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Geotechnical opportunities for the construction of alternative energy production plants in the Baltic states

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Abstract. The energy sector is the most influential industry for the successful functioning of the states' economy and general daily life maintenance. One of the future targets of the Baltic states is reaching the continental European energy network integrity and securing it. Furthermore, regional independence of the energy networks apart from eastern neighboring countries is of the most significant importance as the existing electricity grid is still synchronized with the supply systems of Russia and Belarus. During a tense geopolitical situation, it is crucial to search for alternative energy production options in terms of environmentally friendly and sustainable energy sources and economically viable alternatives. The Baltic states already have hydropower capacity, and Latvia is a leading country in this regard. Also, the energy production sector based on wind power use is developing significantly, and in this niche, the dominant one is Lithuania. Another alternative mentioned at the interstate level is the construction opportunity of a small modular reactor for nuclear fission, where Estonia has taken the first assessment step. In any case, but most significantly for the latter option, the regional geological and environmental situation determines where such strategic energy objects can be safely situated. The dynamic progression of climate change in boreal regions, including the Baltic states, may endanger the structural integrity of energy production infrastructure objects; therefore, geotechnical investigation serves as a key stage in the objects' construction planning.

1. Introduction

The Baltic states – Estonia, Latvia, and Lithuania – are on their pathway to reaching and securing the continental European network integrity of the energy sector, being the most significant industry for the successful functioning of the states' economy and general daily life maintenance. Still, the existing electricity grid is synchronized with the supply systems of Russia and Belarus, which is planned to be terminated in 2025 [1]. During a tense geopolitical situation, searching for alternative energy production options, such as environmentally friendly and sustainable energy sources and economically viable alternatives, is crucial. The Baltic states already have their hydropower capacity, and Latvia is a leading country in this regard, with an energy production capacity of 1,588 MW [2]. Also, the energy production sector based on wind power use is developing significantly, with Lithuania being a leader with an energy production capacity of 800 MW [2].

Another alternative that has been mentioned at the interstate level is the construction opportunity of a small modular reactor for nuclear fission, where Estonia took the first assessment step [3]. In any case, but most significantly for the latter option, the regional geological and environmental situation determines where such strategic energy objects can be safely situated. The dynamic progression of climate change in boreal regions, including the Baltic states, may endanger the structural integrity of energy production plants; therefore, geotechnical investigation serves as a key stage in construction planning. For instance, soil shear strength and stiffness during warmer winters and more often freeze-thaw cycles, increasing moisture, might significantly influence the instability due to over-consolidation in some parts under the structure, activation of possible sliding planes between various layers (especially varved clays), resulting in the risk of structural settlement and instability, also higher possibility of corrosion. Thus, pre-construction studies must include all kinds of risk assessments concerning geotechnics, environment, and logistics. Subsequent damages may shorten the life cycle of the infrastructure and increase maintenance costs, posing financial risks to potential projects [4,5]. Geotechnical tests such as unconsolidated uniaxial and triaxial tests are on the list of appropriate methods in order to establish the basic information for soil stability necessary for building strategic and hazardous objects where additional safety precautionary measures are required to prevent geotechnical as well as climate change-related hazards.

2. Geological and environmental situation of the Baltic states

The Baltic states are situated in the vicinity of the Fennoscandian Shield (the Baltic Shield). In Latvia, silty or sandy loam and clay sediments have the most potential for stable energy infrastructure construction if two main geotechnical and environmental risk aspects are evaluated. The clayey sediments are mostly related to glacial till and ice-dammed lakes, and the best locations for infrastructure objects would be relatively unaffected by groundwater corrosive actions of semi-hard and hard consistency tills with lower than 10^{-9} m s^{-1} filtration properties.

Estonia's most applicable soils/rocks are stable limestones; however, the environmental impact on groundwater in case of accidents must be considered. Therefore, limestone with shale interlayers in North-eastern Estonia might be the best option for stable energy infrastructure construction, as shale has been mined for more than a century, and there are large areas of degraded land that at the same time have a low risk to groundwaters from hydrogeological point of view. Large territories in Estonia are also covered with glacial and glacimarine sediments on top of the limestone and sandstone bedrock.

Lithuania is situated on a syncline structure with a relatively deep crystalline fundament. Multiple artesian water horizons cover it, with thick Quaternary soil layers overlying Mesozoic and Tertiary sediments. The Last Glacial Maximum has ended in the territory of Lithuania; thus, the Quaternary sediments have complicated geomorphological features that require intense geotechnical and environmental risk assessment for strategic and potentially hazardous infrastructure [6].

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3. Geotechnical stability estimation as a cornerstone of pre-construction investigation

Geotechnical stability analysis is essential in foundation engineering to assess the strength, stiffness, and stability of soil and rock layers that support structures. Two fundamental tests used in this analysis are the uniaxial and triaxial testing methods, which provide critical data on material behavior under different loading conditions. Uniaxial tests, where the material is subjected to compressive stress in one direction without any lateral confinement, measure the unconfined compressive strength of soil or rock samples. This test is relatively simple and helps determine the maximum stress the material can withstand before failure.

On the other hand, triaxial testing subjects a sample to axial stress while also applying confining pressure in a lateral direction, which closely simulates actual field conditions. Triaxial tests are more versatile than uniaxial tests as they can replicate varying levels of confining pressure, allowing engineers to evaluate soil or rock behavior under different stress conditions that foundations typically experience. During a triaxial test, the sample may undergo three stages: consolidation, where confining pressure is applied; shearing, where the axial load is increased; and failure, which is analyzed to determine the material's shear strength parameters.

The results of both uniaxial and triaxial tests are crucial for determining key soil and rock parameters, such as cohesion and internal friction angle, which are inputs to the Mohr-Coulomb failure criterion. In uniaxial tests, cohesion can be estimated directly, but with triaxial tests, a more comprehensive understanding of shear strength is possible, as they provide information under different confining pressures, simulating deeper foundation stresses.

Uniaxial testing is often used for shallow foundations, where lateral confinement is minimal, while triaxial tests are preferable for deep foundations subjected to significant lateral stress. Data from these tests allow engineers to evaluate settlement potential, bearing capacity, overall stability, and critical foundation design factors. By analyzing failure patterns and stress-strain curves, engineers can predict potential modes of deformation, such as ductile or brittle behavior, which influence how a foundation might settle or fail under load.

The triaxial test's capability to simulate drained or undrained conditions is particularly useful in studying soils, reflecting how pore pressure changes affect stability. Triaxial testing also enables engineers to observe dilative or contractive character of soils, which has implications for seismic performance and liquefaction potential. Both tests aid in understanding the relationship between stress and strain in foundation soils, providing data to model potential deformation under loading.

The uniaxial test evaluates soils' short-term bearing capacity and slopes' short-term stability. The test makes it possible to determine the shear strength and strength of the soil while simultaneously measuring the pore water pressure. It is also possible to detect such parameters as internal friction angle, cohesion, and undrained shear strength [7].

Geotechnical engineers often integrate these test results into stability analysis software for accurate predictions of foundation behavior. Combining uniaxial and triaxial test data ultimately supports safer, more economical design solutions by predicting how foundation materials may perform over time. The tests collectively help identify design requirements, such as the need for soil stabilization or reinforcement, enhancing the resilience and longevity of foundation systems. Through these analyses, engineers can avoid critical issues such as excessive settlement, slope failure, and foundation instability, which could compromise structural integrity.

The instability and potential threats for accidents in the foundation of prospective areas of energy infrastructure due to complicated mechanical properties of soft soil exist predominantly in marine as well as glacial deposit regions [8]; therefore, various geotechnical studies, especially

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shear strength tests on mechanical properties of soft soil are important to prevent disasters and avoid technical difficulties if the area is assessed as inappropriate for specific construction.

For facies, permeability fluctuation in the complete stress-strain stages affects compaction and elasticity; on the other hand, it increases the possibility of fracture failure and disintegration of the material. Permeability directly correlates with porosity in weakly cemented rocks, affects cementation structure, and it is also linked to mineralogy [9]. Because of naturally large pore diameter and high porosity, the rapid increase of permeability may destroy loose cementation, and clay minerals' geotechnical properties may change in triaxial confinement conditions. The moisture increase followed by permeability fluctuations if infrastructure works are planned must be considered as properties can be influenced dramatically in dynamic conditions. In planning infrastructure works, these properties must be considered as properties influenced dramatically by dynamic conditions.

If the foundation is on clay and glacial sediments, it might be anisotropically versatile; however, in a broad sense, consolidation in some engineering activities, such as the foundation pit excavation and embankment construction, due to loading and unloading cycles can cause various stresses initiating disintegration due to existing micro-fractures, included stones and, especially, if glacigenic till with clay is the subject of unpredictable behavior [10].

4. Alternative energy production options and geotechnical requirements

Geotechnical stability for wind generators is essential to ensure that turbines can withstand static loads (from the structure's weight) and dynamic loads (from wind, seismic activity, and other environmental factors). Stability requirements generally cover the analysis, design, and construction of foundations to prevent excessive movement, tilt, or structural failure. Geotechnical testing includes complementary geological and geotechnical report analysis from historical information as well as detailed studies using drilling techniques, sampling, and subsequent laboratory testing, including soil characterization, permeability and hydraulic tests, compressibility tests, uniaxial and triaxial tests, and others.

For solar panel fields, geotechnical soil testing typically includes assessing soil bearing capacity and settlement characteristics to ensure foundations can support panel loads without excessive movement. Tests often include soil classification, moisture content, and compaction assessments to understand soil stability, drainage, and erosion potential. In areas with expansive or loose soils, shear strength, and consolidation tests may be needed to prevent shifting or tilting of panel supports.

The construction opportunities of small modular reactors have gained growing interest, and the need for new energy sources forces the development of new quality standards for the construction industry related to the foundations of such strategic constructions. The regional geological situation determines whether such objects can be safely situated in any specific area if stable bedrock is present. Among the parameters, clayey deposit properties are usually related to glacial till and glaciolacustrine sediments very common in the Baltic states; thus, geotechnical properties are vastly various, even if their genetic appearance is similar. These properties are determined by structure, texture, plasticity, soil resistivity, shear modulus, moisture content, and other parameters [2,3,11].

A small modular reactor's central construction part should preferably be embedded into the ground because of the stability and, even more importantly, the potential interaction between the reactor unit and surrounding soils. The dynamic progress of climate change in boreal regions, such as the Baltic states, may endanger the structural integrity of the reactor's construction.

It should be noted that Estonia is the only country among the three Baltic states that has estimated potential sites for a small modular reactor's construction. According to the analysis, four locations best suited for a nuclear power plant are located in Toila (Ida-Viru County), Kunda (Lääne-Viru County), Loksa (Harju County), and Varbla (Pärnu County), see Figure 1.

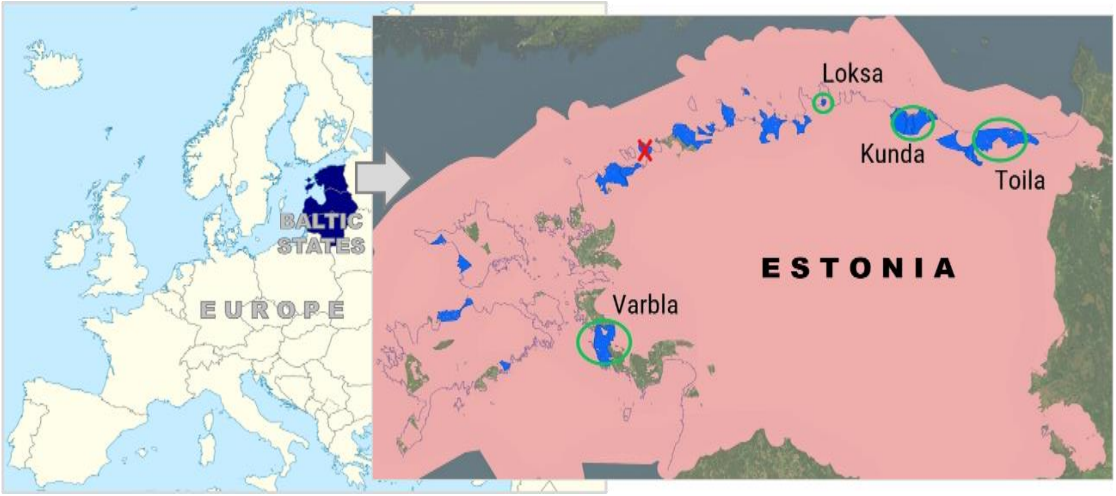

Figure 1. Location of four sites in Estonia assessed as most promising for the construction of strategic energy plants such as a small modular reactor after the potential nuclear power plant spatial analysis. The sites indicated in blue are assessed as permissive areas for the construction of small modular reactors construction, while the pink colouring includes Lake Peipus and areas within Estonia's maritime borders. Authors' work after the Ministry of Finance of the Republic of Estonia [3].

Geotechnical testing for constructing alternative energy production plants and related infrastructure includes many commonly known methods; however, where dynamic loads are in perspective, the uniaxial and triaxial testing for bearing capacity and stability is crucial.

5. Conclusions

The Baltic states have generally favorable geotechnical conditions for both wind turbines and solar panels, though with regional considerations. Coastal areas and offshore zones in the Baltic Sea provide high wind energy potential; however, the sandy soils and soft sediments in some coastal regions may require specialized foundations, such as piles, for turbine stability. Inland areas, particularly in Estonia, have limestone bedrock that strongly supports turbine foundations but may necessitate additional excavation.

For solar panels, much of the Baltic region has stable soils suitable for simple foundations, although careful attention to drainage is needed in areas with clayey soils prone to seasonal waterlogging. The cold climate and freeze-thaw cycles across the Baltics also require durable materials and designs to prevent frost heave and maintain long-term stability for both energy systems. Geotechnical studies are crucial to ensure the appropriate decision-making for alternative energy plants' safe planning and building in the future.

The decision-making on strategic energy production plants' construction options should follow particular stages: 1) assessment of environmental hazards (seismic, fault analysis, hydrogeology, and groundwater flow studies); 2) evaluation of geotechnical conditions (shear

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strength, structure, texture, plasticity, soil resistivity); 3) additional studies of dynamic factors (such as dynamic geotechnical stresses studies through triaxial testing, freeze-thaw cycles studies, consolidation experimental design, sorption of radioactive isotopes properties of surrounding soil if applicable).

Theoretically, after careful analysis of geotechnical and environmental conditions in the Baltic states, any of the three states may establish a small modular reactor in its area.

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References

[1] European Commission, 2023 https://energy.ec.europa.eu/topics/infrastructure/high-level-groups/baltic-energy-market-interconnection-plan_en (accessed on November 11, 2024)
[2] Economist Intelligence, 2023 https://www.eiu.com/n/baltic-states-ramp-up-investment-in-energy-sector/#:~:text=The%20region%20already%20has%20significant,and%20Latvia%20only%20137%20MW. (accessed on November 11, 2024)
[3] ERR News, 2023 https://news.err.ee/1608945686/analysis-reveals-four-locations-for-potential-nuclear-plant-in-estonia (accessed on October 18, 2024)
[4] Hussein E M A 2020 Physics Open 5 100038
[5] Byrne B W, McAdam R A et al 2020 Géotechnique 70(11) 970–985
[6] Klinkvort R T and Hededal O 2014 Can. Geotech. J. 51(9) 966–974
[7] Ning L, Yushi Z et al 2019 J. Pet. Eng. 183 106349
[8] Elkasabgy M and El Naggar M H 2013 *Can. Geotech. J.* **50(5)** 521–535
[9] Zhang S, Fan G *et al* 2023 *Materials* **16(1)** 210
[10] Finno R J and Chung C K 1992 *J. Geotech. Eng.* **118(10)** 1607–1625
[11] Abdulrasool A S, Fattah M Y and Salim N M 2021 In: Karkush M O and Choudhury D (eds.) **112** 365–374