity is an important reservoir management tool, especially for Enhanced Geothermal Systems (EGS), but it is also perceived as a problem in some communities near geothermal fields. Events of magnitude 2 and above near certain projects have raised residents' concern related to both damage from single events and their cumulative effects (Majer et al., 2007). Some residents believe that the induced seismicity may result in structural damage similar to that caused by larger natural earthquakes. There is also fear that the small events may be an indication of larger events to follow, and that not enough resources have been invested in finding solutions to some of the problems associated with larger induced events, or in providing for independent monitoring of the seismicity before embarking on large-scale fluid injection and production in EGS projects.

POSSIBLE STEPS IN ADDRESSING EGS INDUCED SESIMICITY ISSUES

Induced seismicity is one of a number of issues that the developer needs to address in order to proceed with project development. This document outlines the suggested steps that a developer could follow in extending their education and outreach campaign and cooperating with regulatory authorities and local groups. The following steps (not necessarily in the order given) are proposed for handling of the induced seismicity issue as it relates to the whole project.

Step One: Review Laws and Regulations

The developer should study and evaluate applicable laws and governing regulations on seismicity that may affect the project. These legal stipulations may apply at national or local levels of government. Any legal precedents that include induced seismicity, quarry blasting, road noise or similar activities should be identified and assessed relative to the proposed project. In consultation with regulators, the developer should formulate a plan for meeting legal requirements.

Although the above procedure is routine for most operators, legal studies specifically related to geothermal induced seismicity and its effect on the man-made structures and public perceptions are rare. One of the few studies that addresses legal issues in the United States related to seismicity induced by dams, oil and gas operations, and geothermal operations (Cypser and Davis, 1998) points out that:

> ‘Liability for damage caused by vibrations can be based on several legal theories: trespass, strict liability, negligence and nuisance. Our research revealed no cases in which an appellate court has upheld or rejected the application of tort liability to an induced earthquake situation. However, there are numerous analogous cases that support the application of these legal theories to induced seismicity. Vibrations or concussions due to blasting or heavy machinery are sometimes viewed as a `trespass' analogous to a physical invasion. In some states activities which induce earthquakes might be considered `abnormally dangerous' activities that require companies engaged in them to pay for injuries the quakes cause regardless of how careful the inducers were. In some circumstances, a court may find that an inducer was negligent in its site selection or in maintenance of the project. If induced seismicity interferes with the use or enjoyment of another's land, then the inducing activity may be a legal nuisance, even if the seismicity causes little physical damage.’ [Cypser and Davis, 1998]

In other words, in the U.S., there are potential grounds for taking legal action against those who induce seismicity.

Other examples of local regulations include allowable ground motion from quarry operations and local blasting due to construction or road building. These are site specific and usually involve maximum vibration levels rather than any maximum magnitude ranges. A small event close to a structure can be just as annoying in vibration terms as a large event far away from the same structure. Maximum vibration depends on local geologic conditions and the response to the input earthquake. In any case, a review of the governing regulations with respect to vibration, noise and induced seismicity is suggested as a first step in managing the seismic issues of EGS development.

Step Two: Assess Natural Seismic Hazard Potential

If no specific course of action is required by law, the recommended procedure would be to characterize the natural seismic potential of the site and surrounding area using existing public information, including earthquake history (magnitude/frequency), geologic and tectonic setting (stress field, fault system geometry), and source model. In most cases, the necessary information, such as historic earthquake statistics including size, location, and magnitude, will already be publicly available. The approach taken to predict likely earthquake occurrence, with and without the geothermal project, will depend on the geologic situation, rate of seismicity and type of information available; for example, a study based on >40 years of data might only include a b-value statistical approach while one using more detailed data gathered over a shorter period might use a more involved statistical analysis that accounts for known fault sizes, stress analysis and other relevant information.

Step Three: Assess Induced Seismicity Potential

At this stage in the assessment process, the geological structure of the site is assumed to have already been investigated to the extent necessary to characterize the likely nature of the geothermal resource and to design a drilling program. Given this understanding of the site conditions and the results of Step Two, it should be possible to draw conclusions regarding the likely extent of seismicity due to project-related activities.

A geological issue that may not have been considered in the resource assessment but may be important to the assessment of induced seismicity potential is the identification of any areas of unconsolidated deposits, such as alluvium, construction fill, mining tailings, refuse dumps, flood deposits, or landslide deposits. This micro-zoning exercise is particularly relevant if buildings have been constructed on such deposits. Seismic waves reaching the surface of such deposits are commonly amplified and so residents of buildings constructed over them are more likely to be discomforted by otherwise unnoticed micro-seismicity. All of the usual mitigation options apply to such areas provided that all parties are aware of the higher sensitivity of buildings over such deposits.

Estimates for a “maximum probable event” and the likely incident rate and severity of vibration induced by project-related activities can be characterized based on current knowledge about induced seismicity and the nature of the site. (It would be preferable for formal reports on this topic to be prepared by an independent contractor or institution to dispel concerns about conflict of interest.) Although duration magnitude and similar magnitudes used in natural earthquake seismology are also applied to induced micro-seismicity, these parameters can be misleading in quantifying whether such small events can be felt or are likely to cause minor damage. Therefore, analyses should emphasize criteria similar to those used by the mining and civil engineering industries to characterize the potential for nuisance seismicity or vibration damage from activities like quarrying, traffic and construction. Previously developed worldwide standards, based on the parameters peak velocity and dominant frequency, have proven to be effective in characterizing and managing the potential for felt seismicity and damaging vibration.

There is also the potential risk (and public fear) that stimulation could trigger deep, “ready-to-go” earthquakes. A seismic risk study, performed for the Cooper Basin area, Australia, addressed this issue. Here, those segments of existing fault zones that are near-critically stressed for shear dislocations have been identified. Attenuation calculations were then performed to see whether these segments were far enough from EGS sites to represent a significant risk (Hunt & Morelli, 2006).

Based on the analysis of the natural seismic potential and the characterization of likely induced seismicity, mitigation plans required for environmental impact studies and similar regulatory reports can be prepared. A variety of approaches will suit different circumstances. These range from a periodic review by government monitoring agencies in sparsely settled areas, to a “traffic light” approach that might be suitable where communities very close to a development are likely to feel induced events (Bommer et al 2006). Such a plan would include avoidance, mitigation, and treatment plans for both the expected seismicity and for less likely but plausible outcomes; for example, for induced seismicity that exceeds the maximum probable event or that causes damage. It should be pointed out that the “Traffic light” approach is reactive. The action plan can only be implemented after a seismic event has already happened. In some situations (eg Basel) suspension of stimulation activities after a felt event did not not prevent later, stronger events.

Step Four: Establish a Dialogue with Regional Authority

Consultation with community groups and the agencies responsible for permitting and regulating a particular geothermal development is best undertaken prior to, or as soon as possible after, the public becomes aware of the geothermal development plan. At this early stage, the developer is advised to explain the purpose of the project, characterize the site being considered and how it will be developed, summarize the expected effects on the environment and the local residents, and explain the long-term costs and benefits for the community and region. To the extent that induced seismicity is likely to be a significant community or regulatory issue, it is best addressed in each public stage of the development process following the public announcement of the project. These stages might include the following:

- Exploration survey permitting
- Lease/concession acquisition
- Public announcement of the geothermal/EGS project and, in cooperation with regulators, first meeting with local community groups
- Regulatory reports and permits required for exploration and appraisal drilling
- Regulatory reports, permits and hearings required for development and operation

An established protocol for induced seismicity can support the initial public announcement, indicating that the established regulatory process can address induced seismicity issues using standards developed for similar impacts related to traffic, quarrying and construction, and that the regulatory process includes many opportunities for citizen concerns to be heard and answered. Induced seismicity only becomes a topic of discussion with authorities to the extent that the results of the first three steps indicate a need to address the issue.

Step Five: Educate Stakeholders

Regularly scheduled public meetings are an effective approach to encourage involvement by all interested parties and the general public. Experience suggests that briefings are most effective if they acquaint and inform interested persons about the project as a whole as well as about earthquakes. At an early stage in the project, meetings are more likely to put induced seismicity in context if they do not focus on this issue exclusively, although the public should be made aware of the reservoir development process. To the extent that induced seismicity is an integral part of the total project, it will receive attention warranted by the results of the first four steps. Experience has shown that an open dialogue with the general public about relevant issues associated with the project is a prudent approach, one that is likely to result in positive support from stakeholders. Public meetings may be forgone if the population density of the site vicinity and/or number of persons likely to be affected by induced seismicity is negligible. In this case, personal visits to nearby residents informing them of the project may be advisable.

Step Six: Establish Microseismic Monitoring Network

Some means of assessing micro-earthquake activity across a wide range of magnitudes is desirable. This can sometimes be done by utilizing existing networks, but is best achieved by installing a dedicated network. For the type of EGS developments currently conceived, a dedicated network would very likely be installed as part of the diagnostic system that the developer will use in creating the EGS reservoir. There are often advantages to adapting a regional network to accomplish this, particularly if the regional array includes stations in the immediate vicinity and can detect any events that would likely be felt near the developed area, that is, to a radius of several times the depth of the reservoir.

If a regional or a national seismic network does not exist in the vicinity of the EGS site, then a basic micro-earthquake network can be installed to assess the presence of natural earthquakes prior to the establishment of the site. The design of the station geometry will depend on the size and the depth ranges of the reservoir and expected induced seismicity; with arrays typically extending beyond the perimeter of the reservoir by a distance at least equivalent to the depth of the expected seismicity. It is often advantageous to arrange for an independent organization, for example the organization responsible for monitoring regional or national seismicity, to operate the array and analyze the data, particularly with respect to quantifying the size of seismic events. Such information may later become relevant to any inquiry regarding claims of structural damage.

Step Seven: Interact with Stakeholders

A proactive effort to keep stakeholders informed about the project is likely to reduce public anxiety and put unreasonable claims in perspective. Besides regulators, stakeholders include those nearby residents most likely to be directly affected and those who express the most concern.

The following options may be useful as means of achieving appropriate interaction on induced seismicity issues: personal meetings of technical and consenting staff with local residents and regulators; public meetings; media coverage; guided tours; public annual operating reports; call-in line; web site; and scheduled meetings with public officials. For a large EGS operation near a town, periodic newsletters or a visitor center might be effective. Such interactions tend to promote a sense of involvement by stakeholders. Experience at both research and industrial geothermal projects suggests that this leads to greater acceptance of the project by the community as a whole, and puts into perspective any ‘inconvenience’ or ‘nuisance’ aspects of adverse effects.

Insofar as induced seismicity is concerned, the issue should be included among those of general interest or concern to stakeholders. The developer may consider issuing periodic microseismic events reports or providing public access to a call-line/web-site to answer questions or receive complaints. If it appears that micro-earthquakes will become an ongoing significant public concern, a more formal procedure may be needed to address questions and complaints, including involvement by local public officials.

Step Eight: Implement Procedure for Evaluating Damage

If reports are received from the public of felt earthquakes that might originate from or near the reservoir, or if earthquakes detected by a monitoring array indicate that nearby events might be of sufficient magnitude to be felt, then a procedure for monitoring and responding to felt seismicity should be developed. This would assess, for example, any possible structural damage and/or related environmental disturbance. Surface-mounted ‘broadband’ seismometers and/or accelerometers are typically used to determine dominant frequency and peak acceleration. These are the variables used to assess the potential of an earthquake to cause structural damage. To the extent that other cultural sources of noise or shocks may exist, for example, truck traffic or quarry blasting, the monitoring system can be designed to differentiate these from earthquakes. This will provide a quantitative basis upon which an accurate evaluation of any claims can be made which will be fair to both the public and operators. In the case of observable damage like cracks it is recommended that the damage claim registration and mapping is conducted by an organization independent of the EGS project developer.

THE PATH FORWARD FOR AN IMPROVED UNDERSTANDING OF INDUCED SEISMICITY

An EGS-based geothermal energy industry is currently becoming established. Because of its potential impact on public acceptance of this energy resource, technical case histories of induced seismicity will be particularly important to the successful future development of EGS. Experience suggests that, if appropriate mitigation steps are taken, induced seismicity is unlikely to prevent the development of geothermal resources. In fact, induced seismicity provides a direct benefit because it can be used as a monitoring tool to understand the effectiveness of the EGS operations and shed light on the permeability structure of the reservoir. A properly informed community of stakeholders will appreciate the value of the information generated by induced seismicity.

During the process of gathering information for the development of this protocol, including three international workshops and many presentations at geothermal meetings, scientists and engineers working in this field have guided us towards a short and long term path. The short-term path is to ensure that there is open communication and a good working relationship between the geothermal energy producer and the local inhabitants. This involves early establishment of a plan for monitoring and reporting, communication of the plan to the affected community, and diligent follow-up in the form of reporting and meetings. Geothermal operators have consistently shown that it is possible to gain public acceptance and even local support for field development operations that may create noise or other disturbances similar to micro-earthquakes, by ensuring that local inhabitants see the direct economic benefit of those activities. Furthermore, the wider environmental benefits of EGS geothermal projects, and the need to stimulate deep fractures, hence creating occasional ground vibrations at the surface, should be stressed to potentially affected parties. This communication of the effects and benefits ("ground shaking is good for us") will help develop a better 'good neighbour' relationship.

The long-term path will involve the continued improvement in our understanding of the processes underlying induced seismicity and the effective utilization of this knowledge to mitigate risks to the public and improve the management of the resource. Current models of commercial EGS development involve the engineering of subsurface fracture networks with appropriate properties. Micro-seismic monitoring is likely to be the most effective method of imaging that fracture network. Such geothermal applications of induced seismic monitoring will share technology with very similar methods being developed to characterize the response of heavy oil reservoirs to steam floods. Research is focusing on understanding the dynamics of fracturing and the relationship between fractures and fluid behavior. Future research will be most effective by encouraging international cooperation through data exchange, sharing results of field studies and research at regular meetings, and engaging industry in research projects. A desirable goal would be to identify methods of limiting the occurrence of larger events.

EGS applications have the potential of making a significant contribution to the worldwide renewable energy supply. Additional experience and the application of the practices discussed above will provide further knowledge, helping us to successfully utilize EGS-induced seismicity and achieve the full potential of EGS.

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