Machine Learning and Seismology for Real-Time Decision-Making in Stimulation

1. **Cutting-edge application of machine learning, geomechanics, and seismology for real-time decision-making tools during stimulation**

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   - Subcontractors and/or Participating Organizations: University of California Berkeley

   - Project Start and End Date: 4/2024-3/2027

2. **Project Objectives and Purpose**

   Major technical objectives of the project

   2.1 Development of a Real-Time Decision-Making Platform
   - Data Analysis and Seismic Event Detection.
   - Moment Magnitude Calculations.
   - Maximum Magnitude Prediction.

   2.2. Seismo-Geomechanical Characterization
   - Site Characterization.
   - Velocity and Geomechanical Models.

   2.3. Compliance Technology for Real-Time Data Acquisition
   - Data Pipeline Development.
   - Server Deployment.

   2.4. Risk Assessment and Management Tools
   - Geomechanical and Seismological Models.
   - Red-Light Shut-In Tool.
   - Ground Motion Prediction.
   - Nuisance and Fragility Functions.

   2.5. Real-Time Simulation and Tool Validation
   - Model Calibration and Testing.
   - Real-Time Simulations.

   The impact of your research and development
   - The project contributes to making geothermal energy a more reliable, safe, and efficient renewable energy source, thereby supporting its broader adoption and deployment worldwide.
   - Immediate Response
   - Improved Safety
   - Data-Driven Decisions
   - Proactive Risk Mitigation
   - Enhanced Prediction Models
   - Community Safety
   - Infrastructure Protection
   - Reduction of Seismic Risks
   - Optimization of Geothermal Operations
   - Support for Policy and Regulatory Frameworks

3. **Technical Barriers and Targets**

Technical Challenges and Barriers

- Real-Time Seismic Monitoring: Developing a system for accurate, real-time detection and analysis of seismic events during geothermal stimulations. The challenge lies in processing large data volumes from sensors like geophones and DAS systems.

- Predictive Modeling: Creating accurate models to forecast the maximum magnitude of induced seismic events and ground motions. This involves dealing with uncertainties in geological formations and seismic responses.
- Data Integration: Ensuring the developed tools can integrate diverse data sources and scale across different geothermal sites with varying geological conditions.

Technical Targets

- Real-Time Monitoring Platform: Develop a platform for real-time seismic monitoring.
- Seismic Event Detection: Develop detection algorithms for geophones and DAS.
- Predictive Modeling: Create models to predict maximum seismic magnitude and assess risks.
- Data Integration: Integrate diverse data into a unified database.
- Stakeholder Engagement: Conduct workshops and training sessions.
- Regulatory Compliance: Ensure technologies meet regulatory standards.

4. Technical Approach

Here is our technical approach workflow:

4.1. Data Collection and Characterization
- Building a Seismo-Geomechanical Model

4.2. Real-Time Data Acquisition and Analysis
- Data Pipeline Development
- Initial Event Detection

4.3. Machine Learning and Model Integration
- Machine Learning Algorithms
- Coupled Location Model

4.4. Risk Assessment and Prediction
- Geomechanical Risk Assessment
- Maximum Magnitude Prediction

4.5. Ground Motion and Impact Analysis
- Nuisance and Fragility Functions
- Real-Time Hazard Analysis

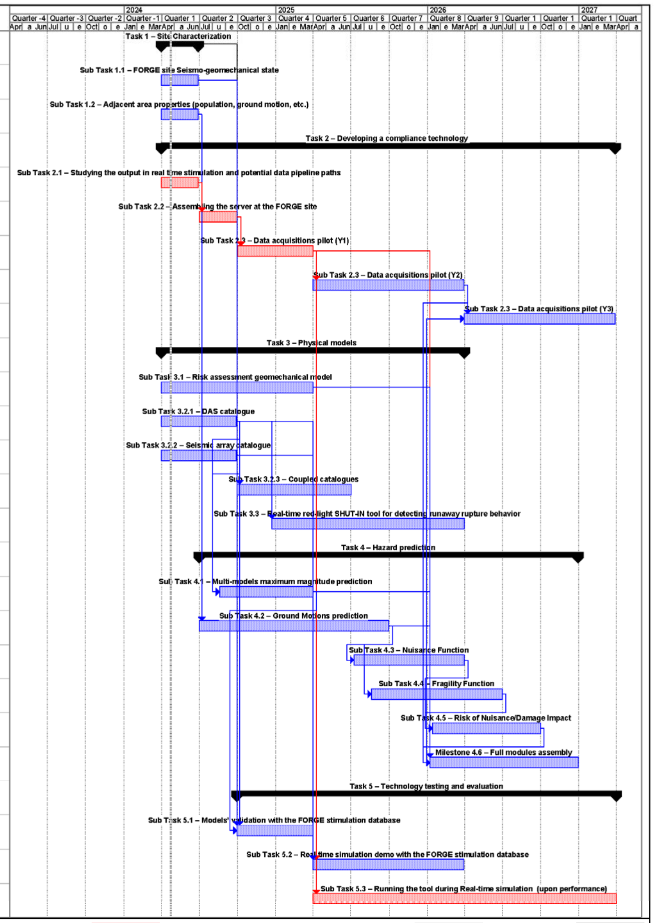
4.6. Technology Testing and Validation

We are now working on Sections 4.4 and 4.5, which support the identification of seismic hazard risks to inform management and mitigation strategies.

5. Project Timeline (list milestones achieved and/or decision points)

Here is the project timeline Gantt chart. We have met all milestones to date and successfully passed the Year 1 GO/NO-GO decision point.

ID	Task Name	Duration	Start	Finish	Predecessors	Notes
1	**Task 1 – Site Characterization**	**65 days**	**Mon 4/1/24**	**Fri 6/28/24**		
2	Sub Task 1.1 – FORGE site Seismo-geomechanical state	65 days	Mon 4/1/24	Fri 6/28/24		UU, UCB, TAU, UC
3	Sub Task 1.2 – Adjacent area properties (population, ground motion, etc.)	65 days	Mon 4/1/24	Fri 6/28/24		UU
4	**Task 2 – Developing a compliance technology**	**781 days**	**Mon 4/1/24**	**Mon 3/29/27**		
5	Sub Task 2.1 – Studying the output in real time stimulation and potential data pipeline paths	65 days	Mon 4/1/24	Fri 6/28/24		UU, UCB, TAU, UC
6	Sub Task 2.2 – Assembling the server at the FORGE site	66 days	Mon 7/1/24	Mon 9/30/24	5	UU
7	Sub Task 2.3 – Data acquisitions pilot (Y1)	130 days	Tue 10/1/24	Mon 3/31/25	6	UCB, TAU
8	Sub Task 2.3 – Data acquisitions pilot (Y2)	260 days	Tue 4/1/25	Mon 3/30/26	7	UCB, TAU
9	Sub Task 2.3 – Data acquisitions pilot (Y3)	260 days	Tue 3/31/26	Mon 3/29/27	8,22SS	UCB, TAU
10	**Task 3 – Physical models**	**522 days**	**Mon 4/1/24**	**Tue 3/31/26**		
11	Sub Task 3.1 – Risk assessment geomechanical model	261 days	Mon 4/1/24	Mon 3/31/25		UU
12	Sub Task 3.2.1 – DAS catalogue	130 days	Mon 4/1/24	Fri 9/27/24		TAU, UC
13	Sub Task 3.2.2 – Seismic array catalogue	130 days	Mon 4/1/24	Fri 9/27/24		UCB, UC
14	Sub Task 3.2.3 – Coupled catalogues	197 days	Mon 9/30/24	Tue 7/1/25	12,13	UCB, TAU, UC
15	Sub Task 3.3 – Real-time red-light SHUT-IN tool for detecting runaway rupture behavior	332 days	Mon 12/23/24	Tue 3/31/26	12FS+60 days,13FS+60 days	UU
16	**Task 4 – Hazard prediction**	**653 days**	**Mon 7/1/24**	**Wed 12/30/26**		
17	Sub Task 4.1 – Multi-models maximum magnitude prediction	161 days	Mon 8/19/24	Mon 3/31/25	12FS-30 days,13FS-30 days	UU
18	Sub Task 4.2 – Ground Motions prediction	327 days	Mon 7/1/24	Tue 9/30/25	3	UU
19	Sub Task 4.3 – Nuisance Function	190 days	Wed 7/9/25	Tue 3/31/26	18FS-60 days	UU
20	Sub Task 4.4 – Fragility Function	225 days	Wed 8/20/25	Tue 6/30/26	18FS-30 days	UU
21	Sub Task 4.5 – Risk of Nuisance/Damage Impact	186 days	Wed 1/14/26	Wed 9/30/26	20FS-120 days,19FS-60 days	UU
22	Milestone 4.6 – Full modules assembly	255 days	Thu 1/8/26	Wed 12/30/26	21FS-190 days,7,18,17,11,8F days	UU, UCB, TAU, UC
23	**Task 5 – Technology testing and evaluation**	**654 days**	**Mon 9/30/24**	**Thu 4/1/27**		
24	Sub Task 5.1 – Models' validation with the FORGE stimulation database	131 days	Mon 9/30/24	Mon 3/31/25	1,2,12,13,17FS-22 days	UU
25	Sub Task 5.2 – Real time simulation demo with the FORGE stimulation database	260 days	Tue 4/1/25	Mon 3/30/26	12,13,7	UU, UCB, TAU, UC
26	Sub Task 5.3 – Running the tool during Real-time simulation (upon performance)	523 days	Tue 4/1/25	Thu 4/1/27	7	UU, UCB, TAU, UC



Task | Progress | Summary | Rolled Up Critical Task | Rolled Up Progress | External Tasks | Group By Summary

Critical Task | Milestone | Rolled Up Task | Rolled Up Milestone | Split | Project Summary | Deadline

6. Technical Accomplishments

The project has advanced microseismic monitoring for EGS by implementing a fully automated, ML-based workflow integrating PhaseNet (phase picking), GaMMA (phase association), and ADLoc (event location refinement). These tools were applied across diverse seismic arrays (DAS, geophones, surface stations), with demonstrated robustness in noisy and complex environments.

The table below lists our current technical progress status:

	Task / Sub Task	**Aug. 2025 status**
Task 1 –	**Site Characterization**	
Sub Task 1.1 –	FORGE site Seismo-geomechanical state	Completed
Sub Task 1.2 –	Adjacent area properties (population, ground motion, etc.)	Completed
Task 2 –	**Developing a compliance technology**	
Sub Task 2.1 –	Studying the output in real-time stimulation and potential data pipeline paths	Completed
Sub Task 2.2 –	Assembling the server at the FORGE site	Completed
Sub Task 2.3 –	Data acquisitions pilot (upon performance)	Completed
Task 3 –	**Physical models**	
Sub Task 3.1 –	Risk assessment geomechanical model	Completed
Sub Task 3.2.1 –	DAS catalogue	Completed
Sub Task 3.2.2 –	Seismic array catalogue	Completed
Sub Task 3.2.3 –	Coupled catalogues	Completed
Sub Task 3.3 –	Real-time red-light SHUT-IN tool for detecting runaway rupture behavior	Tested, waiting for reprocessing results
Task 4 –	**Hazard prediction**	
Sub Task 4.1 –	Multi-models maximum magnitude prediction	Completed
Sub Task 4.2 –	Ground Motions prediction	Model validation and upgrade
Sub Task 4.3 –	Nuisance Function	Model validation and upgrade
Sub Task 4.4 –	Fragility Function	Model validation and upgrade
Sub Task 4.5 –	Risk of Nuisance/Damage Impact	Model validation and upgrade
Sub Task 4.6 –	Full modules assembly	Waiting for the code upgrade
Task 5 –	**Technology testing and evaluation**	
Sub Task 5.1 –	Models' validation with the FORGE stimulation database	Waiting for codes upgrade
Sub Task 5.2 –	Real-time simulation demo with the FORGE stimulation database	Waiting for codes upgrade
Sub Task 5.3 –	Running the tool during Real-time simulation	Aligns with the FORGE project progress

7. **Challenges to Date**
   - In the initial timeline we planned to work on this quarter on the 2024 stimulation data. Once the data is released, we conducted our analysis and met the original timeline.

8. **Conclusion and Plans for the Future**

We are continuing our model development. Action items for the near future include:

- Developeing a model for detecting runaway rupture behavior
- Hazard assessing modeling.

9. **Geothermal Data Repository**

Dvory, N., Lellouch, A., Wygodny, U., Shimony, E., Zhu, W., Song, J., & Zhang, X. (2025). Source Imaging DAS-Based Seismic Event Catalogue ? April 2024 FORGE Stimulation. [Data set]. Geothermal Data Repository. The University Of Utah. https://gdr.openei.org/submissions/1765

10. **Publications and Presentations, Intellectual Property (IP), Licenses, etc.**

Deep Neural Network-Based Workflow for Accurate Seismic Catalog Generation from Low Resolution Seismic Data in Enhanced Geothermal System Operations
X Zhang, W Zhu, RO Salvage, NZ Dvory
PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering

Estimating Fault Slip Potential with CNN-Based Deep Learning: Integrating Mohr-Coulomb and Non-Linear Failure Criteria for Advanced Seismic Risk Assessment
XM Zhang, NZ Dvory
59th U.S. Rock Mechanics/Geomechanics Symposium 408 (ARMA 25–0408)

Workshop 4: Seismic Risk and Reservoir Integrity in Enhanced Geothermal Systems: Mechanisms, Monitoring, and Mitigation
NZ Dvory, University of Utah and N Nakata, Lawrence Berkeley National Laboratory.

Advances in Understanding and Mitigating Induced Seismicity in Geo-Energy Systems
No'am Dvory, University of Utah; Katie Smye, University of Texas at Austin; Yves Guglielmi,University of California Berkeley; Ryan Schultz, ETH Zürich

Integrated Deep Learning and Failure Criterion Approaches for Fault Slip Assessment in Enhanced Geothermal Systems.
Xiaoming Zhang[1], Noam Dvory[1]
(1) University of Utah, Salt Lake City, United States
2025 AGU Fall Meeting

Picking-free microseismic event location with downhole DAS and geophones
Eyal Shimony[1], Uri Wygodny[1], Xiaoming Zhang[2], Noam Dvory[2] and Ariel Lellouch[1], (1) Tel Aviv University, Geophysics, Tel Aviv, Israel, (2) University of Utah, Salt Lake City, United States
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