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TOWARD UNDERSTANDING INDUCED SEISMICITY

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ABSTRACT

Induced seismicity is a phenomenon critical to the success of geothermal energy development as it provides a fundamental tool to assess and interpret geothermal reservoirs. In the case of Engineered Geothermal System (EGS) reservoirs, it is the only method currently employed to routinely image the volumetric distribution and dimensions of a fracture network during the early stages of reservoir development via massive hydraulic stimulation.

The geothermal community is increasingly aware of public perception to induced seismicity as a potential hazard, with a number of international projects being suspended or curtailed due to local public concern. It is clear therefore that the geothermal sector as a whole will benefit from;

1) Facilitating informed awareness of this issue amongst all stakeholders, including regulators, at local, national and international level and,
2) Establishing robust, trustworthy and consistent risk assessment methodologies for determining and mitigating risks associated with induced seismicity which can be applied to any given project.

The development of reliable risk assessment, prediction and mitigation strategies for induced seismicity requires further targeted research to better understand the relationships between geomechanics, physical rock properties and fracture behaviour. For such research to progress however, real world data and case studies from across the spectrum of conventional volcanogenic and hydrothermal geothermal projects through to Engineered Geothermal Systems, need to be collected, collated and made available to the research community and wider geothermal industry.

This paper summarises guidelines and protocols under development by the South Australian Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE), in consultation with the Australian geothermal industry, to assist companies in preparing risk assessment strategies and, to create a repository of publically available data which can be used for future research into understanding induced seismicity. The guidelines and protocols developed are designed to be applicable to the generic case, and be consistent with existing international protocols and appropriate data archiving standards. Used in conjunction with objective-based legislation, the guidelines require such information to be submitted to the regulator, and subsequently released for public scrutiny and research purposes within specified timeframes.

INTRODUCTION

Induced seismic activity can arise from a number of different anthropogenic activities including mining, blasting, pile-driving, construction and filling of dams, sub-surface water or waste injection, geothermal, and oil and gas operations. In recent years, both the wider geothermal industry and relevant regulatory agencies, have become increasingly concerned about the risk of induced seismicity associated with development of Engineered Geothermal System (EGS) reservoirs through stimulation (hydraulic fracturing) (Majer et al, 2008; Bromley and Mongillo, 2008; Morelli, 2009). Once on a production footing however, there can also be ongoing micro-seismic hazards associated with the production and re-injection of geothermal fluids into a geothermal field. In conventional hydrothermal systems it is this latter situation which has generally received greater attention, since massive hydraulic stimulation of conventional reservoirs is rarely undertaken (Majer et al, 2008).

Hydraulic stimulation (hydrofracturing or fraccing) is routinely used in the petroleum, shale gas and coal seam gas industries to artificially enhance reservoir permeability, and is now being applied for this purpose in the geothermal industry (predominantly EGS). In this situation, fluid is injected into the reservoir zone up to the point where the injected pressure either: exceeds effective stress on preexisting fault surfaces, enabling slippage (shear) on those surfaces and/or; exceeds the rock fracture gradient initiating tensile failure and creating a fracture. The resulting micro-seismic events induced via the fracturing process, provide important data about the reservoir and sub-surface structures, including the velocity structure and hydraulic diffusivity of the reservoir, orientation of the in situ stress field and distribution of large fault structures (Shapiro et al, 1999; Kohl 2006, Baisch et al, 2006; Baisch et al, 2009; Julian et al, 2010).

Naturally occurring seismic activity is almost ubiquitous, but only constitutes a hazard if it occurs above a given level close to communities or infrastructure which might be affected. The size of any given event is determined by the size of the fault, the forces available (stored energy) and rock strength. Damaging earthquakes are generally large (Magnitude 4 to 5 or greater) resulting from significant movement occurring along slippage surfaces but are also dependant on local geology, building technologies and the density of populations living nearby. Such earthquakes require an imbalance in the in situ stress field resulting in the storage of significant energy which is released during an earthquake. The forces involved in such events are enormous and by comparison, the energy applied during hydraulic stimulation operations or ongoing geothermal production operations are orders of magnitude smaller (Morelli, 2009, Majer et al 2008).

Due to the relatively small forces involved, hydraulic stimulation rarely constitutes a physical hazard, however the response at each site will be unique as the potential for damage at a site is also related to the local geology, the construction technology and quality of local building infrastructure, and the density of neighbouring communities (Bommer et al, 2006; Majer et al, 2007; Morelli, 2009). Public concerns will also vary between sites depending on the local experience with seismic activity, the level of information available to the community and proximity to the operations site.

Although the likelihood of these types of operations directly being able to cause appreciable damage is limited, events occurring up to Magnitude 2 and 3 near some geothermal projects have raised public fears that hydraulic stimulation operations may directly cause damage or trigger larger damaging earthquakes. It is incumbent upon the geothermal industry and the governing bodies regulating the industry in any given jurisdiction, to address these public concerns by;

1) providing an open and transparent, balanced dialogue with the public on the topic of induced seismicity,
2) initiating appropriate risk assessment and mitigation strategies to avoid or minimise the effects of induced seismicity,
3) assisting in the progression of knowledge and understanding of the causal relationships between induced seismicity, hydraulic stimulation, geomechanics, rock physics, and fracture behavior and propagation, through enabling public access to key data and information.

Assessing the risk of induced seismicity in geothermal operations is not directly analogous to the modeling of natural seismic hazards (e.g. as occurs in earthquake engineering in the construction industry), since there is the possibility of controlling the timing, and location of the activity generating the seismicity, and hence greater certainty around the timing and location of resulting events. Although this is an issue which is rapidly gaining attention, currently there are few guidelines developed on how to assess or mitigate the hazard in the geothermal context (Bommer et al, 2006; Majer et al, 2008; Morelli, 2009). To date, risk assessment and mitigation strategies have progressed based upon the use of on-site seismic monitoring systems which can provide continuous real-time monitoring of seismicity, coupled with the development of a ‘traffic light’ or other risk mitigation strategy (Bommer et al, 2006; Majer et al, 2007, Majer et al, 2008; Hunt and Morelli, 2006) which delineates a series of management activities based on pragmatic motion thresholds. The ‘traffic light’ system was first developed and tested at the Berlin project El Salvador, and has since been modified to local conditions and implemented at a number of EGS sites including Soultz-sous-Forets, Basel, Innamincka in the Cooper Basin and most recently at the Paralana project in the northern Flinders Ranges of South Australia (Haring et al, 2008; Hunt and Morelli, 2006; Hasting et al, 2011).

The principle philosophy of this approach is to determine the natural safe levels of seismicity, and to establish a series of event thresholds which are constantly monitored. The tolerances of these motion thresholds may be based on the stabilities of engineered structures and materials (infrastructure damage) or, as was the case at the El Salvador project, the lower level tolerances of human response to seismic stimulus (i.e. the level of human disturbance resulting from a seismic event of given magnitude and frequency). Stimulation operations (e.g. injection rates / volumes) are adjusted such that the induced seismicity does not exceed these predetermined limits (Majer et al, 2008; Haring et al, 2008; Hunt and Morelli, 2006).

The ‘traffic light’ system has some inherent limitations however. It is by nature a reactive process, whereby operations are modified once the various thresholds have been reached. The method is in no way predictive or deterministic, in that the thresholds are not influenced by the cumulative real time response of the reservoir to stimulation. The thresholds act as triggers to change operations but provide no feedback on the status of the reservoir, nor indication that the micro-seismic response will continue to approach or exceed a hazardous level (Majer et al, 2008; Morelli, 2009; Bachmann et al, 2011). It is possible for large induced events to occur post hydraulic stimulation or in the relaxation of pressure within the system, sometimes occurring many months after operations have ceased. Targeted research is needed in order to develop more predictive tools for risk assessment and mitigation of induced seismicity, which reflect and respond to the active state of the reservoir (GEISER, 2009; Majer et al, 2008; Bachmann et al, 2011; Bromley and Mongillo, 2008). For this developmental work to occur, researchers require access to high quality, real data (i.e. case studies) (e.g. Bachmann et al, 2011; Baisch et al, 2006).

In recognition of this situation, the International Energy Agency Geothermal Implementing Agreement (IEA GIA) and the International Partnership for Geothermal Technology (IPGT) have initiated international collaborative research groups on induced seismicity (Bromley and Mongillo, 2008; Majer et al, 2008), while the Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs (GEISER) consortia has been established solely to address the issue of Induced Seismicity with particular reference to EGS (GEISER, 2009). Importantly, these agencies have recognised the value of acting collaboratively at an international level to address this issue, hosting a series of joint workshops and fostering links between the different research communities.

As the government regulatory agency for geothermal energy in South Australia, and an active participant in the IEA GIA and IPGT research groups on induced seismicity, DMITRE has taken a lead role in developing guidelines and protocols for the submission of seismic monitoring data and supporting reports associated with EGS stimulation operations. The purpose of this paper is to present some of the preliminary results from the work undertaken by DMITRE in conjunction with the Australian Geothermal Energy Group (AGEG), and in consultation with the IEA GIA and IPGT.

CONCEPTUAL BACKGROUND

The fundamental purpose in developing this data protocol is to provide some consistent guidelines on the type and format of micro-seismic monitoring data and accompanying descriptive reports, to be collected and prepared by companies for submission to the relevant regulatory authority, and / or lodgment with an appropriate seismic data management and archiving agency. At this stage in its development the data protocol and guidelines relate specifically to the micro-seismic monitoring and related data gathered during hydraulic stimulation of EGS wells, however the intention is to expand the protocol to be more generic and include all conditions under which micro-seismic data may be collected, including production stages.

Since the protocol needs to be generic and adaptable to any given (potentially international) jurisdiction's legislation, it was considered that submitted data and relevant supporting reports should be grouped together as progressive stand-alone data packages, such that sufficient information would be provided in any one data package for an independent third party to understand the nature and distribution of the monitoring array, re-establish the data set, and interrogate it. Furthermore, just as the processing and interpretation of the data gathered from any single stimulation operation would progress through a work flow of data collation, preliminary and advanced processing through to interpretation, so should the submitted data packages be grouped based on this fundamental work flow.

As a result, the protocol considers the micro-seismic monitoring data and supporting information in terms of "basic" and "interpretive" categories. In general, 'basic' data and supporting information can be considered to be "that data which is normally provided to a seismologist in order to make an interpretation," and it is suggested that this data and supporting information, be available to the public after the requisite regulatory timeframe of any given jurisdiction responsible for collecting the data. "Interpretive" data and information may include a greater degree of subjectivity or interpretive techniques and methodologies and have a greater level of inherent intellectual property (IP) or commercial-in-confidence information. As such this information may have different requisite timeframes for public release, or may not be made available for public release under given jurisdiction's legislation. Such a distinction provides flexibility for these guidelines to be adapted to individual jurisdictions' regulatory legislation.

DATA FORMATS

As a generalisation, there are two aspects to passive source seismic data;

1) the time-series (waveform) data recorded by the seismometer,
2) the parameter (event catalogue) data including time, location, station specific metadata, calibration, magnitude, etc.

Currently the most widely used format for the archiving and exchange of digital seismology data is the Standard for the Exchange of Earthquake Data (SEED) which was adopted as an international standard format for data exchange in 1987 by the Federation of Digital Seismographic Network (FDSN) under the International Association for Seismology and Physics of the Earth's Interior (IASPEI) (FDSN, 2010).

SEED was developed to accommodate differences in recording formats of various data loggers, and is closely related to these formats. A SEED volume consists of two parts; header records (dataless SEED), and time series (data) records (mini-SEED). The header data is in ASCII format and contains additional station specific information to make use of the SEED volume (i.e. station metadata). Each header is made up of a sequence of blockettes, defined as a collection of named fields of fixed length which describe the abbreviations used throughout the volume, operating characteristics of a station and the time span of the data. The data records are raw binary data of the digital seismogram (FDSN, 2010). Similarly, the IASPEI Seismic Format (ISF) was developed and adopted by the Commission on Seismological Observation and IASPEI in August 2001, as the international standard for the formatting and exchange of seismic parameter (event catalogue) data.

The advantages of SEED and the IASPEI Seismic Format (ISF) are; they have many parameter options and provide a transparent and complete method for exchanging data; they are widely used and generally readily converted by existing analysis software; open source software is available for download from international agencies such as IASPEI, FDSN, Observatories and Research Facilities for European Seismology (ORFEUS) and Incorporated Research Institutions for Seismology (IRIS). The miniSEED format is also the most highly compressed data format making it the optimal choice for archival and data transfer. However binary and fixed column (ASCII) formats are relatively inflexible and binary data is machine dependant. In addition the fixed length of the named fields in SEED headers creates problems for the extension of data structures. So although the seismology community has recognised that a revision of the SEED format is needed, the effort required to review and update the enormous amount of waveform data already stored in SEED format makes this undertaking prohibitive. As a result no revision has been attempted since the release of SEED version 2.3 in February 1993 (FDSN, 2010).

The modular nature of the header structure enables SEED format to be adapted to XML (eXtensible Markup Language) however, which has the advantage of flexibility of field design, is written in plain text, and thus directly readable by people and many machines independent of platform. A number of initiatives have emerged to write XML translators for SEED (e.g. XML-SEED, JSeedLink), including the definition of an international XML standard QuakeML which could be used for all types of seismological data including both time series and catalogue/parameter data (Tsuboi and Morino, 2004; Euchner and Schorlemmer, 2008; Schorlemmer et al, 2004). At this stage however, XML is yet to be incorporated in standard earthquake analysis software packages or as an output from commercially available dataloggers.

QuakeML is a joint program developed by a consortia of personnel from agencies including the University of Southern California, Swiss Seismological Institute, GeoForschungsZentram Potsdam, US Geological Survey, IRIS, ORFEUS, European Mediterranean Seismological Centre (EMSC) and Instrumental Software Technologies Inc, and is intended to provide a single open source standard format able to represent waveform and parameter data (Euchner and Schorlemmer, 2008). QuakeML is being designed in 3 parts. Part 1 which describes fundamental seismic event data used in catalogues such as multiple hypocentre locations from different sources, (i.e. origin and origin uncertainties), date/time, picks, amplitudes, magnitude and focal mechanism data, has been completed and QuakeML version 1.1 is available for download via the QuakeML website https://quake.ethz.ch/quakeml/QuakeML. Part 2 extends resource metadata including pick time data, location probability density functions, slip distributions, ground motion information and related information necessary for tomographic studies. Part 3 will provide an inventory of the waveform data and will make use of the existing XML-SEED format to convert SEED data to XML. Parts 2 and 3 remain under development (Tsuboi and Morino, 2004; Euchner and Schorlemmer, 2008; Schorlemmer et al, 2004).

The guidelines proposed here aim to adopt international standard data formats wherever possible to ensure portability and utility of collected data. As a result, the IASPEI sanctioned SEED/MiniSEED formats are recommended for continuous time series (waveform) data and station metadata, whereas the IASPEI Seismic Format (ISF) is the preferred option for event catalogue information (e.g. event locations, phase, magnitudes, etc). It is envisaged that in time QuakeML or other equivalent XML format will become the preferred international standard. Presently these programs remain under development but given the backlog of existing data within the international seismological community, will have capability to convert the older IASPEI formats into XML.

INCIDENT AND COMPLIANCE REPORTS AND DATA

Under the proposed guidelines, the submission of the following reports are recommended as minimum compliance reporting to be submitted by operating companies during the course of stimulation operations, to ensure that timely, factual information is provided to regulatory agencies. These are of particular value in the instance where a regulator may need to respond to public query on the progress or outcomes of a particular operation.

Incident Reports

In the case of a 'significant event' as defined under the relevant risk mitigation strategy for any given operation, the operator should immediately provide an initial alert to the relevant regulating authority by phone, fax or email, to be followed by a detailed report (e.g. within 3 months). This type of reporting is generally required for analogous operational incidents such as drilling accidents and hazardous chemical spills, and as such should be considered a fundamental requirement.

The initial alerting report should include the following information pertaining to the "significant' seismic event in near real time;

- the name and business address of the licencee / operating company,
- the name and contact details of the relevant contact person / safety officer for the event,
- the time and date of the occurrence of the event,
- the place where the incident occurred (using appropriate co-ordinates or distances from significant topographic features),
- the approximate area affected by the incident (if relevant),
- the nature and extent of any injury to a person, and if a death has occurred, the cause and place of death,
- the nature and extent of any damage to the environment or infrastructure that occurred as a result of the event,
- the steps that have been taken to control, mitigate or address any damage to any area affected by the event,
- the event waveform from the most significant station,
- the principal hypocentral (event catalogue) details for this event.

The comprehensive follow-up report should also include the following information;

- the event waveforms (triggered waveform) and station metadata in miniSEED/dataless SEED, and details of the program, algorithms and methods used to calculate this data,
- phase and magnitude information for the above waveform data in ASCII/XL/ISF format,
- the corresponding event catalogue in ASCII/XL/ISF format,
- all data to be Universal Time stamped,
- the results of any assessment or investigation of the conditions or circumstances that caused or contributed to the occurrence of the incident, including an assessment of the effectiveness of the design, procedure and management systems that were in place to prevent / mitigate the incident occurring,
- the nature and extent of any damage to the environment or infrastructure that occurred as a result of the event,
- the steps which have been taken, or are proposed to be taken, to clean up and rehabilitate any area affected by the incident,
- the steps taken, or proposed to be taken, to prevent a recurrence of the incident.

Daily Progress Reports

It is suggested under the proposed guidelines that in addition, short daily progress reports be submitted to the relevant regulating authority during the course of stimulation operations to provide a summary of the micro-seismic event status (i.e. with respect to defined risk mitigation triggers), information of field operations which created any felt or heard events, and any stakeholder feedback. The report should relate to a 24 hour period (ideally a full UTC day for ease of archiving), be submitted within 12 hours of the reporting period and include the following information;

- the name and number of the well being stimulated,
- a report number or the number of days from initiation of the operations,
- a list of activities conducted during the reporting period including a synopsis of data recorded,
- a description of formations, and depth of any formation being tested or affected by the operations,
- a summary of the micro-seismic status with respect to the designated risk mitigation thresholds relevant to the specific operations,
- a synopsis of any heard or felt events, or other stakeholder feedback,

- a specific report on any reportable incident (i.e. confirmation of 'significant event') that has occurred during the reporting period.

BASIC REPORTS AND DATA

The following are considered to constitute basic reports and data which in principle would be released for public access within the appropriate timeframe under a given legislation.

Field Data, Stimulation and Micro-seismic Operations Reports

This data package includes what are considered to be 'irreplaceable' field recorded data. It is suggested that these data and reports are submitted within the relevant regulatory timeframe (e.g. 12 months) after completion of the stimulation operations.

Field data to be submitted includes;

- raw recorded data in the native data logger format.
- raw recorded data in miniSEED (common format)
- supporting data: daily operations logs, station metadata in dataless SEED (common format)
- and a data register needed to identify submitted data.

The Micro-seismic Operations Report provides basic information on the seismic network and supporting information and clarification of the accompanying micro-seismic data, including;

- the name, licence area and location from which the data was obtained,
- significant dates relating to the data collection activities, including recording, starting and finishing dates,
- the operations carried out in acquiring the data,
- locations of all monitoring stations, including a description of the equipment used for positioning and surveying these data, and the geodetic and geophysical datum employed,
- details of monitoring bores (maps, lithological information, casing summaries, and cementing details as appropriate for each bore and details of sonde coupling),
- discussion of monitoring equipment, sensors (total number per string), depth of sensors, location, orientation, sample rates, location codes, equipment response and installation,
- details of data loggers used and native format of data loggers,
- information on the calibration of the array, failures in field, instrumentation issues,
- details of reference event(s) for location of hypocentres.

For the micro-seismic data to be useful in correlating the causal links between hydraulic injection operations and micro-seismic response, researchers will need to know what stimulation operations were applied to the reservoir under investigation. This information should be captured in a Fracture Stimulation Operations Report and a Well Test Analysis Report.

A Fracture Stimulation Operations Report provides details of the stimulation operations actually performed, including;

- well name, date
- fracture type, depth, formation for each fracture stage
- fracture design (fluid system, proppant type and concentration
- injection pressure (downhole and well head pressure) vs. time (universal time stamped)
- pump rates vs. time (universal time stamped)
- flow back volume
- total fluid volume pumped
- total proppant weight placed
- actual fracture fluid composition (including water chemistry)
- data and reports from any logs or other data acquisition techniques (such as those used to measure fracture orientation and stress conditions in the hole).

In contrast, the Well Test Analysis Report describes the pressure tests conducted on a well for the purpose of understanding reservoir and flow characteristics. Pressure tests are conducted both pre- and post-fracture stimulation. The two main well pressure tests are:

1) pressure draw-down test: downhole pressure data is recorded when the well is flowing or put on production,
2) pressure build-up test: downhole pressure data is recorded after a producing well is shut-in.

A well test analysis report should contain;

- well name, date,
- information on the type of test that was carried out (i.e. build-up, draw-down and pre-frac, post-frac),
- the interval tested,
- the quantity of any substance produced,
- the results of the test;
    - pressure vs. time graph, pressure vs. depth graph (static pressure gradient), reservoir pressure, skin, permeability thickness
- any raw data obtained from the test;

- time, depth, pressure, temperature.

The Fracture Stimulation Operations Report and Well Test Analysis Report are considered 'basic' information to be submitted and made public within the requisite regulatory timeframes of any given jurisdiction responsible for collecting the data.

Processed Data and Processing Report

Although data in this data package has had a degree of processing applied, it is considered to be 'basic' data under the proposed guidelines and available for public access after the requisite regulatory timeframe (e.g. 12 months). The processing operations performed at this level are considered the minimum necessary to extract useful information from the data, and perform quality control /quality assurance on the data from a regulatory compliance and / or data archiving perspective.

The processed data should contain at least the following information;

- triggered waveform data in miniSEED,
- phase and magnitude information for above waveform data in ASCII/XL/ISF format,
- event catalogue in ASCII/XL/ISF format,
- all data to be Universal Time Stamped.

The processing report should include a comprehensive data register and provide fundamental supporting information on the processing undertaken on the accompanying micro-seismic data, including;

- the methodologies used to calculate the principal facts (for example, the method used to calculate magnitude and the relevant parameters used in calculation such as, amplitude, frequency, corner frequency,
- a very brief description of picking algorithm,
- the velocity model (i.e. a basic synopsis of the model used for calculation (e.g. 1D, 2D or 3D, and a description of a simplified 1D model that approximates the area),
- outcomes,
- outputs.

INTERPRETIVE REPORTS AND DATA

As distinct from the 'basic' data and information supplied in the field recordings, processed micro-seismic data and various accompanying reports, the interpretive report discusses any advanced processing /interpretive information which provide a cumulative evaluation of the basic data. It may incorporate substantial manual manipulation and / or application of intellectual property. Such information may be released at any time with permission of the company or, depending on the regulating legislation, held confidential until relinquishment of the licence or other mandated timeframe.

The following are considered interpretive information; detailed velocity models (especially 3D models), location probability density functions, slip rates and distributions, ground motion information (other than where required for risk assessment / mitigation /compliance monitoring) and related information necessary for tomographic studies, fault interpretation, mapping of fracture systems toward definition of reservoir distribution, and shear wave splitting studies. Focal mechanism data remain a grey area. First motion data, if determined, should be included in basic data. More complex or experimental methods would currently be considered interpretive however this may vary as research improves.

CONCLUSION

Geothermal Energy and in particular the emerging technology of Engineered Geothermal Systems, have tremendous potential to contribute to the world's renewable energy budget at a time when the demand for environmentally sustainable energy resources is growing unabated. Induced seismicity is a necessary consequence of EGS development but need not be a risk to the public, to neighbouring infrastructure or project development.

Many of the concerns relating to the phenomenon of induced seismicity result from misinformation and lack of knowledge about this topic. Indeed the greatest threat lies in the absence of a technically robust, transparent and balanced dialogue between the geothermal industry, regulators, the public and other stakeholders. One significant element which can assist in this process is the development of reliable, fit-for-purpose risk assessment and mitigation strategies which are predictive and diagnostic of the state of the stimulated reservoir. Development of such tools requires targeted research and testing based on real world data and case studies. The data guidelines and protocol discussed above provide the basis for the collation and archiving of high quality, comprehensive, portable data sets which are appropriate to this purpose.

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