Symposium on Energy Geotechnics
Accelerating the energy transition
3-5 October 2023, Delft, the Netherlands

Peer-reviewed Conference Contribution

# On the long-term behaviour of a deep underground gravity energy storage system: A numerical approach using the HCA model.

Luis Mugele[1] and Hans Henning Stutz[2]*

[1]Institute of Soil Mechanics and Rock Mechanics (IBF), Karlsruhe Institute of Technology, Karlsruhe, Germany; luis.mugele@kit.edu (0000-0002-6491-4034)
[2]Institute of Soil Mechanics and Rock Mechanics (IBF), Karlsruhe Institute of Technology, Karlsruhe, Germany; hans.stutz@kit.edu (0000-0003-3360-1243)
* Corresponding author: hans.stutz@kit.edu

Worldwide, the energy transition is reflected in the constant development of renewable energy sources such as wind power or photovoltaics. These energy sources meanwhile provide cost-effective and mass-available energy. However, renewable energy sources are subjected to natural fluctuations. This can lead to intermittent energy supply and grid instability, highlighting the urgent need for massive energy storage systems to ensure a reliable and resilient energy supply [1].

Gravity energy storage (GES) is a concept for large-scale energy storage [1, 10]. One approach is to store energy in a subsurface cavity. Through this cavity filled with water and covered by soil, potential energy can be stored through a volume and pressure increase. In a practical application, this process can be achieved by pumping water into the cavity. By discharging the water through a turbine, the stored energy can be recovered later. The earliest concepts of this innovative energy storage system proposed a geomembrane-lined bag filled with water and covered with several metres of soil as a ballast [7, 8]. However, to achieve a remarkable energy storage capacity with this concept, large volume fluxes are required. Numerical investigations [6, 9] in addition to large and small-scale laboratory tests [2, 8] show that the resulting large deformations of the soil can cause a stability problem in the soil and can result in large energy losses and soil collapse. To overcome these drawbacks, the concept of a deep cavity was presented in [3], which is schematically shown in Figure 1. The advantage of this new concept, which is the subject of the present work, is that the energy storage is carried out with significantly lower volume fluxes and, in contrast, with increased pressure.

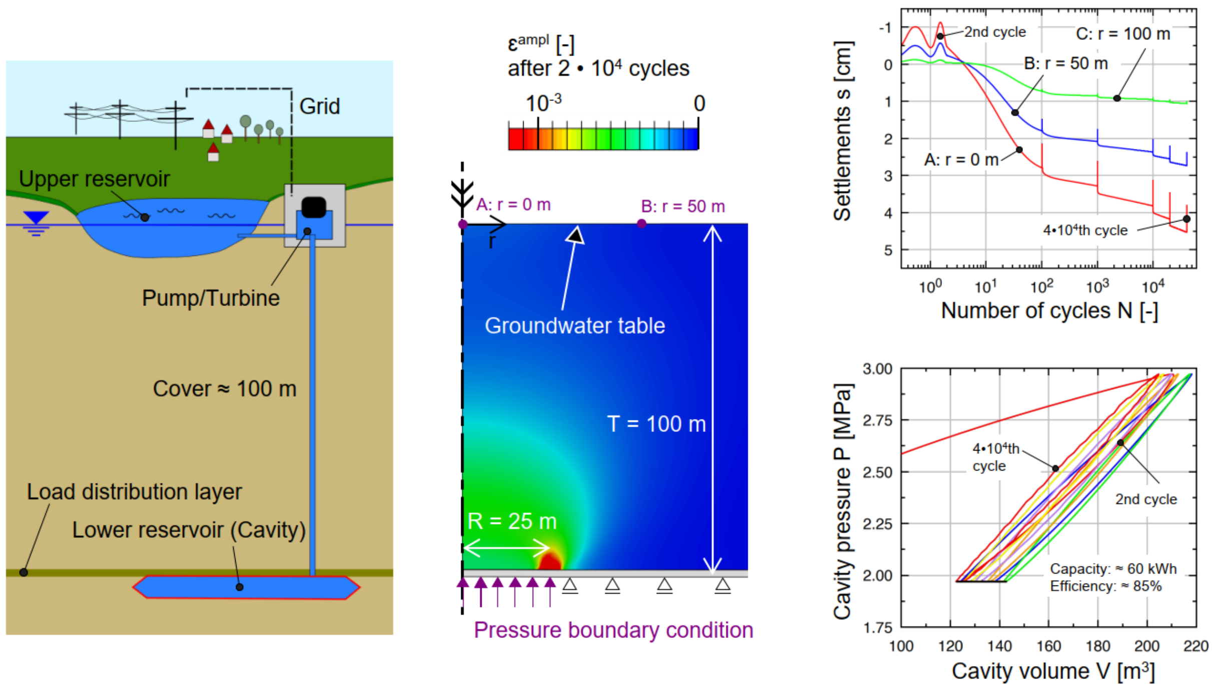


**Figure 1: Concept of a deep gravity energy storage system (GES), axisymmetric FEM model including the strain amplitude after $2 \cdot 10^4$ cycles and preliminary results concerning the settlements of the ground surface and the energy storage**


DOI: https://doi.org/10.59490/seg23.2023.572

This concept leads to a significant reduction of the displacements and strains of the overlying soil, which allows investigations of the long-term stability of the overall system. Using the HCA model [5] in combination with the Hypoplasticity with intergranular strain [4], the cumulative soil behaviour can be modelled and $4 \cdot 10^4$ cycles of energy storage can be simulated numerically. This corresponds to a lifetime of approx. 100 years for daily charging and discharging. Based on the investigations from [3], an extended numerical model is presented in this work and a comprehensive parameter study is carried out. In the finite element calculations, the impact of the groundwater is analysed for the first time in a quasi-static, coupled stress-pore fluid diffusion analysis both on the soil behaviour and on the energy storage. The axisymmetric numerical model and the spatial distribution of strain amplitude after $2 \cdot 10^4$ cycles for saturated sand are shown in Figure 1.

In addition to the energy capacity, energy efficiency and its degradation due to the cumulative soil behaviour as a result of $4 \cdot 10^4$ cycles, the effects on the settlements and inclinations of structures on the ground surface are also investigated. Preliminary results are presented in Figure 1. The results of this extended numerical investigation show that the GES in the presented configurations leads to stable soil behaviour with simultaneously high energy efficiency and acceptable energy capacity. Stability problems were not detected even after $4 \cdot 10^4$ storage cycles. The cumulative effects caused by the cyclic deformation are controllable. This study clearly shows that GES can contribute to energy storage and energy transition in the future.

**Data Availability Statement**

Data will be made available on request.

**Contributor statement**

Luis Mugele: Conceptualisation, methodology, numerical calculations, visualisation, writing - original draft.
Hans Henning Stutz: Conceptualisation, Supervision, writing – review & editing, resources, funding acquisition.

**Acknowledgement**

The authors of this research would like to acknowledge the significant influence and fruitful discussions with Prof. Gerd Gudehus, Prof. Christof Lempp, and Prof. Frank Schilling in the development of a novel energy storage concept. We are grateful for their valuable contributions.

**References**

[1] Aneke, M., & Wang, M. (2016). Energy storage technologies and real life applications – A state of the art review. *Applied Energy*, 179, 350–377.
[2] Franza A., Sorensen, K. K., Stutz, H. H., Pettey, A., Heron, C., & Marshall, A. M. (2022). Field and centrifuge modelling of a pumped underground hydroelectric energy storage system in sand. In *10th International Conference on Physical Modelling in Geotechnics*. Daejeon.
[3] Mugele, L., Niemunis, A., Lamparter, A., & Stutz, H. H. (2023). Investigations on a novel gravitational energy storage system using a high-cycle accumulation model. In *Proceedings 10th NUMGE 2023*. London. Submitted.
[4] Niemunis, A., & Herle, I. (1997). Hypoplastic model for cohesionless soils with elastic strain range. *Mechanics of Cohesive-frictional Materials*, 2(4), 279–299.
[5] Niemunis, A., Wichtmann, T., & Triantafyllidis, T. (2005). A high-cycle accumulation model for sand. *Computers and Geotechnics*, 32(4), 245–263.
[6] Norlyk, P., Sørensen, K., Andersen, L. V., Sørensen, K. K., & Stutz, H. H. (2020). Holistic simulation of a subsurface inflatable geotechnical energy storage system using fluid cavity elements. *Computers and Geotechnics*, 127, 103722.
[7] Olsen, J., Paasch, K., Lassen, B., & Veje, C. T. (2015). A new principle for underground pumped hydroelectric storage. *Journal of Energy Storage*, 2, 54–63.
[8] Sørensen, K. K., Stutz, H. H., Phivos Brødsgaard-Raptis, & Martin Luxhøj (2021). Conceptual physical modelling of a subsurface geomembrane energy storage system. In *Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering*. Sydney.
[9] Stutz, H. H., Norlyk, P., Sørensen, K., Andersen, L. V., Sørensen, K. K., & Clausen, J. (2020). Finite element modelling of an energy-geomembrane underground pumped hydroelectric energy storage system. *E3S Web of Conferences*, 205, 7001. doi:10.1051/e3sconf/202020507001.
[10] Tong, W., Lu, Z., Chen, W., Han, M., Zhao, G., Wang, X., et al. (2022). Solid gravity energy storage: A review. *Journal of Energy Storage*, 53.