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Houston Calling: The 50th U.S. Rock Mechanics/ Geomechanics Symposium

Submitted by David Yale, Symposium Chair

Planning for the 50th U.S. Rock Mechanics/Geomechanics Symposium in Houston from 26-29 June 2016 is well underway. Nearly 650 abstracts were accepted for the symposium. The abstracts suggest there will be very strong oral and poster sessions, spanning petroleum, civil, mining, and interdisciplinary topics in rock mechanics and geomechanics. Continuing the trend from the last few years, a very large number of abstracts and sessions revolve around “interdisciplinary” topics that are of interest to civil, mining, and petroleum geomechanics professionals and showcase the unique value of the symposium to ARMA members.

In addition to the strong technical program, ARMA will host seven geomechanics-related workshops and two short courses. Workshops will be held on Hydraulic Fracturing, Geomechanics in Unconventionals, Laboratory Geomechanics Testing, Reservoir Engineering Applied to Geothermal, Microseismic Geomechanics, Petroleum Geomechanics Testing, and an ARMA Future Leaders-Student workshop. Short courses will be taught on Shale Gas Geoenvironmental Engineering and Modeling of Coupled-Hydro-Mechanical Deformation and Fracturing.

The Symposium will feature the first ARMA Distinguished Lecture, offered by Richard Goodman. The MTS Lecture will be presented by Peter Kaiser; William Ellsworth, Jean-Claude Roegiers, and Charles Fairhurst will be featured in keynote lectures. Technical tours will highlight Houston’s petroleum history (tours to Spindletop and the Ocean Star Offshore Drilling Rig & Museum) and geology (tour of active faults in the Houston area).

The symposium will be held at the Westin Galleria Hotel and Conference Center. Holding the meeting in Houston will allow a larger number of petroleum-related geomechanics professionals to attend and broaden the interaction between the rock mechanics/geomechanics disciplines and industries.

Registration is now open for the symposium:

<http://armasymposium.org/registration>.

Rock Mechanics Research in China, as Applied to Large and Deep Underground Excavations in Hard Rocks

Submitted by Xia-Ting Feng, State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China; and Immediate Past President of the International Society of Rock Mechanics (ISRM)

1. Introduction

Underground excavations in China are steadily growing larger and going deeper. For example, recent underground powerhouses have spans of 26-34m and reach heights of 60-90m. Some of these huge caverns are excavated in high stress zones and they often encounter complicated geological conditions. The maximum strength-stress ratio is often less than 2.0. Some caverns are excavated in rocks traversed by columnar joints, interlayer staggered zones, and steep geologic structures. Under these conditions, large deformations occur due to cracking and rock spalling. Stress-induced cavern collapse can also occur during excavation.

Currently, four headrace tunnels at Jinping II (China) hydropower station were excavated under an overburden of 1900-2525m. Their diameters are 12.4 m (using tunnel boring machines (TBM) or 13m (excavated by "drill and blast" technique). Rockbursts during or after excavation and long term stability of deep large caverns and tunnels are big challenges for the industry [1-4]. To face these challenges, several key rock mechanics research efforts have been undertaken, aimed at successfully carrying out the planned underground projects. These are detailed in the following sections.

2. Laboratory testing systems, *in situ* monitoring systems, and underground research laboratory

Testing equipment has been developed to investigate the mechanical behavior of rockmass during excavation. Figure 1 shows two types of the developed true triaxial compressive systems.

The Jinping underground research laboratories phases I and II have been developed, as shown in Figure 2.

An apparatus that monitors stress distribution has been developed based on Fiber Bragg Grating technique, as shown in Figure 3(a). It enables the recording of multiple-point stress in a borehole using automatic data acquisition. The stress range is up to 150 MPa and the precision is 0.06 MPa. Figure 3(b) shows a new intelligent microseismicity monitoring system.

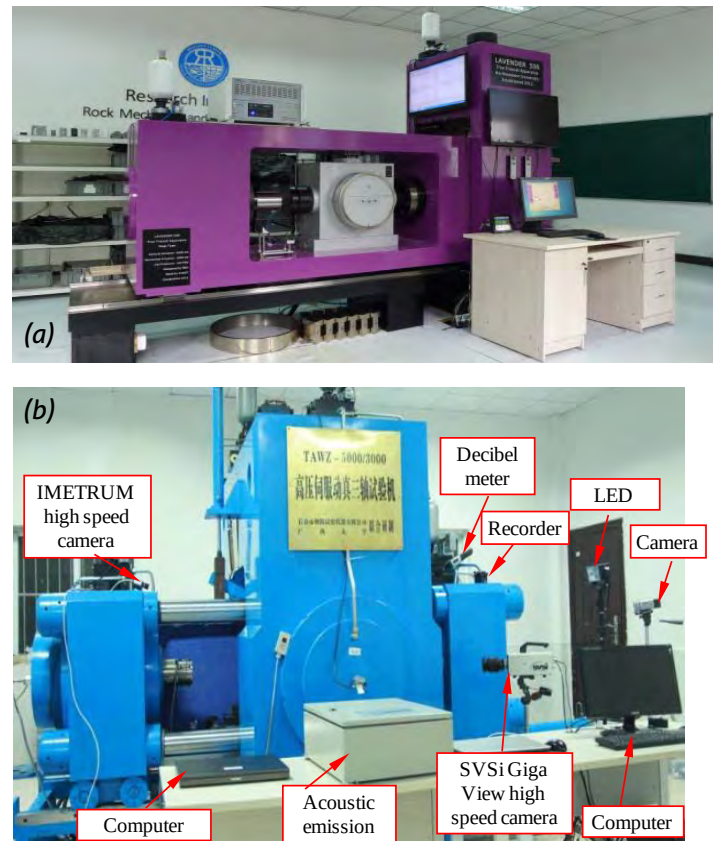


Figure 1. Testing systems designed to investigate the mechanical behavior of rocks and rock masses in large and deep underground excavations. (a) True triaxial testing system for determining the complete stress-strain curve (capacity: max $\sigma_1=1200$ MPa, max $\sigma_2=1200$ MPa, max $\sigma_3=100$ MPa, rock sample size: 50' x 50' x 100mm). (b) A true triaxial system with dynamic disturbance in two directions (max $\sigma_1=500$ MPa, max $\sigma_2=300$ MPa, max $\sigma_3=100$ MPa, cyclical dynamic disturbing load 50Hz in σ_1 and σ_2 directions, rock sample of 50' x 50' x 100mm).

The *in situ* shear and compressive strength of the rock mass have been measured at the exploration tunnels before undertaking the full-size underground excavation. *In situ* monitoring, including displacement by multi-point extensometers, loosening depth using digital borehole viewers and P-wave velocity, blasting vibration, microseismicity, and acoustic emissions during underground excavation process were also carried out [5-7].

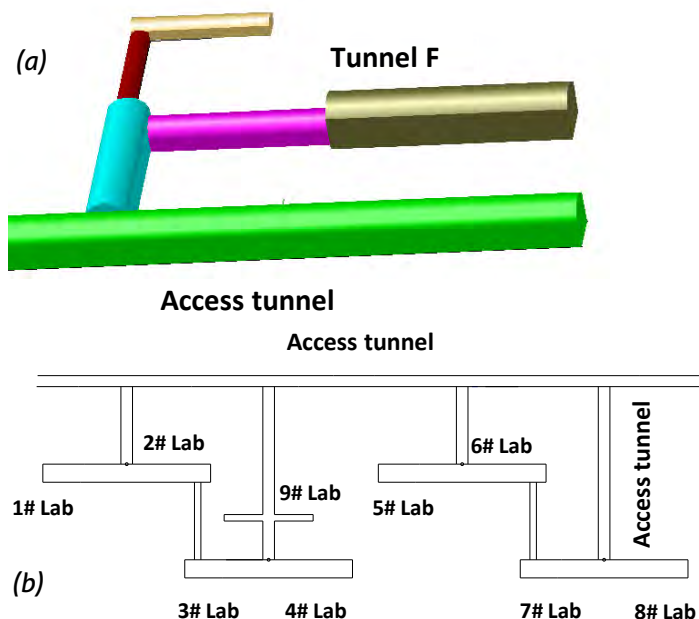


Figure 2. Jinping Underground Research Laboratories, (a) Phase I: cross sections of testing tunnels are 7'8m, 2'3m, 5'5m (D&B excavation), ϕ 12.4m (TBM excavation), overburdens of 1900m, 2430m respectively (testing tunnel F is used for physical laboratory) and (b) Phase II: cross sections of tunnels are 14m in height and span with overburden of 2370m. Some of them will be used for physical detection.

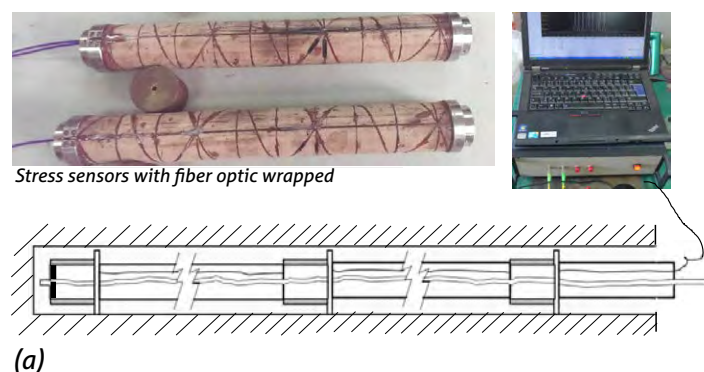
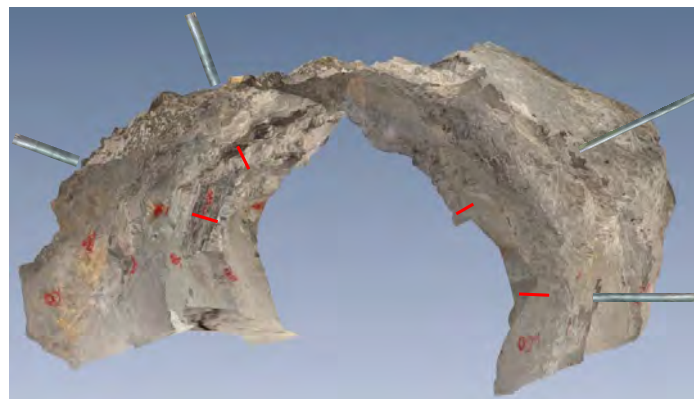


Figure 3. (a) An apparatus for distributed stress monitoring based on Fiber Bragg Grating technique. (b) The developed intelligent microseismicity system with the system sensibility of 2.2 microvolt and PTP with high accurate time clock are adopted.

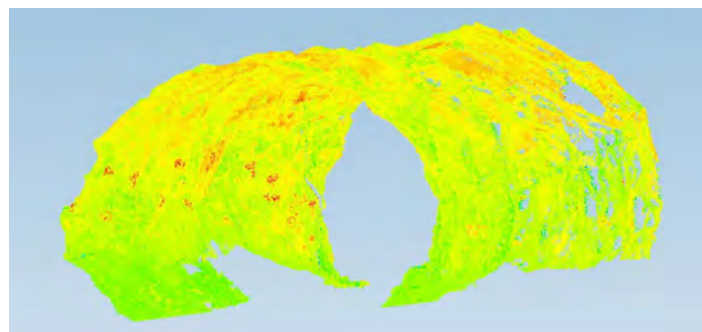
Moreover, three dimensional laser scanning and a geological mapping system were integrated with results of digital borehole televiwers to obtain 3D *in situ* geological models. Figure 4 shows some typical results of the *in situ* testing and monitoring.

3.Continuum–discontinuum numerical analysis method

A continuum-discontinuum numerical analysis method has been developed to simulate the fracturing



(a)



(b)

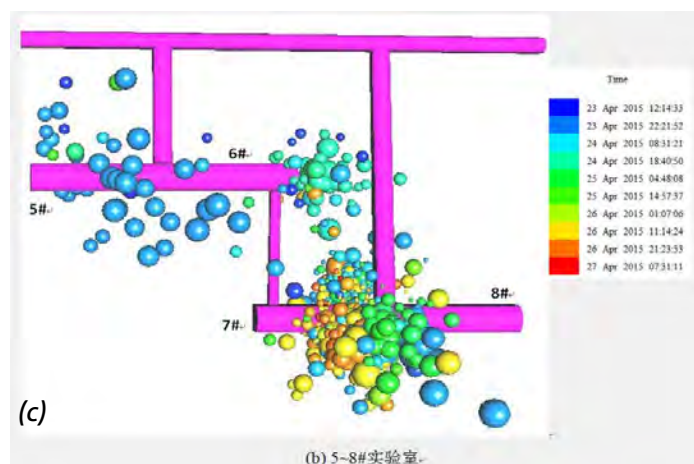


Figure 4. Typical results of (a) digital borehole televiwers and geological mapping system, (b) 3D laser scanning and (c) microseismicity during underground excavation process.

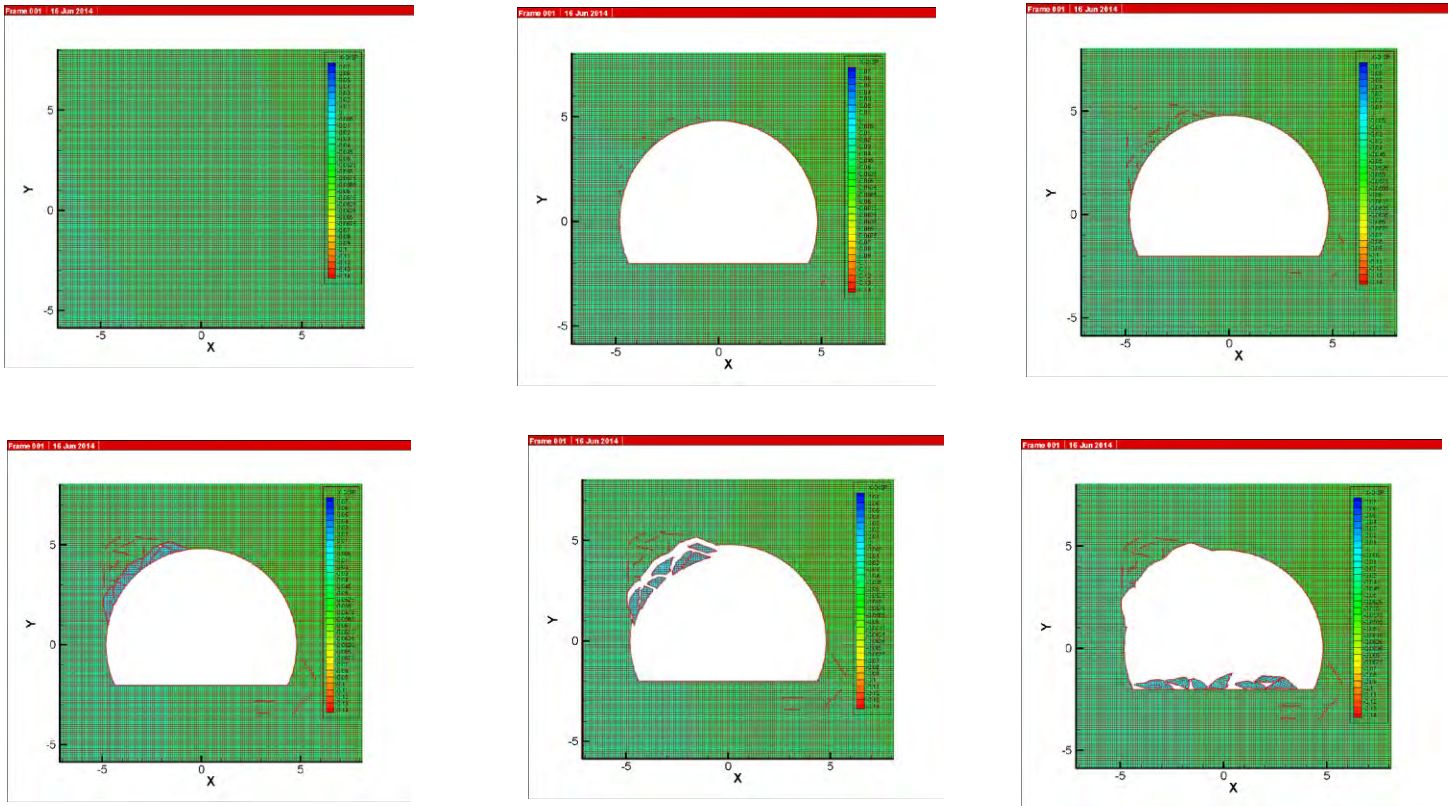


Figure 5. A modeling of rock burst progress of a tunnel at Taipingyi hydropower station in China

process of rocks [8-13]. This method is an integration of multiple techniques and theories of rock mechanics, fracture mechanics, elasto-plastic-brittle mechanics, level set method, cellular automation, partition of unity and computational mathematics. The associated numerical code has been compiled in C++ environment.

The self-developed continuum-discontinuum numerical analysis method has been applied to simulate the fracturing process of rock mass in deep underground excavations. Figure 5 shows the modeling of rock burst progress in a tunnel at Taipingyi hydropower station in China. After excavation, some cracks initiate. With the adjustment of stress, the cracks propagate and at the same time, some other cracks initiate. The cracks propagate and intersect and the intersection of cracks leads to the formation of blocks. Finally, the blocks fly out of the rock mass due to the energy release in the blocks. The simulated final failure pattern of rock burst is in good agreement with observation phenomenon (Figure 6). It is shown that, during this process—i.e., during crack initiation, propagation, multiple cracks intersection, junction, block formation and movement—one set of uniform numerical mesh is used and no remesh is needed in modeling. Using this method, the simulation of the fracturing process is greatly simplified.

4. Dynamic design method

Due to the complicated geological environment, high geostress, large span, and high sidewall, the actual failure modes of the surrounding rock in large underground caverns can vary with position. Hence, a systematic dynamic design method for large caverns has been developed and practiced in many Chinese

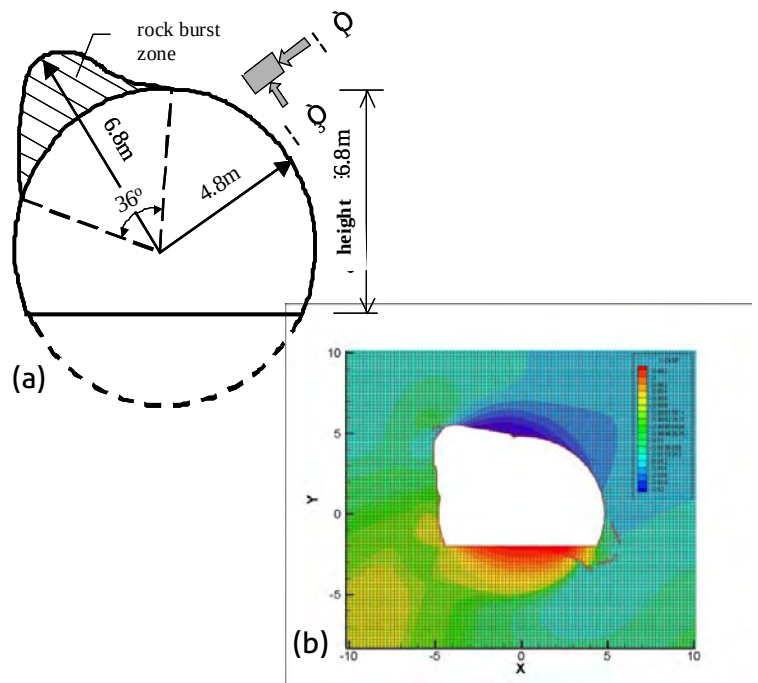


Figure 6. Failure pattern of a tunnel at Taipingyi hydropower station: (a) observation and (b) modeling

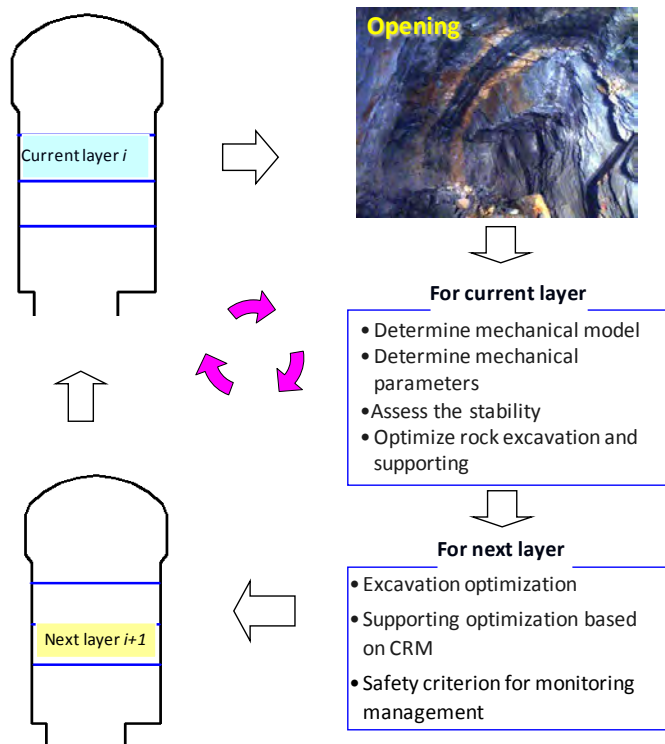


Figure 7. Close-loop structure of dynamic design method for large underground cavern.

hydraulic caverns. This method is a typical close-loop structure and consists of several key techniques (Figure 7), including determining a reasonable constitutive model, identifying reasonable mechanical parameters, dynamically optimizing excavation scheme, dynamically optimizing rock supporting based on the cracking-restraint method (CRM), and employing a safety criterion for monitoring management.

4.1 Mechanical constitutive model

Excavation of underground caverns would unavoidably induce damage and damage accumulation of the surrounding rock [14-16]. Based on detailed laboratory loading-unloading experiments in hard rock, nonlinear relationships between mechanical parameters (e.g., elastic modulus, cohesive strength, internal friction angle, etc.) and the degree of damage can be obtained in functional forms. These special functions can then be embedded into the mechanical constitutive model to describe the rock damage in large underground caverns [17].

4.2 Identification of mechanical parameters

Reasonable mechanical parameters are essential for the evaluation of mechanical safety and unloading behavior of rock mass. An intelligent back-analysis method of displacement and loosening depth has

been developed to identify rock mass mechanical parameters. Dynamic feedback analysis has been conducted. Considering the 3D spatial excavation characteristics of a large underground cavern, the loop recognition method for mechanical parameters of rock mass identifies the equivalent mechanical parameters using multi-monitoring data and an intelligent algorithm at phase i of cavern excavation. Then, the reliability of these identified parameters is validated at phase $i+1$ excavation of cavern. The equivalent mechanical parameters are achieved after several excavation phases of cavern by circular recognition. Application to the caverns of Jinping II underground hydropower station indicates that the proposed method is credible, and the identified mechanical parameters are both reliable and stable [1,18].

4.3 Dynamic optimization of the excavation scheme

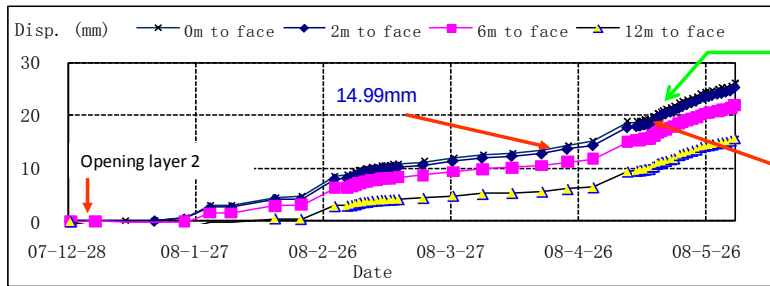
Reasonable excavation procedures can reduce rock damage and improve the safety margin of caverns. An intelligent algorithm can be applied for gaining the ideal excavation scheme with the goal of getting the best stability state. This method can overcome the shortage of practical experience during engineering design and construction.

4.4 Cracking-restraint method

Hard rock tends to develop cracking under high geostress in large underground caverns and tunnels. A cracking-restraint method for supporting design has been developed. It aims to restrain fracture generation, opening, expanding, and interconnection. The design controls the development of excavation damaged zone of the surrounding rock mass. Not only the support parameters, including thickness of shotcrete, spacing, length and arrangement of rockbolts, etc. but also the support time is determined. A successful application of the method in five diversion tunnels at the Baihetan hydropower station, China, indicated that it is an applicable and rational method for restraining cracking in hard rock tunnels subjected to high stress [19].

4.5 Safety criterion for monitoring management

A simple table of safety criteria was proposed for field engineers and managers to provide the bridge between theoretical analysis and practical engineering applications. This table consists of two indexes (displacement increment and velocity), and is divided in three categories (safety, caution, and danger) for monitoring management. Due to its easy interpretation, this device can provide a simple tool both for



Support by anchor cable



Figure 8. Application of safety criterion for monitoring management in the powerhouse of Jinping II power plant

field stability evaluation and as a warning of potential instability issues, which needed to be addressed by reinforcement and support, as shown in Figure 8.

5. Monitoring, warning and mitigation of rockburst

5.1 Monitoring of rockburst in large and deep underground excavations

A real-time microseismicity monitoring method has been devised to record the microseismicity in the rockburst development process. Layout of the microseismicity sensors in one deep-buried tunnel in Jinping is shown in Figure 9(a). Several types of microseismicity sensors are used and multiple monitoring stations are coordinated. The sensors are arranged in such a way that they can be moved as the tunnel face advances.

Layout of the microseismicity sensors in a large underground powerhouse in Baihetan, China, is shown in Figure 9(b). The microseismicity sensors were primarily installed on the east side of the main/auxiliary powerhouse, where the major spalling and rockburst occurred. Different kinds of sensors (i.e., geophone and accelerometer) were used to study their respective applications. The boreholes for installing the microseismicity sensors were drilled from two pre-excavated tunnels.

A sectional velocity model [20] and hierarchical strategy based on particles swarm optimization (PSO) [21] are used for microseismicity source location. Results from numerical simulation show that when using a sectional velocity model, the average location error is reduced by 78.3% (from 13.05 to 2.83 m). The case of the deeply-buried tunnels in Jinping shows that the measured velocities are dependent on the geological conditions.

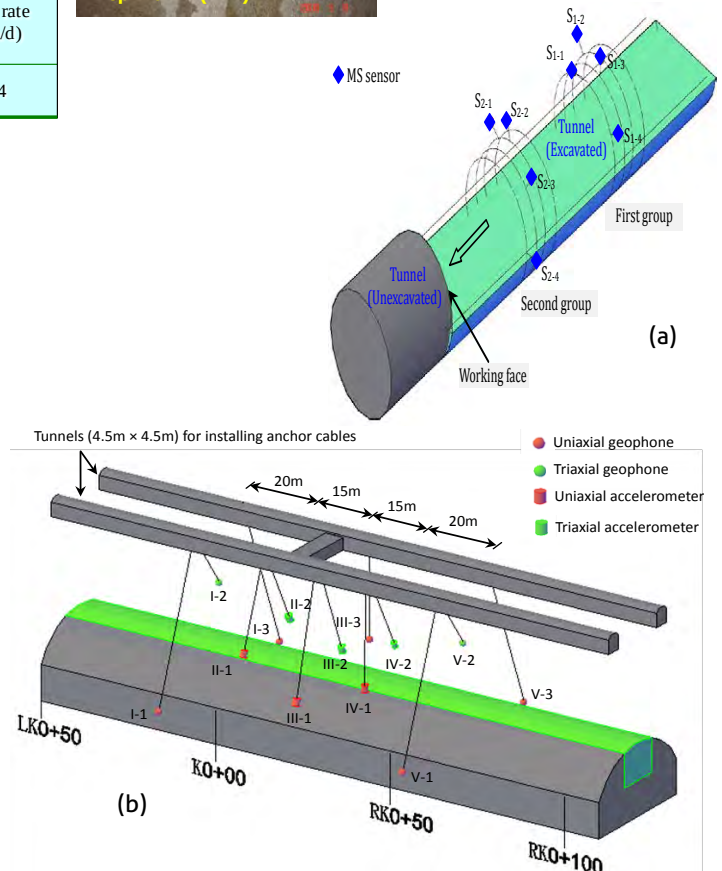


Figure 9. Layout of the microseismicity sensors: (a) in a deep-buried tunnel of Jinping underground plant and (b) in the large underground powerhouse of Baihetan hydro-power station.

5.2 Rockburst warning in deep-buried tunnels

Dynamic rockburst warning activity was conducted in the deep-buried tunnels of the Jinping II hydropower station. The cumulative monitoring length is about 12.4 km. Warnings were given in about 88% of the rockbursts (243 rockbursts in total). As an example, comparison of the warning results with actual occurrence of rockbursts in the given zone of tunnel #3 is shown in Figure 10. During the continuous microseismicity monitoring, there were no serious rockburst casualties.

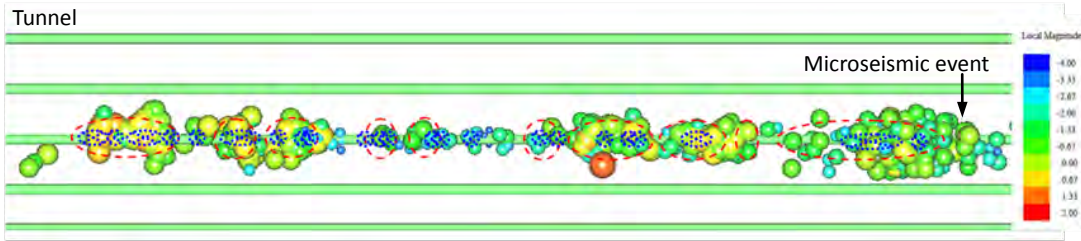


Figure 10. Comparison of the warned zones of rockbursts with actual zones in #3 TBM tunnel at overburden of 1700-2200 m in Jinping II.

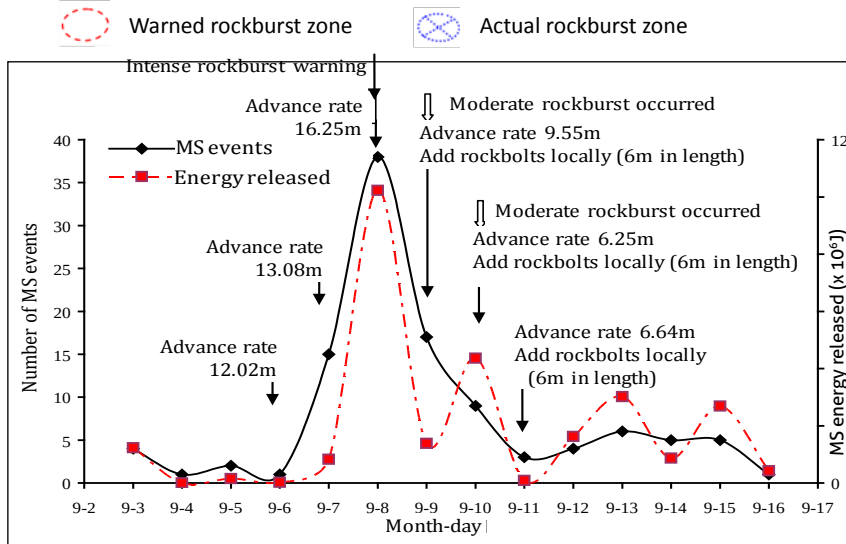


Figure 11. A case of rockburst mitigation process in a deep tunnel of Jinping II hydropower station.

The warning formula for different types of rockburst based on microseismicity can be expressed as [22],

$$P_i^r = \sum_{j=1}^n w_j^r P_{ji}^r$$

where r is the rockburst type (strainburst, strain-structural slip rockburst, fault-slip rockburst); i is the rockburst intensity (extremely intense, intense, moderate, slight, or none); j is the microseismicity parameter; n is the number of microseismicity parameters used to express microseismicity; w is the weighting coefficient; and P is the functional relationship between microseismicity and rockburst. The probability of every rockburst event ranges from 0 to 100%. The larger the probability, the greater the rockburst risk.

Many factors are considered and a variety of means are adopted during the establishment of the above rockburst warning formula, including (a) the rockburst types; (b) the warning results, evolved from whether there is a rockburst or not, to the risk of different rockburst intensities; (c) a dynamic and suitable spatial warning volume for rockburst risk; (d) clustering analysis method to identify and select typical rockburst cases; (e) multiple microseismicity parameters, combined to make a comprehensive rockburst warn-

ing (The mode of combination is to sum the warning results using appropriate weighting coefficients); (f) weighting coefficients which are searched by intelligent global PSO algorithm; and/or (g) a real-time dynamic updating mechanism.

Another way is to establish a neural network model to describe the real-time monitored microseismicity with the intensity and failure depth of the rockbursts [4]. The microseismicity evolution based neural network model can be used to predict the intensity and failure depth of the rockburst in the vicinity of a given zone.

5.3 Mitigation of rockburst risk

A 'three-step' strategy has been proposed to reduce the risk of rockbursts [23]. The three steps are as follows: (a) reducing the concentration of energy and stress induced by excavation; (b) releasing or transferring part of the energy stored in the rock mass; and (c) absorbing part of the energy released by rockbursts. The relationship between stress concentration and stress induced by excavation, including excavation sequences, height of bench, daily advancing rate, etc., is studied for the specific rock mass. A new index, elastic release energy (ERE), is used for this optimization of excavation parameters. The location and spacing of destressing boreholes are analyzed for releasing part of the energy stored in the rock mass. For a given project, the focus is on the potential path of energy transfer. The analysis will determine support of various types to satisfy the design requirements.

Based on the real-time monitoring and warning results, the excavation and support design are dynamically adjusted according to the proposed dynamic control strategies in order to reduce rockburst risk. An example is the deep tunnel of Jinping II hydropower station (Figure 11). The main measures used to mitigate the rockburst risk in this case were to slow down the advance rate and to strengthen the support facilities based on the warning result. Thus, both the microseismicity and rockburst damage were reduced successfully, and no casualties were recorded.

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Injection-Induced Seismicity and Geohazard Risk in Oil, Gas and Geothermal Energy Applications

Submitted by Dr. Azra N. Tutuncu, Professor, Harry D. Campbell Chair and Director, UNGI;
Chair: ARMA – Induced Seismicity Committee

Induced seismicity has become one of the hot topics gaining significant attention from the public, the oil industry, and government regulatory organizations. Since it requires extensive multi-disciplinary geomechanical expertise to minimize and mitigate any potential geohazards originating from induced seismicity events, ARMA established a Technical Committee on Induced Seismicity (ARMA-IS). The mission of the ARMA-IS Committee is 1) to support and conduct activities that contribute to the development and dissemination of the fundamental geomechanics knowledge behind induced seismicity, 2) to engage ARMA members in technical activities around this topic area, and 3) to support the vision of ARMA. The membership of ARMA-IS has been growing since its formation. The Committee's current understanding of induced earthquakes is summarized in this article along with a discussion on the key scientific challenges to be met in assessing this geohazard.

Introduction

The United States has vast gas shale and tight oil reserves, as well as geothermal energy potential. With increasing unconventional activities including innovative techniques, such as horizontal drilling and multistage hydraulic fracturing stimulation, shale formations have become economically feasible reservoirs for oil and gas production. These fields are located in historically low seismicity areas with expectations to have minor induced seismicity potential. Yet, recent sizable earthquakes (2–5.3 Richter scale magnitudes) in Texas, Oklahoma, Colorado, Pennsylvania and Ohio—states originally considered aseismic—have raised concerns and associated interest in the role of fluid disposal operations. Similarly, the role of fluid injection during hydraulic fracturing on induced seismicity has also been scrutinized (Raleigh et al., 1976; Grasso, 1992; Segall et al., 1994; Tutuncu, 2008; Rutqvist et al., 2013; Tutuncu, 2014; McGarr, 2014; Tutuncu and Bui 2015; 2016).

Improved monitoring of earthquakes

The U.S. Geological Survey (USGS) reported significant increases in the number of earthquakes with Richter scale $M > 3$ from an average of 29 per year between 1970 and 2000 to over 100 per year in the period of 2010 – 2015 (as summarized in Figure 1 (Ellsworth, 2013; Folger and Tiemann, 2015; USGS, 2015)). Most of these events have been associated with waste disposal or water injection applications for enhanced oil recovery operations. The magnitude of these small earthquakes typically increases as the total injected fluid volumes increases. Injection pressures as well as the injection rates have been subject to investigation for determining the key influencing factors of these tremors.

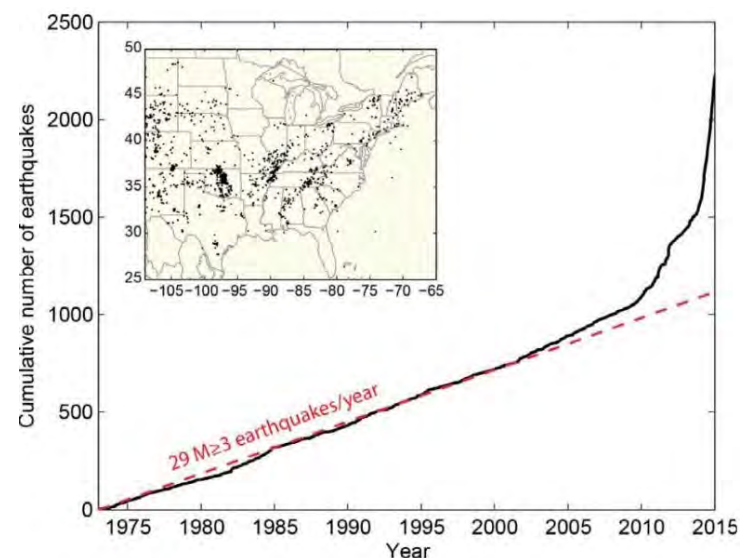


Figure 1. Cumulative number of Magnitude (M) 3.0 or greater earthquakes in the Central and Eastern United States between 1970 and 2014 (after USGS, 2015). The dashed line indicates 29 earthquakes per year between 1970 and 2000. There is a sharp increase in the rate of earthquakes since 2009.

The increasing number of seismic stations in recent years for monitoring seismicity provides more extensive coverage with higher resolution even in the remote corners of the U.S. Further, advanced technologies utilizing the geophone assemblies for recording, data acquisition, signal processing, and communication networks, have increased small magnitude earthquake detection capability. This has occurred in many states that have not been part of the monitoring network due to their aseismic geographic locations. The ability to include observations through network availability has also played a role in the number of increased recorded earthquakes.

Most of these earthquakes are in the Richter magnitude range of 3–4, large enough to have been felt by anyone in close proximity to the epicenter, yet small enough to rarely cause damage. There were a few larger events including the M 5.6 Prague, Oklahoma; the M 5.3 Trinidad, Colorado; and M 4.8 Timpson, Texas, where property damage also occurred. The majority of these seismic activities may be associated with the disposal of wastewater through deep well injection.

Oil and gas related induced seismicity

The microseismic monitoring from the hydraulic fracturing operations in shale gas and tight oil reservoirs indicate event magnitudes ranging typically between -4.0 and -1 depending on the injected fluid volumes, pressure, rate, formation and fluid properties, and geology of the area; in addition, the density and distribution of the natural fractures, the difference between the in situ horizontal principal stress magnitudes, and local tectonics must also be considered.

A classical induced seismicity study was initiated in 1957 in Rangely Field, Colorado, where water injection was practiced for enhanced oil recovery. In 1962, pore pressure in the field noticeably exceeded the original pore pressure of 2,465 psi. The area of injection was experiencing around 50 minor earthquakes per day based on the geophone records 65 km from the field at Uinta Basin Seismological Observatory. When fluid injection ceased, the earthquakes dropped from 50 to fewer than ten per day. Upon restart of injection, the number of events jumped back to over 50 earthquakes per day. The 2-year study indicated a direct relation between fluid injection and level of seismicity (Raleigh et al., 1976).

Induced seismicity events not limited to oil and gas

Induced seismicity has also been observed in civil and mining engineering applications including mine extractions, solution mining, underground nuclear tests (Boucher et al., 1969), large impoundment reservoirs behind dams (Simpson, 1986), Enhanced Geothermal Systems (EGS, Majer et al., 2007; Zang et al., 2014), CO₂ and other fluid injections for Enhanced Oil Recovery (EOR) operations (Raleigh et al., 1976; Zoback, 2010; Zoback and Gorelick, 2012).

An earlier case of induced seismicity was recorded at the Rocky Mountain Arsenal, a chemical weapons manufacturing center in the Denver (Colorado) metropolitan area (Evans, 1966). Evans investigated the correlation between the injection of highly toxic waste fluid from the Rocky Mountain Arsenal into its deep (12,045 ft.) waste collecting well and the recorded seismic activity. The well was cased and sealed to a depth of 11,975 ft. with the remaining 69 ft. left as an open hole for the injection of liquids. Less than a year after injection started, earthquakes began occurring (in 1967, this activity included 2 large earthquakes with magnitudes of 5.3 and 5.2). The use of the well was discontinued in February 1966 due to the triggered earthquakes in the area. The seismic events resulting from the fluid injection had epicenters within five miles of the Arsenal's well and were aligned with the orientation of a system of natural vertical fractures found in the Precambrian rocks in the area. Research showed that the injected fluid interacting with an existing fault system lowered the frictional resistance, allowing fault slippage and rupture and triggering a significant number of

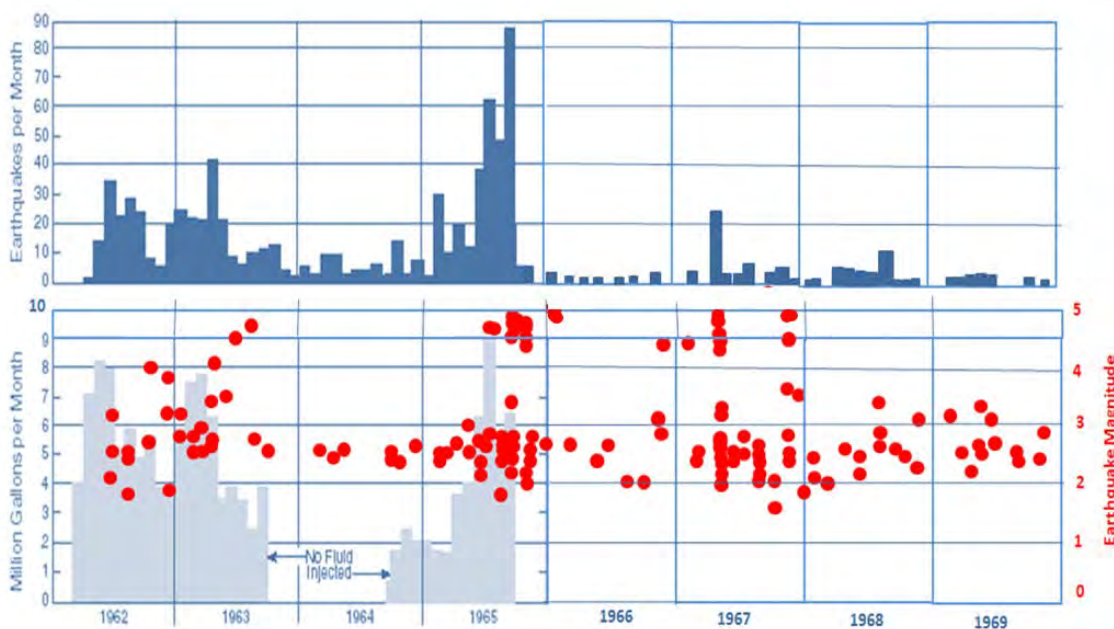


Figure 2. The relationship between the injected water and induced earthquakes in Rocky Mountain Arsenal [modified after Evans (1966)].

earthquakes (Figure 2). The well remained unused for nearly 20 years and was permanently sealed in 1984. The site has recently been reclaimed and is currently used as a public park.

The Basel EGS Deep Heat Mining project is relevant for our discussion here since induced seismicity led first to suspension and then termination of the project. The city is located in a high-stress region related to the largest and most destructive M 6.5 earthquake in Switzerland. (It occurred in 1356, and resulted in the destruction of Basel.) Six geophones were installed in a borehole near the Basel injection well. The geothermal stimulation recorded more than 13,500 potential events (Dyer et al., 2008). During the post-stimulation period from 13 December 2006 onward, a further 350 locatable events were detected up to 2 May 2007, by which time events were occurring sporadically at around one per day. Following a three year study, the Basel HDR project was terminated in December 2009 even though the largest recorded seismicity was only M 3.1 – M 3.2 (in early 2007).

Another EGS project, the European Hot Dry Rock (HDR) site at Soultz-sous-Forêts, is a well-studied example, with a large dataset collected over 15 years in addition to the seismic data. The EGS reservoirs were created at two depths (11,500 ft. and 16,400 ft.), with the deeper reservoir in the high temperature (200 oC) basement rock in Soultz. Concern about induced seismicity has shortened the activities, and no further large-scale hydraulic stimulations in the basement have been planned after a M 2.9 seismic event took place early on in the project.

Characteristics of induced seismicity

The magnitude and orientation of in situ stresses in the vicinity of the fluid injection or withdrawal area, formation pore pressure and its altered magnitude due to the injection/withdrawal process, as well as injection rates and injection/production fluid volume each play key roles in the occurrence of induced seismicity events and associated geohazard risk. Presence, orientation, and properties of the faults nearby the injection area as well as formation geomechanical and petrophysical properties also have important roles.

In most cases, the amount of energy released in seismic waves is estimated from the earthquake magnitude through the semi-logarithmic magnitude-moment relations in Equations 1 (Gutenberg and Richter, 1954) and 2 (Hank and Kanamori, 1976), and presented in Figure 3.

$$\text{Log}_{10} E = 1.5 M + 11.8 \quad (1)$$

$$E_s : E_s = \frac{M_o}{2 \times 10^4} \quad (2)$$

where E is the seismic energy released in erg (converted to Joule), M is the earthquake magnitude, and Mo is seismic moment in dyne-cm.

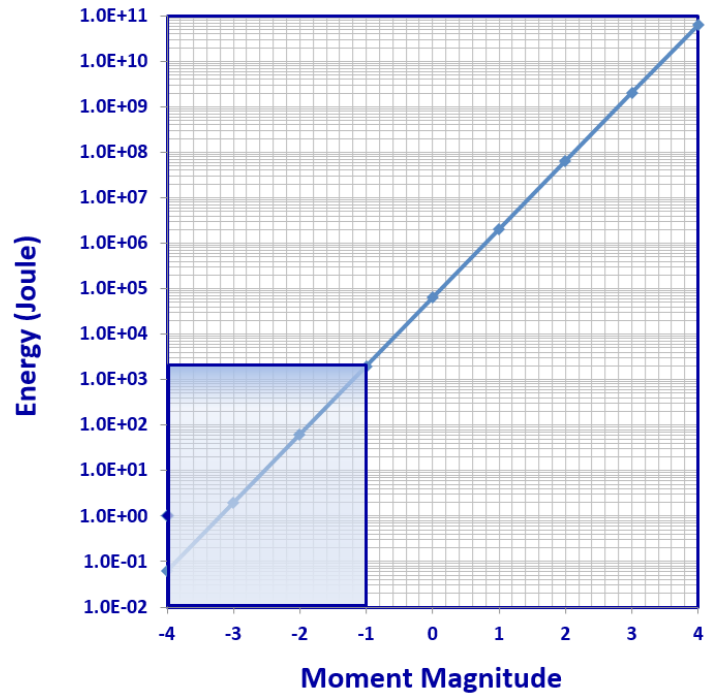


Figure 3. Energy released versus Moment Magnitude in an earthquake. The shaded box corresponds to microseismic events caused by hydraulic fracturing using Equation 1 (Gutenberg and Richter, 1954) and Equation 2 (Hank and Kanamori, 1976) and converting the Energy into Joule.

McGarr (2014) has introduced a correlation between fluid volume injected and upper bound for the seismic moment. This is based on the assumption that fluid is injected into a saturated formation causing deformation seismically and eventually an earthquake having a Gutenberg-Richter magnitude-frequency distribution of b value of 1 and an average shear modulus of $G = 30 \text{ GPa}$.

$$M_{o \text{ max}} = G \Delta V \quad (3)$$

The calculated maximum moment as a function of fluid volumes injected is shown in Figure 4. Rocky Mountain Arsenal was also included in the same figure for comparison. It is evident just from the limited data available that waste disposal operations give the highest potential for induced seismicity. Flow back

fluid after the hydraulic fracturing can be treated and reused in other oil and gas wells. Yet, most often, the waste fluid produced from conventional oil and gas production in the U.S. amounts to over 800 billion gallons every year. More than one-third of it is managed through the underground injection control (UIC) program for permanent disposal in “Class II” wells. The Federal UIC program was introduced in December 1974 with the Safe Drinking Water Act administered by the U.S. Environmental Protection Agency (EPA). The law was intended to protect Underground Sources of Drinking Water (USDW) from impacts related to underground fluid injection practices; it delegated primary responsibility for regulation of Class II UIC wells to the States for underground injection of oil and gas exploration and production waste in 1984.

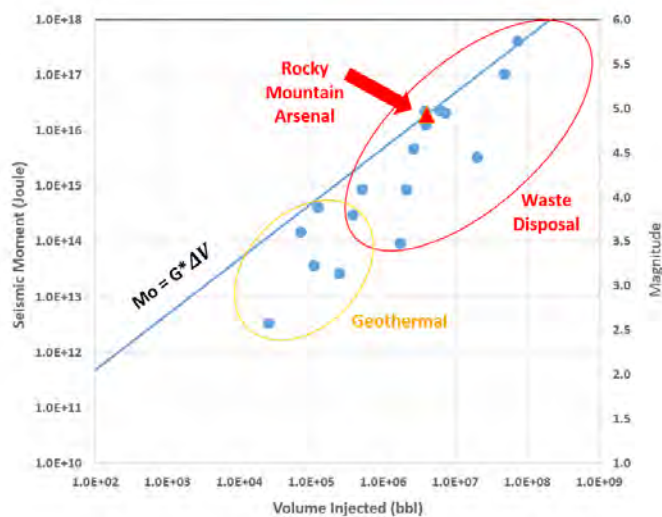


Figure 4. Seismic Moment as a function of injected fluid volume in recent induced seismicity events. Maximum moment was calculated assuming $G=30$ GPa, $b=1$ using Equation (3). The red triangle corresponds to Rocky Mountain Arsenal maximum moment (modified after McGarr, 2014).

The high injection rates implemented in the waste disposal operations are still an active research area. The oil industry and academic efforts have been focused on this for a fundamental understanding of the mechanisms and prevention of any associated induced seismicity and geohazard. If the injection site is close to a fault at these operations, fluid is forced along the fault discontinuity, relieving the stress acting on the fault and altering the stress state. As a result, reactivation of the fault may be imminent. That most often triggers the recorded induced seismic events. There are approximately 150,000 permanent disposal wells in the US and about 40,000 of these

wells are closely associated with the disposal operations connected with oil and gas activities (UIC type II wells, NRC, 2012). Yet, only several cases of induced seismic events have been recorded. Therefore, the presence of fault and injection volumes and rates are not the only critical factors resulting in induced seismicity. The formation properties and the critical stress state of the crust may also introduce key input for the activities. In order to capture this slip, we can revisit the Gutenberg–Richter law that we have discussed earlier for defining maximum seismic energy, but this time using the relationship between total number of earthquakes and their magnitudes: “ $\text{Log}_{10} N = a - b \log M$ ”, where N is the number of events with magnitude greater or equal to M , and a and b are constants.

The slope b is interpreted as an indicator of subsurface tectonic activity. If $b \leq 1$, the activities are considered to be caused by tectonic activation such as fault reactivation (Kratz et al, 2012) while $b \geq 2$, tectonic relation to seismic activity may be dismissed.

An investigation of the microseismic records from a few wells using several techniques including Gutenberg-Richter “ b ” factor indicated that the microseismic events were not the cause of tectonic reactivation of the faults in McMullen County in Eagle Ford. Horizontal wells with 14 hydraulic fracturing stages conducted have been used as examples to represent the controlled microseism in hydraulic fracturing in Eagle Ford, with associated b factor between 1.9 and 2.3 (Figure 5).

The distance to the fault determines how early the fault will slip as a result of the fluid injection operation. Faults near injectors introduce slip conditions earlier than the faults away from the injection well in a no-flow boundary reservoir. The stress acting along the fault will vary as a function of the injection rate, injection time, and distance to the fault. We have recently developed a predictive coupled geomechanical and flow model based on empirical relations useful for estimating the magnitude of earthquakes. An example of estimated seismic magnitude as a function of fault length and associated shear stress changes in an Eagle Ford injection well is shown in Figure 6. More details on the model have been presented in Tutuncu and Bui (2015; 2016).

A case study from a hydraulic fracturing operation with fault reactivation is presented in Figure 7. Maxwell (2011) investigated the microseismic imaging of multistage fracturing on three horizontal wells (A, B, C) in the Montney shale well pad, integrating the mi-

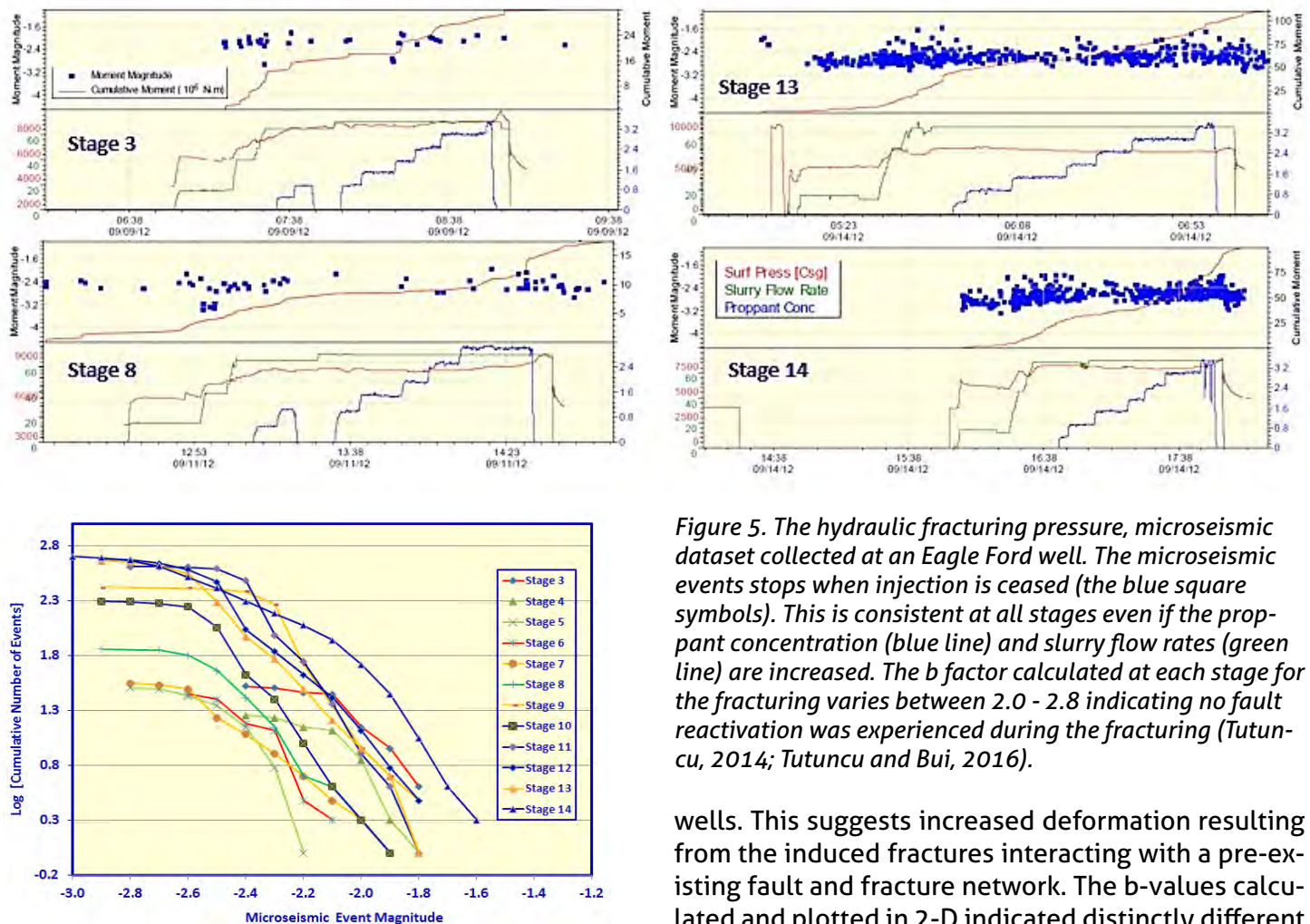


Figure 5. The hydraulic fracturing pressure, microseismic dataset collected at an Eagle Ford well. The microseismic events stops when injection is ceased (the blue square symbols). This is consistent at all stages even if the proppant concentration (blue line) and slurry flow rates (green line) are increased. The b factor calculated at each stage for the fracturing varies between 2.0 - 2.8 indicating no fault reactivation was experienced during the fracturing (Tutuncu, 2014; Tutuncu and Bui, 2016).

well. This suggests increased deformation resulting from the induced fractures interacting with a pre-existing fault and fracture network. The b -values calculated and plotted in 2-D indicated distinctly different values ($b \sim 1$ for fault activation near the NW-SE trend of high seismic deformation and $b \sim 2$ for hydraulic fracturing zones). The linear microseismicity near the A well had higher b -values, consistent with a normal hydraulic fracture orthogonal to the expected minimum stress direction. In this case, the NE-SW trend of events near well A was consistent with a strike-slip shear failure in the same direction. The NW-SE trend near wells A and B was consistent with a dip-slip

microseismic data with other reservoir characterization attributes. The high level of microseismicity occurred in the low Poisson's Ratio areas indicating the magnitudes of the horizontal stresses will be equal to a tectonic component plus a component proportional to vertical lithostatic load and the Poisson's ratio. Relatively large deformation occurred along the NE boundary of the seismically active region, with a continuing trend in a NW-SE direction parallel to B and C

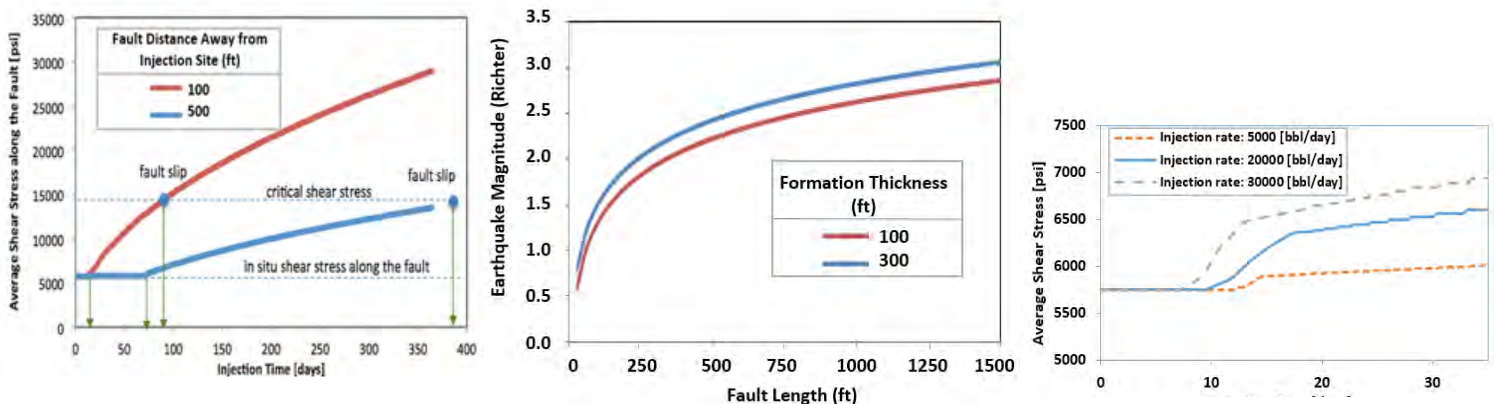


Figure 6. Effect of distance of fault from injection area, fault length and injection rate on the shear stress acting along the fault and associated induced seismicity magnitude predicted using the coupled model developed (Tutuncu and Bui, 2015; 2016).

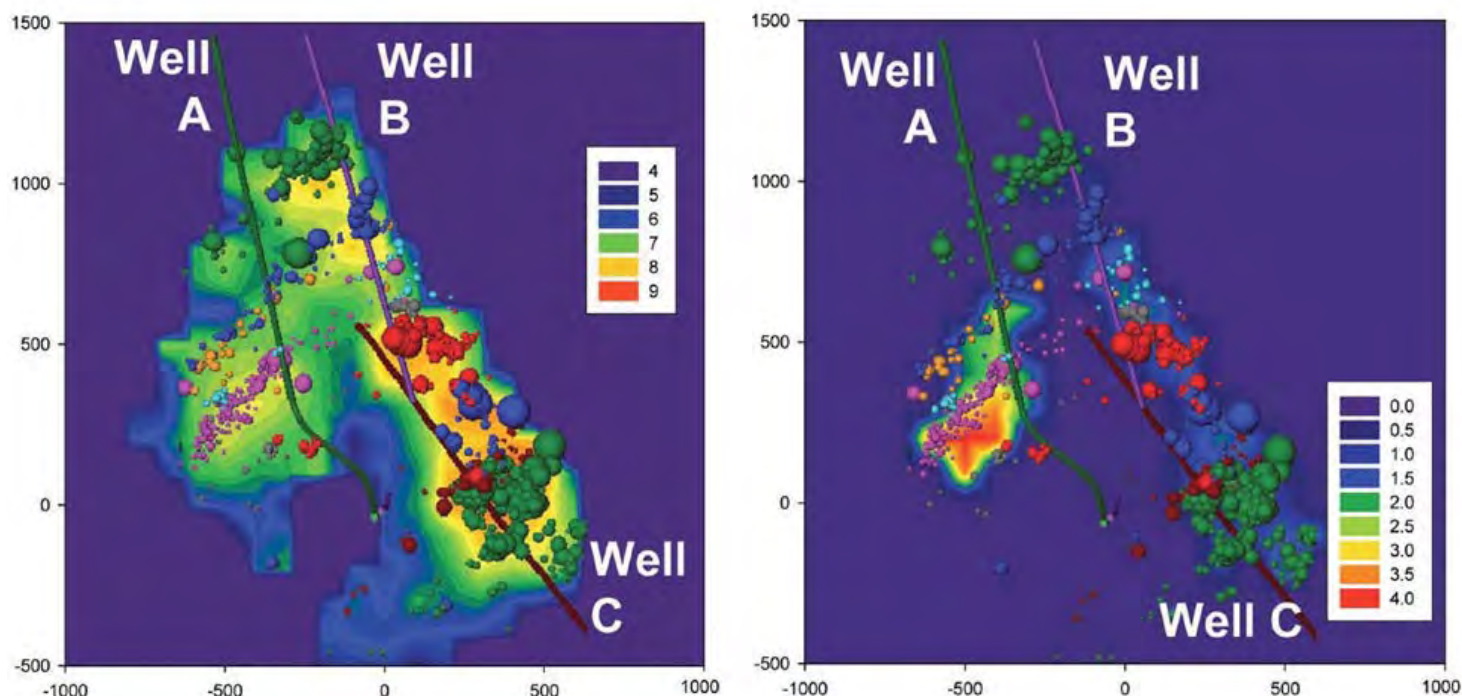


Figure 7. Comparison of microseismicity and log seismic moment density in 3 wells (A, B, C) that were hydraulically fractured in Montney shale (a) microseismicity overlaid on seismic moment density shown with colored contours (left), (b) microseismicity overlaid on b-value colored contours (right) (Maxwell, 2011).

mechanism in the same direction as the main direction of hidden fault detected through the microseismic and other formation property attribute use. This knowledge resulted in changes in the development plan for the field as well as operational parameter changes to prevent any induced seismicity that may create geohazards in the area.

Regulatory requirements for injection-induced seismicity

Disposal well operators are required to report once a year only the monthly averages of injection rates and pressures. Due to the changing regulations addressing concerns about the induced seismicity, there has been significant effort invested in better understanding of the science behind induced seismicity. Ohio and Oklahoma are the first two states to approve new rules requiring operators to collect daily data and to provide them to regulators upon request. Colorado and Texas regulators are also making changes in the rules for providing additional geologic information, including local seismic data from the USGS.

Many states where induced seismicity has been observed have developed Risk Management Plans, using a "traffic light" strategy to classify conditions; a typical illustration of the strategy is presented in the following graphic. The use of a traffic light strategy should be based on local conditions, demographics and codes (after Bull, 2013).

Regulatory agencies in the oil and gas industry have started to use the Modified Mercalli Index (MMI). The index measures the intensity at which effects of a seismic event on the people and structures in a given area range from unnoticeable to devastating. The traffic light strategy is used in handling the induced seismicity activities for a permitting process, in order to ensure operational safety and identify mitigation requirements. An example is a case in Colorado, where the M 3.4 Greeley earthquake on 31 May 2014 was followed by M 2.6 on 23 June 2014. It was related to a disposal well in a seismically inactive area and resulted in the Colorado Oil and Gas Conservation Commission (COGCC) shutting down the well for 20 days for evaluation; reinjection began after 20 days. COGCC implemented a new seismicity protocol after this event and the injection rates have been closely monitored. Since then, seismic events have been limited to no $M \geq 2.5$ events within 2.5 miles of this well. Other disposal wells have been similarly regulated. In Ohio, a comparable limited buffer zone has been set within a three mile radius from the injection site.

The occurrence of the third largest magnitude earthquake (3.9 Richter Scale) in Oklahoma's history on 14 February, 2016 caused Oklahoma state regulators to immediately issue a directive to the operators of the 245 injections wells to reduce wastewater injection volumes by 40 percent. This equates to approximately 500,000 barrels in a 5,200 square-mile area of the

Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	none	none	none	Very Light	Light	Moderate	Moderate Heavy	Heavy	Very Heavy
Peak Acceleration (%g)	<0.17	0.17 to 1.4	1.4 to 3.9	3.9 to 9.2	9.2 to 18	18 to 34	34 to 65	65 to 124	>124
Peak Velocity (cm/s)	<0.1	0.1 to 1.1	1.1 to 3.4	3.4 to 8.1	8.1 to 16	13 to 31	31 to 60	60 to 116	>116
Magnitude	1 – 2.9	3 – 3.9	4 – 4.4	4.5 – 4.9	5 – 5.4	5.5 – 5.9	6 – 6.4	6.5 – 6.9	7.0+
Modified Mercalli	I	II to III	IV	V	VI	VII	VIII	IX	X & GS

Traffic Lights *



Continue Operations — no seismicity felt at surface (MMI I-III+)



Modify operations—seismicity felt at surface (MMI III-IV+)



Suspend operations—seismicity felt at surface with distress and/or damage (MMI V+)

western and central part of the state. Oklahoma regulators had already ordered companies with wells within ten miles of the epicenter of earthquakes to reduce their well disposal activities in January 2016.

Next steps/further research

Further research and continuous microseismic and geomechanical monitoring in pilot operations -- as well as laboratory acoustic emission and geomechanical measurements -- will provide better understanding of the mechanisms controlling the induced seismicity in sedimentary and basement formations. Early detection of undesirable geomechanical changes can be identified using the real time monitoring data and geomechanical models. This will enable the operators to take preventative actions by modifying the injection parameters for safe operations and successfully managing EGS, CO₂ storage, oil and gas stimulation, and production and waste disposal. By placing proper scientific and preventive effort in the design and execution of the injection projects, along with effective regulations, the unconventional resources including geothermal energy resources can be fully unlocked for the energy needs in the foreseeable future.

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■ Online Course in "Reservoir Geomechanics."

Professor **Mark Zoback** (Stanford University, ARMA Fellow) will offer an online course in "Reservoir Geomechanics." This interdisciplinary course encompasses the fields of rock mechanics, structural geology, earthquake seismology and petroleum engineering -- all combined to address a wide range of geomechanical problems that arise during the exploitation of oil and gas reservoirs. The initial session of the course will be 28 March 2016, it will last ten weeks, and will consist of twenty 90-minute lectures. These sessions will be conducted for free. There will be eight homework assignments. A *Certificate of Accomplishment* will be awarded to students with a grade of 70% or better. For more information and to enroll go to the following URL: <https://lagunita.stanford.edu/courses/EarthSciences/ReservGeomech/Spring2016/about>

■ Short courses announced

Professor **Pinnaduwa Kulatilake** (University of Arizona) will offer three 2-day and one 1-day courses, taught in Tucson, AZ in May 2016, on a variety of rock mechanics subjects. Please contact kulatila@u.arizona.edu

■ Forming an ARMA Student Chapter

by Houman Bedayat

As ARMA continues to grow and develop as a professional organization, it is important to ensure continuity. One facet of this is the formation of Student Chapters at institutions with a focus on rock mechanics, geoengineering, and related disciplines. Student membership in ARMA provides a communications link, a forum, and an information resource for members, related organizations, and the public. ARMA also encourages students to participate in activities that will address issues, challenges, and opportunities related to ARMA's mission.

ARMA Student Chapters require a full-time faculty advisor. Application is then made to ARMA; its Board of Directors reviews and approves the application. To receive more information on student chapters contact info@armarocks.org.

Current chapters are located at the Colorado School of Mines, Louisiana State University, University of Utah, West Virginia University, Missouri University of Science and Technology, and Texas Tech University.

■ Catching up with Future Leaders

ARMA's Future Leaders have been involved in a number of recent activities. Upon request by the ARMA Board of Directors, the Future Leaders are updating the ARMA website; this is being done under the leadership of Ghazal Izadi and a small committee. An initial task is posting biographical information on the various committees, groups, and staff of ARMA. Current Future Leaders are in the process of nominating the fourth class of leaders, the Class of 2016. And their traditional work in developing sessions and workshops for the symposium is currently underway.

■ Joining Newly Formed Hydraulic Fracturing Community

by Gang Han, Chair, ARMA Technical Committee on Hydraulic Fracturing

ARMA is pleased to announce the establishment of the **Hydraulic Fracturing Community**. Following the kick-off of TCHF (Technical Committee on Hydraulic Fracturing), the community is open to all ARMA members interested in hydraulic fracturing and willing to share their theoretical development, modeling advancement, lab findings, and field experience. Community members will be updated on TCHF activities, including publications and the Workshop on Hydraulic Frac-

turing in June in Houston (see www.armasympo-sium.org). The committee leads the community activities and steers its developments in three main technical areas: (1) physics and modeling; (2) measurement and diagnostics; and (3) fluid and proppants.

If you are interested in joining the Hydraulic Fracturing Community, please send Gang Han an email with your affiliation and contact information (Gang.han@aramcoservices.com). Meanwhile, feel free to spread the news to your co-workers, faculties, and students.

For more information on the committee, see <http://armarocks.org/sample-page/committees/technical-committee-on-hydraulic-fracturing-tchf-2/>.

■ ARMA Awards

ARMA members are annually recognized for publications in the following categories:

- Rock Mechanics Research
- Applied Rock Mechanics Research
- Case History
- Dr. N.G.W. Cook Ph.D. Dissertation M.S. Thesis in Rock Mechanics
- M.S. Thesis in Rock Mechanics Award
- Outstanding Contributions to Rock Mechanics

The deadline for ARMA Awards is 15 May 2016. Nominations can be made to Steve Brandon at sbrandon@lachel.com. Please refer to: *Awards Criteria and Operating Procedures* at <http://armarocks.org/sample-page/awards>

50th US Rock Mechanics/Geomechanics
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26-29 June 2016



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