2023 Annual report

An integrated research programme to understand subsurface dynamics caused by human activities
The aim of the research programme DeepNL is to contribute to a better understanding of how the deep subsurface behaves under the influence of human interventions. In addition, the programme aims to strengthen and integrate the research community in the Netherlands around this theme.
An integrated research programme to understand subsurface dynamics caused by human activities

- **Phenomena**
- **Measuring techniques**

**Cluster 3**

Subsidence and the response of the Earth's surface to earthquakes

How can we assess and model the impact of deep and shallow subsurface processes on ground motion at the surface?

- Research projects: 5
- Researchers: 9 (co-)project leaders, 11 PhDs and 3 postdocs
- Budget: € 4,516,672.-
- Involved universities: TU Delft, Utrecht University

**Cluster 2**

Monitoring of physical conditions and forecasting

How can we monitor the subsurface conditions that could lead to seismicity, and forecast the occurrence of earthquakes?

- Research projects: 8
- Researchers: 22 (co-)project leaders, 18 PhDs and 5 postdocs
- Budget: € 6,758,953.-
- Involved universities: Eindhoven University of Technology, TU Delft, University of Twente, Utrecht University

**Cluster 1**

Analysis of processes and conditions that lead to seismicity and subsidence

How can we constrain and model deep subsurface conditions and processes that can ultimately lead to earthquakes and subsidence?

- Research projects: 13
- Researchers: 28 (co-)project leaders, 34 PhDs and 10 postdocs
- Budget: € 10,274,704.-
- Involved universities: Eindhoven University of Technology, TU Delft, University of Groningen, University of Twente, Utrecht University

This infographic gives an overview of the subsurface system and main processes that are studied within the DeepNL projects. It includes some of the measuring techniques that are used in conjunction with laboratory experiments and numerical models. This focus of the infographic, and most of the projects, lies on subsidence and induced seismicity due to gas extraction in the Groningen area. However, DeepNL also develops knowledge relevant for assessing the effects of geothermal energy production and subsurface storage of CO2 and hydrogen in other areas of the Netherlands.
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In 2023, the projects resulting from the first large call for proposals approached their completion and the final call for the programme was launched. To achieve the overall DeepNL goals, we decided to take an unorthodox step: the applicants were asked to first submit an Expression of Interest, and in a dedicated workshop they aligned and adapted their initial individual plans to arrive at a more integrated and collaborative set of full proposals. This resulted in eight new projects that have been selected by the assessment committee and awarded by the NWO Domain Science Board in December 2023. In this annual report, the project leaders introduce themselves and present their plans.

Another important development for the DeepNL community was the publication of the report of the parliamentary committee of inquiry on gas production in Groningen and its consequences. As expected, the conclusions and recommendations stressed the need to strengthen the scientific knowledge base concerning the subsurface. So far, the proposal DeepNL and KEM sent to the Ministry of Economic Affairs and Climate Policy in 2022, outlining the development of a national research strategy regarding the effects of subsurface activities, has not seen any follow-up. However, the government’s response “Nij begun” to the recommendations by the parliamentary committee did include an outline of plans to develop a national knowledge infrastructure in a similar direction as formulated in our proposal.

At the end of 2023, I stepped down after having served as a chairman of the programme committee for some 5.5 years. Ever since the preparatory stages of DeepNL, I have fully realised the importance of such a programme, including its highly needed continuation, and I hope I have acted accordingly. I thank the members of the NWO DeepNL team for their truly excellent support and contributions, and the programme committee members for the constructive and pleasant cooperation I have experienced. I explicitly want to express my great appreciation of the commitment and resilience shown by the DeepNL researchers during the years of Covid-related restrictions. Clearly, the programme was at risk, but you managed to navigate through the difficulties caused by the pandemic. To all the researchers involved, to the programme committee and in particular its new chairman Giovanni Bertotti, I convey my best wishes for a successful continuation of DeepNL!

First of all, I want to thank Rinus for his words, and the programme committee and the NWO Domain Science Board for the trust they have put in me. Taking over from Rinus and building on his excellent work is a great challenge. I will do my best to serve the DeepNL community in achieving the goals of the programme in the best possible way. The outstanding and inspiring contribution of the programme committee and the NWO DeepNL team will be key in this endeavour. DeepNL is quite a special programme, in which scientific excellence is strictly interwoven with the ambition to serve society and strengthen knowledge in Dutch knowledge institutions. I am looking forward to meeting you prior to and during the stakeholder meeting on 17 May 2024 in Amersfoort, and to discuss my views on how we as a group can bring this research further. Last but not least, I look forward to years of exciting science!
Looking back on 2023

Netherlands Earth Science Conference (NAC)
NAC is an annual interdisciplinary conference for the Earth and Environmental Sciences. DeepNL researchers contributed to the conference with nine talks during various parallel sessions and twenty-six poster presentations.

Annual DeepNL Stakeholder Meeting
Participants travelled to The Hague to discuss the progress and results of DeepNL and other related research. During the afternoon, three workshops were organised to enhance interaction and discuss geological models, seismological monitoring and how research tools can be used for applications by stakeholders.

Young DeepNL visits DAPwell site
PhD researchers from TU Delft organised a visit to the deep geothermal well doublet at the TU Delft campus. After visiting the drilling site, the participants visited various lab facilities, such as the rock deformation lab, core flooding lab and CT scan room.

Annual DeepNL Scientific Meeting
A key topic at this annual meeting was integration and impact as the first DeepNL projects are approaching completion. The community also discussed overall developments within the programme, using the recommendations of the International Advisory Committee (IAC) as a starting point. Work sessions on the topics reservoir geology and management, faults and seismicity, and ground motion and surface effects focussed on synthesis and identifying next steps.

Funding for eight new DeepNL projects
Eight projects were granted within DeepNL Call 2b. The projects will focus, among others, on developing geological models of the Dutch subsurface, studying processes that can lead to induced earthquakes, developing models that predict these earthquakes and their effects at the surface, and modelling of subsidence in Groningen.

DeepNL Call 2b Workshop
After receiving 22 Expressions of Interests for DeepNL Call 2b, a workshop was organised with two main goals: 1) to outline the aim and assessment criteria of the Call for proposals, and 2) to discuss research ideas and jointly work towards a coherent set of proposals. This included the fine-tuning and alignment of research ideas, formation of new collaborations and elimination of both gaps and overlap.

DeepNL Call 2b
TNO welcomed young DeepNL researchers for a stakeholder visit. They organised talks about the activities of the Geological Survey and more specifically the Groningen seismic hazard and risk analysis. The participants visited the geomechanical laboratory, the core description room and a demonstration of geophysical tools. The afternoon ended with poster presentations of the DeepNL research.

2023

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DeepNL research projects

The eight projects that received funding within the first DeepNL Call form the basis under the DeepNL programme. In the subsequent three Calls for proposals eighteen more projects were added to the programme. Together, these twenty-six DeepNL projects are grouped into three clusters, based on their research focus and the interfaces between projects.

Cluster 1
Analysis of processes and conditions that lead to seismicity and subsidence

FAULTS
- Probing the micromechanics of small magnitude earthquake slip - Niemeijer et al. - Call 1a - p21
- InFocus: An Integrated Approach to Estimating Fault Slip Occurrence - Vossepoel et al. - Call 1a - p24
- µFAULT - scaling friction from micro-contacts to faults at the reservoir scale - Mioic et al. - Call 1b - p29
- Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field - Milingshofer et al. - Call 2a - p37

RESERVOIR AND SEALS
- FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity - Niemeijer et al. - Call 2b - p69
- NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient nature of Induced Seismicity - Vossepoel et al. - Call 2b - p71
- Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields - Jansen et al. - Call 1a - p18
- The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs - Hangx et al. - Call 2a - p16

Cluster 2
Monitoring of physical conditions and forecasting

DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity - Barnhoorn et al. - Call 1a - p42
- PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling - van Dinther et al. - Call 2a - p47
- Deep, deeper, deepestNL; Imaging the Dutch crust and upper mantle using multi-geo-observables (DICTUM) - Fadel et al. - Call 2a - p50
- LabQuakeAI - AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data - Pires de Vasconcelos et al. - Call 2a - p52
- Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions (INTEGRATION) - Alonso et al. - Call 2a - p73
- SHAWave: Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach - Van der Meijde et al. - Call 2b - p75

Cluster 3
Subsidence and the response of the Earth’s surface to earthquakes

Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension - Hanssen et al. - Call 1a - p56
- SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential - Hicks et al. - Call 1a - p59
- DAMPINGSOIL: Providing the missing information of elastic damping ratio and strain-dependent modulus and damping curves for reliable, local site response analysis - Ghose et al. - Call 2b - p79
- Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas field Region - Govers et al. - Call 2b - p81
- NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient nature of Induced Seismicity - Vossepoel et al. - Call 2b - p71
- Constraining uncertainties across scales: From Groningen to future geoenergy applications (CrossScale) - Geiger et al. - Call 2b - p67

The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs - Mioic et al. - Call 1b - p27
- Making digital rocks a practical reality for energy storage within subsurface reservoirs - Rücker et al. - Call 2a - p31
- Impact of fluid extraction on the creep behaviour of clay-rich formations enveloping Rotliegend sandstone reservoirs - Hangx et al. - Call 2a - p35
- Quantitative constraints on pre-production reservoir stresses in Groningen - Geiger et al. - Call 2a - p33
- Impact of fluid extraction on the creep behaviour of clay-rich formations enveloping Rotliegend sandstone reservoirs - Hangx et al. - Call 2a - p35
- Constraining uncertainties across scales: From Groningen to future geoenergy applications (CrossScale) - Geiger et al. - Call 2b - p67
Analysis of processes and conditions that lead to seismicity and subsidence

How can we constrain and model deep subsurface conditions and processes that can ultimately lead to earthquakes and subsidence?

Analogue reservoir rock samples used in the Science4Steer project (Jansen et al.) for the so-called harlequin test. They are constructed using various materials and sandstone to resemble a displaced fault configuration.
A multiscale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction

Research aim
To develop a physics-based model for time-dependent, inelastic compaction of sandstones by including the relevant grain-scale mechanisms that operate under realistic in-situ conditions.

Highlighted results 2023
Having reached the final year of the project, the results from the different researchers are coming together and are complementing previous work done by NAM and others. Systematic experiments have been performed, deforming analogue and Sclotheren sandstone at different rates, ranging from 10 seconds to several weeks in duration. The slowest experiments are performed at the slowest rates possible from an experimental point of view, but are still approximately 1000-10,000 times faster than the slowest rates possible from an experimental point of view. Even more so, if grains are more ‘rough’, displaying surface asperities and irregularities, it is possible that such grain contact roughness could equally lead to grain failure propagating from within the grain contact. This is in line with microstructural observations of experimentally and naturally deformed sandstone samples.

The grain-scale processes identified in the experimental work, combined with the FEM results, formed the basis for the derivation of an analytical model to describe the observed deformation behaviour. At present this model is still under development but shows potential to be able to explain the results. In parallel, additional work has been done on predicting the compaction behaviour of simulated granular aggregates, using Discrete Element Modelling. This DE model offered the opportunity to essentially perform an unlimited number of numerical simulations on aggregates with predefined mineralogy, grain size distribution and porosity, for a range of stress paths. This model enabled the efficient exploration of the effect of lateral and vertical variations in rock fabric with the Groningen gas field, without the need for a large number of experiments. Overall, the DE simulations provided better constraints on the minimum horizontal stress in the field and quantification of the effect of rock fabric on the amount of compaction.

Focus for 2024
This year the project will be finalised, so the focus will be on publishing all 8 papers that are currently in preparation. PhD researcher Shinohara will defend his thesis before the end of the year. It is now possible to present the overarching results from the project to larger audiences such as at the European Geosciences Union General Assembly and European Geography Association Western Regional Congress with a focus on the Groningen gas field.

Collaboration and integration within DeepNL
There has been a tight collaboration with the Science4Steer project, which is reflected in the exchange of personnel between both projects: Mark Jefferd smoothly transitioned from the Science4Steer project to this project, and Hadi Mehranpour in an equally smooth process transferred from this project to Science4Steer. In addition, interesting links exist with other DeepNL projects, such as the SOFTTOP project and the projects led by tenure track researchers Maja Rücker and Johannes Miocic. One of the PhD researchers from the project led by Johannes Miocic will come to Utrecht to perform experiments.

For the new group of DeepNL projects (call 2b), there will be collaboration with FTC (University of Twente’s Faculty of Geo-Information Science and Earth Observation) in the INTEGRATION project. One of the objectives of this project is to construct a database of petrochemical and mechanical data, from which empirical relationships for reservoir behaviour will be derived.

Relevance for stakeholders
This project has provided an indication of the amount of time-dependent compaction that can still be expected now that the field is going through abandonment (i.e. a field compaction rate of “10” per second). Together with work done by others on similar sandstone from the area, the results suggest that an additional 10-20 percent of permanent compaction can still be expected, compared to the amount measured at lab deformation rates of “10” per second.

The developed DEM simulations can be used to make predictions for the amount of compaction that can be expected in the more distal areas from the field, now that pore pressures will decrease in those areas due to pressure equilibration.

Reflection by Takahiro Shinohara, PhD researcher
In this DeepNL project, I had many opportunities to meet colleagues with various expertise. This helped me keep the big picture in mind and understand how my research could contribute to such an important issue in Dutch society. I am proud that I tackled this significant issue from various scientific approaches (experimental, numerical and analytical). On the other hand, this multidisciplinary approach is why every chapter of my thesis had its own unique challenges to overcome. For example, in the second year of my PhD, my months of experimental work and analyses didn’t go well, and I had no idea where to head for a while. From this experience, I learnt how to deal with such situations and that it’s good to always start with something simple. All in all, my PhD project has been inspiring me by the fact that so much is still unknown about grains of sand, and that through the grasp of sand, some important conclusions can be drawn for the large Groningen gas field and beyond. Throughout this journey, it was valuable to receive guidance from my supervisors on every aspect, including rock mechanics, proper scientific methods, presenting and writing. I’d like to build on those learnings and keep working in this fascinating geo-energy field."
Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields

Project leader: Prof. Jan Dvä Janssen (TUD)
Associate project leaders: Dr. Auke Barnhoorn (TUD); Prof. Hadi Hajibeygi (TUD); Dr. Suzanne Hangx (UU); em. Prof. Chris Spiers (UU); Dr. Denis Voskov (TUD)
Postdocs: Dr. Janye Chen (U); Dr. Pawan Cornilsson (TUD); Dr. Mark Jefford (U); Dr. Mohammad Hadi Mehranpour (UU)
PhDs: Milad Naderloo (TUD); Alekssei Novikov (TUD); Sara Shokrollahzadeh Behbahani (TU Delft)
Budget: € 1,491,331 - (Call 1)
Duration: 2019 - 2024

Research aim
To understand the effects of time-varying pressures, stresses and strains resulting from gas production and (re-)injection in the Dutch subsurface as a basis for operational strategies to minimise the seismic hazard of human activities in the subsurface.

Highlighted results 2023
Some of the Science4Steer project objectives proved too ambitious and have been met only partially or not at all. This concerns, in particular, the inclusion of experiment-based constitutive models for fluctuating pressures in simulation software, the development of a multiscale framework to connect lab to field, and the development of an optimal control framework to reduce induced seismicity probabilities. However, the overall goal of ‘significantly increasing the physical understanding of induced seismicity as a basis for the future development of operational strategies’ has certainly been met. Highlights are the development of useful building blocks for simulation software, the significant learnings from various experiments under fluctuation stresses/pressures in Delft, Utrecht and CEA, and most of all, the steep learning curve, especially at TU Delft, in the field of human-induced seismicity and the training of a group of highly skilled professionals who nearly all remain active in the Dutch Earth Sciences community.

The first years of the project were strongly dominated by experiments to learn more about the rock and fault physics related to fluctuating pressures and stresses, and the development of computational techniques to simulate these processes at the lab and field scales. The past year has seen a consolidation of the computational developments providing insights into the applicability of the numerical simulations, and more specifically the accuracy-efficiency trade-off. The studies resulted in useful products in the form of open-source simple research prototypes as well as advanced general-purpose simulators.

Consolidating the experimental findings in the numerical capacities through the development of constitutive models has not yet been achieved as foreseen, but the use of numerical simulation to assist the design of experiments was a successful step to connect the two development lines, as was the first experimental validation of a new step in constitutive modelling of fault friction. The key achievement during the past year was the completion of three PhD theses, with minor delays (Covid-related and maternity-leave-related). Postdoc Pavan Cornilsson left in September 2023, somewhat earlier than planned, to take up a permanent position at Wageningen University and Research Centre. Thus, the Science4Steer project this year delivered four highly qualified professionals with in-depth induced seismicity knowledge to the Dutch Earth Sciences community.

Individual highlights of 2023 were:
- The work is already being further developed with thermal capacities to analyse the hazards of induced seismicity in geothermal operations.
- Development of a hybrid semi-analytical/numerical simulation approach to simulate fault interaction in a quasi-static fashion. This also led to a simple, yet insightful, research simulator to analyse induced seismicity field-relevant highly faulted and heterogeneous two-dimensional systems.
- Detailed simulations of a large-scale (30x30x30 cm) induced fault slip experiment as a preparation for the physical experiments.
- Performance of the physical experiments. Although not very successful, the learnings of the experiments are currently being used to develop an improved design (the so-called harlequin test) for future experiments.
- Several experiments were conducted to analyse the nonlinear mechanical properties of the sandstone rocks under cyclic loading. The failure of the rocks was also studied through acoustic measurements and linked to a microphysical model of inelastic deformation. In addition, fault reactivation experiments showed seismicity sensitivity to the rate and pattern of cyclic loading, that can potentially be incorporated in protocols of cyclic injection and depletion in subsurface reservoirs.

A quantitative assessment has been performed of the effect of reservoir flow on the development of stresses in faults. Results show that the primary effects of changes in reservoir pressure are much more important than the secondary effects of pressure gradient-induced fluid flow. Further development of the (semi-)analytical approach to induced fault slip modelling, based on singular integral equations, led to a surprising correction of the results in two classic textbooks.

Extension of the microphysical basis of an existing constitutive model for fault friction to include effects of oscillating normal stress. The model explains and is validated by experiments that demonstrate that fault weakening and unstable slip are triggered in specific ranges of normal stress oscillation frequency and amplitude.

Focus for 2024
The Science4Steer project has nearly finished, and the remaining activities in 2024 concern the defence of 3 PhD theses and the writing and submitting of several papers. Continuation of several of the research lines will occur through participation of some of the co-PIs and junior researchers in various DeepNL projects and other geo-energy related research at TU Delft and Utrecht University, and via international collaboration on natural and induced seismicity, notably between UU and the China Earthquake Administration CEA.
Collaboration and integration within DeepNL
Continuing pursuit of the ultimate goal that formed the basis for the Science4Steer project – i.e., the development of operational strategies to minimise the seismic hazard of human activities in the subsurface – is ensured through participation of several of the Science4Steer (co-)PIs and researchers in the recently awarded DeepNL NEPTUNUS project and other geo-energy-related academic projects at TU Delft and Utrecht University.

I addition, a strong cooperation was developed with Dr. Bernard Meulenbroek of the Delft Institute of Applied Mathematics, leading to theoretical results that form a promising basis for the development of fast simulation methods. Also the cyclic mechanics experiments were performed and complemented by the modelling of nonlinear mechanics of plasticity, developed in the NWO-Vidi project ADMIRE.

Relevance for stakeholders
Several of the project’s results are directly relevant for stakeholders. In particular the recent expansion of the open-source Delft Advanced Research Terra Simulator (DARTS) with poro-mechanical capabilities (and the ongoing expansion with thermo-poro-mechanical ones) is a potentially very relevant contribution for stakeholders. Another notable result is the inclusion of analytical expressions for fast computation of induced stresses in displaced faults to the TNO-developed open source PANTHER software. A further notable development is the hybrid numerical-analytical induced seismicity modelling framework which is applicable to heterogeneous multi-faulted systems, inspired by the real field complexities. Illumination of the physical processes controlling reservoir rock and fault behaviour, even when only partly quantifiable in constitutive models, also offers value to stakeholders in terms of confidence building and recognition of remaining uncertainties. Experimental results show potential for implementation of guidelines for cyclic injection and depletion to minimise or steer potential results show potential for implementation of guidelines for recognition of remaining uncertainties. Experimental to stakeholders in terms of confidence building and quantifiable in constitutive models, also offers value

Highlighted results 2023
In WP1, a change in personnel occurred as the postdoc had to move back to his home country for personal reasons. A very capable replacement was found in the person of Dr. Qiang Fu, who started on the 1 May 2023 and continued the work of magnetically characterising experimentally sheared fault gouges of Slochteren sandstone. Samples that were sheared in the presence of deionised (DI) water were found to be more magnetic than the starting material. Tiny particles of metallic iron turned out to form in these experiments. Such particles are absent in the sample sheared in the presence of brine. The working hypothesis is that the chemical environment during shearing is fundamentally different in the presence of DI water from that in the presence of brine, which implies that published results on dry gouges cannot be applied to natural conditions. It furthermore implies that magnetic characterisation of natural fault gouges might be used to infer chemical conditions, potentially together with temperature.

In WP2, the effect of fluids on heating and weakening in simulated fault gouges of Slochteren sandstone was further investigated, and further in-situ temperature measurements were conducted using the infrared camera. The results show that the bulk of the weakening

DeepNL research projects

Probing the micromechanics of small magnitude earthquake slip

| Project leader: | WP1: Detecting paleo-temperature anomalies (Fu, Greve, Volk) |
| Associate project leader: | WP2: Weakening and temperature rise during small slip. (Hung) |
| Postdocs: | |
| Dr. Marcel Mizera (UU); Dr. Michael Volk (UU) | |
| Dr. Qiang Fu (UU); Dr. Annika Greve (UU); Dr. Mark Dekkers (UU) | |
| PhD: | |
| Chien-Cheng Hung (UU) | |
| Budget: | € 725,576. (Call 1a) |
| Duration: | 2019 - 2024 |

Research aim
How hot and weak do faults get during small magnitude earthquake slip?

Highlighted results 2023
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In WP2, the effect of fluids on heating and weakening in simulated fault gouges of Slochteren sandstone was further investigated, and further in-situ temperature measurements were conducted using the infrared camera. The results show that the bulk of the weakening
during seismic slip can be explained by thermal pressurisation and that the amount of weakening depends not only on the fluid properties but also on the microstructure of the fault before fast slip, such as porosity and permeability. This highlights the importance of obtaining more information on the fault microstructure in Groningen faults. The thermal measurements indicate that flash heating is suppressed in the presence of water but still occurs to some extent. Some local pore pressurisation due to these flashes is expected and this could provide a first weakening during accelerating slip. All the results obtained in WP2 have been incorporated in the PhD thesis of Chien-Cheng.

Focus for 2024
In the context of WP2, no further activities are planned, other than finalising publications and possibly a few more experiments with temperature measurements. Ongoing magnetic characterisation of different sheared samples is underway, including that of samples that were sheared at elevated temperature.

The main results of the project will be communicated to relevant DeepNL projects through personal interactions.

Collaboration and integration within DeepNL
To estimate seismic hazard, it is crucial to understand the physics of fault movement. This project has provided experimental and microstructural evidence that thermal pressurisation is likely a key weakening mechanism during seismic slip. This notion not only provides constraints for the parameters of current friction laws used to model seismicity, but also highlights the importance of variability in weakening resulting from e.g. varying fault microstructure or pore fluid composition. These external parameters might well play a role in where earthquakes start and stop, and how this affects rupture size.

Relevance for stakeholders
The main take-home message of this project is that dynamic fault weakening cannot simply be represented by two or three parameters. It was demonstrated that fault microstructure as well as pore fluid composition play a crucial role in the amount and rate of weakening, while (effective) normal stress seems to play a limited role.

Reflection by DeepNL PhD researcher
Chien-Cheng Hung, defended his thesis on 23 February 2024
‘Working on a project within the DeepNL programme has been a unique and valuable experience. The annual scientific and stakeholder meetings organised by DeepNL were rare opportunities for me to develop my network and communication skills, which could be helpful for future development in academia and industry. I also enjoyed the summer school where we went to visit our study field, Groningen, and Germany for the excursion. I am quite proud of my findings on the effect of pore fluid on dynamic fault slip of fault gouges. The results not only provide new insight into the estimation of the maximum moment magnitude of Groningen earthquakes, but can also provide input for feasibility studies of injection-induced seismicity where a range of viscosity or salinity is used for the injection fluid. The biggest challenge that I had to overcome was running and designing numerical modelling during the pandemic. It took me plenty of time to address the coding issues while in the meantime, I could not conduct any experiments to continue my main work. Although some numerical results have been published, not all of the initial goals proposed in the project were achieved. Currently, I am looking for a position in an industry related to petrophysics and geomechanics.’

Introduction
new DeepNL researcher
Qiang Fu
Qiang Fu joined the team as a postdoctoral researcher on 1 May 2023. His doctoral research focused on the tectonic evolution of the Tibetan Plateau (China) during the Jurassic and Cretaceous. The methods employed in his research included palaeomagnetism, rock magnetism, geophysics (gravity), and petrography. Concerning the current project, Dr Fu used his expertise in rock magnetism to trace magnetic changes in powdered natural samples of the Slochteren sandstone, which were sheared experimentally under diverse conditions. He is expected to bridge the friction experiments of fault gouges with resultant changes in rock magnetic properties, thereby enhancing our understanding of elevated temperature and/or fluid motion tied to seismic activity. Dr Fu plans to explore the magnetic properties of powders sheared under various conditions, including different fluids, pressure, and velocity, thereby contributing to the ongoing advancement of this research.

The Quantum diamond magnetometer (QDM) at Utrecht University will be used by Qiang Fu for his experiments.
InFocus: An Integrated Approach to Estimating Fault Slip Occurrence

Research aim
To understand earthquake nucleation and recurrence in the Groningen gas field and to assess data assimilation for estimating and forecasting fault stresses and motions in a laboratory setup using coupled earthquake, geomechanical and fluid flow simulations.

Highlighted results 2023
Earthquake sequence model with healing, production, poro-elastodynamics, and asseismic slip
The earthquake sequence models with key capabilities for simulating sequences of induced earthquakes in the Groningen gas field and subsurface reservoir settings were finished. Earthquake sequence models use rate-and-state friction to accurately resolve fault loading with poro-elastodynamics, asseismic slip, earthquake nucleation, propagation, and arrest. This is important for the accurate evaluation of the occurrence and size of first seismic and asseismic slips, as well as for subsequent slip as it accounts for fault healing over both production and tectonic time scales. Fluid flow inside a fault is widened in relation to earthquake and asseismic slip. Earthquake sequence models with rate-and-state friction and fluid flow are openly available in 0D-3D in GARNET.

New understanding of earthquake nucleation and recurrence
Following the discovery of the possibility of nucleating an earthquake on faults that experience strengthening as slip rates increase, seismic potential with and without extreme dynamic weakening has been quantified. A single earthquake can occur in mildly velocity-strengthening Schoeteren sandstones when faults have been inactive for a few tens of millions of years. Other velocity-strengthening rock types require inactive faults for thousands to many billions of years. The latter means that velocity-strengthening rocks are still safe to explore without expecting earthquakes if healing quantified by evolution parameter b is limited. This mechanism has been applied to a typical Groningen configuration with elastic and friction parameters tailored to each lithology. Earthquake nucleation turns out to occur at the top of the mildly velocity-strengthening Schoeteren sandstones, whereas the velocity-weakening Basal Zechstein could not be activated seismically. Within the limited yet targeted simulations, earthquakes propagating into the Carboniferous underburden have not yet been observed, because the soil strengthens as slip rates increase and healing over tectonic time scales did not occur.

New data assimilation methods for fault stresses and motions
The Particle Flow Filter (PFF) and Adaptive Gaussian Mixture Filter have been tested as alternatives for the Ensemble Kalman Filter (EnKF) in data assimilation, as their capacity to deal with non-Gaussian distributions and strongly non-linear dynamics may lead to improved stress and velocity estimation in earthquake sequences. Using synthetic experiments with a 1D Burridge-Knopoff model and the Lorenz-96 model, the three methods yield comparable results in terms of root-mean-square errors. The Particle Flow Filter demonstrates stronger resilience to under dispersion than the EnKF. However, caution is needed with the PFF’s data-driven tendency, which may underestimate key prior information. Finally, the forward model and data assimilation experiments have been set up for the large-scale laboratory experiment.

Focus for 2024
The earthquake sequence models will be finalised and prepared for public usage. Robust answers will be targeted to key questions for determining seismic hazard in Groningen, i.e., where will asseismic slip, earthquake nucleation and arrest occur? Finally, laboratory measurements and their uncertainties will be assimilated into the developed data assimilation framework to combine physics and data in a statistically rigorous manner to estimate and forecast fault stresses and motions. This will allow for the exploration of the importance of data assimilation and the improved methods when accounting for an inaccurate representation of the physics and irregular earthquakes.
which are two critical aspects for adopting ensemble-based data assimilation on natural faults and in industry.

Collaboration and integration within DeepNL
InFocus used input from the DeepNL call 2a project of Ernst Willingshofer and the Call 1a project of André Nemeijer to determine the best possible frictional parameters per single and mixed rock types. InFocus provides input on these parameters for when including healing over tectonic time scales to DeepNL project PhysMmax.

Relevance for stakeholders
It is directly relevant for stakeholders to realise that a single earthquake could occur on faults that strengthen upon speed up. Equally important is to realise that once the healed strength accumulated over millions of years is released, subsequent earthquakes cannot occur on that segment. This segment will act as a barrier to future large earthquakes, thereby limiting the likelihood of a future large earthquake crossing that fault portion. The quantification for assessing corresponding seismic hazard for earthquake sequences with fast slip rates, and second, the successful estimation of aperiodic earthquake sequences by incorporating model errors. These outcomes encourage ongoing research and development in ensemble data assimilation for fault slip occurrence estimation. My most valuable experiences were attending the first in-person conferences since the pandemic, the 2022 EGU meeting in Vienna, and the EnKFi workshop in Bergen. Engaging with other researchers and receiving their feedback enriched my learning and research. The greatest challenge was navigating personal health issues, like the Covid pandemic and knee surgery, alongside project delays due to external factors, all while striving to cohesively integrate the various aspects of the project during these complex times. After obtaining my PhD, I aim to further work in creating solutions and gaining insights into subsurface applications by utilising inversion, data assimilation, and machine learning, effectively combining data with physical models.

Reflection by DeepNL PhD researcher Hamed Diab-Montero, planned to defend his thesis on 24 April 2024

The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs

Project leader: Dr. Johannes Mocic (RUG)
PhDs: Dmitry Bublik (RUG); Sebastian Mulder (RUG)
Budget: € 749,754.- (Call 1b)
Duration: 2021 - 2026

Research aim
To provide a compositional petrographic model of the Groningen gas field and its surrounding aquifers in order to predict reservoir compaction and surface subsidence.

Highlighted research results 2023
Sampling from fifteen wells within the Groningen field and its surroundings has concluded, yielding a total of 430 new thin-sections. Point-counting analyses were conducted on samples from ten wells, while detailed microscopic investigations were performed on select samples utilising scanning electron microscopes at the EPOS-NL facilities in Utrecht. Subsequently, several hundreds of thin-sections were subjected to high-resolution scanning and polarisation imaging at the same facilities. An innovative machine learning algorithm has been developed to automatically discern grain and pore sizes from these images. Moreover, 1000 meters of core slabs from six wells within the Groningen gas field were subjected to short-wave infrared spectroscopy (SWIR). This method enables the continuous identification of rock composition, particularly clay minerals and carbonates, bridging gaps in thin-section data. Additionally, it facilitates the correlation between authigenic mineral phases and depositional environments at a well scale, thereby enhancing the predictability of Rotliegend composition.

Focus for 2024
Over the forthcoming year, the petrographic analysis of all thin-sections will reach completion, culminating in the formulation of a predictive model for sandstone composition within the Groningen field. Concurrently, the SWIR data will undergo thorough examination and integration with thin-section and XRD datasets. Initial trends observed within the SWIR data pertaining to depositional environments and stacking patterns will undergo quantification and validation.

The study of thin-sections from the Groningen reservoir Rotliegend sandstone is the backbone of understanding the spatial differences in reservoir composition. The latter controls geomechanical and fluid flow properties of the sandstones. Furthermore, the machine learning code will be further refined to explore the feasibility of automatically identifying mineral phases based on the optical properties that can be discerned in polarised thin-section scans.

Collaboration and integration within DeepNL
The geomechanical experiments for this project will be conducted in the laboratory in Utrecht, facilitated by close collaboration with Suzanne Bangx. The scanning of thin-section and SEM analysis at Utrecht University receives support from EPOS-NL. The role of clay-minerals and distribution of these within the Groningen gas field is of interest to other DeepNL projects and there have been active discussions with for example Tanmaya Mishra of the µFAULT project regarding clay minerals. Upon completion, the machine learning algorithm designed for analysing sandstone images will be openly accessible. This resource holds potential for broader...
Research aim
To develop physics-based friction models for fault contacts following a bottom-up approach and use these models to compute fault slip resulting in induced seismicity due to subsurface activities.

Highlighted results 2023
In 2023, the research related activities and processes included the development of a new experimental setup for single-grain sliding experiments; the characterisation of quartz mechanical properties; the development of particle-based numerical methods to simulate friction in fault-gouge assembly; and the development of a numerical model to study time-dependent friction behaviour in fault-gouge contacts.

The novel experimental setup enables loading and sliding experiments in single (quartz gouge) grain contacts. First hand model development for centimetre-scale fault-gouge has been done using YADE, a discrete element solver. This model will incorporate the characterised contact laws from micro-scale single-grain experiments and upscale slip to fault-gouge assembly at lab scale, validated using the rotary shear apparatus in Utrecht University. An initial characterisation of the surface mechanical properties such as hardness, stiffness, roughness of quartz, which is the main constituent of reservoir sandstone, was also performed.

The tenure track work package focussed on initial model developments to study frictional ageing in faults. This model takes into account the time dependent friction behaviour in fault-gouge contacts due to the influence on pore-fluid (moisture, water film). This model will be experimentally validated to provide a physical basis to the phenomenological rate-and-state friction model.

Focus for 2024
1. To perform initial experiments to characterise the friction and contact forces at the microscale for quartz specimens using the newly developed single-grain sliding setup. This study aims to look into the effect of water/moisture and material anisotropy in quartz on its frictional and adhesion behaviour.
2. To further calibrate the numerical model developed using YADE to simulate (rotary) shear in fault-gouge aggregate, in order to maximise its computational efficiency. The model will be further benchmarked applications, particularly for individuals seeking to assess the suitability of specific sandstones for gas storage, including hydrogen or CO2.

Relevance for stakeholders
The behaviour of the reservoir is contingent upon its rock properties. Therefore, acquiring hard geological data is of paramount significance in comprehending compaction, subsidence, and seismology resulting from fluid extraction from the underground. This knowledge is essential not only for gas production but also for future endeavours such as subsurface hydrogen storage. Understanding how the data can be used in predictive models is key, and thus a collaboration with TNO regarding this has been started. Dmitry, one of the PhD researchers working on this project, will spend three months at TNO to identify how compositional data can best be integrated into predictive workflows.
Making digital rocks a practical reality for energy storage within subsurface reservoirs

**Project leader:** Dr Maja Rücker (TU/e)  
**Postdoc:** Dr David Rieder (TU/e)  
**PhDs:** Mohammad Hossein Khoeini (TU/e); Gijs Wensink (TU/e)  
**Budget:** € 1,076,055.-, incl. € 350,000.- co-funding (Call 1b)  
**Duration:** 2021 - 2026

**WP1:** Systematic study on the influence of Minkowski functionals on dissolution and precipitation phenomena in porous rocks. (Wensink)  
**WP2:** Minkowski functional based evolution equations for structural alteration processes during multiphase flow in porous rocks. (Rieder)  
**WP3:** Upscaling dissolution and precipitation processes during multiphase flow in porous rocks. (Rücker, Khoeini)

Relevance for stakeholders

The results of this project will help constrain friction in the reservoir faults. This in turn will result in more accurate predictions of the expected magnitudes of earthquakes related to the Groningen gas reservoir. Understanding and modelling of contact ageing will help in the feasibility studies of subsurface (depleted) reservoirs for storage applications. This is relevant for stakeholders like TNO and SodM who are working on the potential use of the subsurface for the energy transition in the Netherlands.

Retention times measured with inverse Gas Chromatography provide insights into the surface energies controlling the rock-fluid interaction at a molecular level. The study investigates how these signals vary in structural and chemical heterogeneous rock, e.g. showing different hydrophobicity and influence the absorption of water. The systematic data measured in the last year will help in developing new analytical tools providing input for computational models aiming to predict various flow processes in subsurface reservoirs.

The 3D printed prototype used to showcase the kinematics of the force-based Force Measurement Mechanism (FMM).
be typical for H₂ storage sites. These nano-scale water fluctuations impact the exposure of the rock’s minerals to potential reactants and hence are expected to influence structural alteration of the rock. This relationship will be investigated in a follow-up study.

The potential of inverse Gas Chromatography (iGC) was investigated to quantify these nano-scale water films using a set of model systems of different wettability. This rich dataset will help in the development of an interpretation framework to quantify the impact of nano-scale water distributions at a relevant (core-)scale. This technique is expected to support the upscaling of the molecular reactions happening between the solid and fluid.

Focus for 2024
- AFM and microCT measurements to investigate the relationship between multi-phase flow and reactive transport
- Development of the interpretation framework for the iGC dataset
- Development of a computational model capturing molecular characteristic of hydrogen on a continuum scale, e.g. to assess diffusion in tight rocks.

Collaboration and integration within DeepNL
This project supports future utilisation of the Dutch subsurface in the context of renewable energy. Contacts exist with tenure track researcher Tanmaya Mishra and with the projects of Suzanne Hangx and Johannes Miocic.

Relevance for stakeholders
The DeepNL programme outlines the gain of knowledge for applications such as underground hydrogen storage or CO₂ storage in porous reservoirs as one of the long-term goals. In particular, the DeepNL programme aims to target associated hazards, such as induced subsurface subsidence and heave, induced triggered seismicity, fluid leakage and aquifer contamination. The currently insufficiently understood interplay between geochemical processes and multi-phase flow across length scales and the associated change in structural and chemical attributes of the material may impact its mechanical properties, leading to increased potential for the failure of its structural integrity. Subsequently, these effects may lead to the aforementioned field scale hazards. This project closes this gap and contributes as such to the DeepNL programme and its societal impact.

Introduction

new DeepNL researcher

David Rieder
David Rieder has been hired as a postdoc on this project. David Rieder recently defended his thesis at the Eindhoven University of Technology with the title ‘A Multiscale Approach to the Drying of Supported Catalysts’, where he investigated the drying of porous pellets with complex pore spaces. He focuses on the multiscale aspects associated with the multiphase transport phenomena in porous media and is looking forward to investigating the flow of hydrogen within the DeepNL framework.

Highlighted results 2023
Stresses are a consequence of driving and resistive forces. In 2023 the focus of the project remained on the Eurasion plate because that is the natural mechanical unit on which forces act. One of the main forces arises where lateral differences in the gravitational potential energy occur. The first part of the project was completed, involving a new method to determine such Horizontal Gravitational Stresses. The method is applicable to all tectonic plates. This is a central ingredient in the mechanical models that are

Horizontal gravitational stresses (HGS) that act on the Eurasian Plate. Colours show HGS magnitude and arrows show directions. HGS constitute one of the major drivers of stresses in Europe. They are caused by horizontal variations in gravitational potential energy, e.g., from gradients in topography or density structure of the atmosphere.
the first objective of the project. A publication on this work is in preparation.

A strongly updated description of the main tectonic provinces, faults, and plate boundaries of Eurasia was published by Hasterok et al. (2022). Based on this, the finite element model this project works with was improved to make it more realistic. The model includes the important Trans-European suture zone (Tornquist zone) and the Upper and Lower Rhine Graben in western Europe. A consequence of this greater detail is that more model parameters need to be estimated in the Bayesian inversion.

The emphasis on the development of the forward model resulted in less progress as previously hoped with developing the workflow of the parameter search.

Focus for 2024

The main goals of 2024 are to finalise the forward (finite element) model; to choose a suitable objective function to quantify the misfit of the modelled and observed stresses, element model this project works with was improved to make it more realistic. The model includes the important Trans-European suture zone (Tornquist zone) and the Upper and Lower Rhine Graben in western Europe. A consequence of this greater detail is that more model parameters need to be estimated in the Bayesian inversion;

The emphasis on the development of the forward model resulted in less progress as previously hoped with developing the workflow of the parameter search.

Impact of fluid extraction on the creep behaviour of clayrich formations enveloping Rotliegend sandstone reservoir

Research aim

In Groningen, gas extraction from the Slochteren sandstone not only leads to reservoir compaction, but also impacts the mechanical response of the clay-rich over- and underburden formations. This project will constrain the creep behaviour of the Carboniferous shale/siltstone and Ten Boer claystone through rock mechanical experiments performed under realistic in-situ conditions, which form the basis for constitutive laws describing the creep behaviour of these formations.

Highlighted results 2023

Focussing on the mechanical behaviour of clay-rich rocks, a start was made with developing a workflow using readily-available claystone, the Opalinus Claystone (OPA), analogous to the Groningen clay-rich rocks. Triaxial compression experiments were performed on dry and water-saturated samples at an initial pore fluid pressure of 10 MPa, at room temperature and an effective confining pressure of 35 MPa, which is for example comparable to the in-situ conditions in Groningen. The material was loaded and unloaded in a stepwise manner either perpendicular or parallel to the bedding of the samples, followed by extended periods of constant applied stress. From these load-stepping experiments, the partitioning of elastic and inelastic compaction during deformation was assessed, as well as the contribution of instantaneous and time-dependent deformation to compaction. Experiments on OPA showed that up to 60 percent of the total compaction is permanent. In dry material, compaction was mainly instantaneous, with little additional compaction over time, whereas water-saturated material showed pronounced time-dependent compaction. Given the pressure-temperature-chemical conditions,
separate experiments will be performed on smaller samples is more heterogeneous on a very fine scale. As a result, initial XRD analysis it is clear that the Ten Boer claystone homogeneous Carboniferous shale samples. From the experimental approach will be applied to the relatively controlling the compaction behaviour. Subsequently, this pore pressure and even pore fluid type to further relevant to the Groningen gas field. A systematic claystone will be further investigated under conditions experiments the compaction behaviour of the Opalinus composition.

XRD measurements on 32 individual layers to assess the measurements were complemented with quantitative XRD (X-Ray Diffraction) measurements were performed on all observable facies in relevant core sections a detailed petrographical analysis is performed of the Ten Boer claystone and Carboniferous shale samples from the Groningen gas field. A complete and detailed set of quantitative XRD (X-Ray Diffraction) measurements were performed on all observable faces in relevant core sections from the Stedum-1 and Zeerijp-3A wells. In total, 13 bulk measurements were complemented with quantitative XRD measurements on 32 individual layers to assess the millimetre/centimetre-scale heterogeneities in mineralogical composition.

Collaboration and integration within DeepNL

This project can make direct contributions to and/or exchange with a total of six out of the eight calls 1a projects. More specifically, tight collaborations exist with the Science4Steer project. In addition, recent discussions with researchers involved in the SOFTTOP project highlighted the possibility of knowledge exchange. There are also links possible to the DeepImage project when it comes to identifying the sources of seismic activity, and insights gained in the Subsidence project on the total amount of settlement are of relevance to understand the compaction of the clay-rich layers above and below the reservoir.

Relevance for stakeholders

To constrain the structure, geometry and rheology of faults and fault zones in the Groningen reservoir at multiple spatial scales through an innovative integration of geological observations from the Groningen field with detailed (micro)structural analysis of field analogues, rock physics experiments and physical analogue modelling.

Highlighted results 2023

Deformation experiments in a rotary shear configuration focussing on the effects of material mixing on the mechanical strength and stability of faults have been completed. These have been complemented by a series of friction healing experiments to establish relationships between fault healing and seismic rupture. For the latter, segmented samples consisting of Slochteren sandstone gouge and halite gouge were used to simulate differential healing rates. The experimental work on heterogeneous gouges provides new insights in the mixing process of lithologies with contrasting mechanical behaviour and associated effects on frictional strength and its velocity dependence. In particular, the results suggest velocity strengthening behaviour for cases where fault sections juxtapose claystone and sandstone members, but velocity weakening behaviour for Slochteren sandstone gouge. A critical amount of shear strain and localisation seems to be required to produce such behaviour. In a rate-and-state friction framework, this suggests that most of the Rottegend reservoir can produce velocity weakening behaviour and is prone to earthquake nucleation. The results of this study are summarised in a publication that is currently in press in Earth and Planetary Science Letters. Available Groningen core material has been re-evaluated focussing on deformation features such as faults, fractures, or deformation bands. Core intervals with centimetre-scale offset faults and deformation bands have successfully been identified, as well as fault gouge from a substantial, metre-scale fault. Qualitative petrographic analysis demonstrated the presence of different generations of cements (including anhydrite, dolomite, siderite, and quartz) related to repeated fault activity. Results from the petrographic analysis and
Collaboration and integration within DeepNL

Constraining the structure, geometry and rheology of faults and fault zones in the Groningen reservoir at multiple spatial scales provides critical input for numerical geomechanical models, reservoir models and dynamic rupture models. As such, fault zone properties and scaling relations inferred from this project are relevant for DeepNL projects like InFocus, Science4Steer, and DeepImage. Close collaboration with the DeepNL project ‘Probing the micromechanics of small magnitude earthquake slip’ is anticipated on comparative studies of fault gouge microstructure in natural and experimental faults. Furthermore, knowledge on fault geometries and fault friction is exchanged with the PhysMmax, LabQuakeAI and ‘Probing the micromechanics of small magnitude earthquake slip’ projects.

Relevance for stakeholders

The relations between fault architecture, along-fault lithology distribution, fault healing and mechanical behaviour are directly relevant for improving the forecasting capabilities of advanced geomechanical and seismic wave field modelling approaches, and hence for improving risk assessment associated with reservoir depletion. This project also fuelled knowledge exchange and collaboration with stakeholders (TNO) on characterising deformation structures within faulted reservoirs in different stratigraphic levels of the Dutch subsurface.

Focus for 2024

In 2024, the research will focus on extrapolating the fault mechanical behaviour from the micro-scale to the scale of faults in the Groningen field. Observations on natural fault gouges from the Groningen field will be used as constraints on the fault properties and fault strength variability due to healing processes. The results will be integrated with observations on fault gouges from outcrop analogues in the UK, including the Clashach fault and the 90-Fathom fault. These outcrops allow for linking microstructures observed in centimetre-scale offset faults to the large deformation structures and fault gouges present in the fault core. The results will be compared with microstructural data from experimental gouges to extrapolate mechanical behaviour in the lab to larger scale deformation of Groningen type faults.

Large-scale structural relationships will be further developed by setting up physical analogue models of fault zone development simulating Groningen-type fault systems. These models will be used to assess how fault formation and re-activation was affected by the present structural strain and the multi-phase tectonic history. Insights from the analogue modelling results will be used to develop a structural kinematic model accounting for rock physics and fault properties. The modelling will aid the interpretation of realistic fault zone geometries both in the Rotliegend reservoir and in the over- and underburden of the Groningen field, which provides critical input for dynamic fault rupture modelling studies.
Monitoring of physical conditions and forecasting

How can we monitor the subsurface conditions that could lead to seismicity, and forecast the occurrence of earthquakes?

NVIDIA GPU card, a central piece of hardware which will be used in the new DeepNL project Digital twin (Trampert et al.).

Most projects in Cluster 2 rely strongly on high-performance computing and/or machine learning.
DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity

Research aim
To develop an integrated methodology for seismic imaging and monitoring of the Groningen subsurface and its induced seismicity based on innovative, scaled rock-mechanics experiments, advanced geomechanical and seismic modelling, and advanced seismic imaging and inversion techniques.

Highlighted results 2023
The DeepImage project has resulted in monitoring methodologies to better locate seismic events; a seismic imaging and processing methodology that can be used to image time-lapse changes in the reservoir, such as pressure changes; a methodology that can be used to monitor changes in stress in a reservoir and can be used to forecast seismicity to occur; and a methodology that can simulate wave propagation through the subsurface from a geomechanically modelled induced seismic event. These are all novel methods the use and success of which are tested on field data from Groningen and on model data and in experiments. Also, all of the methods have been calibrated to real events in Groningen. These methods are very promising and ready to be implemented by the stakeholders from industry and academia to better quantify and forecast the subsurface behaviour related to seismicity and stress changes.

In 2023, WP1a has focussed on processing the dedicated field-seismic data recorded in the summer of 2022 in Scheemda, Groningen province. An image was obtained of the shallow subsurface till approximately 300 meter below the seismic line and S-wave velocity information was obtained using S-wave reflection data, which had never been done before. This showcased the ability to extract S-wave velocity models of the subsurface, which is much needed for monitoring microearthquakes for geothermal projects. In addition to this, for the first time a successful application of the Marchenko redatuming was demonstrated on land data.

WP1b applied the monitoring methodology developed in the previous year to reveal the source characteristic of the 3.4 local magnitude earthquake in Westerwijtwerd village. All in all, the results agreed well with the orientation of the mapped fault in the area, and the depth of the earthquake is projected to be shallower than previously assumed. Most importantly, the method itself has proven to be much more computationally efficient than a generic method. The methodology was also applied to the ten largest earthquakes in the Groningen gas field. Together with revealing source characteristics of the ten earthquakes, the study also added fault directivity investigation to the analysis.

WP2 demonstrated the feasibility of active ultrasonic monitoring as a tool to identify precursors to laboratory fluid-induced earthquakes. Both acoustic emission and active acoustic monitoring were demonstrated to be useful to detect fault reactivation process under stress cycling. It was also shown that a combination of methods and a combination of the analyses of different proxies within the dataset can be beneficial to increase accuracy of monitoring.

In collaboration with Science4Steer PhD student Milad Naderloo, DeepImage PhD student Aukje Veltmeijer prepared and performed an upscaled experiment on a layered sample containing a displaced fault, mimicking the fault system of Groningen. Stress conditions to cause Figure 1: Fault directivity, epicentre and focal mechanisms of 10 investigated earthquakes in the Groningen gas field. The directivity analysis was using two scenarios: (i) assuming the faults only move in one direction or unilateral and (ii) assuming the faults move in two opposite directions or bilateral. Figure 2: Sample design for upscaled fault-displaced experiment.

Project leader: Dr Auke Barnhoorn (TUD)
Associate project leaders: Dr Deyan Draganov (TUD); Dr Ranajit Ghose (TUD); Kees Wapenaar (TUD); Dr Kees Weemstra (TUD/KNMI)
PhD students: La Ode Marzujriban Masfara (TUD); Jingming Ruan (TUD); Faezeh Shirmohammadi (TUD); Aukje Veltmeijer (TUD)
Budget: € 1,053,152.- (Call 1a)
Duration: 2019 – 2023
fault-reactivation were first calculated in the analytical and numerical modelling studies within Science4Steer and used in the experiment, while active acoustics and passive acoustic monitoring was applied. The success of these upscaled experiments show that active acoustic monitoring has potential to see stress changes from acoustics on larger scales.

WP3 further investigated how intersecting faults behave in nucleating a reservoir-depletion-induced earthquake. Discontinuities were observed in rupture propagation and in the maximum slip across the intersection, as well as in propagation of the dynamic rupture from the main fault to the secondary faults. The 2018 magnitude 3.4 Zeerijp event has been simulated. The simulation produced an event of magnitude 3.0 at 26 Mpa depletion of the reservoir. The depletion value is close to the actual depletion known from the production data in this region. Furthermore, by using the appropriate seismic velocity model for the Zeerijp region, comparable seismic observations at chosen borehole receivers located near the hypocentre were successfully simulated. The derived moment tensor aligned well with the field-seismic observation.

Focus for 2024

The four PhD researchers will finalise and defend their theses and will submit their final manuscripts to peer-reviewed international journals.

Collaboration and integration within DeepNL

The work on the reflection seismic data acquisition and processing was performed in collaboration with DeepNL project 3D5011, ERC Advanced Grant project ‘Virtual Seismology: monitoring the Earth’s subsurface with underground virtual earthquakes and virtual seismometers’, and with the Delphi Consortium. With regard to the seismic velocity models, there has been a collaboration with the project of Jeannot Trampert which resulted in two code packages (code-cullison/gnam: First Release (zenodo.org) and code-cullison/pyaspect: First Release (zenodo.org)). A significant part of the experimental programme has been performed together with the DeepNL project Science4Steer, which resulted in joint publications.

Relevance for stakeholders

The developed methodology for layer-specific imaging and monitoring can be used by companies responsible for monitoring reservoirs with a high resolution. The results are reported to such companies, which are sponsors of the e.g. Delphi consortium, and are used by e.g. TNO and KNMI. The algorithm powering this technique isn’t confined to monitoring induced earthquakes alone, making it applicable for various parties seeking to estimate their specific parameters of interest.

The developed active-acoustic monitoring technique can be implemented in real-scale applications to continuously monitor stress changes and the proximity to failure in the reservoirs. Several stakeholders from Dutch companies engaged in CO₂ sequestration and mining companies that are concerned about mine-tunnel stability have expressed their interest. In addition, other research institutes are adapting the active-monitoring strategy.

Highlighted results 2023

Since the end of the project is near, the emphasis is on finishing the sub-projects, with the exception of WP1, which the team is trying to revive.
reservoir. Model order reduction using specific solutions shows even higher gains and can easily be extended to 3D. This approach might thus have a big impact on the computational feasibility of full waveform inversion in certain areas. This is work still in progress by Hamza Khalid.

WP3: A method to monitor compaction in a time-lapse setting using the classical technique of receiver functions was developed. The novelty of the approach is that the technique is formulated using modern adjoint waveform modelling. This part of the project is finished and Janneke de Jong submitted her PhD thesis.

WP4: A method was developed to monitor lateral changes in pore pressure and temperature in the shallow subsurface from seismic ambient noise. The technique works very well for the first few hundred meters of the subsurface. Application to deeper structures depends on the elastic parameters of the subsurface. This part of the project is finished and Eilert Fokker submitted his PhD thesis.

WP5: A non-parametric adaptive kernel smoothing technique was developed to estimate the spatio-temporal seismic hazard in Groningen, based on the spatio-temporal earthquake catalogue, gas production, as well as pore pressure data. Current rate-and-state models fail to correctly predict interevent time statistics of the temporal earthquake catalogue, gas production, as well as pore pressure observations as well as gas production volumes as covariates, is currently being tested. This is work still in progress by Zhuldyzay Baki.

Focus for 2024
The planning is to apply the new method of physics informed machine learning to the imaging problem in the Groningen reservoir. If successful, the approach will produce two deliverables: (i) a rapid forward simulator of seisograms based on a reduced order model parametrised on a neural network; (ii) an imaging tool for elastic structure parametrised on a second neural network. Groningen is the ideal place to test this new technique as there are plenty of recorded seisograms available to train the neural network. Hamza Khalid will finish his work on model order reduction research on specific solutions to the elastic wave equation. Subsequently he will extend it to a model which includes attenuation and derive a reduced model which allows for a rapid simulation response for a new source location. This for instance is important for early warning of earthquakes. He will also submit his PhD thesis.

V. PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling

**Introduction**

DeepNL researcher - Adam Candy

Adam Candy is a postdoc at Utrecht University. He is a theoretical physicist with an interest and enthusiasm for geophysical processes. He is busy adapting an exciting new technique of physics informed neural networks for full waveform inversion to the Groningen setting, and compare the performance of this model for monitoring of induced seismicity to that of NAM's reservoir model. She will also submit her PhD thesis. Eilert Fokker defends his thesis in April 2024. He started working at TNO in January 2024. Janneke de Jong defends her thesis in April 2024. After her maternity leave, she will start working at the Ministry of Economic Affairs and Climate Policy.

**Collaboration and integration within DeepNL**

The transfer of the NARS equipment to the University of Twente has been finalised. With the help of Arne van Wettum, technician of the Utrecht seismology group, all stations have been installed and are collecting data for the DICTUM project. Researchers from this ta project are also involved in developing and testing an ocean bottom seismometer within the DICTUM project.

**Relevance for stakeholders**

Python wrappers have been developed which allow stakeholders to run SPECFEM3D to model wave propagation in the Groningen gas field. The codes are freely available. The NARS broadband data recorded between 2019 and 2023 across the Groningen gas field are openly available via KNMI. Code for non-parametric hazard map estimation (bw.CvL); has been made available in the open source R-package spctm. This can aid an informed decision-making tool, which will be relevant for stakeholders. The method of monitoring pore pressure and temperature in the shallow subsurface using seismic interferometry is very versatile and applicable in many settings. Deltares is keen to test the method for their purposes. Several joint MMax projects are expected to mark the start of a hopefully longer term collaboration.

**Research aim**

To generate physics-based, data-driven probabilistic constraints on the maximum earthquake magnitude (Mmax) that account for interactions between faults in Groningen’s fault network.

**Highlighted results 2023**

A coupled 3D modelling chain was finalised to simulate dynamic earthquake rupture (SeisSol). Stress changes due to the earthquake can be returned to continue loading the fault to subsequent earthquakes. This framework is applied to simulate the sequence of earthquakes observed on the Wirdum fault segment between 1993 and 2022. The heterogeneous, high-resolution simulations are constrained by using an unprecedented amount of high-quality geological and geophysical data. A re-interpreted fault geometry shows kilometre-scale undulations along-strike, a 72 rather than 79 degrees fault dip in the reservoir, and a shallower, listric extension beneath the reservoir. This is embedded in a heterogeneous elastic medium with layering and elastic parameters adopted from the NAM geological model. This leads to along-strike variations in reservoir offset and bi-material regions, where different lithologies are juxtaposed. The frictional parameters on this complex fault vary with lithology and account for mixing in bi-material regions, healing over millions of years, and strengthening upon slip reactivation, as constrained by extensive laboratory experiments and cross-scale earthquake sequence simulations performed in the InFocus project. Pre-production fault stresses are set per lithology following borehole data in neighbouring formations. This leads to an open-source 3D modelling framework accounting for geological and geophysical observations and processes, including the occurrence of previous earthquakes and as seismic slip.

The new DeepNL framework can predict the sequence of many earthquakes on the Wirdum segment between 1993 and 2022. It correctly suggests the location of the first small earthquakes and the locations and sequence of the larger earthquakes. Controlling factors for earthquake occurrence and relative timing are the along-strike variations, strike and dip creating undulations, and relative fault offset. These observations are already evident from the semi-analytical approximations for fault loading. Upon exceeding a theoretical 3D nucleation criterion by a few percent, stresses are exported to simulate spontaneous nucleation at approximately the observed locations. Spontaneous arrest locations and thus earthquake size are dominantly controlled by the along-strike kilometre-scale undulations of the fault geometry. PhysMmax ability to for the first time hindcast an entire earthquake sequence on a complete fault segment confirms the correctness and relevance of its modelling chain as well as the communities understanding of the physics of earthquakes in Groningen.

The first arrivals of the seismic waves emitted by the largest earthquakes largely agree with observed seisograms. These synthetic waveforms have been used for a synthetic moment tensor inversion. Results are compared to moment tensors from inversions to better constrain e.g., fault dip.

Collaborators of the project and postdoc Huihui Weng (Université Côte d’Azur) are also finishing two papers providing the first physics-based probabilistic constraints on maximum earthquake magnitude in Groningen. This uses a theoretical rupture tip equation of motion, which accounts for single faults that do not interact. Accounting for uncertainties on model parameters, the current estimate of Mmax in the Groningen gas field until 2052 ranges from 4.0 to 4.6. Uncertainties in dynamic
friction coefficient and pre-production stresses below the reservoir are particularly critical.

**Focus for 2024**

The hindcasting of the Wirdum earthquake sequence will be finalised and extended to basic forecasting for the Wirdum fault. The case study will be exploited with unprecedented constraints and fit to the earthquake catalogue to learn about processes and parameters frequently out of reach. For example, the aim is to constrain a very poorly quantified frictional parameter that is critical for earthquake slip: the critical slip distance.

The synthetic moment tensor inversions will be further developed to improve the constraints on a key parameter when forecasting earthquake slip: fault dip. Fault dip estimates in Groningen – and likely in other places in the Netherlands and abroad – vary quite considerably between different observations and methods. This might allow for an improvement upon moment tensor inversion methods.

Finally, the project will advance on extending the rupture tip equation of motion to fault branches and step-over jumps, as to provide the best possible estimates for physics-based maximum magnitude for the complete fault network.

**Collaboration and integration within DeepNL**

The data-driven physics-based models developed in this project tightly integrate observations and experiments from DeepNL and NAM projects on Groningen to address key questions about earthquakes and hazard in Groningen. At present data has been used from the project of Ernst Willingshofer, the call 1a project of André Niemeijer, and InFocus. Moreover, there are strong collaborations with TNO for fault loading (Loes Buijze) and KNMI (Elmer Ruigrok, Jesper Spetzler, Kees Weemstra) for moment tensor inversion.

**Relevance for stakeholders**

This project provides the first physics-based estimates for Mmax when accounting for single fault ruptures (4.0-4.6). These values are relatively low compared to previous estimates, although the largest values agree with recently accepted values for Mmax. These values are of critical importance for the seismic hazard in Groningen and need to be processed in TNO’s risk chain, as it may suggest very limited to no casualties. That is of key relevance for people in Groningen and the Dutch society and policy makers.

The 3D physics-based, data-driven framework for hind(and fore-)casting induced seismicity is open source and can be extended to essentially any fault in the Netherlands and worldwide. That means that it can be used for understanding and anticipating any earthquake and ultimately also for a region’s maximum earthquake magnitude.

These integrations will be further prepared for industrial use and extension to geothermal settings in NEPTUNUS, the new DeepNL project that integrates PhysMmax with InFocus and Science4Steer.
Deep, deeper, deepestNL; Imaging the Dutch crust and upper mantle using multi-geoobservables (DICTUM)

Research aim
To develop new high-resolution, multi-physics, seismic velocities, density, and thermal models of the Dutch crust and upper mantle down to 200 kilometres depth using data from a proposed densified broadband seismological network of inland and sea bottom seismometers integrated with the freely available high-resolution Bouguer gravity data and upper crust thermal models.

Highlighted results 2023
The deployment of the land seismological network with 22 stations was completed. This included 2 extra stations as compared to the 20 that were originally proposed. An additional 2 stations are foreseen to improve the coverage in the future. Moreover, a new method was developed to image the crustal thickness of the Netherlands using seismological data in the presence of sedimentary basins that complicate the existing techniques. The new methodology is described in a peer-reviewed article that is currently under review.

A significant part of the data was processed using receiver function techniques to generate a new crustal thickness model across the Netherlands.

Some challenges occurred in installing the marine seismological network in the North Sea due to unfavourable conditions, causing high financial risks associated with possible damage to loaned instruments. However, an alternative solution was proposed, and in a close collaboration with NIOZ, Utrecht University, and KNMI, and supported by NWO, a new installation methodology was developed that fits the conditions of the North Sea. The new installation methodology has been tested at the NIOZ harbour in the Wadden Sea in shallow water. The preliminary results were promising, and the new installation methodology has been further finalised in 2024. A detailed 3D seismic velocity model of the Netherlands will be developed with almost double the resolution of the most recent seismological model available. Moreover, a database of the geophysical observables, e.g., gravity and temperature data, will be organised and prepared for the final multi-geophysical joint inversion that will be carried out in the final year of the project, 2025.

Collaboration and integration within DeepNL
The fundamental and quantitative understanding of the Earth’s resources distributions and the risk of seismic hazard requires high-resolution regional seismic velocity, density, and thermal models. For example, to understand earthquake impact over distances beyond a ten kilometre-radius, accurate regional velocity and density models and their uncertainties are essential for seismic risk assessment and hazard mitigation. Moreover, the derived regional seismic velocity, thermal, and density models can be used for regional prospectivity mapping of the thermal resources in the subsurface.

Relevance for stakeholders
Given the future ambition of utilising the Dutch subsurface for ultra-deep geothermal energy from the deep Dinantian rock formations below five kilometres depth, there is an urgent need to understand and image the crust and upper mantle structure of the Netherlands in great detail. Also, for locating and characterising seismicity, a refined velocity model of the deeper structure is indispensable. The models generated from this project will be made publicly available. They will be very useful for regional prospect mapping and targeting of resources, e.g., geothermal, and can be used to locate high-potential prospects.

Moreover, companies working in the North Sea are already involved in testing the new North Sea seismometer design near some possible test sites, e.g., the Porthos site. The companies are planning to co-finance the development and deployment of at least one sensor in one test site in the North Sea. However, the plans depend on getting permission to access sites and on if the available vessels meet the requirements of the test sites to be able to install the sensors there.

The research focus for 2024 will be mainly to use previous and new seismological data to enrich the 1D seismic velocity structure underneath the seismic stations using seismological techniques, e.g., receiver function and global phase interferometry. The data were partially processed with these two techniques in 2023 but will be further finalised in 2024. A detailed 3D seismic velocity model of the Netherlands will be developed with almost double the resolution of the most recent seismological model available. Moreover, a database of the geophysical observables, e.g., gravity and temperature data, will be organised and prepared for the final multi-geophysical joint inversion that will be carried out in the final year of the project, 2025.

Collaboration and integration within DeepNL
The fundamental and quantitative understanding of the Earth’s resources distributions and the risk of seismic hazard requires high-resolution regional seismic velocity, density, and thermal models. For example, to understand earthquake impact over distances beyond a ten kilometre-radius, accurate regional velocity and density models and their uncertainties are essential for seismic risk assessment and hazard mitigation. Moreover, the derived regional seismic velocity, thermal, and density models can be used for regional prospectivity mapping of the thermal resources in the subsurface.

Relevance for stakeholders
Given the future ambition of utilising the Dutch subsurface for ultra-deep geothermal energy from the deep Dinantian
LabQuakeAI - AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data

Project leader: Dr André Niemeijer (UU)
Associate project leader: Dr Ivan Pires de Vasconcelos (UU/ Shearwater)
PhD: Rens Elbertsen (UU)
Budget: € 358,358.-(Call 2a)
Duration: 2022 - 2026

Research aim
How do we use machine learning techniques on acoustic measurements of complex analogue fault experiments to uncover information about the state of the fault, and how does this method inform predictions of the time to failure?

Highlighted results 2023
The project leader moved to industry but will remain involved in the project. The project lead has shifted to the original associate project leader. A new method was developed to utilise acoustic data to forecast shear stress and time to failure of laboratory earthquakes using an analogue material. These data have previously been used by other researchers to forecast laboratory seismicity using either a relatively simple decision tree-based machine learning approach or a more complex neural network approach. While the second approach performs better than the decision tree-based approach, the obtained predictions are not easily linked to physical processes. The decision tree-based approach is more easily interpretable but does not take into account temporal changes in the calculated statistical features. The method developed in this project utilises a principal component analysis (PCA) and Uniform Manifold Approximation and Projection (UMAP) embedding which feeds into a random forest approach. This method leads to better predictions than using only the statistical features as a direct input, and with it, changes were observed in the importance of different statistical features throughout the seismic cycle. In addition, fundamentally different feature contributions were found for experiments performed under different normal stress conditions which might be related to differences in signal attenuation. The study is currently being written up in a first manuscript.

For the construction of the new large scale biaxial apparatus to be used within the laser acoustic setup, first a smaller version (~5 centimetre scale) was built for testing. This revealed a potential problem in the method of loading the fault. Utilising an electromotor for the shear loading generates too much noise to be able to register clear acoustic signals.

Focus for 2024
In the coming year, the aim is to apply the newly developed method to a rich and unique data set of large scale shear experiments in which both homogeneous and heterogeneous faults were simulated. This will be a direct test of the portability of the method to data obtained in a different setting and for a different faulting configuration. Moreover, the hope is that the obtained predictions can be related directly to actual physical mechanisms operating within the simulated fault. This activity will also inform the types of experiments to be conducted in the to-be constructed biaxial apparatus. This is the second main activity in 2024.

Collaboration and integration within DeepNL
No interactions with other DeepNL projects have occurred yet, since the method has not yet been applied to materials that are more relevant to the subsurface of the Netherlands. However, general discussions on seismicity related directly to actual physical mechanisms operating within the simulated fault. Utilising an electromotor for the shear loading generates too much noise to be able to register clear acoustic signals.

Relevance for stakeholders
The novel, improved data science/AI toolkit could be of interest for stakeholders interested in revealing hidden patterns in time-series analysis. This could be applicable to the analysis of passive acoustics or field seismic data, although the interpretation/meaning of the patterns arising from other types of time series data would be subject of further research. As mentioned, this is not immediately relevant to stakeholders, since the portability of the method to other data is still under investigation.

True (green) and predicted (purple) shear stress from a laboratory stick-slip experiment. The colours in the background indicate whether the features, extracted using a new algorithm, predicted a higher (more red) or lower (more blue) state of stress on the fault.
Subsidence and the response of the Earth’s surface to earthquakes

How can we assess and model the impact of deep and shallow subsurface processes on ground motion at the surface?
Monitoring and Modelling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension

Project leader: Prof. Ramon Hanssen (TUD)  
Associate project leaders: Dr Rob Govers (UU); Prof. Esther Stouthamer (UU); Dr Femke Vossen (TUD)  
PhDs: Wietse Brouwer (TUD); Chayenne Janssen (UU); Samantha Kim (TUD); Marius Wouters (UU)  
Other staff: Marc Bruna (TUD)  
Duration: 2019 - 2025  
Budget: €1,233,808.- (Call 1a)

Research aim
To significantly improve the accuracy of geodetic subsidence estimates, and to better constrain the model parameters that control physical processes in the subsurface.

Highlighted results 2023
In 2023, the Subsidence project aimed to define the overarching model formulation for subsidence over Groningen. Since especially the shallow part of the subsidence can be extremely variable, both spatially and temporally, it was decided to establish a grid- or polygon-based kinematic description of subsidence over time. This implies that for every grid cell or parcel, the vertical and horizontal displacement are described with a model that contains three components: (i) the temporal variability stemming from the deep (reservoir) processes, (ii) the temporal variability stemming from the shallow soil-related processes, and (iii) the temporal variability of man-made constructions. This way, a functional and stochastic kinematic description of surface dynamics is given, and the various driving mechanisms can be disentangled.

The overarching kinematic model requires a physical model as main input. For this reason, the physical mechanisms have been studied, leading to new insights in the behaviour of the deep and the shallow, soil-related, processes. Yet, the high computational expense associated with mechanical simulations in geophysical contexts hinders their practical use in data assimilation. A mechanical model was developed for the Groningen context by reducing the complexity of the reservoir shape and of the regional stratigraphy without affecting the calculated subsidence beyond the observability threshold of InSAR displacement estimates. The model was demonstrated to be about 100 times more efficient than more complete models.

Any fault slip at reservoir depth causes some surface deformation. The potential amplitudes of these surface signals have been investigated, for both co-seismic and aseismic fault slip, and their resolvability from kinematic geodetic displacement estimates was determined. Sismological data were used for the potential amount of co-seismic slip, and 2D finite element models of a frictionless fault in a depleting reservoir layer were built to determine the potential amount of aseismic slip. To compute the surface deformation resulting from the fault slip, a simple 3D analytical elastic half-space solution was used. While the surface imprint of a co-seismic slip of even the largest historic earthquake remains below the resolvability, aseismic slip during SSEs can potentially be resolvable. However, an analysis of GNSS-data has not resulted in detection of SSEs. An upper limit has been provided for the magnitude of SSEs in the Groningen region.

A method was developed to derive the stochastic model for InSAR phase observations. Besides the stochastic model, also the functional model was improved. With InSAR phase observations are obtained for many different scatterers. To estimate the corresponding displacements, a unique functional model has been developed for every scatterer to relate the phase observations to the deformation and other parameters such as the height and atmospheric delays. A data assimilation approach was built to assimilate InSAR-derived displacement time series of subsidence over the Groningen gas field and to identify various subsidence-driving mechanisms. Numerical simulations showed that a deep- and shallow-driven subsidence can be accurately separated in synthetic experiments. In this simulation, a compacting soil is simulated based on a simplification of Groningen’s soil geology and subsidence caused by a compacting reservoir. The same data assimilation experiment using real InSAR displacement estimates shows significantly more uncertainty in subsidence forecasts, pointing out the model error and the limits of model approximations to represent subsidence-driving mechanisms.

An exploratory model study has been carried out to quantify the contribution of groundwater extraction in the Groningen gasfield area to total land subsidence. Hereto, a 3D geohydrological model of the Groningen subsurface (from top to “200 meters depth”) integrating groundwater hydrology and subsurface compaction processes has been developed. By combining a geohydrological dataset (REGIS II) with the iMOD hydrological model, a re-analysis study has been conducted of yearly hydraulic head changes from 1960 to 2020, incorporating groundwater extraction amounts, depths, and spatial distribution of wells. The modelled hydraulic head changes served as input for the SUB-CR compaction model, estimating the resulting contribution to surface subsidence. Continuous measurements have been done at the two sites for measuring shallow (sub) surface processes in the Groningen gas field area in Nieuwolda, Groningen. Preliminary results show a clear correlation between vertical layer movement as measured by the extensometers and groundwater level fluctuations.

Focus for 2024
In 2024, the parameterisation of the grid/parcel-based dynamic model will be finalised, and the parameters will be estimated. The work on the deep processes, the shallow processes, and the data assimilation will be finalised, focusing on the writing of the final dissertations. The work on the improvement of the geodetic estimation will continue, leading to a first region-wide estimation of the deep, the shallow, and the man-made structures components.
methodology developed for the per-parcel estimation of surface dynamics, developed for pasture areas, will be adapted to the more agriculturally diverse area of Groningen.

Collaboration and integration within DeepNL
There are close connections between the different work packages in the project. Results from the geophysical and shallow subsurface modelling work and InSAR observation data are fed into the data assimilation procedure. The data assimilation part of the project is conducted in close collaboration with the InFocus project. Topic-wise, common data are fed into the data assimilation procedure. The predicted stratigraphy captures the spatial variability of the shallow subsurface, specific characteristics of sand and clay layers, and characteristics of induced earthquakes such as short-duration repetitive loading.

Highlighted results 2023
WP1: The FEM Fortran code to simulate the effects of induced earthquakes on the shallow subsurface, accounting for cyclic and coupled hydro-mechanical soil behaviours in 2D, was extended. The following tasks were completed: integration within the code of the anisotropic constitutive framework (developed in WP2) to investigate the effect of sand anisotropy during earthquakes; introduction of a new periodic-based random field strategy to ensure the alignment of material properties at the domain boundaries, thus overcoming the discrepancy between periodic boundaries and the use of traditional random fields. In addition, novel dynamic boundary conditions were developed to simulate earthquakes when lateral boundaries are significantly different with respect to soil profile, namely Tied Free-Field boundaries.

WP2: The capabilities of the multilaminate framework for sands have been further enhanced by incorporating Anisotropic Critical State Theory (micro) and integration point level material property distributions (meso). A novel semi-micromechanical fabric evolution formulation that can simulate the behaviour of laminated sands has been proposed. The semi-fluidised theory has been incorporated to capture the post-liquefaction response of sands. A novel incremental constitutive driver for the semi-micromechanical frameworks and a user-friendly interface have been developed.

WP3: The novel CYC-DoSS device was completed and it underwent a series of validation tests to assess its performance and the accuracy of the in-house developed sensors. This system is utilised for conducting experiments on soft soils under various cyclic loading conditions. It has been proven that the CYC-DoSS can effectively replicate the time history of seismic activity observed in Groningen. Through experimental cyclic testing on Dutch organic soft soils, the bounding surface model has been refined. This enhanced visco-plastic bounding surface model is now able to replicate several key characteristics of the cyclic behaviour of organic soft soils, and to accurately predict the response of cyclic soils over a variety of controlled stress paths tested in the laboratory.

Focus for 2024
The project will be finalised in the first half of 2024. The PhD theses and further journal papers will be submitted. The constitutive model for the cyclic response of soft clays is being validated for various soils and conditions. A
user-defined model routine is being tested for integration with general Finite Element (FE) platforms.

Collaboration and integration within DeepNL
The SOFTTOP project is closely related to the 3DSOIL project, which will provide a clearer picture of the spatial distribution of soil variability in the top 30 metres of the subsoil. Both the numerical and experimental tools that have been developed in SOFTTOP have been (and may be) used to gain a deeper insight into the role of the shallow subsurface in transferring energy from induced earthquakes to the ground surface, as well as quantifying the impact at the ground surface, for example in terms of peak ground accelerations and differential settlements.

Relevance for stakeholders
SOFTTOP improves the capacity to predict earthquake loads on the ground surface by providing new insights into the behaviour of laminated sands and organic soils under cyclic loading, and new information on the impact of the shallow subsurface on the transfer of earthquake loads from deeper geological units to the ground surface. The new cyclic device is expected to serve potential stakeholders in studies on the response of soft Dutch soils subjected to cyclic loads in a variety of engineering applications, including site amplification, foundations under cyclic loads, and railway induced vibrations. The equipment has been illustrated in a number of technical visits to the TU Delft laboratory.

Reflection by DeepNL PhD researcher
Divya Varkey (PD)

‘Working as a postdoc on a DeepNL project was quite insightful, primarily because it related my work to the main geomechanical issues occurring in the Netherlands. It also gave me the opportunity to connect with more people with extensive experience in Dutch underground studies. I am very proud of the fact that we managed to obtain results through collaboration with other DeepNL researchers, since it made my work more comprehensive. My most valuable experience was familiarising myself with the Dutch underground, an opportunity I could not fully experience during my PhD in the Netherlands. The biggest challenge to overcome was integrating my previous experience into the new challenges posed by the Dutch underground, which is quite complex to understand. In the near future, I expect to apply everything I have learnt in my postdoc to my current position at TNO, which is related to the energy transition and Dutch underground.’

Reflection by DeepNL PhD researcher
Hilmi Bayraktaroglu (PhD) is expected to defend his thesis before the end of summer 2024

‘My experience in the DeepNL project during my PhD/postdoc was both challenging and rewarding. It provided an opportunity to contribute to advancements in understanding complex soil behaviour. I am most proud of successfully incorporating a new semi-micromechanical anisotropic formulation that can reproduce the behaviour of soils targeted in this project. The most valuable experience was collaborating with experts throughout the project, and the most significant challenge was addressing complex mathematical and computational aspects, ensuring accuracy in reproducing soil behaviour, and integrating the formulation seamlessly into our in-house Finite Element code. In the future, I aim to contribute to related projects and collaborations, leveraging the expertise gained during my work in the DeepNL project. Whether through academic pursuits, industry collaboration, or continued innovative research, my goal is to contribute meaningfully to the field and its applications.’

Reflection by DeepNL PhD researcher
Ching-Yu Chao (PhD) is expected to defend his thesis before the end of summer 2024

‘My experience during my PhD research in the DeepNL project was very rewarding, but it came with unique challenges, especially during the pandemic and subsequent lab facility lockdowns. While these circumstances were challenging, they also presented opportunities to explore other aspects of research. I am particularly proud of developing a novel equipment in-house at TU Delft, especially given the additional challenges posed by the pandemic. This in-house equipment not only allowed me to conduct crucial experiments but also showcased the innovative spirit of our research group. One of the most valuable experiences during my time in the DeepNL project was the adaptability and resilience I acquired when faced with the pandemic-induced lab facility lockdowns. These circumstances prompted me to explore numerical modelling. It turned out to be an invaluable experience, as it expanded my skill set and allowed me to continue making progress even when experimentation was not feasible. In the near future, I plan to continue my research in the field of geotechnical engineering and soil mechanics, drawing on the valuable experiences gained during my PhD.’
3DSOIL: 3D soil variability in Groningen for accurate, local site response analysis

**Project leader:** Dr Ranajit Ghose (TUD)
**Associate project leader:** Prof. Michael Hicks (TUD)
**PhD:** Eddy Reveleo Obando (TUD)
**Budget:** € 358,991.-(Call 2a)
**Duration:** 2021 - 2025

**Research aim**
Cone penetration test (CPT) offers very detailed information on soil variability in the vertical direction, but such information is missing in the lateral direction. This project aims to derive the lateral soil variability in between CPT locations through innovative use of high-resolution seismic data. The overarching goal is to end up with realistic, local site response analysis for Groningen through incorporation of soil spatial variability in a data-driven manner.

**Highlighted research results 2023**
A workflow has been developed for conducting multi-parameter inversion of full-waveform S-wave seismic data. This workflow is tested on noisy synthetic data. The resolution and accuracy of the velocity model obtained from this inversion approach those from seismic cone penetration tests (SCPTs). The results obtained on noisy, realistic synthetic data show that the lateral variability of soil is reliably captured, as verified at discrete CPT locations. The lateral changes in thickness and stiffness of the sand, clay and peat layers till a depth of at least 30 metres are delineated.

Next, appropriate machine learning (ML) algorithms have been developed to estimate CPT cone-tip resistance (qc) from shear-wave velocity (Vs). For this purpose, the large SCPT databases available for the Groningen region were used. A database was created of high-quality 1D Vs profiles in Groningen containing spatial coordinates and other relevant geological information. Next, suitable ML approaches were investigated, including Support Vector Machines, Random Forests, XG Boost, Light Gradient Boost, and Artificial Neural Networks. A thorough analysis was conducted to test their robustness and accuracy in predicting qc from Vs at new locations that had not been used in training. The results show that properly adapted ML schemes can predict the variations of qc with depth at most locations. Only at a few locations the prediction accuracy is low. This is likely due to the fact that so far, data has been used from a large region to train the ML algorithms. The high prediction accuracy for most of the locations, nevertheless, show that the relationship between the two parameters holds on such a large spatial scale and demonstrates the power of the adapted ML schemes. Strategies to remove the outliers in the training data to improve prediction accuracy have also been considered.

**Focus for 2024**
The work in 2024 will centre around applying the elastic full-waveform inversion scheme tuned so far on synthetic data to field-seismic data in Groningen acquired in 2022 and possibly to another existing dataset from the western part of the Netherlands. Surface waves typically dominate the near-surface seismic data, but surface waves are sharply attenuated with depth. For achieving high resolution and high accuracy also at greater depths, one needs to make more use of the body-wave information in the wavefield. The aim is to understand the relative contributions of body waves and surface waves in the inversion, and the possibility of using them judiciously for achieving further improved results. Concurrently, the focus will be on employing the specially adapted ML techniques to predict geotechnical parameters beyond qc. Finally, laterally continuous sections of geotechnical properties will be derived, calibrated at the CPT locations. In the future, these will be vital inputs to reliable seismic site-response analysis and to forecasting ground settlement and liquefaction. Once successfully tested on both synthetic and field data, all new results and insights will be presented in two journal articles in 2024. Additionally, a physics-informed ML technique will be developed for Vs to qc prediction.

**Collaboration and integration within DeepNL**
There is a close collaboration of the PhD student in this 3DSOIL project with the researchers in the SOFTTOP project and DeepImage WP1a project. During the extensive field campaign, these researchers have worked closely together. To assess the impact of lateral variability in soil on local site response analysis, an early calculation of the site response spectrum is done as a collaboration between multiple projects.

The 3DSOIL project aims to provide crucial input to quantitative forecasting of ground motion due to an induced earthquake (due to human activities in the underground) as well as to estimating the potential of local ground settlements/subsidence and liquefaction. This research directly addresses the challenges due to earthquakes induced by gas extraction in Groningen, and due to other human interventions in the subsurface. These are precisely the objectives of the DeepNL programme. Seismic and CPT address two very different scales. This project addresses the research question: How can we bridge different scales when modelling dynamic systems?

**Relevance for stakeholders**
This project will lead to more realistic, local site response analyses than is now possible for Groningen. The results of the present research (i.e. potential for larger local datasets) will be fed directly into industry through the geo-engineering group’s on-going collaborations with Deltalens and the flood defence, rail and offshore industries, and in particular, through the group’s work with industry in developing a reliability-based assessment framework for large geotechnical infrastructure. There is also a huge need in offshore geotechnical studies where the present research will be valuable. The research outputs will be useful for renewable energy companies looking to improve their understanding of the shallowest part of the subsurface.

![Image](image.png)
Newly funded DeepNL projects
Scientifically, the biggest challenge for the first deliverable energy projects supports the safe and sustainable execution of future geo-research in this project and the wider DeepNL programme. Communicate more clearly that advanced geoscience societal actors that allows us to understand how we can engage in a constructive dialogue to communicate this with their stakeholders. 

What is the aim of your new project?

‘The DeepNL programme studies fluid flow behaviour and resulting rock deformation, all the way from the grain scale up to the 10 to 100km scale. In the CrossScale project, which consists of two key parts, we want to link and integrate those scales. In the first part, we will connect different scales of geological heterogeneity in a new upscaling methodology to design better computer models of a geological reservoir. The second part of the project will facilitate a process of deliberation that creates trust between scientists and societal stakeholders. We want to analyse what insights and understanding different stakeholders need from us as scientists to make well-informed decisions about human activities in the subsurface, i.e. utilising the subsurface to accelerate the transition to a low-carbon energy future. Our ultimate aim is to identify what data companies need so that they can operate future low-carbon geoenery applications without causing deformation to the subsurface or inducing seismicity, and how they can engage in a constructive dialogue to communicate this with their stakeholders.’

What will be the focus for 2024?

In addition to hiring people, as a new project and team in the DeepNL programme our key focus will be to get connected to the DeepNL community. Since we want to add on the results of previous projects, establishing trust and two-way communication with other projects are of vital importance to the success of this project. 

What will be the most exciting result and the biggest challenge?

‘In terms of results, we have defined two key deliverables. The first will be a geologically-informed upscaling methodology to design better computer models of the reservoir. For the deliberation process, the biggest challenge is to create the mutual understanding among stakeholders how scientific insights are derived, what they imply for developing new geo-energy projects, and how they ultimately help us to improve both.’

How is your project connected to other DeepNL projects and what is the added value that it brings to the programme?

‘There are obvious links between this project and the ongoing DeepNL projects of Auke Barnhoorn and Suzanne Hangx on how rocks deform, or the projects of Maja Rücker on multiphase flow and Johannes Miocic on characterising the role of heterogeneity in controlling the geomechanical behaviour of sandstones. In addition, the coupled flow geomechanical modelling method developed within the Science4Steer project will act as a source of inspiration for us. We also hope to connect with the ongoing InFocus and recently granted NEPTUNUS projects when it comes to developing data assimilation strategies. Apart from these, we hope that the CrossScale project can act as a bridge between the different DeepNL projects, and can help to integrate the results from different DeepNL projects to provide further benefits to a wide range of stakeholders.’

What aspects and results will be relevant for stakeholders?

‘We will develop a methodological template and a workflow to design computer models of the reservoir that reliably forecast how geological structures conduct fluid and deform. Our approach can be adapted to other fluid flow processes beyond geo-energy as well, for example surface deformation during groundwater abstraction or groundwater contamination. In addition to the obvious stakeholders like SodM and the Mining Council as supervisory and advisory bodies, or TNO, CMG, and EBN as technology providers and operators, other types of stakeholders such as municipalities, citizen groups and NGOs are welcomed to participate and benefit from our research.’

Better models for sub-surface activities leading to better decision-making

The DeepNL programme studies fluid flow behaviour and resulting rock deformation, all the way from the grain scale up to the 10 to 100km scale. In the CrossScale project, which consists of two key parts, we want to link and integrate those scales. In the first part, we will connect different scales of geological heterogeneity in a new upscaling methodology to design better computer models of a geological reservoir. The second part of the project will facilitate a process of deliberation that creates trust between scientists and societal stakeholders. We want to analyse what insights and understanding different stakeholders need from us as scientists to make well-informed decisions about human activities in the subsurface, i.e. utilising the subsurface to accelerate the transition to a low-carbon energy future. Our ultimate aim is to identify what data companies need so that they can operate future low-carbon geoenery applications without causing deformation to the subsurface or inducing seismicity, and how they can engage in a constructive dialogue to communicate this with their stakeholders.’

What is the aim of your new project?

‘The DeepNL programme studies fluid flow behaviour and resulting rock deformation, all the way from the grain scale up to the 10 to 100km scale. In the CrossScale project, which consists of two key parts, we want to link and integrate those scales. In the first part, we will connect different scales of geological heterogeneity in a new upscaling methodology to design better computer models of a geological reservoir. The second part of the project will facilitate a process of deliberation that creates trust between scientists and societal stakeholders. We want to analyse what insights and understanding different stakeholders need from us as scientists to make well-informed decisions about human activities in the subsurface, i.e. utilising the subsurface to accelerate the transition to a low-carbon energy future. Our ultimate aim is to identify what data companies need so that they can operate future low-carbon geoenery applications without causing deformation to the subsurface or inducing seismicity, and how they can engage in a constructive dialogue to communicate this with their stakeholders.’

What will be the most exciting result and the biggest challenge?

‘In terms of results, we have defined two key deliverables. The first will be a geologically-informed upscaling methodology to design better computer models of the reservoir. For the deliberation process, the biggest challenge is to create the mutual understanding among stakeholders how scientific insights are derived, what they imply for developing new geo-energy projects, and how they ultimately help us to improve both.’

How is your project connected to other DeepNL projects and what is the added value that it brings to the programme?

‘There are obvious links between this project and the ongoing DeepNL projects of Auke Barnhoorn and Suzanne Hangx on how rocks deform, or the projects of Maja Rücker on multiphase flow and Johannes Miocic on characterising the role of heterogeneity in controlling the geomechanical behaviour of sandstones. In addition, the coupled flow geomechanical modelling method developed within the Science4Steer project will act as a source of inspiration for us. We also hope to connect with the ongoing InFocus and recently granted NEPTUNUS projects when it comes to developing data assimilation strategies. Apart from these, we hope that the CrossScale project can act as a bridge between the different DeepNL projects, and can help to integrate the results from different DeepNL projects to provide further benefits to a wide range of stakeholders.’

What aspects and results will be relevant for stakeholders?

‘We will develop a methodological template and a workflow to design computer models of the reservoir that
What is the aim of your new project?

‘To expand our understanding of dynamic fault slip from grain-scale to field-scale through an integrated approach, thereby enhancing our ability to estimate the hazard of induced seismicity due to fault (re)activation. Accurate prediction of fault strength during highly dynamic fault slip requires the development of comprehensive and experimentally validated models across different length scales: microscale, where friction between grains generates heat in fault gouges; mesoscale, featuring the fault microstructure, including pore networks that dominate the generation and dissipation of fluid overpressure and heat; and macroscale, where thermal and stress waves attenuate and propagate along multiple faults.

In this project we will combine experiments and models on fault gouge friction at different scales, and study how the strength of a fault changes as a result of fast movements along the fault plane. We will both perform groundbreaking friction experiments at a single contact level and experiments on collections of particles to unravel the microphysics of dynamic fault slip. Based on these findings, we will develop an efficient, physics-based, multi-scale modelling framework to simulate induced seismicity at the macro level.’

What will be the most exciting result and the biggest challenge?

‘Induced earthquakes due to human activities like gas extraction are the result of fast slip on powder-filled pre-existing faults in the subsurface due to a rapid breakdown of their strength. In this project, we will investigate these weakening mechanisms. Our results will help to better constrain the hazard of induced earthquakes.

The aim is to describe fault strength at the metre level based on micro-scale physics. The biggest challenge will be to determine which scales to take into account to make accurate predictions of where earthquakes will nucleate and how far they will propagate. Furthermore, this project will require a close connection between the experiments on geotribology in Twente and the experiments on fault mechanics in Utrecht. The experiments in Twente will be especially challenging, since they will be the first ever for single contacts in geological minerals at these speeds.’

How is your project connected to other DeepNL projects and what is the added value that it brings to the programme?

‘There are strong links to the Science4Steer project, the PhysMmax project, and the InFocus project, since FastSlip provides the input they need to constrain the strength of the fault in their models. In terms of experimental methods and numerical models, there are clear connections to the jFAULT project of associate project leader Tanmaya Mishra and my own previous DeepNL project on how hot faults get. In addition to that, the laboratory apparatus built in the LabQuakeAI project for dynamic shear of fault-gouge will be relevant for testing the large scale fault reactivation models in FastSlip.’

What aspects and results will be relevant for stakeholders?

‘Properties of fault gouge determine whether and how an earthquake accelerates and how it stops again. By understanding the fault mechanics better, we can better estimate the magnitude of the seismicity which has a strong control on the ground motion that is experienced at the surface. For this specific project, the primary stakeholders will be TNO and SodM. But in principle, the results of this project will be relevant for anyone who is working with earthquake models, to get a grip on the input parameters.’

What will be the focus for 2024?

‘First, we will focus on hiring the right people. Once hired, they will start with a comprehensive literature review and take the first steps toward building a dynamic slip setup for single-grain contact and developing a coupled THM-DEM (Thermo-Hydro-Mechanical/Discrete Element Method) model for the fault gouge friction behaviour.’

FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity

Project leader: Dr André Niemeijer (UU)
Associate project leaders: Dr Hongyang Cheng (UT); Dr Tanmaya Mishra (UT)
Budget: € 1,021,627.- (Call 2b)
Duration: 2024 - 2028
The project consists of 3 work packages, carried out by 1 postdoc and 2 PhDs
The novelty of the proposed research brings several challenges. The application of data-assimilation using field data of induced seismicity is difficult because we cannot measure the stress field at the fault, which is a very important variable in the occurrence of seismicity. In addition, when a fault slips seismically or aseismically it is not well understood. Another challenge is to model, test, and incorporate the effect of sub-seismic fault fabric as the sub-seismic faults cannot easily be verified with observations but are well known to follow fractal geometric relationships with larger scale fabric and might be nuclei of induced events.

How is your project connected to other DeepNL projects and what is the added value that it brings to the programme?

In essence, the main question that is addressed in this project is how to translate knowledge acquired in projects like InFocus, PhysMmax, and Science4Steer into seismic activity forecasting tools that can be used on a common pc or laptop. In a later stadium, we foresee relevant links to the CrossScale project on how to translate our results into useful additions to decision-making tools for policymakers.

What aspects and results do you expect to be relevant for stakeholders?

This project will increase the predictive capacity of geomechanical models for geothermal energy production in clastic reservoirs with a particular focus on the transient evolution of induced seismicity, or the lack of seismicity, in geothermal operations in the West Netherlands basin. Thus, the results of this project can feed directly into existing or upcoming seismic hazard assessments for future subsurface use. In addition to this, our project will clarify to what extent specific observations can give relevant information on the observed system. This is relevant for operators and regulators, who need to know which operational variables (pressure, temperature) should be monitored to minimise the risk of induced seismicity. Imposing limits to certain variables can help to stay within the envelope of safe operations.

The outcomes of the project can have substantial economic impact when integrated in regulations. By providing more accurate limits for safe operations, operational space for, e.g., geothermal operators may increase as injection can occur at lower temperatures or higher flowrates and pressures, thereby increasing the revenue of their operations and the contribution of geothermal solutions to the energy transition without compromising safety.

What will be the focus for 2024?

‘We will first hire the three PhD researchers for this project, who will then start to work on the physics-based modelling workflow, the data assimilation workflow, and on building a synthetic earthquake catalogue.’

The project leaders of NEPTUNUS, a project in which they will investigate the transient nature of induced seismicity, and combine observations and models to estimate the variables and parameters that govern the occurrence of induced seismicity.
DeepNL research projects

Interview with project leader Juan Carlos Afonso

Harvesting on investments: integrating data for final subsurface model

What is the aim of your new project?
‘This project capitalises on the complementary information content and combined sensitivity offered by datasets collected by a variety of publicly funded acquisition programmes in the Netherlands over the past five decades. For the first time, all of the available geophysical, geodetic, petrophysical and geochemical datasets about the Dutch subsurface will be integrated in an internally-consistent model of the stress state, viscosity, lithology, composition, seismic velocities, temperature, permeability and density of the entire crust and lithospheric mantle. Specifically, we will adopt and expand a simulation-based, multi-observable probabilistic platform capable of inverting all available datasets simultaneously.’

What will be the most exciting result and the biggest challenge?
‘The final output of the project will be the first multi-observable probabilistic platform capable of inverting all available datasets simultaneously. This project acts as a final multiplier on all of the public investments that have been made, both in the scope of the DeepNL programme and in other data acquisition efforts, in understanding properties of the Earth and features of the subsurface that are of importance for assessing the risks of underground human activities. We aim to use as much of the available data as possible and integrate results and datasets created in all previous DeepNL projects, like laboratory experiments and analysis, single parameter models, and acquired geophysical field data. By combining all of the available data, we can not only fully disclose all of the information the individual datasets encompass, but also identify blind spots, inconsistencies and uncertainties. Our probabilistic approach leads to populations of possible models, which provide us with key data on what additional information is needed to further constrain certain properties.’

What aspects and results do you expect to be relevant for stakeholders?
‘We aim at creating a unifying, synergetic and realistic view of the physical state of the subsurface, that will act as a basis for policy and decision-making related to hazard mitigation actions, management of critical resources and other subsurface activities. We will develop integrative and internally-consistent models of the stress state, viscosity, lithology, seismic velocities, temperature, permeability and density structures that honour all available geophysical, geodetic, and geochemical data that have been collected in the Netherlands. This model will have enhanced explicative and predictive power and will be relevant to the geothermal, geotechnical, and CO₂ or H₂ storage industries. As an additional outcome, the project will deliver dedicated advanced data processing techniques of wide applicability and a comprehensive library of curated data, both of which will be made publicly available.’

What will be the focus for 2024?
‘We will first organise team meetings to refine the proposed work packages, define the requirements for the people we want to hire on this project and start the hiring process. The newly hired researchers will first create a petrological and geochemical database, preprocess the data and define a data cleaning strategy.’

Mark van der Meijde and Juan Carlos Afonso at University of Twente. Together with Suzanne Hangx, Islam Fadel and Bart Root they will lead INTEGRATION, a project that will create a novel data-fusion technique to make optimal use of the unprecedented amount of data that is available for Dutch subsurface.

Integrated subsurface modelling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions (INTEGRATION)

Project leader: Dr Juan Carlos Afonso (UT)
Associate project leaders: Dr Islam Fadel (UT), Dr Suzanne Hangx (UU); Prof. Mark van der Meijde (UT); Dr Bart Root (TUD)
Budget: € 903,601,- (Call 20)
Duration: 2024-2028
The project consists of 3 work packages, carried out by 2 postdocs and 1 PhD
What is the aim of your new project?
‘To address the effect of subsurface geological topography to provide a full picture of potential groundshaking phenomena in relation to future exploitation activities. In our approach, we will consider both the deep and shallow subsurface and the elastic as well as the anelastic effects.

The subsurface contains high mountains of bedrock separated by deep valleys filled with sediment layers consisting of sand, gravel, clay and peat. This subsurface mountain landscape strongly influences how seismic waves propagate to the surface, resulting in very local, but strong, variations in seismic intensity at the surface. When the wave originates from a rock formation, it can be amplified at the peak of the mountain, leading to groundshaking. While in the case the wave originates from the shadow side of a subsurface rock mountain, it can reflect and disperse its energy horizontally, not reaching the surface at all. This 3D effect has not yet been included in predictions of hazards and risk analysis in the Netherlands.’

What will be the most exciting result and the biggest challenge?
‘The ultimate aim is to build a spatially resolved model that can be used to predict seismic risks at different locations based on probability forecasting. This model should be able to determine for example which location would be the safest in terms of seismic hazards for drilling a geothermal well in a certain region.

One of the main challenges will be to determine the required resolution to model realistic effects. Another major challenge will be how to couple models for elastic waves in the deep subsurface to those describing anelastic waves in peat and clay in the shallow subsurface. And to determine at what depth we should make the transition between the two.’

How is your project connected to other DeepNL projects and what is the added value that it brings to the programme?
‘There are links to many projects, and we will also use data from presently running projects, like the DICTUM project led by Islam Fadel. So far, the ground motion prediction equations that have been developed are of a 1D nature. We will build on those to expand them to 3D applications.

What’s really nice about this SHAWave project is that it brings together groups that have never collaborated before: my group at UT working on the deep subsurface, and a group at TU/e focusing on the shallow subsurface effects. We found each other through the DeepNL call, and jointly developed a proposal that is extremely interesting, both from a scientific and from a societal point of view.’

What aspects and results do you expect to be relevant for stakeholders?
‘The results of this project will be relevant to forecast seismic risks as result of newly to be deployed human activities in the subsurface. We will not only be able to predict the average surface effects in a certain area, but more importantly, also the relevant variations in them. How large will the maximum surface movements be and where will they occur? Where can we expect bullwhip effects from the subsurface geological topography and how can we avoid them? The new law on mining and SHRA for geothermal operations requires that the right level of seismic hazard is assessed before the operation starts, as part of the permits process. Such a study for a traditionally a-seismic region is not trivial with the current tools available, and this project can provide a new standard for this.’

What will be the focus for 2024?
‘We will start by hiring the postdoc and PhD researchers to be appointed on this project. Their first activities will be aimed at analysing different models and simulating them with different mesh resolutions to develop computationally efficient models that lead to accurate seismic signal predictions’. 
What is the aim of your new project?
‘To provide a radical new angle on understanding and forecasting induced seismicity, by building a digital analog for earthquakes that mimics seismic stick-slip dynamics. With this digital twin, based on a numerical model of soft-glass dynamics, we want to forecast the timing and magnitude of earthquakes that occur as a result of taking fluids out of the subsurface. We have already demonstrated that a soft-glass system can exhibit a generic stick-slip behaviour similar to that of earthquakes following all known seismic scaling laws. The digital twin will not be based on phenomenological laws, but on exact momentum equations of a mixture of immiscible fluids. The earthquake resembling physics emerges from this system in a natural way. We now want to train the soft-glass to mimic the seismicity observed in a specific area. To do this, we will use Groningen as a test case for this novel technique, since it is a well-documented area with a well-mapped fault system and a known gas production history.’

What will be the most exciting result and the biggest challenge?
‘The essence of this project is to investigate whether we can force our soft-glass to behave like an existing seismic fault system. The most important result of this project will be to train the soft-glass to mimic the seismicity observed in a specific area. To do this, we will use Groningen as a test case for this novel technique, since it is a well-documented area with a well-mapped fault system and a known gas production history.’

What aspects and results will be relevant for stakeholders?
‘For this specific project, the primary stakeholders will be fellow scientists since this is a new high-risk scientific endeavour. If our approach turns out to be successful, the method will be relevant for anybody who intends to move fluids around in the subsurface. You can think of geothermal energy, underground water drainage, CO2 sequestration or H2 storage. For all these applications it is of vital importance to know how and where to inject fluids without inducing dangerous levels of seismicity.’

What will be the focus for 2024?
‘To hire the PhD candidates who will start by familiarising themselves with the numerical methods, codes and infrastructures. We also hope to get an early confirmation of whether or not this approach is going to work.’ •

Interview with project leader Jeannot Trampert

A digital twin for modelling and forecasting induced seismicity

Project leader: Prof. Jeannot Trampert (UU)
Associate project leader: Prof. Federico Toschi (TU/e)
Budget: € 1,077,489.− (Call 2b)
Duration: 2024 - 2028
The project consists of 4 work packages, carried out by 1 postdoc and 3 PhDs
Forecasting local site response to earthquake-induced ground-shaking

What is the aim of your new DeepNL research project?
‘To make a breakthrough in forecasting the local site response to ground-shaking due to an earthquake, through incorporation of spatial variability of the relevant soil properties and structures in a data-driven manner. Site response refers to the strong effect of the shallow subsurface on an incoming vibration or wave. So far, damping ratio and strain-dependent modulus and damping curves are not properly incorporated, causing large uncertainties in site response forecasting, and hence risks. In this research we will develop a novel approach combining seismic inversion, soil testing and nonlinear-dynamics-based modelling to provide a complete characterisation of the soil parameters that are crucial for forecasting the site response for soils containing soft peat and clay and relatively stiff sand layers. With this information, we can estimate both the shape of the frequency spectrum and the amplitude of shaking in a reliable way.’

What will be the most exciting result and the biggest challenge?
‘For the first time we will obtain accurate and in-situ estimates and high-resolution spatial variability information of the most important soil properties that determine the site response. The nonlinearity of the soil will be taken care of. This is particularly crucial for soils containing problematic soft clay and peat layers, typical in the Netherlands. The shallow (till 20-30 m depth) soil layers in the Netherlands are highly heterogeneous and highly nonlinear in behaviour. SOFTTOP uses Cone Penetration Test databases in Groningen. However, the large distance between CPTs means there is no detailed lateral information. This is where the project 3DSOIL makes a significant contribution, providing variability data between the CPTs. However, the information of in-situ damping ratio and strain-dependent modulus and damping curves, including their variability, are still missing. This missing information critically hinders site response analysis in the SOFTTOP project. The site-specific damping-ratio and strain-dependent modulus and damping information from this new project, and shear velocities and laterally varying CPT information from 3DSOIL, will enable reliable, local site response analyses. The complete set of soil properties will also be supplemented to the SOFTTOP project to improve reliability. Finally, in this new project, it will also be possible to incorporate the effect of wave propagation and dissipation, thereby accounting for effects such as focusing, diffraction and scattering.’

What aspects and results do you expect to be relevant for stakeholders?
‘The results of this project are of critical importance for minimising structural and human catastrophes caused by any structure or activity that creates vibration in the underground, ranging from geothermal energy exploration, CO2 or H2 storage, and underground mining activities, to foundation-pile driving, moving trains, salt-mining activities or wind farms. The results of this project will, therefore, be of direct relevance to the stakeholders of the DeepNL programme, especially KNMI and TNO, and companies like Fugro. Beyond DeepNL, the results of this project will be fed directly into rail and offshore industries through ongoing collaborations with Fugro, OYO, Siemens Gamesa Renewable Energy, and Deltares. The outputs will be relevant also to other projects where Hardt Hyperloop, Witteveen+Bos, Nevomo, EuroTube, NS, ProRail, European Hyperloop Centre, Strukton, Rijkswaterstaat and Zeleros are involved. In addition, the inversion code that is going to be developed is generic and will be applicable to other inversion problems as well.’

What will be the focus for 2024?
At first we have to find two suitable PhD students. In the remaining time available in 2024, the first PhD student will focus on developing the new stochastic seismic inversion scheme for spatially varying, reliable estimation of the in-situ damping ratio in soil and testing the scheme on synthetic data. At the same time, the second PhD student will use field and laboratory experimental data to model strain-dependent modulus and damping curves accounting for nonlinear phenomena, and will ascertain the uncertainties.’

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**What is the aim of your new project?**
'To distinguish the individual contributions of reservoir compaction, soil consolidation, soil swell, and fluctuations related to crop farming to the total subsidence as measured in geodetic observations (In-SAR, GPS, levelling). With this information, we will develop a quantitative, coupled, physical model to hindcast and forecast horizontal and vertical surface deformation above the Groningen gas reservoir as a result of both deep and shallow driving mechanisms. The model will combine InSAR data, a quantitative model for the response of the deep reservoir and surrounding rock layers to gas production and its aftermath, a model for consolidation of shallow soils driven by precipitation and evaporation, and a dedicated data assimilation method.'

**What will be the most exciting result and the biggest challenge?**
'Building on the existing knowledge that has been acquired over the past five years about the structure of the subsurface, material properties, compaction mechanisms, ground water levels and precipitation levels, we will build a novel model to forecast subsidence. This model can help answer questions such as the expected duration and magnitude of subsidence after gas production cessation. This is a very challenging task, since the reservoir compaction effects we are looking for make up only a small portion of the measured subsidence signal. Since the start of gas production, the total subsidence of the Groningen area amounts up to some 38 centimetres. In previous research, the speed of subsidence as a result of compaction is determined to be about 7 millimetres a year. That is very close to the resolution of the satellite data the measurements are based on. Depending on precipitation, ground water levels change. Especially in areas where there is a lot of peat, in times of excessive rains that layer acts like a swelling sponge. In times of drought, the peat layer subsides. In extremis, the difference between both cases can be tens of millimetres. In addition to that, agricultural activities like ploughing cause variations in the satellite measurements in the order of 10 centimetres. We are going to use contextual information to identify correlations and to fill in the blanks in between individual measurements. The NWA-project ‘Living on Soft Soils – Subsidence & Society’ (LOSS) will be instrumental to the latter.'

**How is your project connected to other DeepNL projects and what is the added value that it brings to the programme?**
'This project builds on models for the deep subsurface developed in previous DeepNL projects and will add more specifics on the shallow subsurface like flows in the salt that is above the reservoir and depth dependent material properties to determine elasticity of the layers. There are logical links with the projects of Suzanne Hangx and André Niemeijer, and the more accurate estimates of the subsidence driving compaction from our project will be highly beneficial for DeepNL seismicity studies, more in particular PhysMmax.'

**What aspects and results will be relevant for stakeholders?**
'Our model will be useful to predict the expected duration and magnitude of further subsidence after cessation of gas extraction. But the ultimate dream is to end up with an instrument that can be used in court to assess damage liability as a result of human activity in the subsurface.'

**What will be the focus for 2024?**
'After having hired the two PhD researchers, the first PhD researcher will start working on adopting a data-assimilation approach for spatially correlated geodetic data, with a specific focus on the question how to maximise information and minimise computational costs. The second PhD researcher will start developing a surface deformation model for unsaturated soils in the shallow subsurface, above the water table.'
News from the DeepNL network

The preparation of a heterogeneous sample for the rotary shear apparatus at Utrecht University, which is used to simulate fault mechanics (project Willingshofer et al.)
Multiscale research facilities
For the larger part, the funds will be used to buy, develop and install new research equipment. At UU, planned equipment is largely intended to investigate dynamic processes controlling the behaviour as observed in laboratory tests, as opposed to post-test, static investigation. At TU Delft, a geothermal doublet was recently installed. In a few years’ time, EPOS-eNLarge funds will be used to realise a third well close to this doublet. This well will be up to 4.5 kilometres deep and will be developed purely for scientific monitoring and deep geothermal research. New partner TNO brings in a unique lab for large-scale fluid transport and rock mechanics testing: the Rijswijk Centre for Sustainable Geo-energy. They will develop a modular system to make long-range fluid transport testing at the scale of 1 to 400 metre much easier, with state-of-the-art monitoring. KNMI will develop a new and ambitious data service for central access to fibre optics data; a potentially transformative but notoriously difficult-to-handle type of data.

International data sharing
Significant funds are being used to ensure that data published by Netherlands-based researchers can be easily found at the European data portal of EPOS (europe.eu/dataportal). The Netherlands has great subsurface databases. Such databases are hosted at a.o. Voda (UU), 4TU ResearchData (TU Delft, Universities of Twente, Eindhoven and Wageningen), NLOG (TNO), and ORFEUS (KNMI). EPOS aims to make the solid Earth scientific data located in these depositories centrally and internationally discoverable through EPOS, for much more efficient reuse in future research.

To make data findable in EPOS, DeepNL researchers need to keep publishing their data open access, ideally at one of the repositories mentioned here. The EPOS team is currently working on smart ways to automatically find these data and include them.

New labs for anyone to use, free-of-charge
As in previous years, EPOS continues to provide national and international researchers with free-of-charge access to research laboratories in EPOS-NL and EPOS-eNLarge. One of the new labs the organisation now provides access to is TNO’s Rijswijk Centre. This lab facilitates multiscale rock mechanics experiments and up to hectometre-scale fluid transport tests to help researchers address key upscaling questions, like how the behaviour as observed in lab tests on centimetre-scale samples translates to the metre-scale mesh-sizes typically used in field-scale models.

More information about the use and specifications of the EPOS labs can be found on the website EPOS-NL.nl.

KEM strategy and modus operandi 2023-2027
In 2022, KEM has been externally evaluated. It was concluded that KEM was largely effective and efficient. The main recommendation was to continue executing the main task of KEM, which is to carry out applied research on the effects of mining. The Ministry of Economic Affairs and Climate Policy and the State Supervision of Mines subsequently decided to continue KEM for the period 2023-2027. The suggestions for improvements by the evaluators have resulted in a new KEM strategy and modus operandi 2023-2027 document. KEM has been acting accordingly since 2023. In addition, KEM has started the process of extending its scope and panel by including the societal effects of mining. This will be effectuated in 2024.

KEM activities in 2023
As in previous years, the KEM scientific expert panel has assured the quality of the KEM research by aligning research questions and coaching and evaluating KEM research projects. In 2023, KEM and DeepNL have not organised joint colloquia to exchange and discuss the results of KEM and related DeepNL projects and associated research priorities. This will be resumed in 2024.

The KEM subpanel on seismic hazard and risk model (SHRA) development continued to advise the Ministry EZK and State Supervision of Mines on additional development and validation of the public SHRA model of TNO, as well as on the state-of-the-art model version to be used for the annual risk assessments. In 2023, TNO executed the third independent assessment of seismic risks related to the annual gas production plan for the Groningen reservoir.

Status of KEM projects
Finished in 2023/early 2024
• Thermo-mechanic seismicity risks of geothermal systems (KEM-15)
• Subsidence hazard and risk-modelling tools applied to 3 complex pilot areas (KEM-56)
• Monitoring requirement for offshore CO₂ surface storage sites (KEM-27)
• H₂ subsurface storage in conglomerates of salt caverns (KEM-28)
• Safe operational bandwidths of H₂, N₂ and CO₂ storage in abandoned gas reservoirs (KEM-39)

Ongoing in 2024
• Subsidence hazard and risk modelling tools focus on groundwater and surface water movement (KEM-16b)
• Groningen post-abandonment effects, southwestern aquifer (KEM-18b)
• Preliminary assessment of beneficial effects of N₂ injection in depleted reservoirs (KEM-24b)
• 3D ground motion modelling (see KEM-04) and GMMV7 (KEM-36)
• Salt cavern bled-off behaviour and risks (KEM-45)
• Modelling impact of subsurface heterogeneities on subsidence above a gas fields (KEM-47)
• Cumulative effects of mining in the Grijpskerk area (KEM-48)

Results of all KEM projects (and KEM strategy 2023-2027) are or will be published on kemprogramma.nl.
Looking ahead to 2024

**13-16 May**
InterPore conference in Qingdao, China

**17 May**
DeepNL Stakeholder Meeting 2024 in Amersfoort
This annual meeting is aimed at researchers and professionals from the public and private sector, who are interested in subsurface dynamics caused by human activities. The aim is to provide a networking occasion and a platform for knowledge dissemination and discussions.

**4-7 November**
EAGE Global Energy Transition Conference (GET2024) in Rotterdam

**1-5 July**
TU Delft Summer School on Carbon Capture and Storage

**2-5 September**
European Conference for Mathematics of Geological Reservoirs (ECMOR) in Oslo, Norway

**8-12 September**
Near Surface Geoscience conference in Helsinki, Finland

**22-27 September**
General Assembly of the European Seismology Commission in Corfu, Greece

**3-5 April**
European Geothermal PhD days 2024 in Delft

**8-10 April**
EAGE GeoTech conference in The Hague

**14-19 April**
EGU General Assembly in Vienna, Austria

**1-13 June**
EAGU Annual 2024 in Oslo, Norway

**26-28 June**
SPE Europe Energy Conference in Turin, Italy

**30 June**
Deadline for JSG special issue
The Journal of Structural Geology will publish a special issue as a tribute to the late Prof. Janos Urai

**9-13 December**
American Geophysical Union meeting (AGU24) in Washington D.C., United States
Organisation of the DeepNL programme

A 30x30x30 cm reservoir analogue including a displaced fault, which is used in large-scale fault reactivation experiments (project Jansen et al.)
DeepNL programme committee

The programme committee is the driving force in realising the overarching objectives of DeepNL and advises NWO on the implementation of the programme. It monitors the coherence and progress of the research, initiates activities that facilitate this coherence, and encourages the sharing of knowledge with stakeholders and the public. The programme committee advises on the design and scope of the different Calls for proposals and the implementation of the reserved funds for opportunities and programme activities.

In 2023, the programme committee convened in five dedicated meetings. They discussed topics such as the progress of the research projects, scope of the final Call, planning of events and the position of DeepNL in a broader national subsurface research landscape. At the end of the year, the composition of the committee underwent some changes with committee member Giovanni Bertotti taking over the chair role from the resigning Rinus Wortel and Martyn Drury joining the committee.

DeepNL annual report 2023

International Advisory Committee

The IAC has the overall task to monitor and evaluate the progress and impact of the DeepNL programme from an independent and international state-of-the-art perspective. They provide recommendations to the research projects, programme committee and board of the NWO Science Domain for the duration of the DeepNL programme.

In 2023, the IAC discussed the progress of the DeepNL programme using their previous recommendations as a starting point. The progress was discussed with the programme committee and researchers during the DeepNL Scientific Meeting in November 2023.

Prof. Torsten Dahm
GFZ German Research Centre for Geosciences Potsdam

Prof. Saskia Goes (chair)
Imperial College London

Prof. Inga Moeck
University Göttingen / Leibniz Institute for Applied Geophysics

Prof. Francesca Verga
Politecnico di Torino

Prof. Robert Zimmerman
Imperial College London

NWO programme office

The NWO programme office executes the practical realisation of DeepNL activities and funding rounds. It acts as a point of contact for DeepNL researchers, committees and stakeholders. The programme office supports the activities initiated within the network and facilitates the overall communication and outreach.

Dr Niels van den Berg
Coordinator

Dr Barbara Dammers-Szenasi
Programme officer

Maxime de Jong
Communication advisor

Ajita Ramautar
Programme officer

Cindy Remijnse-Schrader
Programme officer

DeepNL annual report 2023
Financial framework

The DeepNL budget is divided over several sequential Calls for proposals, an earmarked budget for opportunities (small projects for integration and application) and a dedicated budget for programme activities and communication. The overall financial framework for DeepNL was originally based on a budget of 20 M€, of which the NAM contributed 15 M€ and NWO 5 M€. In addition, the programme received a budget of 4.23 M€ from the Netherlands Enterprise Agency (RVO) through an allowance scheme for public private partnerships (PPS-toeslag). This results in a total DeepNL budget of 24.23 M€.

<table>
<thead>
<tr>
<th>Year</th>
<th>Call 1a</th>
<th>8 large research projects - Awarded budget € 8,831,353</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Call 1b</td>
<td>3 tenure track projects - Awarded budget € 2,242,797</td>
</tr>
<tr>
<td></td>
<td>Call 2a</td>
<td>7 small research projects - Awarded budget € 2,412,899</td>
</tr>
<tr>
<td></td>
<td>Call 2b</td>
<td>8 large research projects - Awarded budget € 8,080,278</td>
</tr>
<tr>
<td></td>
<td>Opportunities - To be determined: small projects for integration and application - Reserved € 814,683</td>
<td></td>
</tr>
</tbody>
</table>

Programme activities - Meetings, outreach & communication - € 1,000,000

Programme costs - Execution by NWO - € 900,000

- NAM CONTRIBUTION: M€ 15
- NWO CONTRIBUTION: M€ 5
- PPS ALLOWANCE RVO: M€ 4.23
- TOTAL BUDGET DEEPNL: M€ 24.2
Overview of DeepNL researchers

Dr Hemmo Abels
TU Delft
- PhD student: Project leader. CrossScale: Constraining uncertainties across scales. From Groningen to future geoenery applications.

Dr Juan Carlos Afonso
University of Twente

Stephen Akinremi
University of Twente
- PhD: Deep, deeper, deepestNL: Imaging the Dutch crust and upper mantle using multi-geo-observables (DICTUM).

Job Arts
Utrecht University
- PhD: Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field.

Zhuldyzay Baki
University of Twente
- PhD: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Dr Auke Barnhoorn
TU Delft
- Project leader: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Wietske Brouwer
TU Delft
- PhD: Monitoring and Modeling the Groningen Subsurface based on integrated Ground and Geophysics, improving the space-time dimension.

Dmitry Bublik
University of Groningen
- PhD: The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs.

Dr Adam Candy
Utrecht University
- Postdoc: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Ching-Yu Chao
TU Delft
- PhD: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.

Dr Hongyang Cheng
University of Twente
- Associate project leader: FastSlip: Bridging Dynamic Fault Slip Multiphysics to AI Relevant Scales of Induced Seismicity.

Dr Pavan Cornelissen
TU Delft
- Postdoc: Science4Slip: A scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

Dr Aad Correljé
TU Delft
- Associate project leader: CrossScale: Constraining uncertainties across scales. From Groningen to future geoenery applications.

Dr Karel van Dalen
TU Delft
- Associate project leader: DAMPNSOIL: Providing the missing information of elastic damping ratio and strain-dependent modulus and damping curves for reliable, local site response analysis.

Hilmi Bayraktaroglu
TU Delft
- PhD: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.

Dr Alexandros Daniilidis
TU Delft
- PhD: CrossScale: Constraining uncertainties across scales. From Groningen to future geoenery applications.

Dr Mark Dekkers
Utrecht University
- PhD: InFocus: An Integrated Approach to Estimating Fault Slip Occurrence.

Hamed Ali Diab-Montero
Utrecht University
- Project leader: PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling.

Dr Ylona van Dinther
Utrecht University

Dr Ylona van Dinther
Utrecht University

Dr Deyan Draganov
TU Delft
- PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Prof. Martyn Drury
TU Delft
- PhD: The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs.

Dr Qiang Fu
Utrecht University
- Postdoc: Probing the micromechanics of small magnitude earthquake slip.

Prof. Sebastian Geiger
Utrecht University
- Project leader: CrossScale: Constraining uncertainties across scales. From Groningen to future geoenery applications.

Dr Ranajit Ghose
TU Delft
- Project leader: 3DSOIL: 3D soil variability in Groningen for accurate, local site response analysis.

Dr José León González Acosta
TU Delft
- PhD: Probing the micromechanics of small magnitude earthquake slip.

Dr Islam Fadel
University of Twente

Eldert Fokker
Utrecht University
- PhD: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Dr Adam Candy
Utrecht University

Prof. Hans-Johan Rijks
University of Twente
- PhD: Monitoring and Modeling the Groningen Subsurface based on integrated Ground and Geophysics, improving the space-time dimension.

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- Project leader: PhysMmax: Constraining the maximum magnitude in Groningen through 3D multi-physics, data-driven modeling.

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Dr José León González Acosta
TU Delft
- PhD: Probing the micromechanics of small magnitude earthquake slip.
Dr Rob Govers
Utrecht University
- Project leader: Quantitative constraints on pre-production reservoir stresses in Groningen.
- Project leader: Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region.
- Associate project leader: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Renato Gutierrez Escobar
Utrecht University
- PhD: Quantitative constraints on pre-production reservoir stresses in Groningen.

Prof. Hadi Hajiobjegi
TU Delft
- Associate project leader: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

Dr Suzanne Hangx
Utrecht University
- Project leader: A multi-scale, multi-physics framework for modeling the geomechanical response of sandstone reservoirs to pure fluid extraction.
- Project leader: Impact of fluid extraction on the creep behaviour of clay-rich formations enveloping Rotliegend sandstone reservoirs.
- Associate project leader: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.
- Associate project leader: INTEGRATION: Integrated subsurface modeling beneath Groningen and on-shore Netherlands from multi-data probabilistic inversions.

Prof. Ramon Hanssen
TU Delft
- Project leader: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.
- Associate project leader: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Vincent van der Heiden
Utrecht University
- PhD: PhysicsMax: Constraining the maximum magnitude in Groningen through 3D multi-physics data-driven modeling.

Prof. Michael Hicks
TU Delft
- Project leader: SOFTTOP: investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.
- Associate project leader: SOFTTOP: investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.

Chien-Cheng Hung
Utrecht University
- PhD: Probing the micromechanics of small magnitude earthquake slip.

Prof. Jan Dirk Jansen
TU Delft
- Project leader: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.
- Associate project leader: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient nature of induced Seismicity.

Chayenne Janssen
TU Delft
- PhD: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Malek Jaran
University of Twente
- PhD: µFAULT - scaling friction from micro-contacts to faults at the reservoir scale.

Dr Mark Jefferd
University of Twente
- Project leader: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.
- Associate project leader: Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region.

Dr Johannes Miocic
University of Groningen
- Project leader: The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs.
- Associate project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications.

Dr Tanmaya Mishra
University of Twente
- Project leader: µFAULT - scaling friction from micro-contacts to faults at the reservoir scale.
- Associate project leader: FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity.

Sebastian Mulder
University of Groningen
- PhD: The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs.

Milad Naderloo
TU Delft
- PhD: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

La Ode Marzujiban Masfara
TU Delft
- PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Prof. Mark van der Meijde
University of Twente
- Project leader: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.
- Associate project leader: Deep, deeper, deepestNL: Imaging the Dutch crust and upper mantle using multi-geo-observables (DICTUM).
- Associate project leader: INTEGRATION: Integrated subsurface modeling beneath Groningen and on-shore Netherlands from multi-scale probabilistic inversions.

University of Twente
- PhD: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Dr Helen King
Utrecht University
- Associate project leader: A multi-scale, multi-physics framework for modeling the geomechanical response of sandstone reservoirs to pure fluid extraction.

Dr Mandy Korff
TU Delft/Deltares
- Associate project leader: FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity.

Meng Li
Utrecht University
- PhD: InFocus: An Integrated Approach to Estimating Fault Slip Occurrence.

Prof. Marie-Colette van Lieshout
University of Twente/CWI
- Associate project leader: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Janneke de Jong
TU Delft
- PhD: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Mohammad Hamza Khalid
University of Twente
- PhD: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Mohammad Hossein Khoenei
Eindhoven University of Technology
- PhD: Making digital rocks a practical reality for energy storage within subsurface reservoirs.

Samantha Kim
TU Delft
- PhD: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Dr Johannes Miocic
University of Groningen
- Project leader: The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs.
- Associate project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications.

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- Associate project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenery applications.

Dr Tanmaya Mishra
University of Twente
- Project leader: µFAULT - scaling friction from micro-contacts to faults at the reservoir scale.
- Associate project leader: FastSlip: Bridging Dynamic Fault Slip Multiphysics to All Relevant Scales of Induced Seismicity.

Sebastian Mulder
University of Groningen
- PhD: The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs.

Milad Naderloo
TU Delft
- PhD: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.
Dr André Niemeijer
- Project leader: Probing the micromechanics of small magnitude earthquake slip.
- Project leader: LabQuakeAI: AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data.
- Project leader: FastSlip: Bridging Dynamic Fault Slip Multiplikativ to All Relevant Scales of Induced Seismicity.
- Associate project leader: InFocus: An Integrated Approach to Estimating Fault Slip Occurrence.

Alessio Novikov
- TU Delft
- PhD: Science4Seer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

Dr Hanneke Paulsien
- Utrecht University
- Associate project leader: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Dr Ivan Pires de Vasconcelos
- Utrecht University/Shearwater
- Associate project leader: A multi-scale, multi-physics framework for modeling the geomechanical response of sandstone reservoirs to pore fluid extraction.

Dr Oliver Plümper
- Utrecht University
- Project leader: Developing a Data-Driven Forecasting Model of Surface Deformation in the Groningen gas Field Region.

Dr Anne Plummers
- TU Delft
- Project leader: CrossScale: Constraining uncertainties across scales: From Groningen to future geoenergy applications.

Dr Joris Remmers
- Utrecht University
- Project leader: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Eddy Revelo Obando
- TU Delft
- PhD: 3D SOL: 3D soil variability in Groningen for accurate, local site response analysis.

Dr David Rieder
- Eindhoven University of Technology
- Postdoc: Making digital rocks a practical reality for energy storage within subsurface reservoirs.

Dr Bart Root
- TU Delft
- PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Dr Maja Rücker
- Eindhoven University of Technology
- Project leader: Developing a Data-Constrained Forecasting Model of Surface Deformation in the Groningen gas Field Region.

Mike Sep
- Utrecht University
- PhD: Impact of fluid extraction on the creep behaviour of clay-rich formations enveloping Rotliegend sandstone reservoirs.

Takahiro Shinohara
- Utrecht University
- PhD: A multi-scale, multi-physics framework for modeling the geomechanical response of sandstone reservoirs to pore fluid extraction.

Faeez Shirmohammadi
- TU Delft
- PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Sara Shokrollahzadeh Behbahani
- TU Delft
- PhD: Science4Seer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

Dr Kathrin Smetana
- Stevens Institute of Technology (formerly UT)
- Associate project leader: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Prof. David Smeulders
- Eindhoven University of Technology
- Associate project leader: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.

Dr Denis Voskov
- TU Delft
- PhD: Science4Seer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

Dr Divya Varkey
- TU Delft
- PhD: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.

Aukje Veltmeijer
- TU Delft
- PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Prof. Cedric Thielen
- TU Delft
- Associate project leader: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics improving the space-time dimension.

Prof. Frederico Toschi
- Eindhoven University of Technology
- Associate project leader: A digital twin for modeling and forecasting induced seismicity.

Prof. Jeannot Trampert
- TU Delft
- PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Dr Femke Vossepoel
- TU Delft

Dr Clemens Verhoosel
- Eindhoven University of Technology
- Associate project leader: SHAWave - Seismic Hazard Assessment for Future Subsurface Activities: A Waveform-based Approach.

Hannah Vogel
- Utrecht University
- Other staff: A multi-scale, multi-physics framework for modeling the geomechanical response of sandstone reservoirs to pore fluid extraction.

Dr Aukje Veltmeijer
- TU Delft
- PhD: DeepImage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity.

Dr Divya Varkey
- TU Delft
- PhD: SOFTTOP: Investigating heterogeneous soft top soils for wave propagation, cyclic degradation and liquefaction potential.
Overview of former DeepNL researchers

Dr Henk van Waarde
University of Groningen
- Associate project leader: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient nature of Induced Seismicity.

em. Prof. Kees Wapenaar
TU Delft
- Associate project leader: DeepImage: Multiscale geophysical imaging, monitoring and forecasting of induced seismicity.

Dr Kees Weemstra
KNMI (formerly TU Delft)
- Associate project leader: DeepImage: Multiscale geophysical imaging, monitoring and forecasting of induced seismicity.
- Associate project leader: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient nature of Induced Seismicity.

Prof. Jan-Diederik van Wees
Utrecht University/TNO
- Associate project leader: PhysImager: Constraining the maximum magnitude in Groningen through 3D multi-physics, datadriven modeling.
- Associate project leader: NEPTUNUS: Novel methods for the Evaluation and Physical understanding of the Transient nature of Induced Seismicity.

Gijs Wensink
Eindhoven University of Technology
- PhD: Making digital rocks a practical reality for energy storage within subsurface reserves.

Dr Ernst Willingshofer
Utrecht University
- Project leader: Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field.

Marius Wouters
Utrecht University
- PhD: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Marc Bruna
TU Delft
- Postdoc: Monitoring and Modeling the Groningen Subsurface based on integrated Geodesy and Geophysics: improving the space-time dimension.

Dr Jianye Chen
Utrecht University/TU Delft
- Postdoc: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.

Thomas Cullison
Utrecht University
- PhD: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Dr Mohsen Goudarzi
Utrecht University/DIANA FEA, NL

Dr Annika Greve
Utrecht University
- Postdoc: Probing the micromechanics of small magnitude earthquake slip.

Dr Rhys Hawkins
Utrecht University
- Postdoc: Comprehensive monitoring and prediction of seismicity within the Groningen gas field using large scale field observations.

Dr Mohammad Hadi Mehranpour
Utrecht University
- Postdoc: Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields.
Appendix 1: Research output 2023

Cluster 1

Analysis of processes and conditions that lead to seismicity and subsidence

- A multiscale, multi-physics framework for modelling the geomechanical response of sandstone reservoirs to pore fluid extraction (Hango et al.)
- Jansen, J.D. and Meulenbroek, B.J. (2023). Induced fault slip in large-offset faults taking into account the coupling between neighboring slip patches. Oral presentation HS48-05. American Geophysical Union.

Science4Steer: a scientific basis for production and reinjection strategies to minimize induced seismicity in Dutch gas fields (Jansen et al.)


Probing the micromechanics of small magnitude earthquake slip (Niemeijer et al.)


InFocus: An Integrated Approach to Estimating Fault Slip Occurrence (Vossepoel et al.)


The role of heterogeneity in controlling the geomechanical behaviour of sandstone reservoirs (Moicic et al.)


Presentations
of the sedimentary-petrographic properties governing the geomechanical behaviour of a siliciclastic reservoir. 15th Euroconference on Rock Physics and Mechanics (EUROCONFP).


**Quantitative constraints on pre-production reservoir stresses in Groningen (Govers et al.)**

**Scientific publications**


**Making digital rocks a practical reality for energy storage within subsurface reservoirs (Rücker et al.)**

**Scientific publications**


**Impact of fluid extraction on the creep behaviour of clay-rich formations enveloping Rotliegend sandstone reservoir (Hange et al.)**

**Presentations**

- Sep, M.K., Hangx, S.J.T., De Bresser, J.H.P., Trabucho Alexandre, J.P. (2023) Coupling rock mechanical experiments with detailed mineralogical analyses to better understand compaction in the clay-rich formations enveloping the Groningen gas field. Nederlands Aardwetenschappelijk Congres (NAC)

**Geological analysis of multi-scale faults in reservoir systems and implications for fault mechanical behaviour in the Groningen field (Willingshofer et al.)**

**Scientific publications**


**Monitoring of physical conditions and forecasting**

- Deepimage: Multi-scale geophysical imaging, monitoring and forecasting of induced seismicity (Barthoon et al.)

**Scientific publications**

Boundary and volumetric sensitivity kernels of teleseismic receiver functions for mantle discontinuities in the transition zone. Geophysical Journal International, 235(6), 303-316.


Presentations

PhysMmax: Constraining the maximum magnitude in Groningen through 3D multiphysics, data-driven modeling (van Dinther et al.)

Scientific publications

LabQuakeAI - AI-driven prediction and monitoring of laboratory earthquakes from passive and active acoustic data (Niemeijer et al.)

Presentations
Appendix 2: List of abbreviations

- AFM: Atomic Force Microscopy
- BSE: Backscattered Electron
- CEA: China Earthquake Administration
- CL: Cathodoluminescence
- CPT: Cone Penetration Test
- CWI: Dutch national research institute for mathematics and computer science
- CYC-DoS: Dynamic simulator for Organic Soft Soils
- DARTS: Delft Advanced Research Terra Simulator
- DEM: Discrete Element
- DEM: Discrete Element Model
- DI: de-ionised
- DSS: Direct Shear Stress
- EDX: Energy-Dispersive X-ray Spectroscopy
- EGU: European Geosciences Union
- EnKF: Ensemble Kalman Filter
- FEM: Finite Element Model
- GNSS: Global Navigation Satellite System
- HGS: Horizontal Gravitational Stresses
- iGC: inverse Gas Chromatograph
- InSAR: Interferometric synthetic aperture radar
- ITC: Faculty of Geo-Information Science and Earth Observation at University of Twente
- KEM: Knowledge Programme Effects of Mining
- KNMI: Royal Netherlands Meteorological Institute
- ML: Machine Learning
- NAC: Netherlands Earth Sciences Congress
- NAM: exploration and production company
- NARS: Mobile seismic network operated by the seismology group of the Faculty of Geosciences, Utrecht University
- NGO: Non-Governmental Organisation
- NIOZ: Royal Netherlands Institute for Sea Research
- NWO: Dutch Research Council
- OPA: Opalinus claystone
- PANTHER: Physics-based semi-Analytical Tool for Human-induced Earthquake Rupture
- PCA: Principal Component Analysis
- PFF: Particle Flow Filter
- PI: Principal Investigator
- RVO: Netherlands Enterprise Agency
- RUG: University of Groningen
- SCPT: Seismic Cone Penetration Test
- SEM: Scanning Electron Microscopy
- SedM: Dutch State Supervision on Mines
- SHRA: Seismic Hazard and Risk Analysis
- SSE: Slow Slip Events
- SWIR: Short-Wave Infrared Spectroscopy
- THM: Thermo-Hydro-Mechanical

DeepNL annual report 2023
The aim of the research programme DeepNL is to contribute to a better understanding of how the deep subsurface behaves under the influence of human interventions. In addition, the programme aims to strengthen and integrate the research community in the Netherlands around this theme.