NRAP Phase II
Tools and Workflows
at the 2021 GWPC Annual Forum

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Short term seismic forecasting – a tool to assess seismicity during injection operations and the RiskCat tool

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Overview

• Introduction to both STSF and RiskCat
  • Tools in a Nutshell
  • Background and Context

• How to run to the tools
  • Input / Output
  • Challenges

• Examples
Use observed earthquake catalogs and measured (and/or controllable) injection parameters to forecast earthquake rates
RiskCat tool – in a Nutshell

Use earthquake catalogs – observed or calculated - to determine seismic hazard and risk over the project lifetime.
Traditionally, induced seismicity projects are monitored with a traffic light systems (TLS)

- Reacts to single incidents like:
  - Recorded seismic events above threshold
  - Measurement of acceleration / ground motion above threshold
  - Public response

New system that incorporates all recorded seismicity

- Adapt established seismic model to induced seismicity
- Incorporate injection parameter to calculate influence on rates
STSF – Future

New release planned for end of Phase II

- Current model includes **one** statistical model
  - Epidemic type aftershock model (ETAS)
- Include a suite of models

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Injection Data + Microseismic Catalog
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Forecasting Methods

\[ \lambda_1 \times \text{OpenSHA} \]
\[ \lambda_2 \times \text{SI}_1 \]
\[ \lambda_3 \times \text{SI}_1 \]
\[ \lambda_4 \times \text{ETAS}_1 \]
\[ \lambda_5 \times \text{ETAS}_2 \]
\[ \lambda_6 \times \text{CRS}_1 \]
\[ \lambda_7 \times \text{CRS}_2 \]
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Weighted Average

Seismicity Forecast
• Epidemic Type Aftershock Sequence Model (ETAS)
• Originally developed by Ogata in 1988 to determine the occurrence of aftershock after a main shock / large event.
  • Each earthquake has the ability to trigger aftershocks
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• **Epidemic Type Aftershock Sequence Model (ETAS)**

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  • Each earthquake has the ability to trigger aftershocks
  • ETAS is a cascading model
    • Mainshock triggers aftershocks
    • Aftershocks can trigger aftershocks
    • After and mainshock are purely temporal terms. If aftershocks are larger than main shocks, there is often a re-classification to foreshock / mainshock.
STSF – Seismic Model

• Epidemic Type Aftershock Sequence Model (ETAS)
• Originally developed by Ogata in 1988 to determine the occurrence of aftershock after a main shock / large event.

\[ \lambda_i(t) = \frac{K}{(c + t - t_i)^p} 10^{\alpha(M_i-M_{\text{min}})} \]

\[ \lambda(t) = \lambda_0 + \sum_{i:t<t_i} \lambda_i(t) \]

K, α = productivity parameters
c = delay term (time)
p = decay term

Background Term
➢ Describes natural / background seismicity

Triggered Term
➢ Describes increase in seismicity due to disturbance
To adapt for injection induced seismicity, a term is added into the background:

$$\lambda_0(t) = \mu + c_f \times F_r(t)$$

- $c_f$ is a scale parameter
- $F_r(t)$ is a measured injection parameter
  - Can be the injection rate, measured pressure etc.
  - When using a parameter that can be changed by the operator, different scenarios can be calculated
    - Earthquake rate if injection rate doubles?
    - Earthquake rate if injection rate is reduced by half?
STSF – Tool installation


• The tool package is a zip file
  • Unpacking the zip file creates a folder with all files needed

• Currently only tested on Mac OSX and Linux
  • Currently not supported under Windows

• Requires Java Runtime Environment (JRE) version 8 update 40 or newer

• Requires gcc and Perl
STSF – Running the tool

• To run the GUI
  • sh bin/application

• Enter parameters will prompt a new window where all parameters are picked
  • Parameters are described in manual
  • Support for parameters in the EDX forum (link at the end)

• Run Simulation runs one simulation with chosen parameters and writes output files
STSF – Examples – Paradox Valley

- Brine water injection over 20 years
- Relatively remote area in Colorado
  - Earthquake rate per five days
  - Different injection periods lead to different seismicity in the early stages
  - STSF underrepresents changes in seismicity during constant injection
  - STSF models late changes due to large events
• EGS project, injection for six days before TLS triggered reduction and shut in
• Urban area in Switzerland
  • Earthquake rates for 1/4-day
  • E2, E4 and E5 are different realizations of the model
    • Different fixed and varying variables that are described in the manual
• **Tool is not designed to work as a site characterization before injection**
  • Minimum number of events is needed

• **Tool relies on seismic event data**
  • Seismic network with high detection rate / low magnitude of completeness
  • Seismically inactive injection might not provide enough data

• **Tool has not yet been applied to an area in real time**
  • Only pseudo real time testing after project was complete or was in operation for a long time already
RiskCat – Background

• Developed as a collaboration between LLNL, LBNL and an independent contractor
• Makes no assumptions about the time and space distribution of seismicity, can accommodate any type of time and space non-stationarity
• Uses simulated or recorded seismic catalogs as input

➢ Induced seismic hazard and risk very well suited as it his highly non-stationary
RiskCat – Installation

• The RiskCat code is on gitlab
  • [https://gitlab.com/NRAP/RiskCat](https://gitlab.com/NRAP/RiskCat)

• Unlike other NRAP tools, RiskCat is not a GUI
  • More suited for non-lay users

• Install is described in the readme file
  • The ‘make’ file includes the whole installation
  • Only tested on linux and Mac computers
RiskCat – Running the tool

• ../riskcat KingIS.menu will run the example file
• Example file will create hazard and risk output for a subset of a simulation for King Island
  • Example run will both save files and PDF files with example curves
• Results are saved in the EQSimrisk folder
• The manual explains all input parameters in depth and how to manipulate them
  • Manual still work in progress and will be updated in the next phase
RiskCat – Examples / Hazard

• Based on a simulation of induced seismicity
  • Earthquake catalog with RSQsim
  • Injection with TOUGH2

• Probability of exceeding a pre-defined acceleration threshold

• Four different time periods
  • Pre (background)-, co-, post and late-post injection periods
  • Covers the whole project lifetime

➢ Difference most significant for largest accelerations
Risk is for pre-defined surface site
  • Site conditions need to be known
  • Population density and building stock is important
Risk of nuisance for the same four time periods as the last slide
  • Nuisance indicates lower risks, but important for induced seismicity where public acceptance of the project is key
Nuisance risk is elevated for all levels over background (red)
RiskCat – Challenges

• RiskCat is not a GUI like other tools
• Usage of RiskCat is not straightforward, especially for lay users
• Backward combability to work with other datasets is not always guaranteed
• Technical support is not always straightforward
Questions and Discussion

Thank you!

NRAP Website: https://edx.netl.doe.gov/nrap/
Sign up for NETL EDX: https://edx.netl.doe.gov/user/register

Support for the tools is available in an online forum
https://edx.netl.doe.gov/workspace/dashboard/nrap-tools