PASSIVE LONG TERM SAFETY OF DISPOSAL SYSTEM FOR LOW- AND INTERMEDIATE-LEVEL RADIOACTIVE WASTE

Stasys Motiejunas¹, Roland Pusch², Diana Urbanaviciene³ and Virginijus Sackus⁴

¹ Vilnius Gediminas Technical University, Saulėtekio 11, LT-10223 Vilnius, Lithuania, E-mail: aak@ap.vgtu.lt
² Geodevelopment AB, IDEON Research Center, SE-22370 Lund, Sweden, E-mail: pusch@geodevelopment.ideal.se
³ Radioaktyvių atliekų tvarkymo agentūra (RATA), Algirdo 31, LT-03219 Vilnius, Lithuania, E-mail: d.urbanaviciene@rata.lt
⁴ UAB „Geoprojektas“, Trilapio 10, LT-92191 Klaipėda, Lithuania, E-mail: info@geoprojektas.lt

Abstract. About 100 000 m³ of solid conditioned low- and intermediate-level radioactive waste is to be disposed in a near-surface repository in Lithuania. In the previous studies in Lithuania quarried Triassic clay has been identified as the main candidate soil to seal radioactive waste disposal vaults. A large scale compaction test was performed in field similar conditions in order to investigate compactability of the Triassic clay and to confirm performance of the clay barriers as well as to select barriers emplacement methods. Two industrial compaction methods were applied and compared. The results of the test confirmed very good mechanical and isolating properties of the compacted Triassic clay and that the required characteristic of the clay layer can be reached using the both investigated compaction methods. This smectite rich Triassic clay can be applied in disposal facilities of radioactive as well as other dangerous wastes.

Analysis of longevity and performance of the clay liners confirmed high safety level of the near-surface repository. Use of natural clay for engineered barriers yields a high performance. The proposed multiple barrier system provides adequate isolation of disposed waste within a required period of time. Safety of the repository is achieved by passive methods not requiring further supervision and maintenance.

Keywords: Radioactive waste, engineered barriers, disposal, near-surface repository, smectite clay, compaction, hydraulic conductivity, Ignalina NPP.

1. Introduction
1.1 General background

Radioactive waste shall be managed in a way which ensures that there is no unacceptable risk or detriment to humans, other biota or the environment, at present, and that future risks or detriment will not exceed those currently accepted. The general approach to radioactive waste disposal is to isolate the waste by minimizing its contact with water and reducing the release of radionuclides into the environment. Accepted international practice is that solid low- and intermediate-level and short-lived radioactive waste is suitable for disposal in near-surface repositories. Multiple engineered barriers have been incorporated into design of such facilities to help isolate the waste and to discourage inadvertent intrusion. This type of facility provides the required isolation for this type of waste to decay to acceptable levels of radioactivity within a period of time for which institutional control of the repository can be expected to continue [1, 2].

As part of the obligations of the European Union Accession Treaty, Lithuania is shutting down Ignalina NPP units 1 and 2 by 2005 and 2009, respectively. Taking into account all possible threats, Lithuania has selected immediate dismantling strategy, implying that about 100 000 m³ of solid conditioned low- and intermediate-level wastes will be generated during operation and decommissioning of the Ignalina NPP. These wastes will be disposed in a near-surface repository to be built in vicinity of the NPP at Stabatiskė site [3, 4].

1.2 Concept of a near-surface repository and design principles

A concept of modular near-surface repository with concrete vaults constructed above the groundwater level has been selected after analyzing operational experience of existing near surface
repositories. Geomembranes, geosynthetic clay liners, geonets, geotextiles are some of the geosynthetics are often used in the liner-barrier systems in waste disposal facilities. However, organic substances should be avoided in engineered barriers firstly because testing of their longevity suggests that the tightness cannot be relied on for more than decades or possibly a century, and secondly because they may serve as nutrients for microbes that can cause physical degradation of the clay [5]. The geo-membrane liner typically provides an impermeable barrier, damage to the liner, in the form of small tears or punctures, may occur when the protective soil cover is placed over the liner, thereby affecting its integrity and reliability.

These considerations are particularly important for containing radioactive waste because of the long-term isolation required. For these reasons geosynthetics should be excluded as barrier components in the near-surface radioactive waste disposal system. In order to promote the cap’s longevity, infiltration barriers should be covered by a soil layer sufficiently thick to extend below the frost line, to accommodate the rooting depths of native plants, and to extend below the probable depth of animal burrows.

The basic principles of the conceptual design of the planned "hill"-type repository with reinforced concrete vaults are [4, 6].

- Engineered and natural barriers limit the amount of water that can come in contact with the radioactive waste and prevent or retard migration of released radionuclides;
- A bottom bed layer beneath the reinforced concrete vaults consists of low-permeable and very low-compressible smectite clay;
- During the closure of the repository the sides and top of the vaults should also be covered by smectite clay barriers;
- The whole disposal system should be covered by a long-lasting erosion-resistant cover consisting of a vegetation layer on top of a drainage layer.

The cover forms a barrier between the waste and the environment, thereby shielding humans and the environment and limiting the migration of the waste contents. A cap must restrict surface water infiltration into the contaminated subsurface to reduce the potential for contaminants to leach from the site. The vegetation layer protects disposal system against erosion. Also, vegetation reduces a depth of frost penetration and enhances evapotranspiration of water [7], so reduces risk of potential water penetration into the disposal vaults.

Geological media of the site provides natural barrier for the near-surface repository. Properties of this natural barrier as well as migration of radionuclides through it are already well investigated [8]. The present paper is addressed to the engineered barriers.

The main functions of the low-permeable clay barrier surrounding the vaults with waste are the following: 1) to protect concrete vaults and waste packages from intrusion of water; 2) to eliminate or delay leaking of contaminated water from the repository after degradation and dissolution of the waste matrix; 3) to retard diffusive migration of radionuclides from the repository. The principal requirements for the barrier system are robustness and ability to function during sufficiently long time without active maintenance measures.

The required properties of the clay layers are low hydraulic conductivity, limited swelling pressure, chemical resistivity, sufficient gas permeability and longevity.

Hydraulic conductivity. The hydraulic conductivity of the (finally) fully water saturated clay should not exceed 10^{-10} m/s. The clay must be compactable to a density that gives the required hydraulic conductivity.

Swelling pressure. The swelling pressure of the fully water saturated clay should not exceed 100-200 kPa. The clay should contain about 15 weight percent of smectite with sodium as major adsorbed cation. This yields the required tightness and limits the swelling pressure to what can be provided by a suitable overburden without any risk of expansion if the dry density of the clay is in the right interval.

Chemical properties. The clay should not contain significant amounts of soluble substances like Fe-oxides or hydroxides or Ca carbonate that can cause cementation of the clay component to an extent that its expandability and tightening potential are threatened. The composition and properties of the clay material and the other soil components must be checked throughout the construction work.

Gas permeability. Gas produced in the vaults must be released through the surrounding medium without degrading it. Gas will pass through the clay barriers, which must have a sufficient self-sealing capacity to close channels formed at the penetration of gas. It is estimated that this capacity is sufficient if the clay has a swelling pressure of 100-200 kPa.

Longevity. The isolating capacity of the clay layers must be retained for 300 years, which means that smectite conversion must not happen and that precipitation of chemical complexes must not lead to significant cementation.

1.3 Triassic clay as a candidate soil for sealing

In curse of previous studies [6] smectite (montmorillonite) rich Triassic clay has been identified as the main candidate soil for sealing the disposal vaults of the repository. Chemical composition of the Triassic clay quarried at Šaltiškiai is known from the previous studies [9]. The following values were determined as a result of chemical analyses: SiO_2 – 47.10%, TiO_2 – 0.64%, Al_2O_3 – 12.87%, Fe_2O_3 – 6.36%, CaO – 10.37%, MgO – 3.71%. High stability of composition was observed.
The granular and mineral compositions of the clay are summarized in Table 1.

### 1.4 Goal

In the previous studies Triassic clay has been identified as the main candidate soil for sealing the disposal vaults of the repository. The main goal of investigations summarized in the present paper was further investigating properties of this clay, analyzing engineered barriers emplacement methods as well as to demonstrate constructional characteristics, performance and functionality of the engineered clay barriers.

**Table 1.** Mineralogical and granulometric data of the Triassic clay [9]

<table>
<thead>
<tr>
<th>Grain size data</th>
<th>Weight percentage of size fractions</th>
<th>Mineralogical data</th>
<th>Weight percentage of minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>4.5</td>
<td>Rock-forming Minerals</td>
<td>100</td>
</tr>
<tr>
<td>Silt and microaggregates</td>
<td>78.6</td>
<td>Rock-forming minerals</td>
<td>100</td>
</tr>
<tr>
<td>Clay</td>
<td>16.9</td>
<td>Smectite</td>
<td>56-71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Illite</td>
<td>17-30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chlorite</td>
<td>9-17</td>
</tr>
</tbody>
</table>

A scope of this work is examination properties and performance of the clay from Šaltiškiai quarry in field conditions.

### 2. Methods

#### 2.1 Large scale compaction test

In order to find optimal clay compaction conditions large scale compaction tests were performed. Triassic clay from industrial Šaltiškiai quarry was taken for large scale compaction test. Two industrial compaction techniques were applied: compacting by use of a 420 kg vibrating plate (Fig 1) and by 7 t vibrating roller with smooth drums (Fig 2).

![Fig 1. Compaction with 420 kg vibroplate](image)

Compaction of about 12 tons of Triassic clay has been made indoors in beginning of June, 2006. The clay had been mined in early May and stored in a cement factory. Three weeks before the test the clay was transported from stockpile of the cement factory to the test site. All the time the clay was protected from rain and sunshine.

![Fig 2. Compaction by use of a 7 t vibratory roller](image)

The material with granule size varying from a few tenths of a millimetre to several centimetres was spread out on a concrete floor to a thickness of 15 cm over an area of about 15 m² and to 30 cm over about 25 m². The first mentioned fill was compacted by use of a 420 kg vibrating plate that was moved 10 rounds (2x10 runs in two directions) over the clay layer that got a thickness of about 11 cm and appeared to be homogeneous and dense. The other area was compacted by 10 rounds (2x10 runs in two directions) of a 7 t vibrating roller with smooth drums, yielding a thickness of the clay layer of 17 cm. A second layer with 25 cm thickness was then applied and compacted in the same way as the first one but this layer was less effectively compacted and had an average thickness of 21 cm. The dominant horizontal part of the layer appeared to be homogeneous and dense.

#### 2.2 Determination of water content and density

Prior to the compaction test representative samples containing 30-40 g of the clay were taken for determination of water content. The samples were taken from various clay layers and granules of different size.

The density and water content were determined for samples taken from the horizontal surfaces of the compacted clay. Samples were taken with a ring from the horizontal surfaces of the two areas for determination of density and, water content. The ring had 10 cm height and 10 cm diameter.

The clay samples were dried in an oven at about 105°C temperature during 24 hours until no further loss of weight was observed.
The samples were weighted before and after drying in order to determine the content of water.

2.3 Shear testing of compacted clay

The shear testing was performed according to DIN 18137 standard. A shear test apparatus PPG-PSH was used for the experiments. A 140 cm³ shear box had 7.14 cm diameter and 3 cm height. Five unconsolidated undrained quick shear tests have been made with normal pressures of 100 kPa, 200 kPa and 300 kPa. Shear stresses applied in 5 kPa steps.

3. Results and discussion

3.1 Water content

Content of water in the clay was determined before compaction test. 26 samples were taken for water content measurements. The water content of the clay, which had a grain (granule) size varying from a few tenths of a millimetre to several centimetres, ranged between 16 to 26% while the average was about 19%. Also, the water content and density were determined for compacted clay samples. The results are compiled in Table 2. An optimal water content being about 20% was determined in the previous studies [9]. The results demonstrate that there is no need for special clay drying or wetting.

3.2 Density and compactability

Large scale compaction of Triassic clay has been made indoors in beginning of June. The clay had been mined in early May and stored in a stockpile. All the time the clay was protected from rain and sunshine. Two different techniques were applied to compact the clay. After compaction the dominant horizontal parts of the layers appeared to be homogeneous and dense. The density and water content were determined for samples taken from the horizontal surfaces of the two areas; the results are presented in Table 2. It is recognized that the both techniques gives sufficiently good results. However, the vibrating roller seems slightly more effective. Also, the upper layer was slightly less effectively compacted.

The density determines the hydraulic conductivity and swelling pressure of the clay. These experiments indicate that Triassic clay with 17-20% water content can be compacted to a dry density of at least 1550 kg/m³, corresponding to 1950 kg/m³ density at complete water saturation. Using results of previous laboratory investigations [10] can be found that the corresponding hydraulic conductivity will not exceed 10⁻¹⁰ m/s.

Also, it is estimated that clay of this type could be more effectively compacted by using vibrating sheepor pad-foot rollers and these tools or heavy dynamic impact machines.

<table>
<thead>
<tr>
<th>Table 2. Properties of compacted clay layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer/ sample No.</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>1/1 Vibrating plate</td>
</tr>
<tr>
<td>1/2 Vibrating plate</td>
</tr>
<tr>
<td>1/3 Vibrating plate</td>
</tr>
<tr>
<td>1/4 Vibrating plate</td>
</tr>
<tr>
<td>1/1 Vibrating roller</td>
</tr>
<tr>
<td>1/2 Vibrating roller</td>
</tr>
<tr>
<td>1/3 Vibrating roller</td>
</tr>
<tr>
<td>2/1 Vibrating roller</td>
</tr>
<tr>
<td>2/2 Vibrating roller</td>
</tr>
</tbody>
</table>

3.3 Shear testing of compacted Triassic clay

The shear tests of compacted Triassic clay samples were performed. The results the shear tests are summarized in Table 3 and Fig 3.

<table>
<thead>
<tr>
<th>Table 3. Strength parameter values according to the shear tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Density of clay ρ, kg/m³</td>
</tr>
<tr>
<td>Layer compacted by vibrating roller</td>
</tr>
<tr>
<td>1940 24 22 0.1207 0.0983</td>
</tr>
<tr>
<td>Layer compacted by vibrating roller</td>
</tr>
<tr>
<td>1960 29 28 0.1083 0.0667</td>
</tr>
<tr>
<td>Layer compacted by vibrating roller</td>
</tr>
<tr>
<td>1800 28 27 0.0850 0.0683</td>
</tr>
<tr>
<td>Layer compacted by vibrating roller</td>
</tr>
<tr>
<td>1940 25 24 0.1300 0.0750</td>
</tr>
<tr>
<td>Layer compacted by vibrating plate</td>
</tr>
<tr>
<td>2030 29 28 0.1217 0.0500</td>
</tr>
</tbody>
</table>
and serve as short-circuits of the top liner. However, if the clay layer is effectively compacted at a low water content and located at about 4 m depth below the ground surface, where the temperature is low and the moisture largely preserved in the upper soil layers, no continuous desiccation cracks are expected.

Erosion and physical disturbance by piping may cause transport of fine particles within and from the clay-based liners, resulting thereby in a more permeable liner. The risk of such degradation, which depends on the flow rate and hence on the hydraulic gradient, is low for dense liners with high clay contents like the Triassic clay but high for soils prepared by mixing smectite clay and ballast. Hence, erosion by percolating water is deemed to be of no problem but the risk of loss of particles downwards requires that the clay be placed on a bed of well compacted silt with a void size smaller than 100 µm.

Chemical impact would occur if the covering layers contain sulphide minerals and if precipitation is in the form of acid rain. The both would cause a drop in pH of the pore-water. However, the chemical buffering capacity of the thick cover is estimated to be sufficient to maintain a pH value in the range of 6-8. The most important issue is the chemical interaction of clay and concrete. Ordinary Portland cement gives a very high pH, which is known to degrade smectite that is in contact with it. However, at low temperatures this interaction is very slow [11]. Low pH cement is favorable for the vaults but strength criteria must be fulfilled.

Liquefaction may be a serious problem for any water-saturated landfill with low density. Seismically induced shearing could cause contraction and development of a porewater overpressure that can reduce the effective pressure. However, for densities exceeding about 1800 kg/m3, this is not a problem as long as the expected seismic events represent values lower than 6 on the Richter scale.

Wide-ranging analyze of experience of existing near-surface disposal facilities was done by the authors through scientific visits, technical meetings as well as literature studies. Strengths and weaknesses of Maišiagala (Lithuania; recently upgraded), El Cabrile (Spain), l’Aube (France), Rokasho (Japan), Puspokszilagy (Hungary), Vaalputs (South Africa) and other near-surface repositories has been summarized. Distinctive features of the concept proposed to Lithuania are the following: 1) No degradable materials will be used in the repository structures and natural materials will be applied as engineered barriers; 2) Some of above mentioned facilities have galleries below the disposal vaults containing tubings for water drainage and monitoring of leakages. However, it was recognized in the course of the present investigation that these tubes and interconnections are the most critical and sensitive easy degradable structural elements of such repositories. They need for continuous inspecting and

![Diagram](image.png)

**Fig 3.** Shear test results

The tests did not involve water uptake and the degree of clay saturation with water was about 75%. The internal friction angle $\phi$ of the compacted clay is about the same irrespective of the compaction technique while the cohesion $c$ is lower for samples taken from lower layers.

### 3.3 Performance analysis

The waste isolation capacity of the NSR depends on the performance of the engineered barriers, of which the smectitic clay component of the top cover is of particular importance.

Hydration of the clay layers is very important for safety of the near-surface repository. The hydration mechanism is basic to the prediction of the water saturation of the clay. The process is very slow. Reaching about 100% degree of saturation of a 0.3 m layer of smectitic clay takes about 125 years while a 0.5 m layer will require somewhat more than 400 years to reach the same state [10]. Theoretically, a 1 m thick clay layer will be completely water saturated after more than 1000 years while one with 1.5 m thickness would require several thousand years for complete saturation.

Longevity of the clay liners depends on external impacts. A number of stability problems can occur in top liners that are related to the microstructural constitution of the liners caused by freezing, desiccation, erosion, chemical impact or liquefaction.

Freezing of porewater in ordinary clay soils takes place at around 0°C or somewhat lower depending the thermal properties of the clay-water system, and on the chemical composition of the porewater. Frost heaving and formation of ice lenses occur in soils if water for ice lens growth is available. The important thing is that frozen clay of Triassic type will not retain its initial microstructural constitution after thawing; it will be heterogeneous and much more permeable than before freezing. The clay must be prevented by burying sufficiently deep down.

Desiccation of a clay top liner can cause cracks if the water content drops below the shrinkage limit. Desiccation cracks can be filled by pervious soil material falling from the overburden, primarily from the adjacent filter that contains silt in its lowest part.
maintenance. The engineered barriers proposed in this paper are very robusts. No leakages can be observed during all design time. So, alternative monitoring methods boreholes for ground water sampling and for gamma spectrometric in-situ measurements have been proposed [4] instead of the safety compromising galleries. Safety of the proposed repository is achieved by completely passive methods not requiring further supervision and maintenance, like water pumping replacement of degraded parts.

4. Conclusions

Triassic clay demonstrates very good isolating and functional properties and is a major candidate material for sealing the radioactive waste disposal facility. Use of natural clay for engineered barriers will yield high performance of the near-surface repository.

The two industrial compaction techniques give sufficiently good results. The vibrating roller seems slightly more effective. Triassic clay with 17-20% water content can be compacted to a dry density of at least 1550 kg/m³. The hydraulic conductivity of the clay will not exceed $10^{-10}$ m/s.

Only non-degradable long lived natural materials should be applied as engineered barriers of the near-surface repository. Safety of the repository should be achieved by passive methods not requiring further supervision and maintenance.

The proposed multiple engineered and natural barrier system provides required isolation of disposed waste within a period of time required to decay to acceptable levels of radioactivity assures internationally accepted safety level.

Acknowledgements

The authors are expressing gratitude to Dr. Ramutis Bonifacas Mikišys, Jonas Jonynas, Roland Turner as well as UAB „Kerista“, SKI (Sweden) and Vilnius University for generous and valuable help.

References