SHEER WP4 Report, 30.4.2016
(WP Leader S. Cesca GFZ, representative IGF-PAS, AMRA, KNMI, Keu, KNMI)

Short summary of the progresses of the period

Please provide a concise overview of the progress of the work in line with the structure of Annex I to the Grant Agreement (DoA)

- **List of the staff actively involved in the WP**

Simone Cesca, WP leader, GFZ Potsdam
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Bernard Dost, KNMI
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- **Objectives expected after 6 Month**

The activity of WP4 on induced seismicity has four main objectives: the characterization of induced seismicity, tracking migration of induced fractures, and thus the motion of fluids, and assessment of the seismic hazard induced by shale gas exploitation operations. WP4 planned activites are: advanced seismic data processing, statistical description of the induced seismic process, multi-physical modelling of the fracturing process and timedependent seismic hazard assessment and mitigation.

The objectives for the 6 months period were achieved, as discussed in the following section for each task separately.

- **A summary of progress towards objectives and details for each task in the first six months;**

WP4.1

- ✓ The installation/monitoring work of WP3 allows a first large dataset of seismic signals at the Polish site. At the time of writing, no fracturing operations have been performed, but continuous waveforms during quiet conditions as well as drilling operations are available; these analysed to assess the seismic noise conditions.
- ✓ We extended our tools to generate realistic synthetic catalogues and synthetic waveforms, which are now combined to real noise, to simulate realistic seismicity.
- ✓ We developed first techniques to assess the detection performance of the network, upon the noise conditions, in order to infer an estimate of the magnitude of completeness.
- ✓ New implementations of waveform based detection algorithms are ongoing and will be tested in the continuation on the project both to realistic synthetic and real data.
- ✓ Progress was made in increasing the accuracy of source location in Groningen (paper submitted) and a white paper was published on the relation between ML and Mw and measured stress-drop, also for Groningen (Dost et al., 2016). We are currently extending this work and preparing a publication
- ✓ The Groningen network has become operational in 2015. Induced seismicity is detected with about 60 vertical arrays with sensor placements between 0 and 200 m depth.
- ✓ Using seismic interferometry, the orientation of the downhole sensors has been estimated
- ✓ An algorithm has been developed to invert for an enhanced seismogram at each borehole location. This enhanced seismogram enables detection and characterization of smaller magnitude events than was previously possible

WP4.2

Within T4.2 the following research topics are being realized in IGF PAS:

- ✓ Evaluation of the possibility to incorporate static stress drop into seismic hazard assessment.
  Within this topic the influence of static stress drop on seismicity distribution at The Geysers geothermal site has been checked. In order to do this, preliminary analyses of event groups and sequences locations in relation to interpolated static stress drop values has been performed.
- ✓ Use of multi-dimensional clustering to reveal the role of physical processes that control seismogenesis.
  Multi-dimensional clustering in X, Y, Z and R (distance from the injection well) equivalent dimensions has been performed using dataset from The Geysers geothermal site according to methodology proposed by Lasocki (2014). Additionally, correlation between spatio-temporal seismicity evolution and variation of the injection/ production data from this site has been analyzed.
- ✓ Use of seismic interferometry to monitor changes in reservoir due to fluid injection.
  Four broadband seismic stations have been installed at the Wysin site in order to register data needed for analyses.

WP4.3

- ✓ T4.3.1 Modelling of fracture networks
  A new Fracture Networks model based on the Presse Hall site has been created using the Fracman sofware and an animation produced to show the development of hydrofracs during pumping operations. Parameterisation models are being run to get the range of fracture properties (e.g., number for fractures, length, stresses etc) over practical operating criteria (e.g., pumping rates, pressures, etc).

- ✓ T4.3.2 Tracking fluid migration
  The same models are being used to assess the fluid volumes and flow length to help evaluate fluid migration parameters for future analysis of flow pathways.

WP4.4

Contribution of AMRA

The main objective for this period has been an assessment of the SoA in available approaches for seismic hazard assessment associated with induced seismicity, and based on that define the characteristics of the models to be developed/improved within T4.4. This activity has been done and we are now moving forward in specific activities as follows: (a) To work out and test an algorithm for aggregated interval estimation of hazard functions characterizing the seismic sources (IGF-PAS); (b) assessing requirements for integrating seismic hazard assessment in the multi-risk framework of WP7 (AMRA)

Contribution of KNMI

- ✓ Publications on developing application specific ground motion models for induced seismicity (Bommer et al, 2016), probabilistic hazard for Groningen (Dost and Spetzler, 2015 and preparing for another publication on this topic)
- ✓ Contribution to develop a regional site-response model for the Groningen field (paper submitted)

- **Highlight clearly significant results;**

WP4.1:

- ✓ Extension of the synthetic catalogue/waveform generator toolbox to account for real noise conditions; a dataset is prepared for the Wysin site.
- ✓ Development of a method to estimate the detection performance and magnitude of completeness for each station and the whole network.
- ✓ Improved accuracy of source location (depth) at Groningen

WP4.2

- ✓ First analyses give promising results for the use of static stress drop in seismic hazard assessment, however bigger dataset needs to be analyzed in order to confirm this hypothesis.
- ✓ Clear correlation between seismic activity and production parameters at The Geysers geothermal area is observed.

WP4.3

- ✓ Development of a method to estimate the detection performance and magnitude of completeness for each station and the whole networkDeveloped new, more relevant models of hydrofracking that relate to practical operations. This will help constrain future operational criteria (such as pumplin rates) for efficient shale gas recovery.

WP4.4
In concordance with points (a) and (b) in the previous item:

- ✓ The algorithm worked out and tested, the manuscript of publication prepared
- ✓ Input to the multi-risk framework from seismic hazard assessment (intensity measures, hazard functions) have been identified and defined for proper integration

In reference fo the anlysis/interpretation of Groningen data:

- ✓ Development of Groningen GMPE's

- **If applicable, explain the reasons for major deviations from Annex I and their impact on other tasks.**

Not applicable

- **If applicable, explain the reasons for failing to achieve critical objectives and/or not being on schedule and explain the impact on other tasks as well as on available resources and planning.**

Not applicable.

- **If applicable, propose corrective actions.**

Not applicable

- **Publications and papers in print**

Bommer, JJ., B. Dost, B. Edwards, P. Stafford, J. van Elk, D. Doornhof and M. Ntinalexis, 2016, Developing an Application-Specific Ground-Motion Model for Induced Seismicity, Bull. Seism. Soc. Am., 106: 158-173.

Dost, B. and J. Spetzler, 2015, Probabilistic Seismic Hazard Analysis for Induced Earthquakes in Groningen; Update 2015, KNMI report ((https://cdn.knmi.nl/system/data_center_publications/files/000/052/459/original/KNMI_PSHA_update__Groningen_2015.pdf?1445526758)

Leptokaropoulos K., Staszek M., Lasocki S., Kwiatek G.: Preliminary results for Space-Time Clustering of Seismicity and its Connection to Stimulation Processes, in North-Western Geysers Geothermal Field, 35th General Assembly of the European Seismological Commission, Trieste, Italy, submitted.

López Comino, J. Á., Kriegerowski, M., Cesca, S., Dahm, T., Mirek, J., and Lasocki, S., 2016. Assessing the monitoring performance using a synthetic microseismic catalogue for hydraulic fracturing. Geophysical Research Abstracts, Vol. 18, EGU2016-7031, EGU General Assembly 2016, Vienna, Austria.

López Comino, J. Á., Cesca, S., Kriegerowski, M., Heimann, S., Dahm, T., Mirek, J., and Lasocki, S., 2016. Seismic monitoring performance for hydraulic fracturing, 35th General Assembly of the European Seismological Commission, Trieste, Italy, submitted.

López Comino, J. Á., Heimann, S., Cesca, S., , Milkereit, C., Dahm, T., and Zang, A., 2016. Automated detection and location of microseismicity of hydraulic fracturing experiment using continuous waveforms, 35th General Assembly of the European Seismological Commission, Trieste, Italy, submitted.

Ruigrok, E., Paulssen, H., Dost, B., 2016. Enhanced seismograms from vertical arrays, 35th General Assembly of the European Seismological Commission, Trieste, Italy, submitted.

Staszek M., Orlecka-Sikora B., Kwiatek G.: Static stress drop of induced earthquakes in seismic hazard assessment: Preliminary results from The Geysers geothermal site, 35th General Assembly of the European Seismological Commission, Trieste, Italy, submitted.