Ground Expansion and Seismic Hazard Induced by the Hutubi Natural Gas Repository, Xinjiang, China

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1. Introduction

Although increasing seismologic observations reveal numerous earthquake hazards linked to anthropogenic activities, ground displacements were not directly linked to several induced seismicity regions using focal mechanisms and analysis techniques (e.g., Noda et al., 2010; Stix et al., 2015; Stix et al., 2016). Moreover, these limited studies only focused on surface uplift or subsidence induced by fluid injection/extraction, with little attention on the horizontal deformation. On the other hand, geodetic observations of ground deformation have been demonstrated effective in assessing the natural seismic hazard, whereas very preliminary attempts were conducted for induced hazards.

To date, the Hutubi natural gas repository (HNGR), located near the boundary between Tum Shan and Janggai Basin, Xinjiang Province, is the largest underdeveloped gas storage facility in China. Two seismologic and geodetic studies revealed that the operation of the HNGR has induced both seismicity and ground displacements:

- The seismologic study found that five M<2.5 earthquakes occurred only 52 days after the operation on 9 June 2013 with distances of only 2.2±0.6 km from the HNGR (Jiang et al., 2013).
- The geodetic study only investigated the vertical displacements measured by GPS and InSAR and found they were commensurate to ground deformation (Jiang et al., 2013).

Therefore, the HNGR is a unique case with both induced earthquakes and ground displacements, due to cyclic gas injection and extraction.

Here, we focus on horizontal GPS observations and make efforts to extract robust deformed signals of the region. In addition, a hydrogeological model for the HNGR is built up by using multiple geologic and geophysical data. Fully-coupled poroelastic simulation is conducted to investigate the physical mechanisms of ground deformation and to assess the induced seismic hazard:

- Detect robust horizontal displacements and unveil its physical mechanism.
- The induced seismic hazard.
- Determining the physical mechanisms of induced seismicity and assess its hazard.

2. Methodology

To inspect the physical mechanism behind the induced seismicity and to evaluate the seismic hazard linked to the HNGR, we propose a physical-based scheme based on fully-coupled poroelasticity (Rice and Cleary, 1976).

- Build up a hydrogeologic model for the HNGR based on multiple geologic and geophysical data.
- Calibrate the hydraulic parameters of the reservoir layer using constraints from GPS observed horizontal expansion and well-head pressure changes.
- Build up the physical mechanics of capillary-tension/variation of induced seismicity.
- Assess seismic hazard including the occurrence range of induced seismicity and the maximum potential earthquake.

Besides, in this study, COMSOL Multiphysics is employed to conduct numerical simulation.

3. Hydrogeologic model

A hydrogeologic model is essential for investigating the physical mechanism of observed ground expansion as well as induced seismicity linked to the HNGR. We build up a 3D-evolved-scale and 3D-evolved-reservoir model based on multiple geophysical and geological data including five seismic profiles, drilling data, local velocity model refined by an aeromagnetic, well logging data, and rock physics experiment results of the reservoir layer. A method is developed to characterize the hydraulic properties of the reservoir layer jointly using the observed pressure changes and geophysical and geological data.

- The porosity and permeability of the reservoir layer play a significant role in investigating the hydraulic parameters of the reservoir layer, which are jointly used by the observed pressure changes and geophysical data.
- We increased the porosity and permeability of the reservoir layer from 0.03 to 0.1, and from 0.0 to 1000 mD, respectively, to conduct numerical simulation.
- The simulated horizontal displacements and bottom-hole pressure changes were compared with the observed values.

4. Induced horizontal ground expansion

Our local GPS network includes 3 continuous stations and 35 campaign stations. A campaign station is defined as a GPS station that was not configured during the 2015 period for more observations and cross-validation. The cumulative displacements were further referenced to station H7R4 near the HNGR center for two purposes:

- To remove the regional deformation trend included in the cumulative data.
- To only represent the horizontal ground displacements induced by the HNGR.

We employed a classical method to process the GPS data. The resulting time series of the 13 stations were used to measure the cumulative horizontal ground displacement of the region, which can be used to cross-check the numerical results. In total, the cumulative displacements were compared with the observations from the HNGR center for two purposes:

- To remove the regional deformation trend included in the cumulative data.
- To only represent the horizontal ground displacements induced by the HNGR.

Furthermore, we projected the relative displacements into the direction perpendicular to the strike of the southern faults fault (SFP).

5. Calibration of poroelastic model

The porosity and permeability of the reservoir layer play a significant role in investigating the hydraulic parameters of the reservoir layer, which are jointly used by the observed pressure changes and geophysical data. In this study, we increased the porosity and permeability of the reservoir layer from 0.03 to 0.1, and from 0.0 to 1000 mD, respectively, to conduct numerical simulation.

- The fitting residual of pressure decreases with both permeabilities and porosities, exhibiting a nonlinear trend.
- Ground expansion is more sensitive to the porosity than the permeability.
- Artificial neural network (ANN) learning and 0.05 ± 0.07 cm, slightly larger than the average of the four pressure profiles.

6. Physical mechanism of induced seismicity

In further investigating the physical mechanism of induced seismicity, we calculated Coulomb stress changes induced by the HNGR. In general, Coulomb stress changes are calculated using the orientation of induced seismicity.

- Ground expansion is mainly induced by cyclic gas injection-extraction.
- Vertical GPS observations are controlled by groundwater pumping.

7. Induced seismic hazard

We provide a physical-based framework to investigate the physical mechanism of ground expansion and seismicity induced by the HNGR and to assess the associated seismic hazards including location and maximum magnitude.

- The maximum horizontal ground expansion is up to 1.57 cm.
- An hydraulic model is built by integrating multiple geophysical and geotechnical data.
- A method is developed to characterize the hydraulic properties of the reservoir layer using GPS data.
- Field observations reveal that the maximum horizontal ground expansion is up to 1.57 cm.
- The magnitude of horizontal ground expansion increases laterally from the HNGR center and reaches the maximum at ~3 km from the center, then decreases gradually.
- The largest expansion after four injection phases approaches 0.5 cm.
- The maximum uplift at the center is only 0.45 cm and then decreases laterally.
- At the distance of 6 km from the center, the horizontal ground expansion is about four times larger than the uplift at the end of the 4th injection phase.

8. Conclusions

We provide a physical-based framework to investigate the physical mechanism of ground expansion and seismicity induced by the HNGR and to assess the associated seismic hazards including location and maximum magnitude.

- A hydrogeologic model is built by integrating multiple geophysical and geotechnical data.
- A method is developed to characterize the hydraulic properties of the reservoir layer using GPS data.
- Field observations reveal that the maximum horizontal ground expansion is up to 1.57 cm.
- Dramatic increase of seismicity is associated with the distances of secondary injection phases (Panel b and d) have a close maximum value of 0.8 cm. The maximum uplift at the center is only 0.45 cm and then decreases laterally.

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