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ENGINEERING-GEOLOGICAL MODELLING OF THE SILLAMÄE RADIOACTIVE TAILINGS POND AREA

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree or examination

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SILLAMÄE RADIOAKTIIVSETE JÄÄTMETE HOIDLA TERRITOORIUMI INSENER-GEOLOOGILINE MODELLEERIMINE

HARDI TORN

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LIST OF ORIGINAL PUBLICATIONS

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PAPER II. Tammemäe O., Torn H., Risk management in environmental geotechnical modelling., Geologija No. 61 (1). P. 44–48, Lietuvos mokslų akademijos leidykla 2008.

PAPER III. Valgma, I.; Torn, H.; Erg, K. (2006). The impact of infiltration dam on the groundwater regime in the Kurtna landscape reserve area. Oil Shale, 23(1), 3 - 14.

PAPER IV. M.Mets, H.Torn, Stability of the Dam of Sillamäe Nuclear Waste Depository, Proceedings of the Third International Congress on Environmental Geotechnics, Lisboa, Portugal, Balkema, Rotterdam, Brookfield, 1998, Vol. 2 925-932, ISBN 90 5809006 X

PAPER V. M.Mets, P.Talviste & H.Torn, Strength of Paleozoic clays, Proceedings of the Eighth Baltic Geotechnical Conference, Balkema, Rotterdam, Brookfield, 1995, 43-47, ISBN 90 5410 587 9

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1. INTRODUCTION

The issue of human activities related to radioactive waste management has become topical all over the world. Uranium mines and their inseparable satellites – radioactive waste depositories – can be found in 35 countries [1]. These depositories differ from ordinary mine waste depositories by the content of hazardous substances that migrate by air, dissolve into water bodies, or filtrate into groundwater. Isolation of a depository from the surrounding environment – the process of sanitation – assumes the co-operation of many specialists starting from geologists and ending with sociologists. In the mining industry, waste depositories often constitute a critical factor. These technogenic constructions carry risks for the environmental and human health, and land use capacities. Ignoring these risks results in higher responsibilities, bigger insurance fees and pollution taxes as well as potential pecuniary loss to the landholder.

Closing down a depository is a complicated process where a variety of factors has to be taken into consideration. A fundamental factor is the geological structure of the region and its geotechnical conditions, which serve as a basis for environmental impact assessment and elaboration of a sanitation programme.

The world practice in sanitation of waste depositories shows that problems arise at every stage of project development – during investigation, in designing, at sanitation work and during future exploitation of the object. The aim of the closure of a depository is its complete and long-term isolation from the surrounding environment without any further maintenance. However, the experience shows that the initial expectations tend to be fairly optimistic and usually the need for accompanying environmental measures and supplementary investments comes up much earlier than planned.

The present work is based on the engineer-geological investigations, carried out on the Sillamäe Radioactive Tailings Pond, and monitoring data covering the last 15 years. The obtained experience is analysed and compared with the technological solutions used in the world practice. Based on the obtained information, the engineer-geological and geoecological conditions and risks of the area are assessed. An engineer-geological model of the area around the radioactive tailings is compiled. Problems to be solved in the future are formulated.

The practical outcome of the work is the analysis of the development plan of the Sillamäe free economic zone and harbour, and compilation of an engineer-geological model for the area under consideration. Silmet Ltd continues to operate in the area and the waste it generates has to be treated in the future. The understanding of topical issues and potential dangers in the initial stage is important for the developers and future investors of the area to assess potential risks and to plan their activities.

2. RECULTIVATION OF RADIOACTIVE TAILINGS IN THE WORLD PRACTICE

The chapter deals with the world practice in mining of uranium ore and utilization of waste. The results obtained during the course of investigations are discussed. Despite the fact that uranium occurs in extremely different conditions on all continents, the technologies used for its mining and enrichment are much the same everywhere. Owing to this, it is possible to compare the storage of waste and its impact on the environment in different parts of the world. The

greatest differences are due to the area's specific geological conditions, geomorphological peculiarities and risks.
Most of the uranium ore is mined by the open pit method, which is simplier and cheaper than underground mining. In the uranium ore the uranium content is generally 1.1...0.1%. In the ore mined at Sillamäe, it is only 0.036%. This means that a large volume of rock has to be mined and the quantity of waste to be deposited after the treatment of the ore is also great. The world uranium resources are illustrated in Figure 2.1 [1].

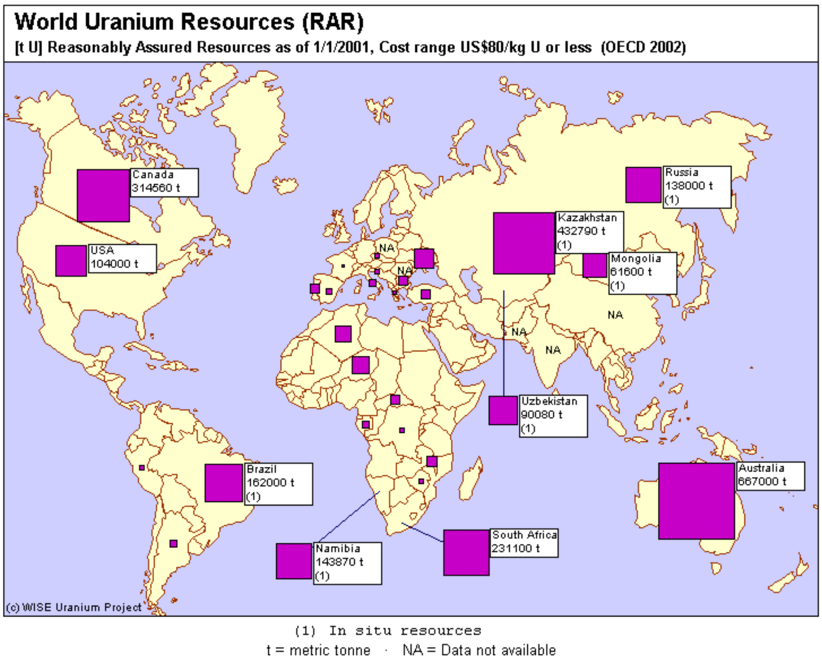

Figure 2.1. World uranium resources

About 1/3 of world's uranium is produced in Europe. The greatest producers are Germany, France and Czech Republic [2]. For instance, in Germany the environmental impact of uranium mining is estimated in an area of 32 sq km. Sanitation of waste depositories is assumed to take 15 years and recultivation ca 7 billion EUROs [4]. The assessment given to waste depositories in France in 1992 proved shocking – all depositories were in bad condition, they had not been inspected and there was no adequate information concerning their environmental impact [4]. The USA has the longest experience in the history of waste depositories sanitation – the first depository was closed down in 1985. By today, 23 depositories have undergone sanitation, and almost the same number will be closed down by 2026 [1].
In developing countries the waste depositories are in much worser state. Often there is no fixed conception for waste deposition; quite often waste finds its way into the environment, ignorance of inhabitants and officials is a common phenomenon.
On the one hand, the construction of waste depositories resembles other engineering constructions that have been built for hydrotechnical purposes. The difference appears at the assessment of the temporal factor and the risks. Taking into account the lifespan of radionuclides, waste depositories are supposed to "work" for 1000 years (in Scandinavia, 10,000 year periods are being considered).

Relative toxicity of highly radioactive compounds and low-activity industrial uranium waste and its changes in time can be compared using the amount of water needed for diminishing the content of each radioactive element to the level that would correspond to the drinking water standards. It appears that the so-called "low-enriched" uranium waste is one order of magnitude more toxic in its whole concentration range as compared to the content of highly radioactive single elements, and the impact of hazardous waste on the environment may go on for millions of years [5]. The results are presented in Fig. 2.2. The question arises: how long should the estimated time period be, and are we able to calculate such temporal distances basing on contemporary know-how?

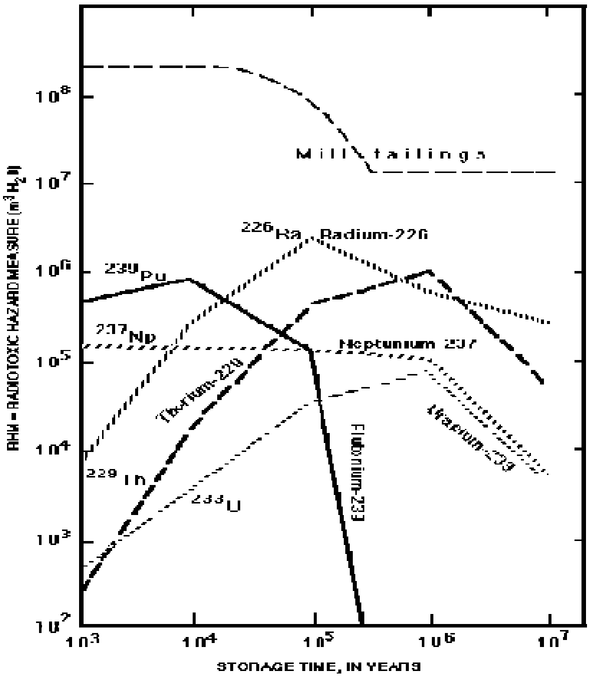

Fig. 2.2. Comparison of toxicity of low-activity uranium mill tailings with high-activity radioactive elements

The world experience shows that the initial assessments concerning the management of waste depositories have been too optimistic. The experts are of the opinion that „the planned long-term environmental measures do not guarantee the desired result. Supplementary maintenance and extra investments will be needed in a relatively short time after the closure of a depository“ [6].

2.1. Mining of uranium ore and construction of waste depositories

Uranium ore is mined either by open-pit or subsurface method. Mining in open pits is cheaper and, therefore, the open-cast method has found wider application in the world. Waste is generated as a result of ore enrichment during which uranium is removed from the rock. The content of uranium is extremely small in the total rock mass, waste forms a greater part of the treated material and contains heavy metals, radioactive elements and several other toxic substances. The waste mass is characterised by low mechanical stability which is due to the high content of fine-grained material and water.

2.2. The construction of overground waste depositories

Typical WD dams are constructed according to the amount of generated waste and filling of depository with waste [7]:

- Upstream
- Stage-by-stage
- Downstream on a permanent basis outside the crest of the previous dam

- Centerline

Underground depositoris are divided into shallow and deep ones. They are widespread in Scandinavia [8] and other countries. Shallow depositories are located mostly at a depth opf 50...100 m below land surface. The depth of deep depositories could reach up to 1000 meters.

2.3. Analysis of data concerning the environmental impact of waste depositories

The impact of waste depositories on the surrounding environment and the impact of the environment on depositories is reciprocal. Every impact is followed by a reaction or a process, which eventually affects man. Generally, the effect is a negative factor, which changes in time. If we are able to manage the processes, the environmental impact on nature and man is relatively moderate, i.e. remains within the limits of the norm-validated criteria and is accepetable for both human health and the environment. However, if the process gets out of control, the result is a catastrophe.

The main environmental impacts related to the exploitation of waste depositories are as follows:

1. Radiation and release of radon;
2. Hazardous dust and its migration;
3. Filtration of precipitation into the natural environment under the waste depository;
4. Migration of technogenic waters into groundwater or open bodies of water;
5. Environmental changes connected with removal and cleaning of WD waste water;
6. Stability of the waste depositories, including surrounding dams;
7. Changes in engineering-hydrogeologic conditions due to the closure of depositories;
8. Environmental impacts related to the cleaning of polluted surface and groundwater;
9. Future use of the waste depository ground;

Waste depositories have a long-term impact on the environment, however, at the present-day level of knowledge it is not possible to solve all problems because:

- the system of fixed priorities concerning necessary observations, investigations and stages of designing is lacking;
- insufficient attention has been paid to analysing mutual connections between the geomorphological entirety of the cultivable areas and processes;
- designing of waste depositories without maintenance expenses is complicated;
- natural processes work effectively against defence measures;
- stability of used materials in time has been insufficiently studied;
- insufficient attention has been paid to permanent monitoring and analysis of processes;

insufficient financing of essential works is a proximate cause of additional expenditures to be made later.

3. ASSESSMENT OF HYDROGEOLOGICAL AND GEOECOLOGICAL CONDITIONS AT THE SITE OF THE SILLAMÄE RADIOACTIVE TAILINGS POND

The present chapter gives a survey of the construction of the Sillamäe radioactive tailings pond, engineer-geological and geotechnical conditions, and investigations carried out in the territory [9].

3.1. Analysis of geotectonics and geodynamical factors

The studies at Sillamäe show that the environmental state and geodynamic situation of the waste depository are affected by five closely connected factors: geotectonic, hydrodynamic, slope processes, erosion and shore processes. Tectonic factors and the influence of glacier have created preconditions for the development of macro- and micro-fissures. For this reason, the Cambrian clay is more sensitive to technogenic influence and its strength is lower than that of the other similar clay stratum distributed on the North-Estonian coast.

The studies show that the coasts in the immediate vicinity of Sillamäe starting from Voka settlement in the west and extending as far as a small cape with accumulative gravel shore on the eastern border of the city is subject to very intensive wave action.

The stability of the slopes of the waste tailings dam is discussed in 9–24. The stability of the dam was assessed using minimal strength parameters, which is in accordance with the world practice.

The analysis of the results shows that the initial persistance of the slopes is not ensured. Based on bench marks movement, two kinds of slope processes were distinguished. On the one hand, there is a large-scale deep creep, which includes the depository and the underlying blue clay massif both in its northern and eastern part. On the other hand, there are local creeps in the dam body and related movement of under-slope bench marks.

The studies and measurements showed that before the sanitation work was started the depository's dam was unstable. This was caused by insufficient shear strength of the Cambrian clay under the dam. The problems related to the strength of blue clay and the impact of solutions filtrating from the dam on geotechnical properties of clays are not yet entirely clear. Alteration of clay's properties over time may adversely affect the stability of the dam.

3.2. Analysis of physical-mechanical properties of natural and technogenic soils

The geotechnical parameters of the soils spread in the area of waste depository are analysed during earlier investigations [9-11; 20; 23]. The strength of Lower Cambrian clay is the most important factor controlling the stability of the dam of the waste depository. In view of this, main attention focusses on the study of the properties of Lower Cambrian clay underlying the dam, and on its behaviour. The properties of Lower Cambrian clay are presented in Table 3.1.

3.3. Shear strength of Cambrian clay

To assess the strength of clay soils, undrained stabilometer tests, one-axial compression tests and drained shear tests are mainly used. During the stabilometer tests and one-axial compression tests, undrained maximum shear strength Cu_r and the shear strength of creep limit Cu_y is determined. The followers of L. Šuklje [25] and S. Vjalov [26] have recommended to use the characteristics of creep limit.

Drained shear strength of clay

Hvorslev [27], N. Maslov [28], A.W. Skempton [29] a.o. have divided the shear strength into different components, which is in accordance with the standpoints expressed by Tiedemann and Hvorslev in 1937. In 1960, the physical shear strength components of water-saturated clay soils were summarized by M. Hvorslev [27]. Bishop and Henkel [30] analysed the results of stabilometer tests and reached the same conclusion.

The studies carried out by H. Schmertmann and J.O. Osterberg [31] reveal a principal difference in the mechanical behaviour of the angle of internal friction and cohesion in different clay soils. The cohesive component of shear strength reaches its maximum at relatively low pressure, while in the case of the angle of interior friction higher pressure is needed (Fig. 3.1). The mechanical essence of the shear strength components is clearly different.

Table 3.1. Physical and mechanical properties of Lower Cambrian clay.

Geol. index			*Cm 1ln*	*CM 1ln*	*Cm 1ln*
Soil description			*Cambrian clay weathered*	*Cambrian clay fissured*	*Cambrian clay*
Physical properties					
Natural water content	w_n	%	20	18	16
Liquidity limit	w_L	%	63	65	69
Plasticity limit	w_p	%	28	28	31
Plasticity index	I_p	%	35	37	38
Void ratio	e_n		0,56	0,55	0,55
Natural unit weight	ρ_n	kN/m^3	20,5	21,0	21,1
Dynamic sounding test (DPTH)					
Number of blows per 0,2 m	n	n/20cm	20	40	80
Mechanical properties					
Undrained shear strength (norm.)	C_{uf}	kPa	90	150	200
(design value 0,95% probability)			55	80	160
Drained shear strength (norm.)					
Angle of internal friction (norm.)	ϕ'	deg	27	26	
Cohesion (norm)	C'	kPa	45	60	
Hudraulic conductivity	k	m/day	10^{-6}	10^{-6}	10^{-6}

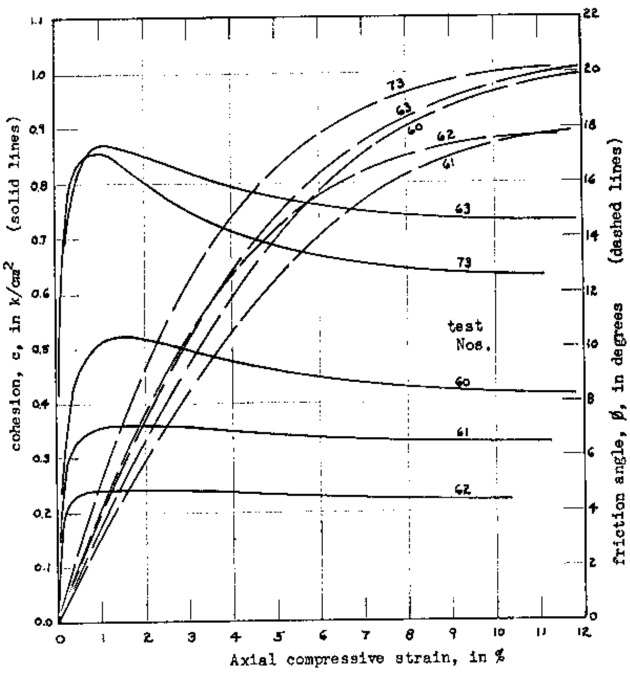

Fig. 3.1. Dependence of cohesion and angle of interior friction on stress, Boston (Cambridge) blue clay

Undrained shear strength of clays

During geotechnical studies, the Cambrian clays of Estonia have been divided into four strata with a very different strength. This is basically due to the weathering and microfissures in the upper part of the clay [32]. However, the studies have shown a good connection between the shear strength of the clay and natural water content with the latter serving often as a criterion for studying microfissures (Fig. 3.2). In practice, Cambrian clays with water content ranging from 15...27% are more frequently encountered. The strength of tested clay samples changes in wide ranges and depends on sample dimensions (usually small samples with a diameter of 40 mm are used, sample S=12.56 cm^2). Test results are considerably affected by the amount of microfissures and their orientation in the sample (Fig. 3.3).

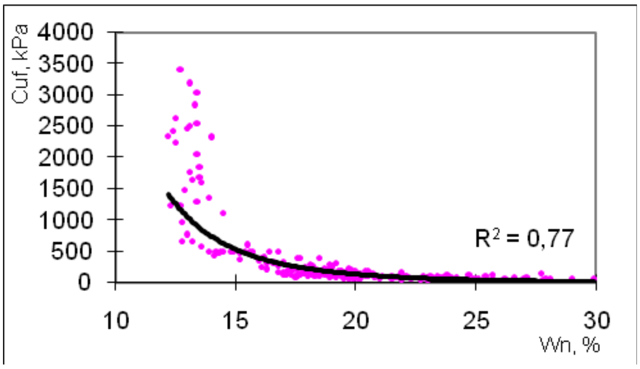

Fig. 3.2. Dependence of Cambrian clay undrained shear strength on natural water content

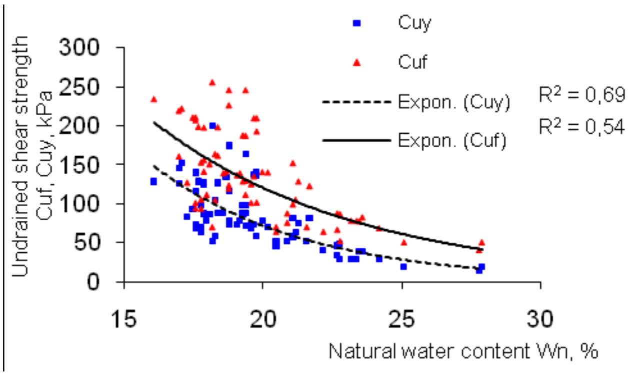

Fig. 3.3. Dependence of maximal shear sterngth and shear strength at creep limit of the weathered part of Cambrian clay on natural water content, one-axial pressure test (sample S=12.56 cm^2)

Tests with six times bigger samples (S=78.5 cm^2) in a stabilometer gave practically the same results as the creep limit determined by one-axial compression tests (Fig. 3.4).

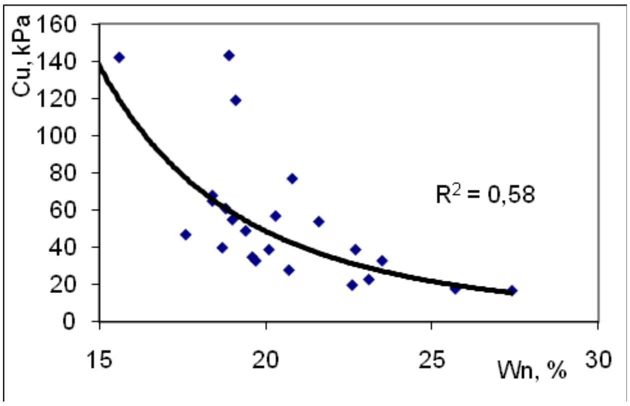

Fig. 3.4. Dependence of undrained shear strength on natural water content, stabiolometer test (sample S=78.5 cm^2)

The studies [33] aimed at evaluating the impact of microfissures showed that the latter is a decisive factor controlling the strength of overconsolidated clay. While treating test results, one has to consider the so-called scale effect. Its impact is illustrated in Table 3.2. and Fig. 3.5.

Table 3.2. Clay strength depending on the size of the sample

Base area of the sample, cm^2	One-axial compresive strength, σ_5, kPa	Deformation modulus E_o, MPa
20…25	700…900	15…25
40…50	240…500	5…9
98	100…140	4…5

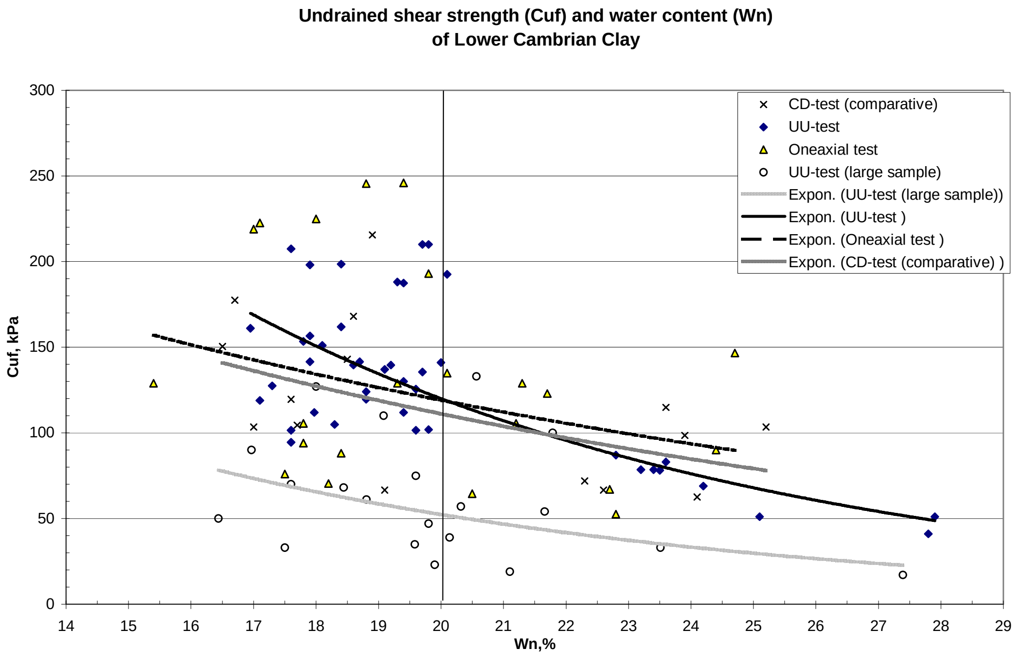

Figure 3.5. The dependence between natural water content W_N and shear strength C_{uf}

The results of laboratory tests with Sillamäe clays shows (Fig. 3.5) that smaller samples studied by different methods yield relatively similar results. The results are rather scattered due to the heterogeneity of the material.

Testing of samples with a large surface area ($S=98\ cm^2$) yields 2...2.5 times lower results. In the upper part of clay where the natural water content $W_N>20\%$, the maximal undrained shear strength Cu_f=30...140 kPa. If the water content decreases, the shear strength of clay increases Cu_f=50...250 kPa. The shear strength of creep limit is characterised by the dependence $Cu_f=0.6xCu_f$.

4. MODELLING OF CREEP PROCESSES OF THE CAMBRIAN CLAY

4.1. Basics of viscous soil modeling

The key point of viscous modelling is that this type of stress reduction (Mohr-circle squeezing) also takes place below the Coulomb failure line. According to *Van Baars* [34], viscosity is a sort of slow and rate-depending plasticity without reaching the Coulomb criterion. The numerical model is developed for finite elements based calculation software Plaxis.

In Mohr-Coulomb constitutive model the elasto-plastic (effective) stress increments are calculated from the total and plastic strain increments by (pressure and strain reduction taken positive):

$$\Delta\vec{\sigma} = \vec{\vec{D}} \cdot \left(\Delta\vec{\varepsilon}_{tot} - \Delta\vec{\varepsilon}_{plas}\right)$$

with the constitutive matrix

$$\vec{\vec{D}} = \begin{bmatrix} A & B & B & 0 & 0 & 0 \\ B & A & B & 0 & 0 & 0 \\ B & B & A & 0 & 0 & 0 \\ 0 & 0 & 0 & G & 0 & 0 \\ 0 & 0 & 0 & 0 & G & 0 \\ 0 & 0 & 0 & 0 & 0 & G \end{bmatrix} ; \Delta\vec{\sigma} = \begin{bmatrix} \Delta\sigma_{xx} \\ \Delta\sigma_{yy} \\ \Delta\sigma_{zz} \\ \Delta\sigma_{xy} \\ \Delta\sigma_{yz} \\ \Delta\sigma_{xz} \end{bmatrix},$$

in which the pivots are defined by:

$$A = F\left(1-\nu\right) \; ; B = F\nu \; ; G = F\left(\tfrac{1}{2}-\nu\right).$$

and:

$$F = \frac{E}{\left(1+\nu\right)\left(1-2\nu\right)},$$ or by depending on max isotropic stress $$F = \frac{3p_{\max}}{\left(1+\nu\right)\lambda^{*}},$$

in which the isotropic stress p is defined as:

$$p = \tfrac{1}{3}\left(\sigma_1+\sigma_2+\sigma_3\right) = \tfrac{1}{3}\left(\sigma_{xx}+\sigma_{yy}+\sigma_{zz}\right)$$

$$\varepsilon = \lambda^{*}\ln\left(\frac{p}{p_{initial}}\right).$$

, where

$\Delta\sigma_{xx..}$	-	stress increments
$\Delta\varepsilon$	-	strain increments
F	-	stiffness factor
E	-	Young`s modulus
ν	-	Poison´s ratio
$p_{\max}$	-	maximum isotropic stress (pre-overburden pressure)
$\sigma_{1,2,3}$	-	principal stresses
λ^{*}	-	soil stiffness

The plastic stress increments follow from the stress state shown in Figure 4.1. The radius r of the Mohr-circle divided by the radius of the Mohr-circle during plastic failure $r^{*} = r_{\max}$ gives the relative shear R. In case of no shear (isotropic loading) R=0 and at failure R=1. If the stresses in the calculation go beyond the Coulomb criterion (plasticity; R>1), then the stresses will be reduced in such a way that the size of the Mohr-circle is squeezed between the Coulomb lines (back-to base method) and around the isotropic stress ***p*** to avoid volume changes.

$$\frac{\sigma_{ii}^{*}-p}{\sigma_{ii}-p}=\frac{1}{R}\ ;\ \frac{\sigma_{ij}^{*}}{\sigma_{ij}}=\frac{1}{R}$$

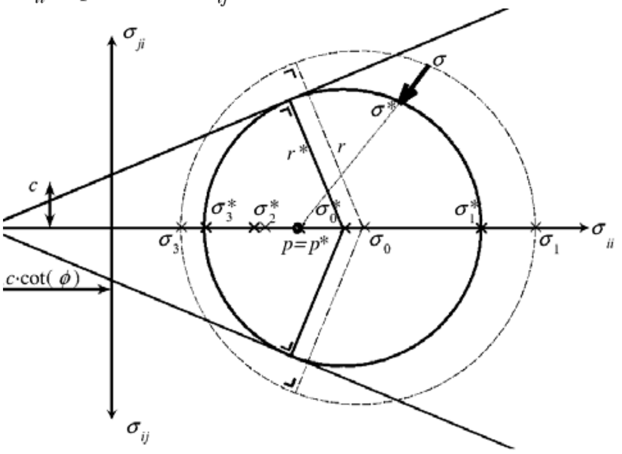

Figure 4.1. Effective stress state before plastic reduction .[60]

The normal and shear stresses at plastic failure σ* are reached by adding incremental plastic stresses:

$$\sigma_{ii}^{*}=\sigma_{ii}+\Delta\sigma_{ii,plas}\ ;\ \sigma_{ij}^{*}=\sigma_{ij}+\Delta\sigma_{ij,plas}\ ,$$

The incremental plastic normal stress will be:

$$\Delta\sigma_{ii,plas}=-\left(1-\frac{1}{R}\right)\left(\sigma_{ii}-p\right)\quad (\mathrm{R}>1)$$

and the incremental plastic shear stress:

$$\Delta\sigma_{ij,plas}=-\left(1-\frac{1}{R}\right)\sigma_{ij}\quad (\mathrm{R}>1).$$

Viscoplasticity is a sort of slow and rate-depending stress reduction process where the Coulomb failure line will not be reached. The rate of viscoplasticity depends on the normalized shear stress X (a function of relative shear R), a certain viscosity constant C_{vp} and a power m which characterize the viscous behaviour of the soil (see Fig. 4.2).
There can be a point at which there is no viscous behaviour and no creep: R_0. The maximum value for viscosity R=1 (X=1). Using the neutral relative shear stress R_0, a normalized relative shear stress X can be defined (Fig. 4.2.). The minimum value of the relative shear stress R_0 for which viscosity occurs is the stress state of K_0 (X =0).

$\partial R/\partial t$	-	rate of viscoplasticity
C_{vp}	-	viscosity constant
m	-	viscosity constant =0...1
R	-	relative shear
X	-	normalized shear stress

The long-term drained triaxial test results (by Bishop and Lovenbury 1969, Mitchell 1993), show the viscosity rate declines over time. According to Van Baars, the viscosity rate is not time dependent but depends on the amount of viscosity in the past and on stress.

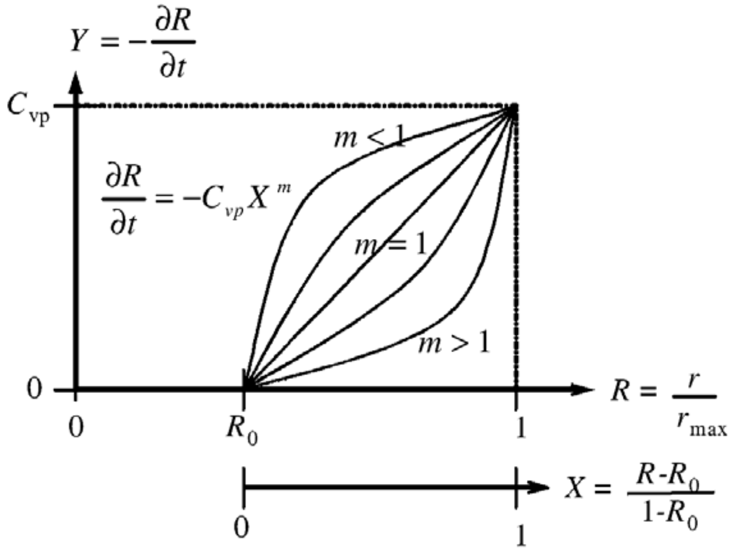

Figure 4.2. Reduction rate Y of relative shear stress as function of this relative shear stress R.

For all time steps (excl. t=0), the sum Z_t of the stress times viscosity rate is:

$$Z_t = \int_0^t p_t \frac{\partial R}{\partial t} dt = Z_{t-\Delta t} + p_t \cdot \Delta t \cdot \frac{\partial R}{\partial t}.$$

For first time step the following equation is used:

$$Z_{\Delta t} = \frac{-p\left(Y_X \Delta t\right)^{(1-n)}}{(1-n)}$$

This model was tested by Plaxis software using triaxial tests (figure 4.3.) and oedometer tests and results were compared to real testing data (Fig. 4.4). The declining deformation rate at constant stress state shows very identical results.

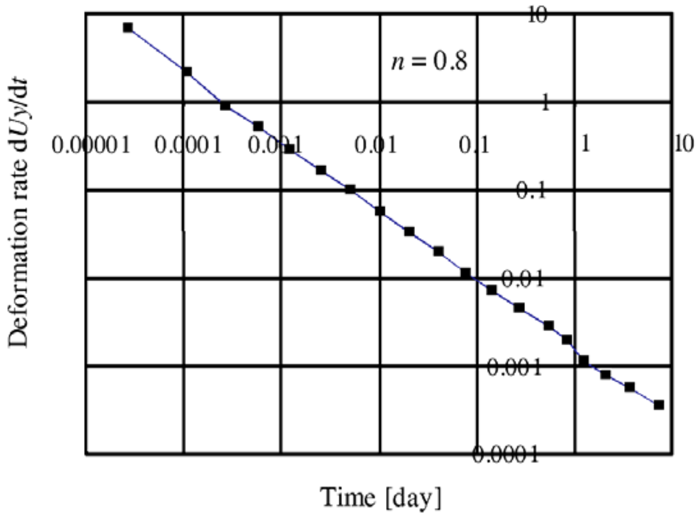

Figure 4.3. Undrained triaxial test with Plaxis Viscous Soil Model with declining deformation rate.

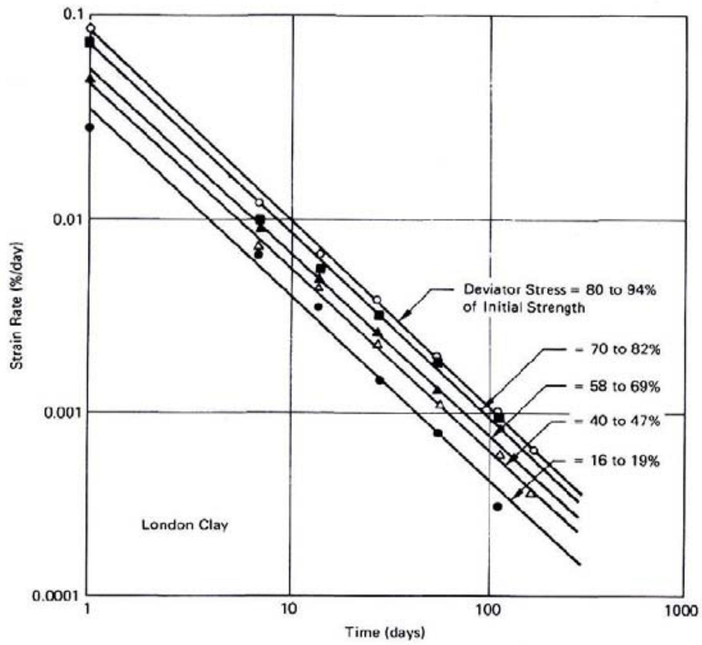

Figure 4.4. Undrained triaxial test from Bishop (1966) with declining deformation rate.

4.2. Alternative phenomenological creep model and neurocomputational model

The described alternative model was used to predict the carbon PMC (polymer matrix composites) creep behaviour [35; 36]. The recommended input to the neural network is an array of 3×1 cells where the elements of each cell represent the [material parameter T°; normalized stress level; time], respectively. The targets are chosen to be the corresponding values of the creep strain for each input cell. The normalization of the stress level was done with respect to the strength at the working temperature T.

The datasets were produced from a combination of eight temperatures (25, 35, 45, 50, 55, 60, 65, and 75°C), six normalized stress levels (30%, 40%, 50%, 60%, 70%, and 80%), and 36 time steps with 100 s increment, i.e. 100; 200; . . . ; 3600 s. The total number of data points produced were calculated as: $8(T°) \times 6(\sigma) \times 36(t) = 1728$ input-target cells.

After scaling the 1728 cells of inputs-targets, the scaled results were splitted into three subsets; one set was used for training, another set for validation, and the last set for testing the network

performance. The training and validation sets consist of 1200 (roughly 2/3 of the entire dataset) pairs of scaled data that cover the temperature ranges of 25, 45, 55, 60, and 75°C. These 1200 data points were splitted into 800 pairs for training and 400 pairs for validation. The remaining 528 cells left that cover the creep tests at temperatures 35, 50, and 65°C were kept aside to test the neural network prediction of creep after the network has been trained and validated.
It is important to randomize the data sets so that the training process of the network should not consist of a table look up problem, and to eliminate any bias that might exist in the training dataset.

Based on the Universal Approximation Theorem, Hornik et al. (1989) proved that *''A two hidden layer network is capable of approximating any useful function''*.
Also, Hornik stated that the mapping power of feed forward neural network is not inherent in the choice of a specific activation function; rather *''it is the multilayer feed forward structure that leads to the general function approximation capability''*.

The performance of several structures of neural networks have been investigated earlier by Al-Haik (2002) where the **[6-20-1]** structure (six neurons at the first hidden layer, 20 neurons at the second hidden layer and a single neuron at the output layer) achieved an optimal number of neurons. This optimal structure produced MSE = 0.12105. The results of this crude network were used to improve the performance index, i.e. the mean square error. The structure of this optimal-size network is shown in Fig. 4.5. The calculation results and performance of optimization methods are presented in Table 4.1.

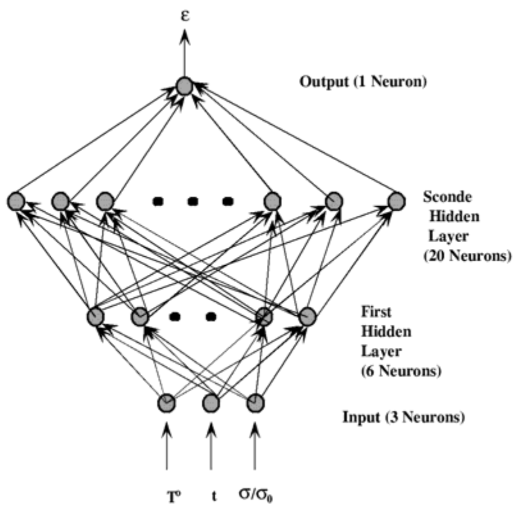

Figure 4.5. The structure of the proposed neural model to predict the creep behaviour of PMC.

Table 4.1. Performance of three different algorithms for the implicit creep model using the **[6×20×1]** topology with tansigmoid activation functions in the hidden layers [37].

Training algorithm	MSE	Epochs
Steepest descent	0.11967	1000
Conjugate gradient (Polak–Ribiere)	0.06997	113
Truncated Newton with CG-preconditioner	0.01323	160

The experimental creep behaviour of the composite together with viscoplastic model simulation and the neural network simulation are presented in Figure. 4.6.
Unlike the explicit viscoplastic model, the neural network model predicted more accurate results at different stress–temperature conditions especially under the conditions of relatively high temperature.

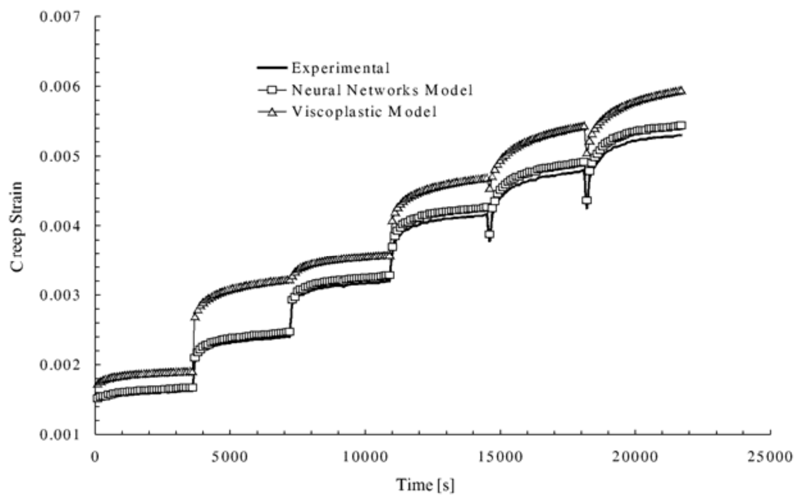

Figure 4.6. Validation of the viscoplastic and neural network models (truncated Newton) for the creep evolution at T=50°C and stress levels 30%, 40% and 50%, 60%, 70% and 80% of the composite strength at this temperature.

4.3. Conclusions

The phenomenological creep model showed a close agreement with experimental data at low temperature–low stress conditions. An alternative model employed neural networks formulation to capture the creep behaviour of the carbon PMC. The neural network model was trained to predict the creep strain based on the stress–temperature–time values. The performance of the neural model is represented by the mean squared error between the neural network prediction and the experimental creep strain results. To minimize this error, several optimization techniques were examined. The minimization of the error when carried out by the truncated Newton method outperforms both the steepest descent and conjugate gradient methods in terms of convergence rate and accuracy.

1. The both models utilize the representation of stress/time data during relatively short-term load relaxation tests to predict a relatively longer-duration creep behaviour.
2. It was noted that there is no uniform trend on how the materials parameters (A, n, m and K) are behaving in case of phenomenological viscoplastic model.
3. Some of the problems involved with the phenomenological creep models, include:
   a) The models are simply based on the phenomenological investigation of material properties while the actual behavior of the material is very complex. Therefore, inevitably the model contains errors.
   b) All these models are limited in their mathematical form and because they are written explicitly, they require an appropriate set of data for parameter identification.
   c) Compared to homogeneous materials, composite materials as well as soil require extra parameters for their characterization like fiber or particle orientation, volume fraction, fiber–matrix interface, orientation or degree of microfissuring etc. These parameters will raise the degree of complexity of the constitutive models.
4. Unlike the explicit viscoplastic model, the neural network model utilizing the truncated Newton algorithm predicted more accurate results at different stress–temperature conditions. Moreover, in building the neural network creep model, only one type of data is required, that is creep data at different thermomechanical histories, while the viscoplastic model requires both tensile tests data together with load relaxation data, and of course creep data still required to verify the performance of the model.
5. The analysis of the models shows the possibility to adopt those methods into the soil mechanics. Moreover, the novel optimization techniques enables to handle the problems arised with large variability of the results of laboratory testing data.

6. As the neural network model *''is the multilayer feed forward structure that leads to the general function approximation capability''*, it could be adopted to analyze the different mechanics phenomena and processes.

5. REMEDIATION OF THE SILLAMÄE RADIOACTIVE TAILINGS POND

5.1. Objectives of remediation of the Sillamäe Radioactive Tailings Pond

The main goals of the remediation project were covering of the pond and reinforcement of the dam to prevent it from sliding into the Baltic Sea and to reduce the emissions to water and air [38]. The long-term objective was to ensure an acceptable environmental safety of the Tailings Pond. The project concentrates on dry remediation of the Tailings Pond and this means no longer using it as a tailings pond for wastewater, dehydrating the content. The most important specific targets of the remediation project were:
1. Stabilization of the Tailings Pond seaside unstable dam against failure.
2. Protection of the Tailings Pond seaside dam against sea erosion and wave attack.
3. Cut-off groundwater inflow from the hinterland into the Tailings Pond.
4. Minimization of the seepage from the Tailings Pond's interior into the Baltic Sea to a sustainable and acceptable level, in compliance with international standards and agreements. Functional requirement for minimizing the seepage from 5 to 10% of the total amount of natural precipitation, leading to no more than 20 000 m³ of seepage per annum. The multimaterial cover system as being the preferred option to minimize the seepage. This 2.3 meters thick final cover will consist of five different layers.
5. Elimination of the radiation in the Tailings Pond area, elimination of the spreading of radioactive dust to the surrounding environment and minimization of the emission of radon to acceptable limits for the town of Sillamäe. The requirements set a target for remediation at 0.3 μSv/h dose speed on ground, also on the surface of the final cover. The soil cover eliminates the dust problem and the final cover will reduce the radon emanation to the level of natural background as presented in Figure 5.1 [39].

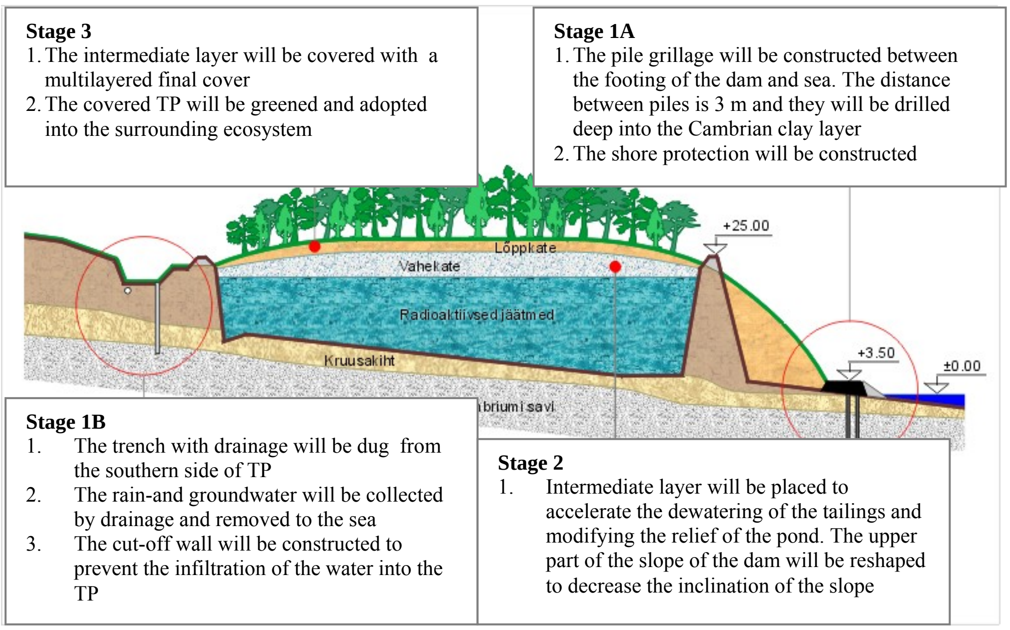

Figure 5.1. The schematic solution of the remediation of TP (ÖkoSil 2002).

5.2. Engineering-geological and environmental monitoring of the Sillamäe Radioactive Tailings Pond

Technical and financial framework for the environmental monitoring plan has been established. The decision was taken to embed the environmental monitoring program into a broader Project Monitoring and Control program, which would cover, besides environmental monitoring, also issues of overall project implementation monitoring, supervision and control.
This plan consisted of:
a) monitoring and control of the implementation of construction works;
b) Monitoring and control of the stability and the environmental performance of the Tailings Pond, short-term and long-term.
The environmental monitoring plan included monitoring of the following parameters:
1. Gamma radiation measurements;
2. Radon exhalation measurements;
3. Measurements of the radon concentration in air;
4. Measurements of long-live alpha-aerosols in air;
5. Measurements of radio nuclides and heavy metals during the vegetation period;
6. Monitoring of seawater;
7. Monitoring of bottom sediments;
8. Measurements of radio nuclides and heavy metals in fish, mollusks and bottom fauna;
9. Sampling and analyzing of seepage water;
10. Water level and quality measurements in the diaphragm wall wells;
11. Geotechnical monitoring of the dam stability;
12. Monitoring of tailings pond settling after finalization of the remediation program;
13. Visual long-term erosion control of the shoreline protection system;
14. Visual long-term erosion control of the covered tailings pond;
15. Control of the functional performance of the final cover.

5.3. Results of the engineering-geological and environmental monitoring

Parameters, presented under this chapter, are the ones that will be influenced in a predictable manner by the remediation steps of the Sillamäe radioactive tailings pond remediation project [40].
<u>Water level measurements</u> have been activated in full since July 2003. Difference in water levels on both sides of the diaphragm wall is stable with some fluctuations, varying from 2.6 to 6.4 metres at different points (wells) of the wall. The composition of water in two existing wells of the diaphragm wall showed during the 1st quarter of 2008 the following results: pH 9…8.2; total nitrogen varying between 6 and 20 mg/l; heavy metals remained considerably under trigger values while uranium and radium were higher than the established trigger value (U: 0.12 mg/l, limit value 0.1 mg/l; Ra: 0.115 Bq/l; trigger value: 0.036 Bq/l).
<u>Monitoring of the geotechnical stability of the tailings pond dam</u>
Inclinometric measurements have shown summary inclinations (from the beginning of the system installation) at different depths from 0 to 50 mm, except the tops of casings.
<u>Visual monitoring of the long-term performance of the shoreline protection system</u>
The condition of the shoreline protection system was not an issue of concern during this monitoring period.
<u>Monitoring of the tailings pond surface settling</u>
Initial parameters of the installed settlement monitoring points indicate the first vertical movement since placement.
<u>Monitoring data on final cover functional performance</u> were gathered from 5 completed lysimeters by the end of the 1st quarter of 2008. The observation period of 16 months for the earliest installed lysimeter M4 has shown a total seepage of 0.0567 mm since its installation.
<u>Water level measurements, sampling and analysis of water from monitoring wells of the diaphragm wall</u> show a stabile difference in water levels on both sides of the diaphragm wall.

The wall is working and there are different water tables in and outside the tailings pond area. Whether the quality of the wall is sufficient and stabile in all its sections, is difficult to determine – a longer observation period is needed. Neither is it possible to quantify the residual seepage, i.e. to determine the precise effect of the wall. pH of the water in wells is neutral or slightly alkaline, carrying some traces of the past pollution with the trend towards decrease (nitrogen, radionuclides).

Monitoring of the geotechnical stability of the tailings pond dam

Horizontal movements, recorded during the measurement sessions have not clearly indicated.

Developments at casings no 5 and no 6 are unclear and need a longer observation period – new zero readings have been recently established for both of these casings due to elongation, so no trend could be observed at present.

Visual monitoring of the long-term performance of the shoreline protection system

The shore protection system has not shown any developments of direct or potential concern.

Monitoring of the tailings pond surface settling

Settlement prediction was performed for different time periods by the designer of the final cover system – Wismut GmbH, using model calculations. Along with the cover construction advancement more settlement monitoring points were installed. All installed points are periodically measured and points' new elevations are added to the database. Review of the data gathered by spring 2008 allows to state that the measured settlement values are in general in line with the settlement prediction.

Monitoring of the final cover functional performance

The present results are not yet likely to represent the realistic long-term percolation, as it is expected that the clay layer saturation with water takes much longer time. The results, however, demonstrate that the sealing layer has no major problems – cracks or other defects in the designated area of lysimeters. The lysimeter and final cover performance and monitoring are illustrated in Figure 5.2.

Figure 5.2. The lysimeter and final cover structure monitoring window (ÖkoSil 2008).

6. ENGINEERING-GEOLOGICAL AND GEOECOLOGICAL MODEL OF THE SILLAMÄE TAILINGS POND

6.1. Principles of the engineering-geological model based on mutual influence of processes

6.1.1. Objectives of the model

The objective of the concept is first and foremost the formulation of problematic issues from the standpoint of the technical and future development of the area. It is the model through which problems and hazards are communicated on the one hand, while, on the other hand, it provides solutions for control of risks and use of the area in the future in such a way that the environmental impact would be acceptable, proceeding from the established standards and standpoints of the public opinion. Furthermore, it should guide the developer of the area while finding optimal solutions (risk–price–result) and lead to long-term sustainable decisions. In reality it means for the developer or investor a decrease of responsibility, environmental impact and pollution charges and creation of favourable conditions for bringing potential investments into the area [41].

If the objective is environmentally sustainable development of the whole area in a longer perspective, the starting point should be engineering-geological and environmental geotechnical conditions of the whole territory and the influencing factors.

Considering the specifics of the area under consideration, the concept of the engineering-geological model of the Sillamäe industrial area proceeds from the situation of the tailings pond, its environmental impacts and problems. In the case of all future projects one has to consider the factors resulting from the tailings pond or having an adverse impact on it. The concept of the engineering-geological model and reciprocal impacts are presented in Figure 6.1.

Since the impact of waste depository on the environment and the influence of the environment on the waste depository is reciprocal, the process as a whole has to be regarded as the entirety of factors that depend on each other and change over time. Every impact is followed by a reaction or a process, which eventually affects man and the environment.

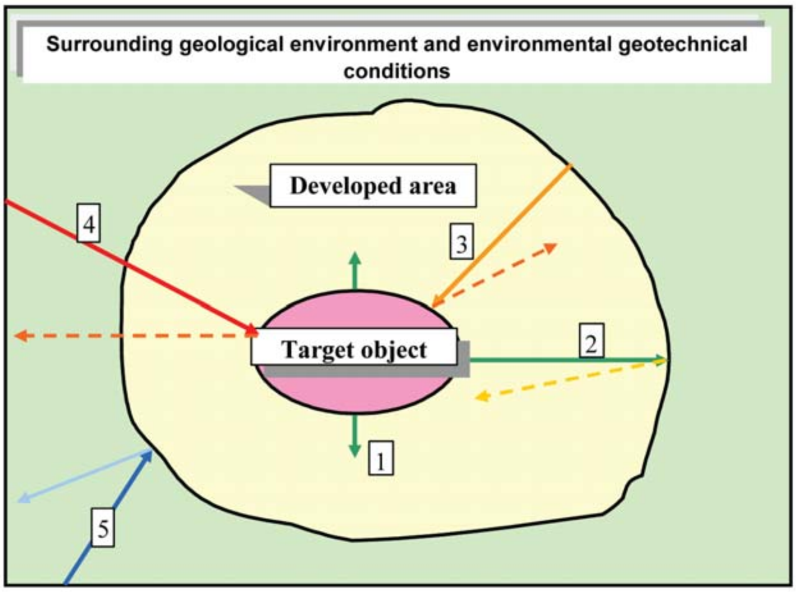

Figure 6.1. Concept of the engineering-geological and geoecological model.

In Fig. 6.1 the arrows show the effects that should be taken as a basis for risk assessment:

1. Effects proceeding from the target object and accompanying risks.
2. Risks for the object, caused by interaction of the target object and the developed area.

3. Risks for the area caused by interaction of the target object and the developed area.
4. Risks for the target object and change of environmental geotechnical conditions of this object in time, caused by environmental geotechnical conditions.
5. Risks for the developed area, caused by overall engineering-geological and environmental conditions.

Assessment of interaction of various risks enables analysis of the so-called cumulative effect. This is the total risk formed by a simultaneous occurrence of various single effects.

6.1.2. Main trends in the development of the region

The industrial zone in the town of Sillamäe lies on the western side of the town, in the area between the Gulf of Finland and the Tallinn–Narva–St.Petersburg highway. The central object in this area is the *Silmet* factory. In the area of the factory, there are the power station of the town, the former auxiliary buildings of the plant, storehouses and the servicing infrastructure. The free economic zone developed by the *Silmet Group*, the old uranium mines, and the waste depository are in the immediate vicinity. A port is being built at the eastern side of the waste depository, into Sillamäe Bay. A few kilometres away from the plant area, there lie empty and half-constructed industrial buildings dating back to the end of the Soviet era. An outline of the described area is presented in Fig. 6.2 [39].
In the future perspective – at a novel technological level – also reproduction of metals from waste and the underground deposition of hazardous waste could be considered. Preliminary research has proved that lantanium (La), scandium (Sc), niobium (Nb) and strontium (Sr) could all be produced from the material deposited at the Sillamäe waste depository. Currently, the production of these metals would not be economically effective.

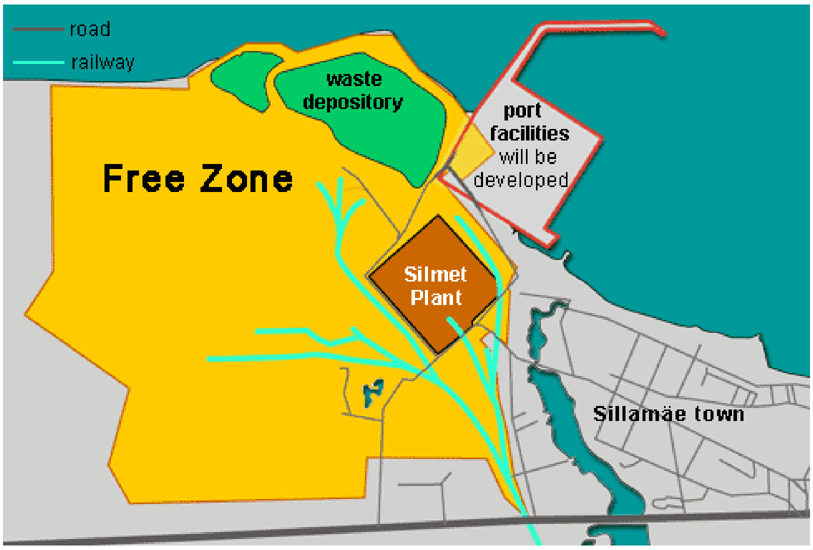

Figure 6.2. Development plan of the Sillamäe harbour and free economic zone (ÖkoSil 2002)

From the above chapters follows that the geoecological and engineering-geological conditions in the area under consideration are complicated. There are questions that have remained unsolved so far. The main hindrance to solving those problems is both the lack of funding and the absence of engineering-geological conception and model. As investigations have proven, such a a conception is missing in most of the recultivation projects in the world.

6.1.3 Current situation

At the time being, the sanitation of the waste depository is practically completed. During the last 6 years the area around the depository has remarkably changed. Instead of the initially planned one quay, two quays were constructed; the territory of the port was widened on account of sea, an oil terminal, modern infrastructure, etc. were built. As a whole, the development of the area has been rapid and exceeded the initially planned volumes. In this environmentally complicated and from the standpoint of human activities an important area, monitoring must be ongoing in the future as well. Actual situation is illustrated in Fig. 6.3.

Figure 6.3. View to Sillamäe WD and surroundings (ÖkoSil 2007).

6.2. Risk analysis and risk management in engineering-geological environment

Risks accompany all human activities and risk management is nowadays used broadly in financial activities, agriculture, industry, logistics and other branches of the economy [42].
The results of not accounting for risks are increased responsibility for the administrator of the territory with accompanying insurance payments, unforeseeable pollution charges and often also damage caused by accidents or unpredictable events. In order to manage risk, as well as any other process, it should first be identified, formulated, then assessed and a solution should be found for risk mitigation. The objective of risk management is control of risks through the investigations, data analysis, public relations, updating the legislation, risk management and monitoring as shown in Figure 6.4. This enables us to obtain new knowledge, which could be used in the further risk mitigation process on higher qualitative level.

6.2.1. Risk analysis

Risk analysis determines the probability of processes, their possible development scenarios and resulting consequences. It includes determination of undesirable cases, analysis of probability of occurrence and provides assessment, which are the consequences and effects and if the process is manageable. Risk characterization includes two major components: risk estimation and risk description.
Risk estimation combines exposure profiles and exposure-effects. Exposure profiles are descriptions of the patterns (spatial and temporal) of how particular contaminants come in contact with specific species of plants or animals. A key to risk description is the documentation of environmental contamination levels that bound the threshold for adverse effects on the assessment endpoints.

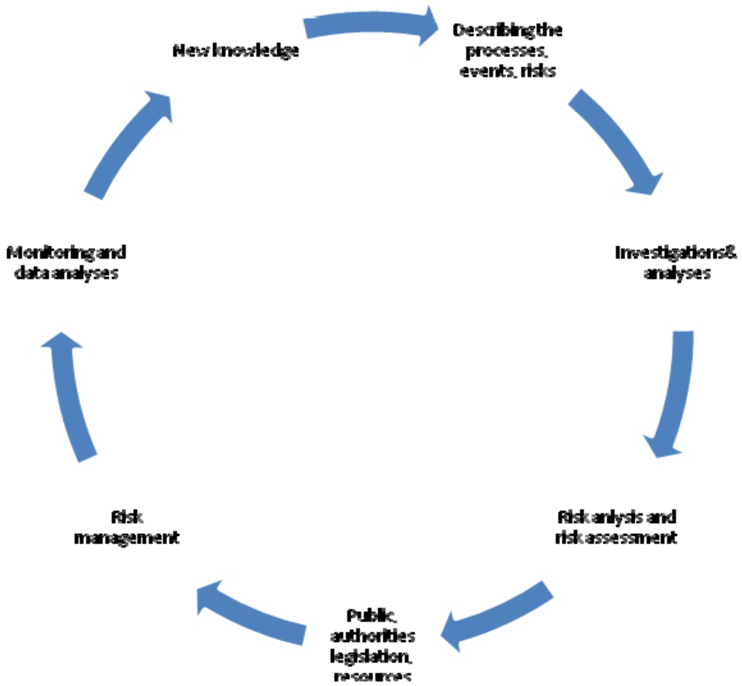

Figure 6.4. Basic scheme of cyclic environmental risk management procedure

The problems, why the methods of risk analysis developed for various branches of industry have not been used, e.g. in the case of dams.
It was concluded that the main reasons were:

- inadequate data
- the fact that all dams are unique
- the complex interactions involved in the behaviour of a dam
- unrealistic or meaningless results
- the fact that the risk of dam failure is perceived to be negligible
- concern about the cost of risk assessment
- scepticism
- problems with terminology (risk, hazard, etc)
- difficulties in understanding or applying the output from any form of risk assessment
- lack of knowledge of risk assessment techniques by the dam community.

6.2.2 Risk assessment

The objective of risk assessment is to provide an answer to the question, whether the consequence resulting from realisation of the risk exceeds the tolerance limit of the environment or not. This can be assessed with criteria and standards certified with legislation, risk levels accepted by the public and limit values established in specific conditions. On the example of the Sillamäe waste depository, a shared risk responsibility can be developed between dam owners, safety authorities and the public due to a better consideration and as an open analysis and characterization of the dam benefits and risks as well as a mitigation or control action to protect the area according to an accepted social risk level.
An essential part of risk assessment and management is feedback – monitoring network and supervision of processes, enabling to make necessary corrections in addition to the control of the situation.
In Estonia such monitoring is in most cases an obligation of the entrepreneur, whose activities involve essential risks. Additional public monitoring has been organised on territories with risk

for accompanying cross-border effects or interference with public interests – e.g. Sillamäe WD, Port of Muuga, Narva power stations.

There are four main goals of an engineering-geological and geoecological risk assessment:

1. To determine whether harmful processes or effects are likely for geodynamic stability, wild animals, plants and human;
2. If there is significant risk, to calculate a protective remediation and cleanup level that would reduce the risk to wild animals, plants and human;
3. To determine the potential impact of remediation and cleanup activities on the geotechnical conditions, habitats, plants, or animals; and
4. To provide information that can be used as a baseline for long-term geoecological monitoring programs to determine whether the remediation and cleanup activities are effective or not.

6.2.3. Risk management

In the risk management process, the results of the risk assessment are integrated with other considerations, such as economic or legal concerns, to reach decisions regarding the need for and practicability of implementing various risk reduction activities.

Risk factors are specified according to the priorities, measures are developed for their elimination or mitigation. This requires mapping of the resource needed for risk management and determination, on which level one or another risk should be managed (institution, city, the state). Upon the lack of resource the risk cannot be managed.

This then identifies the high-risk elements according to their potential need for remedial works and also the need for investigative works. Combining their criticality score with the impact score also allows for a comparison of these elements against the risks posed by elements at other sites.

6.2.4. Cyclic risk management procedure based on monitoring results

As seen in Figure 6.4, monitoring gives an exhaustive answer to the questions related to interactions between natural and technogenic environments, enables to control the long-term isolation of the waste depository from the surrounding environment, to assess the efficiency of protection measures and the risk level. Besides, monitoring provides experience, favours adequate and objective communication with officials and inhabitants and enables to regulate relevant legislation. Since the waste depositories have to last for generations, the monitoring must be prolonged. This enables the assessment of current predictions in the future and direct the processes towards risk management. The cyclic risk management procedure enables to mitigate risks, depending on our priorities, but also to assess, plan and manage the resources.

Table 6.1. summarizes the cyclic risk assessment and the results of risk management. Time intervals are relatively arbitrary because the aim of the analysis was not an exact chronological description of the events. At the same time, it illustrates, on the one hand, the level and development of our knowledge and possibilities; on the other hand, it reflects the alteration of the environmental risk level over time. Based on the presented information, it may be firmly stated that the measures taken for managing the engineering-geological and environmental risks have been correct and the invested resources have been effectively used.

The risk analysis also confirms the necessity to continue systematic monitoring because at the time being there is no sufficient information showing whether the trend of one or another risk towards its safety is ongoing or not. In order to decide about continuation of different kinds of monitoring sufficient monitoring data are needed.

Table 6.1. The results of the cyclic risk assessment.

RISK DESCRIPTION / ASSESSMENT & MANAGEMENT	Quality of air	Quality of sea water	Quality of sea sedimentation	Qquality of marine organisms	Quality of groundwater	Quantity of groundwater (seepage flow)	Quality of nearby natural resources	Direct exposure of gamma radiation	Geotechnical stability of the tailings dam	Geotechnical stability of the shoreline	Functional performance of the final cover	Accidents caused by human
Situation in 1994												
Do we have a risk?	Y	?	?	?	?	?	?	Y	?	?		Y
Is the risk acceptable?	N	?	?	?	?	?	?	N	?	?		N
Priority	H	?	?	?	?	?	?	H	?	?		?
Can we manage it?	?	?	?	?	?	?	?	?	?	?		?
Resources	?	?	?	?	?	?	?	?	?	?		?
Need for monitoring?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		?
Situation in 2000												
Do we have a risk?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y
Is the risk acceptable?	N	N	N	N	N	N	N	N	N	N		N
Priority	H	M	M	M	M	M	L	H	H	H		L
Can we manage it?	Y	Y	?	?	?	Y	?	Y	Y	Y		Y
Resources	?	?	?	?	?	?	?	?	?	?		?
Need for monitoring?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y
Situation in 2004												
Do we have a risk?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Is the risk acceptable?	N	N	N	N	N	N	N	N	N	N	N	N
Priority	H	H	H	H	H	H	H	H	H	H	H	H
Can we manage it?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Resources	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Need for monitoring?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Situation in 2008												
Do we have a risk?	N	N	M	M	N	N	N	N	L	L	L	Y
Is the risk acceptable?			Y	Y					Y	Y	Y	N
Priority			H	H					H	H	H	H
Can we manage it?			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Resources			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Need for monitoring?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Situation in 2015												
Do we have a risk?	N	N	?	?	N	N	N	N	?	?	?	Y
Is the risk acceptable?												N
Priority												H
Can we manage it?												Y
Resources												Y
Need for monitoring?	N	N	Y	Y	N	N	N	N	Y	Y	Y	Y

Labels: Y - yes, N - no, L - low, M - moderate, H - high, ? - no information

7. CONCLUSION

In the research, a survey is given of the engineering-geological and geoecological problems related to the recultivation of the waste depositories in the area of the Sillamäe Radioactive Tailings Pond and in the world as a whole. Interactions between depositories and the environment are analysed. The engineering-geological conditions, important from the standpoint of the stability of depositories are discussed. The results of the investigation show that the problems relating to waste depositories are topical all over the world. The impact of waste depository on the surrounding environment depends on natural and technogenic conditions and the risks are connected with human health, life quality, economic development and public opinion. The results arising from the study provide a basis for the conclusion that although the problems are much the same all over the world, they cannot be solved by using similar methods.

The analysis shows that a passive strategy and typical solutions are used for waste depositories isolation and recultivation. However, the practice shows that the depositories that have been isolated so far, need additional maintenance in a very short time after their closure. At the level of present day knowledge, final solution of all problems is not possible. The common conception of waste depository isolation is at variance with the laws of nature – people attempt to concentrate energy into order, while, at the same time, the surrounding environment is working for the sake of its release and creation of disorder.

The impact of waste depositories on the surrounding environment and the impact of the environment on the depositories is reciprocal. If we are able to predict and manage the processes, the environmental impact will remain within the limits of the norm-validated criteria and be acceptable for both human health and the natural surroundings. The author is of an opinion that for reaching a better result, an active strategy should be used. Taking into account the reciprocal impact of long-term natural processes and recultivated waste depositories, actual natural energy should be implemented for reaching the goal rather than creating a barrier working against the forces of nature. An important step in solving this problem is the environmental-geotechnical model that is based on risk analysis and the assessment and prognoses of reciprocated influences. In making the analyses and giving evaluations, an important role is played by the information that is acquired via monitoring.

The monitoring must deliver an adequate view of the completion of natural processes, the reciprocal impacts of natural and technogenic environments and enable the long-term isolation of waste depositories from the surrounding environment and determine the effectiveness of the planned defence measures in the longer perspective. As the waste depositories must last for generations, the monitoring must be prolonged, thus enabling the assessment of the adequacy of current predictions in the future and direct the processes towards risk management.

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ABSTRACT

In the research, a survey is given of the engineering-geological and geoecological problems related to the recultivation of the waste depositories in the area of the Sillamäe Radioactive Tailings Pond and in the world as a whole.

The present work is based on the engineer-geological investigations, carried out on the Sillamäe Radioactive Tailings Pond, and monitoring data covering the last 15 years. The obtained experience is analysed and compared with the technological solutions used in the world practice. Based on the obtained information, the engineer-geological and geoecological conditions and risks of the area are assessed. An engineer-geological model of the area around the radioactive tailings is compiled.

The impact of waste depository on the surrounding environment depends on natural and technogenic conditions and the risks are connected with human health, life quality, economic development and public opinion. The results arising from the study provide a basis for the conclusion that although the problems are much the same all over the world, they cannot be solved by using similar methods.

Closing down a depository is a complicated process where a variety of factors has to be taken into consideration. A fundamental factor is the geological structure of the region and its geotechnical conditions, which serve as a basis for environmental impact assessment and elaboration of a sanitation programme.

The analysis shows that a passive strategy and typical solutions are used for waste depositories isolation and recultivation. The common conception of waste depository isolation is at variance with the laws of nature – people attempt to concentrate energy into order, while, at the same time, the surrounding environment is working for the sake of its release and creation of disorder.

The author is of an opinion that for reaching a better result, an active strategy should be used. Taking into account the reciprocal impact of long-term natural processes and recultivated waste depositories, actual natural energy should be implemented for reaching the goal rather than creating a barrier working against the forces of nature.

An important step in solving this problem is the environmental-geotechnical model that is based on risk analysis and the assessment and prognoses of reciprocated influences. In making the analyses and giving evaluations, an important role is played by the information that is acquired via long-term monitoring.

The monitoring must deliver an adequate view of the completion of natural processes, the reciprocal impacts of natural and technogenic environments and enable the long-term isolation of waste depositories from the surrounding environment and determine the effectiveness of the planned defence measures in the longer perspective. As the waste depositories must last for generations, the monitoring must be prolonged, thus enabling the assessment of the adequacy of current predictions in the future and direct the processes towards risk management.

The practical outcome of the work is the analysis of the development plan of the Sillamäe free economic zone and harbour, and compilation of an engineer-geological model for the area under consideration.

KOKKUVÕTE

Uurimistöös on antud ülevaade jäätmehoidlate rekultiveerimisega seotud insener-geoloogilistest ja geo-ökoloogilistest probleemidest maailmas ja Sillamäe jäätmehoidla alal.

Käesoleva töö baseerub viimase viieteistkümne aasta jooksul Sillmäe RJH alal tehtud insener-geoloogiliste uurimistööde ja seireandmete tulemustele. Analüüsitakse ja võrreldakse saadud kogemusi ning maailmapraktikas kasutatavaid tehnoloogilisi lahendusi. Kogutud informatsioonile tuginedes on hinnatud ala insener-geoloogilised ja geo-ökoloogilised tingimused ning riskid. Koostatud on JH ümbritseva ala insener-geoloogiline mudel.

Jäätmehoidla mõju ümbritsevale keskkonnale sõltub looduslikest ja tehnogeensetest tingimustest ning riskid on seotud inimeste tervise, elukvaliteedi, majandusarengu ja avaliku arvamusega. Töö tulemustest võib järeldada, et kuigi probleemid on sarnased kogu maailmas, ei saa neid lahendamisel kasutada ühesugust metoodikat.

Jäätmehoidla sulgemine on keeruline protsess, kus tuleb arvestada väga paljude erinevate faktoritega. Üheks fundamentaalseks faktoriks on konkreetse JH piirkonna geoloogiline ehitus ja insener-geoloogilised tingimused. Need on lähteandmed, millest algab keskkonnamõjude hindamine ja saneerimiskava välja töötamine.

Analüüs näitas, et keskkonnamõjude vähendamiseks kasutatakse JH'te isoleerimisel ja rekultiveerimisel passiivset strateegiat ning tüüplahendusi. Tavapärane JH sulgemise kontseptsioon on vastuolus loodusseadustega - inimesed üritavad kontsentreerida energiat korrapärasusse samal ajal kui ümbritsev keskkond töötab selle energia vabastamise ja korralageduse loomise nimel.

Autor jõudis järeldusele, et parema tulemuse annaks aktiivse strateegia kasutamine. Eesmärgi saavutamiseks tuleb rakendada looduse enese energiat, arvestada pikaajaliste looduslike protsesside mõjuga rekultiveeritavatele jäätmehoidlatele, mitte rajada loodusjõudude vastu töötavat barjääri.

Üheks oluliseks osaks rekultiveeritavate alade probleemi lahendamisel on insener-geoloogiline mudel, mis põhineb riskianalüüsil ja protsesside vastatikuse mõju hindamisel. Analüüside tegemisel ja hinnangute andmisel on tähtis osa informatsioonil, mis põhineb pikaajalise seire tulemustel.

Seire annab ammendava vastuse looduslike protsesside toimumisest, loodusliku ja tehnogeense keskkonna omavahelistest mõjudest, võimaldama kontrollida JH pikaajalist isoleeritust keskkonnast ja hinnata kavandatud kaitsemeetmete effektiivsust. Kuna jäätmehoidlad peavad püsima põlvkondi, peab ka seire teostamine olema pikaajaline. See võimaldab tulevikus hinnata tänaste otsuste kompetentsuse üle ja juhtida protsesse riskide maandamise suunas.

Töö praktiliseks tulemuseks on Sillamäe vabamajandustsooni ja sadama arengukava analüüs ning kogu vaadelkdava piirkonna insener-geoloogilise mudeli koostamine.

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ENVIRONMENTAL GEOTECHNICS IN THE SERVICE OF SUSTAINABLE DEVELOPMENT ON THE EXAMPLE OF NORTH-EAST ESTONIA – SILLAMÄE

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The aim of the current paper is to analyse the environmental problems associated with harbour construction at Sillamäe, waste depositories (WD) and recultivated areas in the mining industries, and to offer solutions that would actually promote sustainable development. The authors have chosen the Sillamäe WD as a sample area, for the complexity of problems in that area makes the case a warning example.

Introduction

Human activities have affected the environment since the dawn of mankind; with the acceleration of development, these influences and accompanying risks have only grown. With the development of application of nuclear energy, the issue of the human activities connected with radioactive waste management has become topical all over the world. Uranium mines and their inseparable satellites – radioactive waste repositories – can be found in 35 states [1]. These repositories differ from ordinary mine waste repositories by the content of hazardous substances that migrate by air, dissolve into water bodies, or filtrate into groundwater.

Disintegration of radioactive waste is a long-term process that humans cannot control. Therefore, the only way to protect human health and nature would be isolation of waste repositories from the immediate organic world. One solution is to deposit the waste underground. This is an expensive and often impossible undertaking, as the old mines are often destroyed, flooded, or amortized. Another solution would be isolation of the WD from the surrounding environment. Separating a WD from the organic world – the process of sanitation – demands the co-operation of many specialists from

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geologists to social scientists. At the same time, a waste depository is an engineering construction that has to maintain its functionality and constancy for hundreds of years irrespective of the reigning policies, legislation, or currency.

In the mining industry, the environmental effects connected with WDs and the recultivated areas often constitute the critical factor. These are technogenic constructions that are associated with risks in the environmental, medical, human resource and land use capacities. Ignoring these risks results in higher responsibilities, bigger insurance fees, and pollution taxes for the landholder

From the engineering-technological point of view, the closing down of a WD and the recultivation of mines is a complicated process that requires the consideration of a variety of important factors. A fundamental factor is the geological make-up of the region and the geotechnical conditions at play there. The environmental effects brought about by human influence on the geosphere, also the accompanying risks and the possible solutions are nowadays being studied within a new, evolving science – environmental geotechnics – that combines in itself geology, hydrogeology, engineering geology, geotechnics and other adjacent disciplines. The resulting synthesis provides us with initial input that leads on to the evaluation of the environmental condition and the planning of the sanitation process – an exploit that has been followed actively since the 1950s. In the temporal context of geological processes, this is a very short time.

The environmental impact of waste repositories and the possibilities for alleviating those issues

The world practice in waste depository sanitation proves that problems will rise in all the stages of the project – during investigation, in designing, at sanitation works and during the future exploitation of the object. Even though the aim is to isolate the depository entirely from the surrounding environment – for a long time and with no further maintenance – experience shows that the initial expectations tend to be fairly optimistic and the need for accompanying environmental measures and extra investments usually comes up much earlier than it has been foreseen [2].

On the one hand, the construction of waste repositories resembles other engineering constructions that have been built for hydrotechnical purposes. The difference appears at the assessment of the temporal factor and the risks. The main problem in waste depository sanitation tends to be the lack of experience in considering the time factor. Taking into account the lifespan of radionuclides, waste repositories are supposed to “work” for a 1000 years (in Scandinavia, 10,000 year periods are being considered).

Scientists comparing relative toxicity of highly radioactive compounds and industrial uranium waste and its changes in time have reached very interesting results. They compared radiotoxic hazard of these compounds determining the amount of water needed for diminishing the content of each radioactive element to the level that would correspond to the drinking water standards [3]. The results have been presented in Fig. 1.

The research results prove that the so-called “low-enriched” uranium waste is one order of magnitude more toxic in its whole concentration range as compared to the content of highly radioactive single elements, and the impact of hazardous waste may go on for millions of years. This provokes the question: how long should the estimated time period be, and are we able to calculate such temporal distances, basing on contemporary know-how?

It is believed that depositories should function according to the set requirements for at least 200 years without any need for more serious maintenance. Considering the time factor, the resistance of the used materials must be assessed.

The predicted age of technogenic materials (e.g. concrete, geotextiles, asphalt) is up to 100 years.

If natural soils are used, their resistance to weather and time can be assessed during a longer period (e.g. investigations of the erosion crust of silt- and clay soils) and, consequently, also a prognosis made about the environmentally hazardous exploitation of waste repositories in the future.

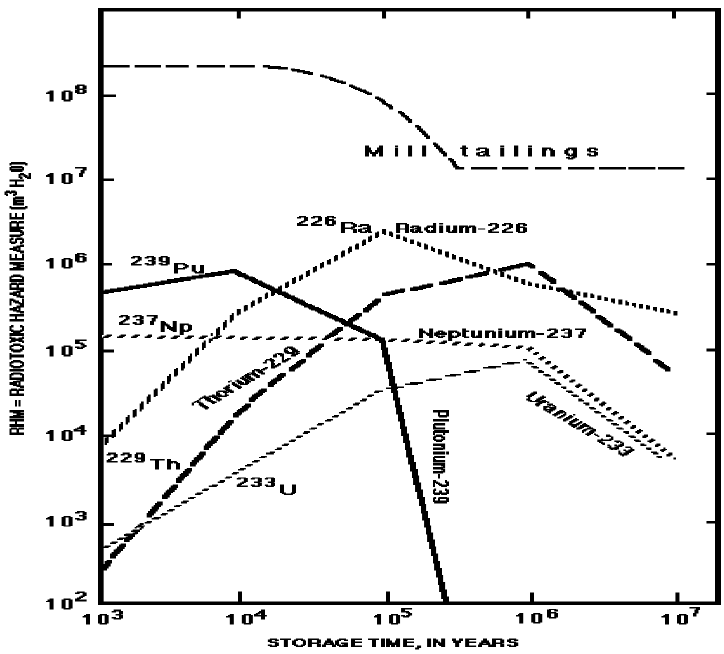

Fig. 1. Comparison of toxicity of low-enriched uranium mill tailings with radioactive elements from high-enriched uranium

For this, all the factors influencing the functionality and perseverance of WDs should be studied very carefully. The main environmental changes brought about with the exploitation of WDs are the following:

1. Radiation and release of radon;
2. Hazardous dust and its migration;
3. Filtration of precipitation into the natural environment under the waste depository;
4. Migration of technogenic waters into groundwater or open-water bodies;
5. Environmental changes connected with removal and cleaning of WB waste water;
6. Permanence of the waste depositories, including surrounding dams;
7. Changes occurring in engineering- and hydrogeological conditions because of the closing down of depositories;
8. Environmental impacts related to the cleaning of polluted ground- and surface-waters;
9. Future use of the WD grounds;
10. WD-conditioned restrictions in the future land use (e.g. planning) in the surrounding area.

World practice of environmental impact and investigations of WDs show that while the above-mentioned environmental impacts are characteristic of all repositories, the proportion of particular impacts varies and depends on natural and technogenic conditions. In solving WD problems, the environmental impacts to be considered should be approached as a whole.

The risks and risk management of the geotechnical hazards to the environment

Investigations and measurements have proved that the stability of the dam of Sillamäe WD has not been reinforced with a sufficient reserve. This has been induced by the deficient shear strength of the Cambrian clay layer lying under the dam. As for soil properties, the questions concerning the strength of blue clay and the impact of the dilutions filtrating from the dam on the geotechnical properties have remained unclear. The change of clay properties in time has an unfavourable effect on the tenacity of the dam.

The analysis of geodynamic processes shows that the perseverance of the waste depository will in the future be depending mainly on three main factors:

1. The erosion brought about by coastal processes and the consequent decrease in counterbalance, which alters the balance in soil.
2. Changes in the deposition conditions and physical-mechanical properties of soils that have been induced by geodynamic processes. The decrease in the strength of the Cambrian clay that is located under the dam facilitates the development of creep processes, and the water infiltrating from the depository will penetrate the micro-fissured clay massif.

3. Hydrodynamic regimes that can, when changed, increase or decrease the hydrodynamic strength affecting the overall strain. Due to the hydrogeological make-up, groundwater moves through the pebble layer resting under the WD towards the sea from its hinterland side.

At the same time, one should not underestimate the storm-induced changes that can raise the water level over 150 cm above the usual average (increases coastal erosion) with the westward winds in the Gulf of Narva or decrease the water level by the eastward winds down to 110 cm below the Kroonlinn zero (the counterbalance mass of the WD slope is decreasing and thus also the safety factor of the slope).

Taking into account the above-mentioned processes, the aim of the counter-measures and the WD sanitation plan has been to increase the counter-balance of the WD dam, to ensure a set hydrodynamic regime and to slow down coastal erosion.

After sanitation, the depository will look like a hill covered by vegetation, and the surface will no longer be releasing radioactive dust. Water will run down the sides of the slope without filtration into the soil; the surface water coming from the mainland will be directed elsewhere by a trench and a diaphragm wall.

The waste will keep on emitting radon, but this will disintegrate through the depository cover, i.e. before reaching the ground (the half-life period of radon lasts ca 3.5 days).

A belt of concrete piles that will be erected on the coast will secure the stability of the dam; also a coastal reinforcement will be built to safeguard against the erosive activity of waves.

Influences induced by regional development in the waste depository area

The industrial zone in the town of Sillamäe lies on the western side of the town, in the area between the Gulf of Finland and the Tallinn–Narva–St.Peterburg road. The central object in this area is the *Silmet* factory. On the factory area there stand the power station of the town, the former auxiliary buildings of the plant, storehouses and the servicing infrastructure. The free economic zone developed by the *Silmet Group*, the old uranium mines, and the waste depository are in the immediate vicinity. A port is being built at the eastern side of the WD, into the Gulf of Sillamäe. A few kilometers away from the plant area, there lie empty and half-constructed industrial buildings dating back to the end of the Soviet era. An outline of the described area is presented in Fig. 2.

Due to the favourable location and geographical conditions of the old harbour site from the beginning of the previous century, the new port was built on the same site. The old harbour had been used up till the 1940s. In order to protect the safety of the secret uranium plant, the harbour was

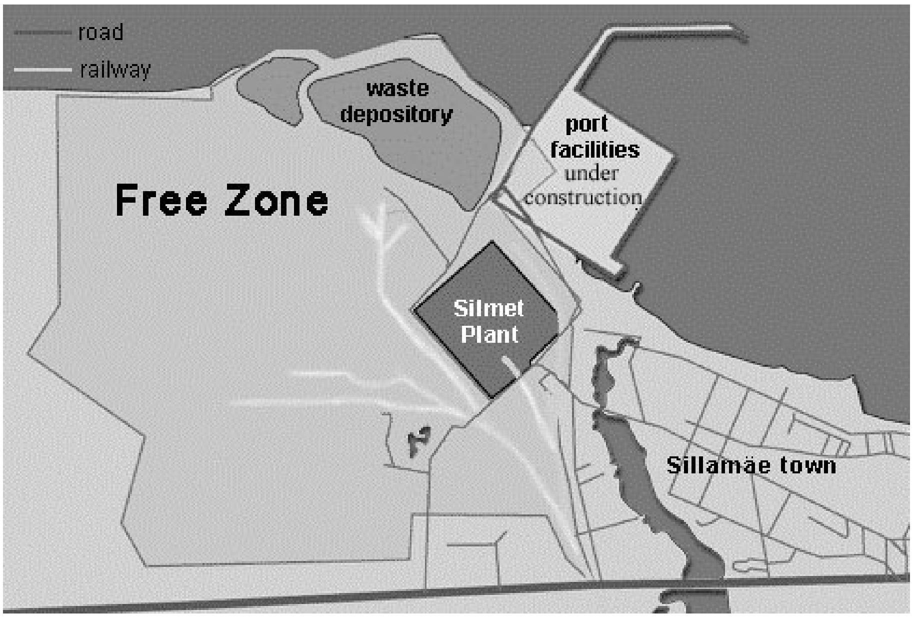

Fig. 2. The development plan of Sillamäe harbour and the free economic zone [4]

closed down and demolished. Now a modern, multifunctional commercial port is planned to be erected here as a part of the Sillamäe free economic zone. In the 1990s, preparations were made for constructing an oil port west of the WD, but these plans remained unfulfilled mainly due to heightened environmental requirements and the lack of sufficient resources for meeting these demands.

The pulp and waste water accompanying the production of rare earth metals, tantallium, and niobium is being channelled to the WD from the *Silmet* factory. Contemporary waste contains a lot of nitric compounds and other matter hazardous to the Baltic Sea.

Even though the amount of waste water is much smaller than a few years ago, this kind of waste management does not meet the EU standards, and the enterprise requires environmental reorganisation.

The shutting down of industrial production at Sillamäe resulted in complicated social issues that are hard to solve. The hydrometallurgical works along with the power station gives jobs to the majority of the Sillamäe inhabitants, making it the main employer in the town. The social and environmental issues of Sillamäe should therefore be viewed in the context of the whole industrial region of Northwest Estonia.

In the future perspective – at a novel technological level – also reproduction of metals from waste and the underground deposition of hazardous waste could be considered. Preliminary research has proved that lantanium (La), scandium (Sc), niobium (Nb) and strontium (Sr) could all be produced from the material deposited at the Sillamäe WD [5]. Currently, the production of these metals would not be economically effective.

Joining the EU and the accompanying investments into infrastructure and the development of small enterprising, the founding of the port and the continuance of the plant create favourable preconditions for the development and intensive use of the area in the future. As this is a territory that has been in use for some time already, dangers and influences related to the former exploitation of the area should be taken into account in the planning of new enterprises and constructions. The main conditions determining the future use of the territory will be economic, social, legislative and environmental-geotechnical.

The investigations and prognoses that have been launched there point out that the environmental-geotechnical conditions in the described territory are very complicated. Many questions still remain unsolved. The main hindrance to solving those problems is not even the lack of funding, but the lack of a general conception and model. As investigations have proved [2], such a conception appears to be missing in most of the recultivation projects in the world.

The principles of the conception of environmental-geotechnical model

It is especially important to develop an environmental-geotechnical model at Sillamäe, because one of the most hazardous sources of pollution in the Baltic Sea is situated there and dynamic human activity is foreseen in the area in the future. All this calls for a finer definition of the goal, the starting point and the criteria.

If the main aim is the closing down of the WD and its isolation from the surrounding environment and further maintenance, then the starting point should be the environmental-geotechnical conditions, their change in time and the accompanying risks. The criteria should be made up of measurable and assessable quantities, including the legislatively validated limits of hazardous substances, the quantities of the slope processes/positions and other quantities that depend on monitoring results.

If the aim is the founding and exploitation of the port, the starting point should be the engineering-geotechnical conditions on which the tenacity of engineering-technical buildings, the risks and environmental impact all depend on. The criteria would again be comprised of the technical parameters that can be measured at monitoring.

If the aim is the environmentally sustainable development of the whole developed region, the starting point should be the environmental-geotechnical conditions of the whole surveyed territory and the affecting factors as a whole. It is important to explicate the change of these conditioned by time, also the tenacity of constructions and their mutual impact, the human impact and the accompanying risks. Processes, phenomena and influences should be prioritised. The criteria should be determined on the basis of risk analyses of the above-mentioned processes and impacts; by managing the risks, they can be reduced to an acceptable level for both man and nature. It is also important to acknowledge who will be responsible for managing the risks and to estimate the required resources. If resources are deficient, the risks cannot be managed.

The aims and principles of future environmental-geotechnical investigations

The aims and content of the planned investigations will be determined in accordance with the developments in the future use of the area, the monitoring of the engineering-geological processes of the area and the results of risk analyses. The main principle of the research methodology is the conceptualisation of the area as one geomorphologic whole.

It must be taken into account that both geodynamic processes and geotechnical conditions are influenced not only by a variety of technogenic processes, but also by hydrometeorological conditions (changes in the water level of the Gulf of Narva); it should also be assumed that traditional theories may not necessarily apply for explaining and assessing the phenomena.

Up till now, undeservedly little attention has been paid to assessing the impact of the technogenic factors [6, 7]. Even though the future possibilities of utilising the old mines have to some extent been researched, these investigations have neglected to take a comprehensive view of all the environmental-geotechnical aspects. For example, the impact of the operating mines on the hydrogeological conditions in the area still remains unclear; also the possible impact of the hydrotechnical constructions of the future port on the coastal processes and thus also on the slope reinforcements of the WD have not been considered to the full. A northward-directed 510 m long mole and the adjacent 730 m long quay cut across the leeward, east-bound current in the lower part of the Sillamäe aquatory; they probably also influence the compensating upwind current moving westward in the deeper part of the aquatory.

Conclusions

The impact waste depositories will have on the surrounding environment in the future intensive exploitation of the areas is an issue that has remained unsolved all over the world. An important step in solving this problem is the environmental-geotechnical model that is based on risk analysis and the assessment and prognoses of reciprocated influences. In making the analyses and giving evaluations, an important role is played by the information that is acquired via monitoring. The longer and more detailed the sequence of monitoring results is, the more information we have for assessing future risks and hedging them. Following the described conception will create the prerequisites for developing an environmental-geotechnical model at Sillamäe and for using an analogous methodology for other areas that need recultivation.

The impact of WDs on the surrounding environment and the impact of the environment on the repositories is reciprocal. If we are able to predict and manage the processes, the environmental impact will remain within the limits of the norm-validated criteria and be acceptable for both human health and the natural surroundings.

The authors of the article have come to the conclusion that for reaching a better result, an active strategy should be used. Taking into account the reciprocal impact of long-term natural processes and recultivated waste repositories, actual natural energy should be implemented for reaching the goal rather than creating a barrier working against the forces of nature.

An important part in solving the problem of recultivated areas is the environmental-geotechnical model that is based on risk analyses and the assessment of the reciprocal impact of the processes. Information plays an important role in ensuring the quality of the analyses, prognoses and assessments; this information can be gained with long-term monitoring and also the integrated analyses that is enabled by the use of environmental geotechnics.

The monitoring must deliver an adequate view of the completion of natural processes, the reciprocal impacts of natural and technogenic environments and enable the long-term isolation of WDs from the surrounding environment and determine the effectiveness of the planned defence measures in the longer perspective. As the WDs must last for generations, the monitoring must be prolonged, thus enabling the assessment of the adequacy of current predictions in the future and direct the processes towards risk management.

One must not underestimate the importance of communication in the recultivation process of WDs. This is a complicated topic that requires mutual understanding by all the sides – the legislative powers, the local municipalities, the general public and various specialists. With growing effect, the development of environmental legislation keeps converting the responsibility for activities dangerous for the environment and human health into economic responsibilities. Therefore curbing the impact of similar activities simultaneously supports the compliance with the principles of sustainable development in the society.

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Risk management in environmental geotechnical modelling

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The objective of this article is to provide an overview of the basis of risk analysis, assessment and management, accompanying problems and principles of risk management when drafting an environmental geotechnical model, enabling the analysis of an entire territory or developed region as a whole. The environmental impact will remain within the limits of the criteria specified with the standards and will be acceptable for human health and environment. An essential part of the solution of the problem is the engineering-geological model based on risk analysis and the assessment and forecast of mutual effects of the processes.

Key words: risk analysis, assessment, management, environmental geotechnics, modelling, dams

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INTRODUCTION

Risks accompany all human activities, and risk management is nowadays widely used in financial activities, agriculture, industry, logistics and other branches of economy.

The results of not accounting for risks are increased responsibility for the administrator of the territory with accompanying insurance payments, unforeseeable pollution charges and often also damage caused by accidents or unpredictable events. In order to manage risk or any other process, it should be first identified, formulated, then assessed, and a solution should be found for risk mitigation. The objective of risk management is control of risks.

The risk management process as a whole includes analysis of risks, assessment of risks and treatment of risks:

1. Risk analysis should determine what is risk.
2. Risk assessment should find the answer to the question whether the risk is acceptable.
3. Risk management should set up activities for risk mitigation.

Risk analysis determines the probability of processes, their possible development scenarios and consequences. It includes determination of undesirable cases, analysis of the probability of occurrence, and provides an assessment the consequences and effects and whether the process is manageable.

Mark Morris et al. (2001) have described why the methods of risk analysis developed for various branches of industry have not been used, e. g., in the case of dams.

It was concluded that the main reasons were:

- inadequate data
- the fact that all dams are unique
- the complex interactions involved in the behaviour of a dam
- unrealistic or meaningless results
- the fact that the risk of dam failure is perceived to be negligible
- concern about the cost of risk assessment
- scepticism
- problems with terminology (risk, hazard, etc.)
- difficulties in understanding or applying the output from any form of risk assessment
- lack of knowledge of risk assessment techniques by the dam community.

The principal conclusions and recommendations from this stage of the project were that:

- The application of risk assessment could help to improve reservoir safety in the UK and it should therefore be welcomed.
- A relatively simple and easily understood risk assessment methodology would be which is cheap to implement would be preferred.
- Full probabilistic risk assessments using fault trees, etc. were not needed, although a simplified approach may be appropriate in some cases.
- Hazard indexing would be useful in identifying the potential consequences of failure and in the classification of reservoirs.

Two radical behaviours or paradigms can be detected: an extreme confidence in dam safety, because all aspects were considered during the project (a typical specialist position) or because there is a blind faith in technological power (a typical position of a believer in absolute engineering efficacy), and a strong suspicion and fear of the uncertain consequences of a new technological environment or constraint (Betâmio de Almeida, 2001).

RISK ASSESSMENT

The objective of risk assessment is to provide an answer to the question whether or not the consequence resulting from realisation of the risk exceeds the tolerance limit of the environment. This can be assessed employing criteria and standards required by legislation, risk levels accepted by the public, and limit values established in specific conditions. A comparison may be made between the FN curve derived for the UK Dams between 1831 and 1930 and the FN curve produced in the ACDS (Advisory Committee on Dangerous Substances) report for the total national societal risk from handling dangerous substances in all UK ports, or the national societal en-route risks for transport of dangerous substances by road and rail (Fig. 1).

The data for ports, road and rail have been synthesized from representative accident scenarios, assuming dangerous goods transport rates and traffic data from the mid-1980s: they do not therefore represent historical cumulative accident data in the same way as for the dams. The ACDS data do not have a time span: they are a snapshot in time at the date of publication (1991).

An essential part of risk assessment and management is feedback – establishing a monitoring network and supervision of the processes, making the necessary corrections possible in addition to the control of the situation.

In Estonia, such monitoring is in most cases the obligation of the entrepreneur whose activities involve essential risks. Additional public monitoring has been organised in territories with a risk of accompanying cross-border effects or interference with public interests, e. g., Sillamäe WD, Port of Muuga, Narva power stations.

RISK MANAGEMENT

In risk management, risk factors are specified according to the priorities. Measures are developed for their elimination or mitigation. This requires mapping of the resources needed for risk management and determination of the level at which each risk should be managed (institution, city, or state). If there is a lack of resources, the risk cannot be managed.

On reviewing and scoring all appropriate elements for a site, the next stage is to prioritise these elements so that the risk they pose may be considered in detail. Prioritisation is undertaken through a twin approach: to consider the product of *Consequence* × *Likelihood* and also the value of *Confidence* alone. The *Confidence* value may be related to the need for investigative works while the product of *Consequence* × *Likelihood* may be related to remedial works. All of the elements scored are therefore prioritised through the following steps:

1. Initial ranking of all elements according to their *Criticality* score.
2. Rank elements, primarily according to their *Consequence* × *Likelihood* product
and secondly by their *Criticality* score.
3. Rank elements, primarily according to their *Confidence* score and secondly by their *Criticality* score.

This then identifies the high-risk elements according to their potential need for remedial works and also the need for investigative works. Combining their criticality score with the impact score also allows for a comparison of these elements against the risks posed by elements at other sites.

On prioritising and identifying the key risk elements it is then essential that the assessor reviews the scoring and justification behind each high risk element to ensure that the risk assessment is justified. Only by reviewing the score justification tables and understanding the nature of the risk posed will the assessor be in a position to manage those risks through appropriate measures (Betâmio de Almeida A., 2001).

RISK MANAGEMENT PRINCIPLES UPON DRAFTING AN ENVIRONMENTAL GEOTECHNICAL MODEL

Risk management principles can be used when drafting an environmental geotechnical model, as they enable to assess the interaction of various natural and technological processes, prioritise objectives and start developing solutions of the most essential problems in the first stage.

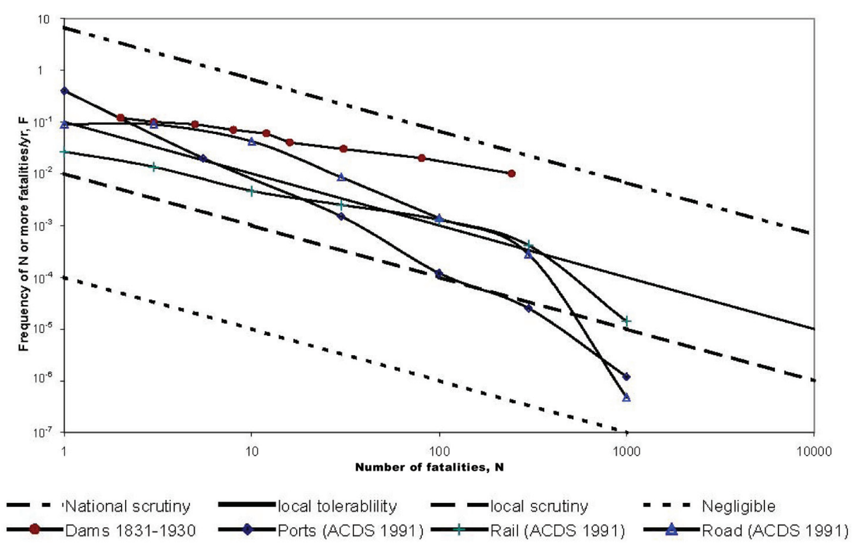


Fig. 1. Historical FN Curve for UK Dams (1831–1930) compared with ACDS National Risk from Ports, Road and Rail transport of dangerous substances (Mark Morris et al., 2001)

1 pav. Didžiosios Britanijos (1831–1930) užtvankų nelaimių skaičiauvs ir uostų, kelių bei geležinkelių transporto pavojaus kreivių palygimas (Mark Morris et al., 2001)

For example, researches and forecasts (Tammemäe, Torn, 2006) confirm that the geo-ecological and engineering-geological conditions of developed lands are often complicated. There are many questions that have not yet been solved. The main obstruction to the solution of these questions is not the lack of fiscal resources, but the lack of the general environmental geotechnical concept and model. Such concept is lacking, for example, for the planning of most of cultivated land in the world (Torn, 2003; Tammemäe, Torn, 2006).

The objectives and content of planned research are specified according to the development of the further use of the land, results of investigations of engineering-geological conditions, monitoring of processes and risk analysis of the area. The principle of research methodology shall be treatment of the territory as one geomorphological entity.

For example, analysis of geodynamic processes of the Sillamäe waste depository (WD) (Torn, 2003) showed that the stability of the waste depository in the future will depend on three main factors:

1. Erosion due to coastal processes and the resulting decrease of counterweight, causing changes in the balance condition of the soil massive.

2. Changes in bedding conditions and physical-mechanical qualities of soils due to geodynamic processes. A decrease of the strength of Cambrian clay under the dam with time facilitates development of creep processes; water infiltrating through the waste depository penetrates the micro-fractured clay massive.

3. The hydrodynamic regimen, whose change can increase or decrease the hydrodynamic force influencing the general strength situation. Due to hydrogeological constructon, groundwater moves through the pebble layer located under the WD from the clint terrace towards the sea.

At the same time, changes of water level due to storms should not be underestimated, which in the case of Western winds in the Narva Bay can raise the water level up to 150 cm over the long-term average (increasing erosion hazard for the coast) and in the case of permanent Eastern winds can in turn lower the water 110 cm below the Kronstadt zero level (decreasing the mass of the counterweight body of the WD slope, thus also the stability factor of the slope).

Taking account of the described processes, upon planning countermeasures and cleanup of the WD, the objective was to increase the counterweight of the dam of the WD, ensure the developed hydrodynamic regimen and stop coastal erosion.

Drafting the concept of the engineering-geological model at Sillamäe is especially necessary, as one of the most essential pollution sources of the Baltic Sea in the region is located on the territory and active human activities are foreseen in the future in its immediate vicinity. This requires definition of the objective, starting point and criteria.

PRINCIPLES OF THE CONCEPT OF ENVIRONMENTAL GEOTECHNICAL MODEL BASED ON MUTUAL EFFECT OF PROCESSES

The objective of the concept is first and foremost the formulation of problematic issues from the standpoint of the technical and future development of the area. It is the model through which problems and hazards are communicated from one side, while from the other side it provides solutions for control of risks and use of the area in the future in such a way that the environmental impact would be acceptable, proceeding from the established standards and standpoints of the public opinion. Furthermore, it should guide the developer of the area while finding optimal solutions (risk–price–result) and lead to long-term sustainable decisions.

In reality it means for the developer or investor a decrease of responsibility, environmental impact and pollution charges and creation of favourable conditions for bringing potential investments into the area.

If the objective is environmentally sustainable development of a whole area in a longer perspective, the starting point should be engineering-geological and environmental geotechnical conditions of the whole territory and the influencing factors.

SAMPLE TABLE OF CRITERIA AND RATES

Taking account of the specificity of the area, the concept of engineering-geological model of the Sillamäe industrial area is proceeding from the waste depository, related environmental impacts and problems. In all projects planned in the future, account shall be taken of the factors proceeding from the WD and having a negative effect on it. The concept of the engineering-geological model and mutual effects are shown in Fig. 2. Every impact is followed by a reaction or process whose final result is the effect on human beings and the environment.

In Fig. 2, the arrows show the effects that should be the basis for risk assessment:

1. Effects proceeding from the target object and accompanying risks.

2. Risks for the object, caused by interaction of the target object and the developed area.

3. Risks for the area caused by interaction of the target object and the developed area.

4. Risks for the target object and change of environmental geotechnical conditions of this object in time, caused by environmental geotechnical conditions.

5. Risks for the developed area, caused by overall engineering-geological and environmental conditions.

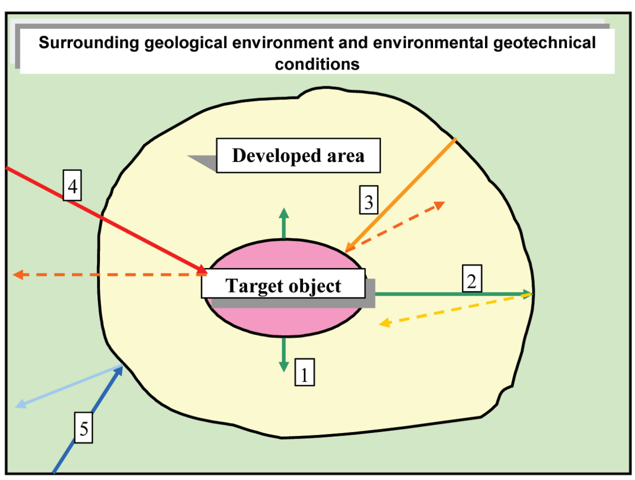
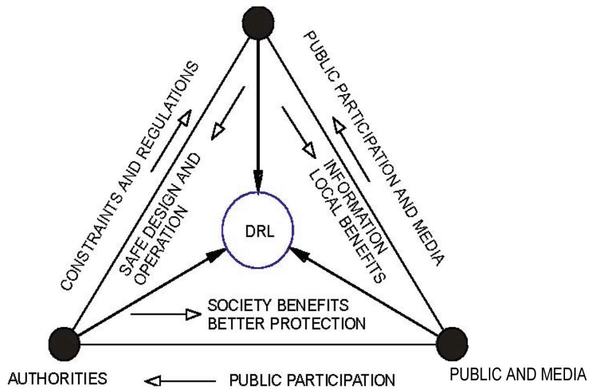


Fig. 2. Concept of the environmental geotechnical model
2 pav. Aplinkos geotechninio modelio koncepcija



DRL - DOWNSTREAM RISK LEVEL ACCEPTED AND SHARED BY THE THREE ACTORS

Fig. 3. Dam risk sharing among dam owners, public and authorities
3 pav. Užtvankos rizikos priklausomybė nuo jos savininko, visuomenės ir valdžios

On the example of the Sillamäe waste depository in North East Estonia, a shared risk responsibility (Fig. 3) can be developed between dam owners, safety authorities and the public due to a better consideration and as an open analysis and characterization of the dam benefits and risks as well as a mitigation or control action to protect the area according to an accepted societal risk level (e. g., the integrated and shared risk management can be a positive way to consider the problem of balancing these competing needs).

Fig. 3.

Assessment of interaction of various risks enables analysis of the so-called cumulative effect. This is the total risk formed by a simultaneous occurrence of various single effects.

CONCLUSIONS

The problem of human impacts on the surrounding environment in the context of further intensive use of areas has not been solved in the whole world. An essential part of the solution of the problem is an engineering-geological model based on risk analysis and assessment and forecast of mutual effects of the processes. The impact of developed areas on the surrounding environment always causes countereffects of the environment. If we can forecast and manage the processes, the environmental impact will remain within the limits of the criteria specified with the standards and will be acceptable for human health and environment.

Monitoring shall provide sufficient details about the existence of natural processes, the interaction of natural and man-made environments. This will enable in the future to assess the correctness of current forecasts and manage the processes towards control of risks.

The importance of communication should not be underestimated upon assessment of risks. It is a complicated theme where mutual understanding of different groups of interest – legislators, representatives of local power, the public and various specialists – is important.

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Olavi Tammemäe, Hardi Torn

PAVOJAUS ĮVERTINIMAS IR GEOTECHNINIS APLINKOS MODELIAVIMAS

Santrauka

Remiantis aplinkos sąlygų geotechniniu modeliavimu, nagrinėjant tiriamas teritorijas ir besivystančius regionus kaip vientisą sistemą, straipsnyje pateikiami pavojaus analizės pagrindai ir numatomos prevencinės priemonės jam išvengti. Pavojus lydi visą žmonių veiklą, tačiau finansiniu požiūriu ypač svarbu išvengti rizikos žemės ūkyje, transporte ir kitose ekonomikos srityse. Neatsižvelgus į galimą pavojų didėja už juos atsakingų asmenų atsakomybė, išauga draudimo išlaidos, kyla užterštumo ir katastrofinių pasekmių grėsmė.

Atliekant aplinkos geotechninį modeliavimą, minėti principai padeda įvertinti įvairių gamtinių ir technogeninių veiksnių sąveikos rezultatus, numatyti pagrindinius tikslus ir pasirinkti tinkamus svarbiausių problemų sprendimus. Dažnai nagrinėjamuose plotuose geoekologinės ir inžinerinės geologinės sąlygos yra sudėtingos, todėl lieka daug neišspręstų klausimų. Pagrindinė priežastis yra ne finansinių resursų trūkumas, bet geotechninių koncepcijų ir modelių, kurie įvertintų tiriamąjį rajoną kaip geomorfologinį vientisą objektą, nebuvimas. Kelių negatyvių veiksnių sąveikos įvertinimas leidžia prognozuoti bendrą kylantį pavojų.

Inžineriniai geologiniai stebėjimai ir priežiūra sukaupia būtiną informaciją apie esamus gamtinius procesus ir gamtinės bei technogeninės aplinkos sąveiką. Gauti rezultatai padeda įvertinti priimtų sprendimų efektyvumą ir esant būtinybei pakoreguoti mūsų veiksmus mažinant pavojaus galimybę.

Олави Таммемяе, Харди Торн

УПРАВЛЕНИЕ РИСКАМИ ПРИ ГЕОТЕХНИЧЕСКОМ МОДЕЛИРОВАНИИ ОКРУЖАЮЩЕЙ СРЕДЫ

Резюме

Рассматриваются основы анализа, оценки и управления рисками при создании геотехнических моделей окружающей среды, которые позволяют исследовать территории или развивающиеся регионы как одну целостную систему. Риски сопровождают деятельность человека во всех отраслях, и управление рисками в настоящее время широко используется в финансовых, сельскохозяйственных, транспортных и других отраслях экономики.

Пренебрежение рисками сопровождается повышением ответственности управляющего территориями, повышенными страховыми взносами, непредвиденной нагрузкой загрязнения и, часто, разрушениями в результате непредсказуемых чрезвычайных происшествий. Чтобы управлять рисками, их, как и любые другие процессы, в первую очередь следует идентифицировать, сформулировать, оценить, затем – разработать меры решения, направленные на понижение опасности. Целью управления рисками является их контроль. Процесс управления рисками в целом включает в себя анализ риска, его оценку и непосредственно управление:

1. Анализ риска покажет, в чем состоит риск;

2. Оценка риска должна показать, является ли данный риск акцептируемым;

3. В ходе управления риском разрабатываются действия и мероприятия по его понижению до акцептируемого уровня.

Принципами управления рискам можно пользоваться при геотехническом моделировании окружающей среды, поскольку методика позволяет оценить результаты взаимодействия различных природных и техногенных процессов, определить приоритетные цели и в первую очередь начинать разработку решений для самых важных проблем. Часто геоэкологические и инженерно-геологические условия в пределах разрабатываемых территорий сложны и многие вопросы не решены. Главной причиной при этом является не отсутствие финансовых ресурсов, а отсутствие геотехнической концепции и модели, которая позволила бы рассматривать исследуемый район как единое геоморфологическое целое. Оценка взаимодействия рисков позволяет анализировать кумулятивный риск, т. е. риск происшествия, которое может произойти при совпадении нескольких негативных факторов.

Инженерно-геологические наблюдения и мониторинг дают необходимую информацию о существующих природных процессах, о взаимодействии природной и техногенной среды. Результаты мониторинга позволяют оценить эффективность принятых решений, при необходимости корректировать действия и контролировать риски.

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THE IMPACT OF INFILTRATION DAM ON THE GROUNDWATER REGIME IN THE KURTNA LANDSCAPE RESERVE AREA

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The area of Kurtna Landscape Reserve is situated between oil shale mines. This area is an important part of the Estonia deposit, and the located mining conditions there are good. Narva surface mine pumps groundwater from the area of Kurtna Lakes. It is able to minimize the influence of surface mining. Testing of mining technology and hydrogeological modelling show that mine front may be closed for stopping water flow instead of leaving an open trench by the border of the area of the lakes. According to modeling, hydraulic conductivity of the dam must remain 0.1 m/d to avoid sinking of water level in the lakes, and filtration basins must be supplied with water in an amount of 7000 m^3/d as yearly average. As the result, the landscape will be reclaimed, overall look and shape will be smoothed. Abandoned fields of peat milling will be reclaimed, and their fires will be avoided.

Introduction

The influence of the power and mining industry on Kurtna Lakes located in the centre of the oil shale mining area in North-East Estonia has been a discussion object for the last fifteen years. Oil shale mines surround the area of Kurtna Lakes. There are 40 lakes in a 30-km^2 area above a 70-m deep buried valley [1]. Two mines – Estonia and Narva – exert the greatest influence on this. Both mines pump out water from the area and lead it back to the lakes or rivers in the same area. The question is how much the mining influences protected lakes and species. Besides Narva surface mine neighbouring the lakes has claimed the permission to pump groundwater from the lake area (see Fig. 1). Surface mining was stopped at a distance of 2 km from the protected area since the problem had not been solved, thus the mining company asked independent research groups to perform corresponding analyses and to test the mining technology used in this area.

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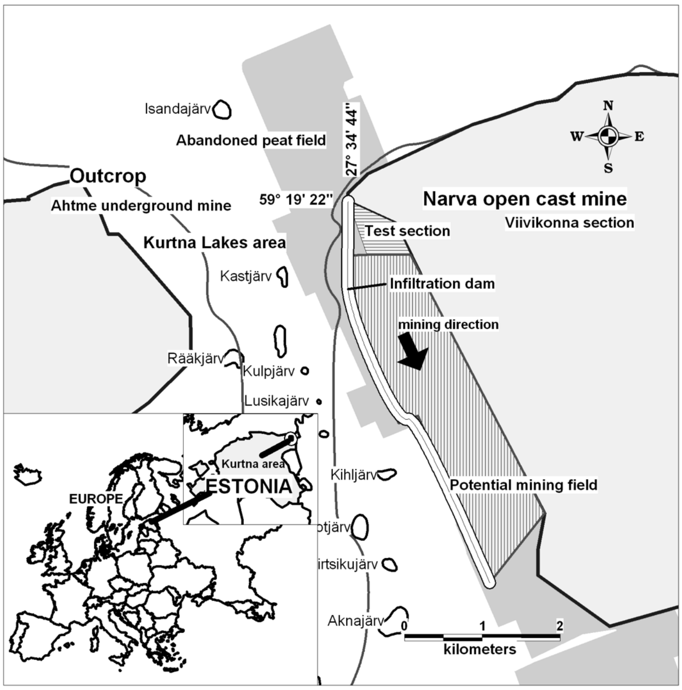


Fig. 1. Location of the Kurtna Landscape Reserve, mining section and infiltration dam

There are two main reasons for mining oil shale in the area. The first reason is oil shale resource. Local reserves represent an important part of the Estonia Oil Shale Deposit [2]. Energy rating of oil shale is one of the best among the potential mining areas reaching 44 GJ/m^2, and depth is relatively low (10 to 15 m) compared to 22 m in the rest part of the surface mining area [3, 4]. This resource is of great economical importance because when mined, total costs of mining will remain stable. On the other hand, pressure on mining oil shale in unsuitable areas will become actual in the future [5]. From these aspects, the application for mining permit is reasoned.

Since Estonian main oil shale-fired power plant has been renovated, and new boilers require oil shale of a more stable quality than the former ones, the need for oil shale mining remains actual for at least 25 years, which corresponds to the resource in current minefields [6]. New power units operate applying a new, fluidised-bed technology that guarantees less impact on the environment. Total resources of oil shale in the Estonia deposit guarantee operating of power plants for 60 years [2, 5].

Due to low oil shale quality in the most part of the deposit and additional environmental restrictions, the quantity of mineable oil shale is not as great as it seems. Compared to 50% total loss of oil shale resource in the case of underground room-and-pillar mining, the loss in open cast mines reaches 30% [7]. The losses are due to differences in official and actual resources and oil shale remaining in supporting, protective and barrier pillars. As for the usage of resources, surface mines are more valuable [8]. The main problems concerning mining fields are related to mining conditions and environmental restrictions. Surface mining is reaching depth limit, while underground mining is confronted by low quality of oil shale, bad roof conditions and environmental restrictions [4, 9]. For these reasons continuation of mining in the section neighbouring the area of Kurtna Landscape Reserve is advisable. Mining in the test section should be performed under continuous monitoring for calibrating dynamic modelling with groundwater software.

Influence of oil shale mining on the area of Kurtna Landscape Reserve

The influence of mining on the lakes has been investigated from the hydrogeological aspect, recommending the usage of infiltration basins and regulation of water flow [10–14]. Water chemistry has been investigated proceeding from the effect of oil shale mining on sulphate content of water [15]. The influence on the landscape and plants has been studied by analysing plant species and mining waste [16–19]. The set of water wells and lakes in the water monitoring program has been set to analyse changes in ecological situation. Unfortunately, it has not given a clear answer to the question about the influence of mining on the groundwater flow in the area. The reason for that has probably been complexity of situations and lack of an interested party who would evaluate all the aspects concerning this region.

The closest lakes (Kastjärv, Aknajärv, Jaala, Kihljärv, Nootjärv, Valgejärv and Virtsiku) are located in a distance 1.5 to 3 km from the front of Narva surface mine. Data of observation wells show that the level has not been remarkably changed due to surface mining operation during the last five years. All these lakes are located in the area of boggy, glaciolacustrine and -fluvial deposits. Drawdown of groundwater has been formed due to an intensive consumption of groundwater at the water intake in the central part of the Vasavere buried valley. Quaternary aquifer is an unconfined water-bearing stratum. The values of porosity and permeability of Quaternary aquifer depend to a large extent upon the degree of sand cementation. Consequently, these values are generally expected to be much higher for the central part of the valley than for the slopes. A study of the samples shows that porosity values exceeding 33% are common for the central part, whereas those less than 20% are usual for the southern part of the valley. Similarly, intergranular permeabilities average 2500–2700 $m^3\,d^{-1}m^{-2}$ in the central part and drop to 10–50 $m^3\,d^{-1}m^{-2}$ at the border of the valley [20]. Seasonal factors, changing flow and various forms of recharge may all produce fluctuations in the water level of about 1 m.

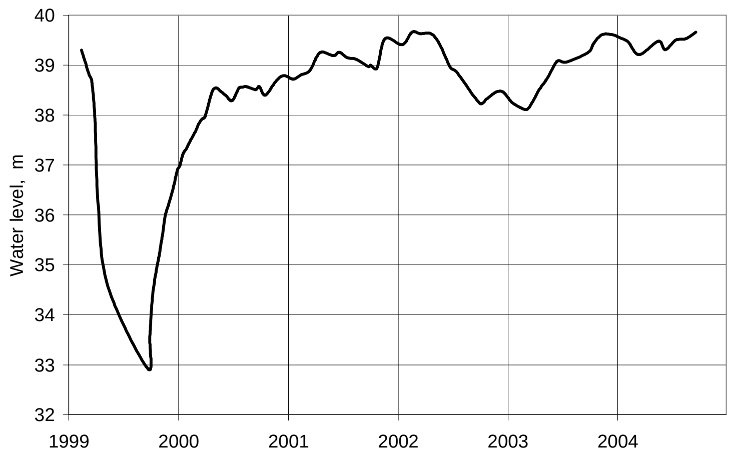


Fig. 2. Sinking of water level shows sand inflow to the trench and quick normalisation of the state after closing the flow. Water wells B 6-1 ja B 6-2 are located between Lake Kastjärv and the dam

Fig. 3. Technogenic valley formed after sand flow into the trench in March 1999

Water table of L. Valgejärv lowered 2 m in 1984, caused by water usage for stopping peat fires. For the year 1996, water level was normalised again. Only one remarkable event happened in 1999 when sand basement of the peat field flew into mining trench (see Fig. 2, 3). This happened because the spoil was piled on ice, and when ice melted sand spoil became unstable. The water-table diagram shows that original water level was restored quickly after closing sand inflow.

Mining technology

The influence of Narva surface mine at the east side of the lakes' area could be minimised. First, the mine front can be closed for stopping water flow instead of leaving an open trench in the border the area of lakes. Second, the overburden material that is used for closing the trench can be piled in such a way that it has lower permeability than soil in the nature. Besides, a part of that area is covered with abandoned fields of peat milling. Thickness of the residual peat layer reaches up to 3 m being a good material for decreasing permeability of the final dam material. For testing these assumptions, a test section was planned and designed by Mining Department of Tallinn University of Technology in 1997. The purpose was to test whether the filtration dam will decrease the sinking of water level in the area. Test mining in this section started in 1998. The idea originated from dam-piling experiences in the same mine where a dam has been piled with careful dumping and mixing of overburden material (see Fig. 4). This resulted in accumulation of water behind the dam, a water body now called Lake Vesiloo named after the designer of the dam. Water level in the upper lake has remained stable for 45 years, which proves permeability of piled overburden material consisting of limestone, clayey sand and peat.

For evaluating the influence of mining on a larger area, a modflow-groundwater model was set up by independent company AS Maves in co-operation with Mining Department of Tallinn University of Technology [19]. The model is supported by continuous monitoring of water wells and mine-dewatering data.

For closing the existing open trench, placement of mine front and stripping technology were changed. The direction of mine front had to be changed by 45 or 90 degrees (see Fig. 5). This could enable building of an infiltration barrier between the lakes and the mine at the end of the trench where only a 30-m-wide pit would be temporarily opened for water infiltration.

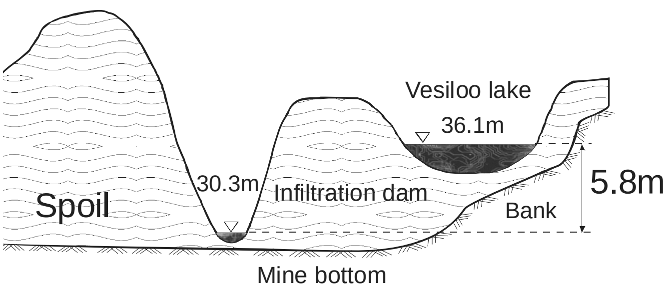


Fig. 4. Cross-section of infiltration dam in the mined-out area of Viivikonna section. Water level in Lake Vesiloo has remained 6 m higher from water level in lower lake for 45 years

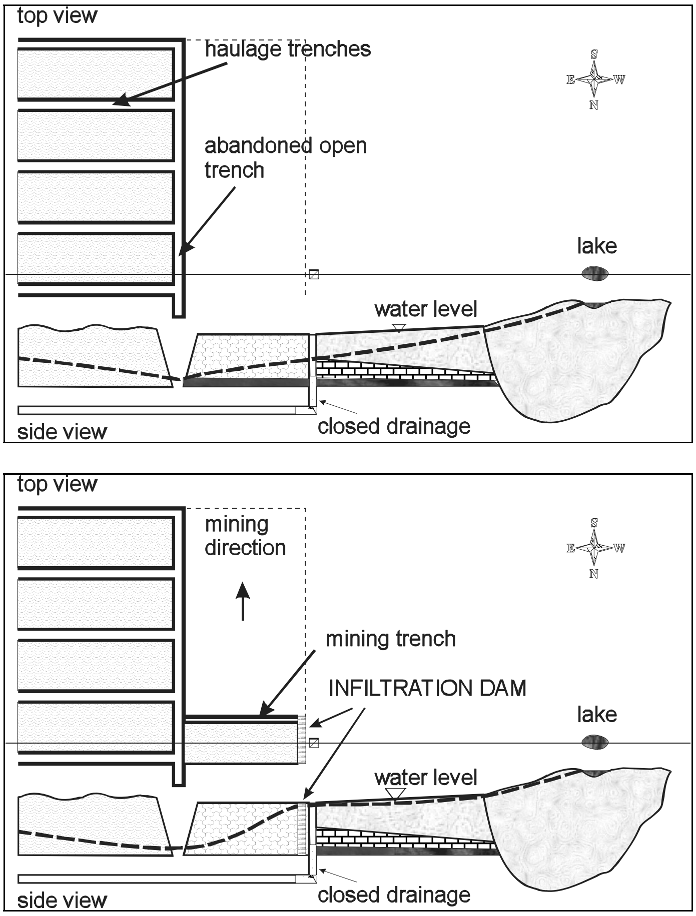


Fig. 5. Layout of water inflow to the mine applying old technology (above), new technology (below)

Dragline ES-10/70 is used for piling the dam. Ordinary selective piling of the overburden will be finished at 50 m from the border. Beginning from this point, the material will be disposed homogeneously. Different materials are dumped on top of each other. This should guarantee low permeability of the dam. Important is that the material be dumped from the maximum height of dumping position of the dragline and onto different locations. The width of the dam should be at least 25 m, and the high wall should be covered with a mixture of clayey material and peat. Stripping productivity in the section will be decreased by several factors. Dragline's cycle time increases because of hauling of the bucket to the maximum height of the dump, repositioning of the boom in every cycle, and careful monitoring of homogenisation of the spoil.

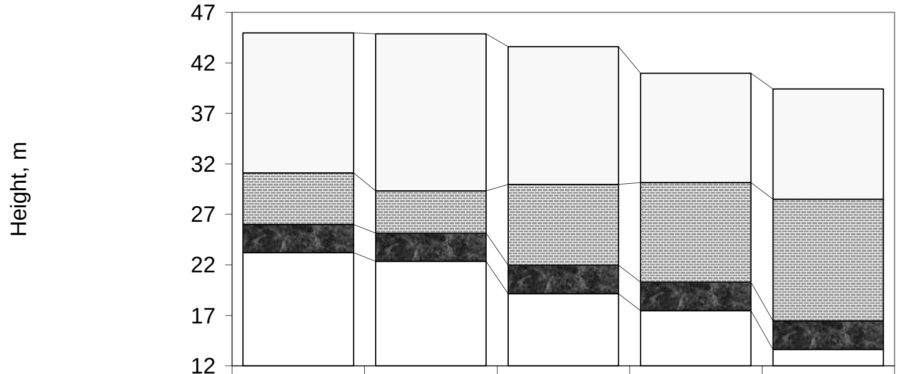
Besides, technology of seam extraction in the dam area is affected by many factors. Oil shale interlayer C/D has to be hauled away from the location of the dam because of its high swelling value (up to 200%). Hydraulic conductivity of this loose material could reach 1000 m/d. Alternatively, the seam has to be extracted non-selectively, leaving a 30-cm limestone layer in the output material. The overall productivity will decrease because the trench is short – 700 m, the optimum length being 1.5 km [21]. This concerns organising stripping, haulage and dam operations in a short section. Optimum length of the section was achieved by positioning the trench at 45 degrees instead of planned 90° in relation to the original North-South direction. (see Fig. 5)

The groundwater model was made on several assumptions. Groundwater discharge from the mine should be within certain limits to keep the decrease in the water level of the lakes below the agreed limits. According to the model, hydraulic conductivity of the dam material should not exceed 0.1 m/d. Besides, infiltration basins which are located between the mine front and the lakes should be fed with water in an amount of 7000 m^3/d for complementing soil water of the surroundings and keeping water level in the area stable.

Dam material consists of silty fine-grained sand whose modulus of hydraulic conductivity k = 0.1–0.8 m/d depending on density and compaction index of the material, and the content of clay particles. Provided that the test section was piled according to the design, the modulus of hydraulic conductivity of the material in this section could be in limits k = 0.1–0.2 m/d. In addition, the overburden contains moraine (k = 0.01–0.05 m/d), fine-grained sand (k = 0.5–2 m/d) and loose broken limestone (k = 100 m/d). Spoil material dumped conventionally is characterised by k = 0.5–50 m/d. It is assumed, basing on the experience gained from the test section, that fine material will fill spaces in coarse material decreasing permeability of the bank dam. The given solution will not work with drains that could form in the case of piling C/D layer, or with open dewatering tunnels under oil shale bed. The influence of mining on water level and quality of lake water near the test section is unnoticeable that proves the suitability of the technology. However, the conditions will become more complicated in southern direction (see Fig. 6).

There are peat, sand and moraine layers in the cross section of the Quaternary sediments and Ordovician limestone in hard overburden, causing high permeability of the spoil. An increase in the thickness of limestone seam in southern direction causes most of the dumping problems in dam building. Additional amounts of sand have to be scraped from aside, probably rehandling the overburden, and, in addition, compactors should be used for achieving proper modules of hydraulic conductivity.

Dam piling was modelled applying the geometric model that is used for determining the ultimate pit depth for draglines [9]. The model yields figures about suitability of draglines, need for rehandling and additional scraping, and also differences in the final height of the ground (see Figures 7 and 8). The test section has shown that it is difficult both organisationally and technologically to establish all these parameters. For evaluating the effectiveness of the dam in the southern part, several tests on density, compression and permeability of the spoil material have to be performed and compared with data obtained using the hydrogeological model.



	1-North	2	3	4	5- South
Soft overburden	13.9	15.5	13.6	10.8	10.9
Hard overburden	5.1	4.2	8.0	9.9	12.1
Oil shale seam	2.8	2.8	2.8	2.8	2.8
Bottom layer	23.2	22.3	19.2	17.5	13.6

Fig. 6. Thickness of limestone overburden increases in southern direction causing dumping difficulties for draglines and higher hydraulic conductivity of overburden material

Fig. 7. Pit at the end of the trench before 1997. Limestone pile on the bottom of the trench forms under spoil drainage channels

If the technology of dumped spoil fails, the compactors on the spoil and a geomembran barrier on the bank wall made using contour blasting, or a clay barrier must be applied.

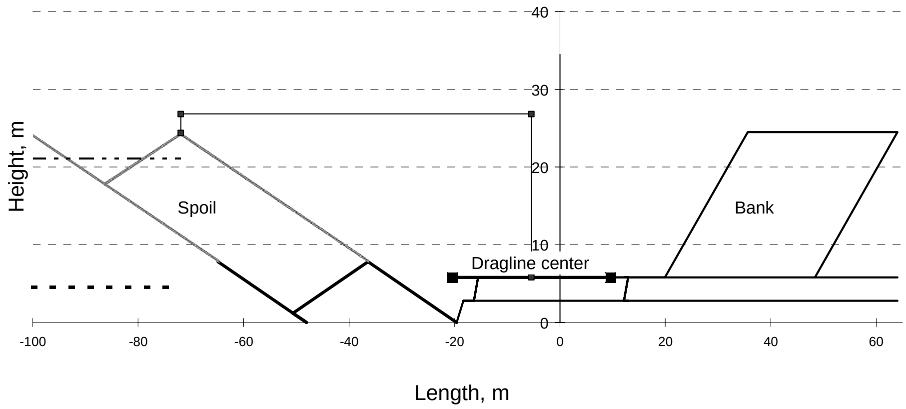


Fig. 8. Pit layout and modelling of surface height using geometrical model

Different materials and constructions are widely used to reduce hydraulic permeability at exploitation of mines, quarries and waste depositories. Depending on purposes, the barriers, dams, sheet piles or cut-off walls of different permeability could be constructed. In Estonia, hydraulic barriers are designed and constructed around Sillamäe Radioactive Waste Depository (bentonite slurry cut-off wall) and Tallinn old municipal landfill (vinyl sheet-pile wall). Watertight clay barriers are widely used in construction of new landfills.

Vertical slurry cut-off walls

Slurry cut-off walls are vertical walls constructed by excavating a trench and simultaneously filling the trench with a bentonite slurry. The bentonite slurry forms a thin (typically ≤3 mm) filter cake of low hydraulic conductivity (<10-8 cm/s) on both sides of the trench. The filter cake minimises slurry loss from the trench, stabilises native soil on the side walls of the trench, and provides a plane for slurry stabilisation in the excavated trench. The bentonite slurry contains typically 4% to 7% (w/w) sodium bentonite mixed with water.

Three main types of slurry walls, used to locate polluted groundwater, are soil-bentonite (SB) walls, cement-bentonite (CB) walls, and composite slurry walls (CSW). Soil-bentonite slurry walls are constructed by displacing bentonite slurry in the excavated trench by backfilling with a mixture of bentonite slurry and excavated trench spoils. Cement-bentonite (CB) walls are constructed by using a mixture of cement and bentonite slurry to maintain the stability of the excavated trench; i.e. no backfill materials are required. Therefore, CB walls are typically constructed in the case when suitable backfill materials are not available. Composite slurry walls (CSW) are constructed simply by inserting a geomembrane into the slurry in the trench.

Alternative passive barriers

Aside from slurry cut-off walls, other passive vertical barriers include walls constructed using deep soil mixing or jet grouting using chemical grouts (e.g., silicates, resins, and polymers), grout curtains, and sheet-pile walls. Although these technologies are used extensively in more traditional geotechnical engineering applications, such as dams and construction excavations, none of these technologies have been used extensively as passive containment barriers for remediation of contaminated land.

A comparison of the construction costs for the vertical barriers shows that the costs associated with used material of alternative barriers is typically greater and the construction rates lower than for the more traditional SB and CB slurry walls.

Biobarriers

The concept of using bacteria to form biofilm barriers, or biobarriers, in otherwise highly permeable media (e.g., sands) through plugging or fouling the massif to reduce the migration of contaminant plumes has recently gained attention. Reductions in hydraulic conductivity from one to three orders of magnitude have been reported for a variety of porous media using many types of bacteria and different treatment methods, including stimulation of indigenous bacteria (biostimulation) and injection of full-size living and dead bacteria as well as ultramicrobacteria (bioaugmentation). A significant additional research must be performed before biobarriers can be used routinely for practical application.

Conclusions

In the test section of the Estonia deposit near Kurtna Lakes the influence of mining on the water level in lakes is low. The technology of dam construction has been proved. However, geological and geotechnical conditions will be more complicated southwards. According to modelling, hydraulic conductivity of the dam must remain 0.1 m/d to avoid sinking of water level in the lakes, and filtration basins must be supplied with water in an amount of 7000 m^3/d as yearly average. After oil shale mining east of the area of Kurtna Lakes the area will be recovered as

- landscape will be reclaimed, overall look and shape will be smoothed
- abandoned fields of peat milling will be reclaimed and their fires avoided.

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Stability of the dam of Sillamäe nuclear waste depository

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ABSTRACT: The article gives a survey about environmental investigations, carried out in the territory of Sillamäe nuclear waste territory, geotechnical situation, problems and also recommendations for solving the problems.

1. INTRODUCTION

The waste depository is situated in North-Virumaa, in the western part of the town Sillamäe on the coast of the Gulf of Finland. The sea border is 30..50 metres from the dam. Here and there the consolidations have been built on the water border, protecting the coastal terrace against wave erosion. Part of the coast is unprotected and is subject to intense denudation process.

The building of the depository was started in 1950-s. At first it was planned to surround the depository with 12 metres high dam. For the time being the height of the dam is 25 metres. Under the influence of geodynamical processes there is a real danger that the dam of the waste depository will lose its stability. In case of landslide nuclear waste falls into the sea. For solutions of the problem Estonian, Norwegian, Swedish and Finnish specialists have been involved in the investigations. For the time being the initial data have been collected and analysed, some additional urgently needed investigations have been made. The assessment of the situation has been given and recommendations for further work have been compiled.

2 REVIEW OF THE WORKS MADE IN THE TERRITORY OF THE WASTE DEPOSITORY

The materials of 12 works, made in 1965...1992, are in the archives. Mainly they have been geodetical measurements, geological and hydrogeological investigations. During this period no special geotechnical investigations have been made. In the last five years the waste depository of Sillamäe has practically continuously been investigated in the framework of different projects. Nine reports have been published. All the information available about the geological structure of the area and the exploitation of the waste depository has been gathered together. With a view to specify the data additional geotechnical investigations have been made, on the basis of which the geotechnical model of the area has been drawn up and the assessment to the stability of the depository, environmental impacts and different project solutions has also been given. The network of geotechnical surveillance has also been established, on the basis of its data geodynamical processes can be analysed and the effectiveness of projected countermeasures can also be evaluated.

3. GEOLOGICAL STRUCTURE AND HYDROGEOLOGICAL CONDITIONS

3.1. Relief

The depository of radioactive waste lies on the pre-limestone marine plain, on the first sea terrace where the absolute heights of the ground fluctuate from 2.2 to 5.5 m. The measures of the depository are 500x1000 m; its surface is at the absolute height of 24.5...25.7 m. In south-west and West the depository is surrounded by Silurian plateau that is surrounded by the limestone shore terrace in the West and North. The surface of the plateau is even, with a small inclination to south-east. It is jointed by single 2..3 m high and 100...300 m long walls, also there are some single Karst forms. The absolute heights on the surface of the limestone shore terrace are 40...42m.

3.2.Geological structure

As natural grounds marine sediments (mIV), glacial sediments (gIII) and Low Cambrian clays (Cm_1) are presented in the waste depository section.
Marine sediments (mIV) occur in the first marine terrace, being also the natural ground of the dam. They consist mainly of pebbles or gravel sand. The thickness of the layer amounts to 7.9 m.
Glacial sediments (gIII) occur in the eastern part of the depository and in the region of the Gulf Sillamäe as grey silts of plastic consistency. The containing of coarse detritus amounts to 25 %, the open thickness of the layer increases towards east up to 0...15 m.
The Low Cambrian clays (Cm_1) are presented in the whole territory by the blue clays of Lontova stratum, lying under Quaternarian sediments. The surface of blue clays has an inclination to the North (0.025...0.004) and lies at the absolute height of 0...6 m. The upper part of the blue clay is decomposed, the whole massif can be characterised by microcrackedness. The total thickness of Cambrian clays on the basis of universal geological data is more than 50 m.
The waste depository consists of three different soil groups : gravels-sands, ash and silts-clays. Due to the different origin and transport methods, the composition and properties are very much variable.
Gravels-sands are the main components of the dam's body. In the course of building the dam, sand was not compressed. Therefore it is loose or medium dense. According to the grain size distribution fine or silty sands dominate, here and there - silts. The layer of marine sand or gravel is a floor of a seam. Gravel and gravel sand are presented in the upper part of the dam. The thickness of layers depends on the dam's height and does not exceed 25 m.
Ash occurs in the dam's body as well as in the waste depository in thin layers of various properties. It is due to the different composition of the material flowing in pipes by hydrotransport. The regularity in stratiality is missing, there are layers of flowing consistency as well as cemented layers. The thickness of the layers and their continuity is also changeable, the maximum thickness does not exceed 10.7 m. Ash is sensitive to water and temperature: it becomes easily wet, but being dry it becomes decomposed, crumbles away and be aired.
Clays and silts (radioactive waste) fill the depository, representing a weak mass of flowing consistency. The containing of clay particles increases towards the depth. The total thickness of the layer is in limits of 10...20 m. The geological structure of the waste depository is illustrated in the figure 1.

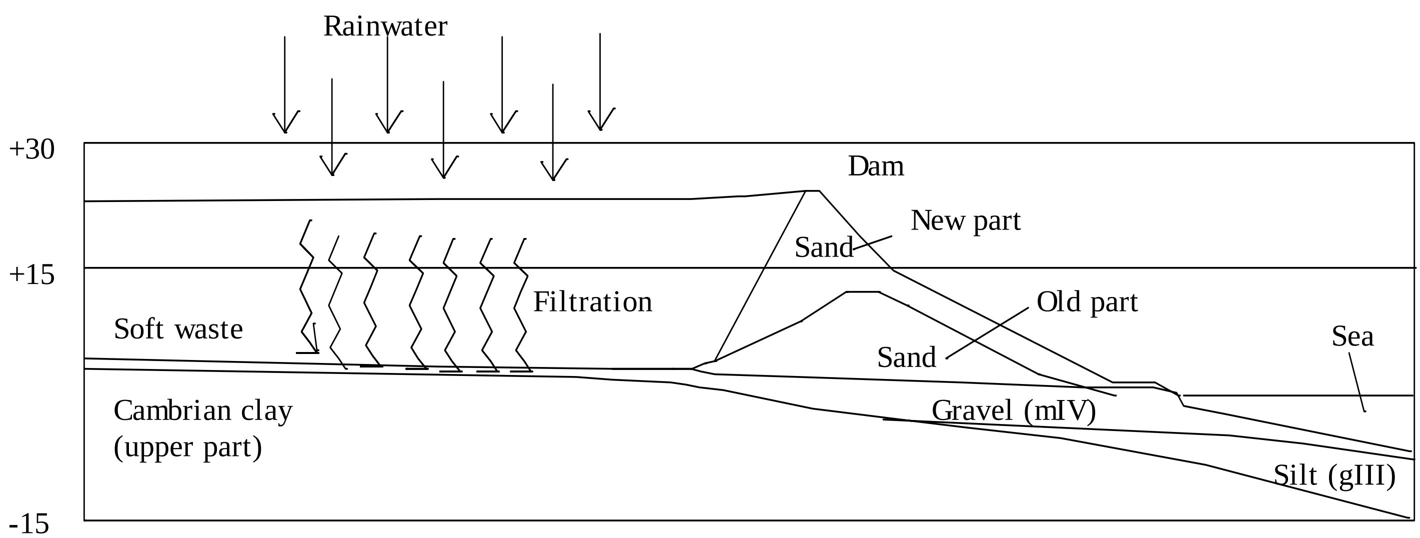

Figure 1. Geological section of the waste depository

4. HYDROGEOLOGICAL CONDITIONS

4.1. Natural water

In the investigated territory two hydraulically connected between themselves Quaternarian and Cambrian-Ordovician water strata can be distinguished. The water of the upper Quaternarian water stratum may conditionally be divided into soil water and technical water.

The horizon of the groundwater lies in the marine sand and in the pebble layer at the depth of 0.0...3.5 m from the ground. It has a free surface. The horizon feeds on the precipitation water, the technical water percolating through the dam and the water of Low Cambrian-Ordovician water stratum, the outflow is into the sea. The blue clays of Lontova layer are watertight. The horizon is in hydraulic connection with the lower Cambrian-Ordovician water stratum. The inclination of the water surface towards the sea is 0.04. The chemical composition of the water is determined by the containing of chemical components in the water. Earlier investigations shows that the water is polluted. It has a high level of mineralization. The mineralization is 10426...21208 mg/l, exceeding 20..40 times the natural mineralization of groundwater and 3...7 times the containing of minerals in the sea. The approximate amount of salts flowing into the sea per day is 16...34 tons.

The Cambrian-Ordovician water stratum lies on the limestone shore area and in the region of limestone plateau, to the South and West from the waste depository. The water stratum has a free surface, feeds on the precipitation water and is hydraulically connected with the horizon of the groundwater, but the mineralization is considerably smaller than that of the Quaternarian water stratum. The outflow of water has the inclination towards the sea. From the waste depository to the South, on the limestone plateau area, the water is used as drinking and household water.

4.2. Technical water

The area of distribution of technical water is restricted to the dam of the waste depository, through which the water is mixed with the groundwater. The chemical composition of the technical water is complicated and depends on the chemical composition of waste. The hydrogeological situation in the territory of the waste depository has been formed in the last years. The waste depository is partly covered with precipitation water seeping through waste and the dam’s body into the sea. The precipitation water (600 mm per year) and the water segregating as a result of the compression of weak soils filtrate through the waste massif. They move into the layers of marine sand and gravel of high permeability (k=0,01 m/s) under the waste depository. On the basis of approximate calculations the amount of sewage water transported into the sea is 152,500 m^3 per year. The main part of the amount is formed by the percolation of precipitation water through the waste depository (150,000 m^3), the amount of the water received in the course of consolidation process of soils is only 2,500 m^3 per year, forming 1.6 % of the water amount filtrating through the wastes. The water movement is illustrated on the geological section, figure 1.

As to the dam’s stability - such hydrogeological regime is the optimum for it. Due to the natural layers of high permeability, lying under the dam, the fall of the depression will be before the dam’s body, excluding the influence of hydrodynamical forces on its stability.

5. GEOTECTONICAL CONDITIONS

The territory of Sillamäe lies on the area where the surface of the earth slowly rises. It involves the activation of shore and erosion processes. As a result of these processes the shear stresses develop in the dam of the waste depository and the relative importance of the counterbalance block will be reduced.

6. GEOTECHNICAL CONDITIONS

6.1. Soil properties

In waste depository investigations *in situ* CPT, DPT, plate load tests and pressiometrics have been used. Also the soil samples for laboratory investigations, for experiments in Estonian as well as Norwegian Institute of Geotechnics have been taken. Soil properties are collected in the table 1.

The investigations showed that Low-Cambrian clays (Cm_1) lying under the dam of the waste depository differ from classical clays lying on the shore of North Estonia by lithological composition as well as mechanical properties. The soil is clayer, there are no strong thin sandstone layers characteristic to Cambrian massif. As the territory under investigations lies on the slope of the old, filled with the Quaternary sediments, primeval valley, the clay massif has strongly been under the influence of

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earlier occurred geological processes (decomposition, glacier etc.).

Table 1. Calculation parameters of soils

Soil	Geol. index	γ_n kN/m^3	ϕ °	c kPa	E_0 MPa	k m/s
Waste depository and dam						
Sand	tIV	21.0	32	0	30	0.003
Grav. sand	tIV	21.0	34	0	30	0.003
Ash	tIV	20.0	0	100	25	3E10^{-5}
Silty sand	tIV	19.0	0	5	0,5	3E10^{-7}
Silt	tIV	18.0	0	15	10	3E10^{-7}
Natural soils						
Sand	mIV	20.5	33	0	20	0.005
Gravel	mIV	21.5	38	0	35	0.01
Silty sand	gIII	21.5	0	50	10	-
Weathered clay	Cm_1	20.0	0	80	10	-
Clay	Cm_1	20.5	0	90	15	-

The water content of the upper part of the blue clays with thickness of up to 15 m is considerably high, up to 29 %. The one-axial pressure strength of the soil is 70...230 kPa, that is 4...5 times smaller than usually. The water content of the clay decreases towards depth (W_n=15...20 %) and the pressure strength increases up to 100...250 kPa. The dependence graph between one-axial pressure strength and natural moisture content is given in the figure 2, dependence between natural water content and shear strength is in figure 3. Usually the water content of blue clays of equal depth is 12...15 % and one-axial pressure strength increases up to 500...1000 kPa. On the investigated area - on the basis of penetration tests and drilling results - the strong Cambrian clay begins only at the depth of 20...25 m from its surface (usually in the same conditions at the depth of 2...6 m).

6.2. Geodynamical situation

The analysis of investigations and factors having impact on the stability of the waste depository's dam shows that three closely involved processes have impact on the formed geodynamical situation: hydrodynamical processes, slope and shore processes. Less attention deserved tecnogenic influences and geotectonical processes may also be mentioned, but it does not mean that that they will not be taken into account in the future.

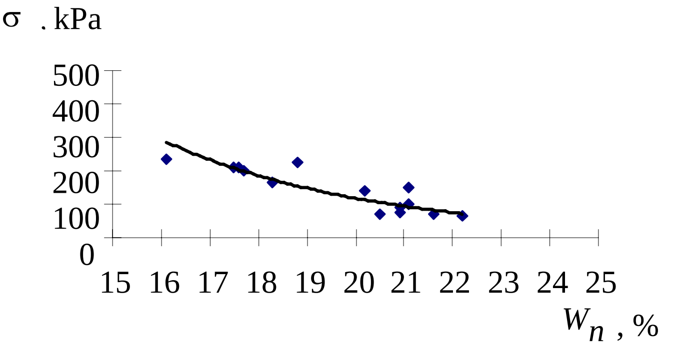

Fig. 2. Dependence between natural water content and one-axial pressure strength of Cambrian clay's.

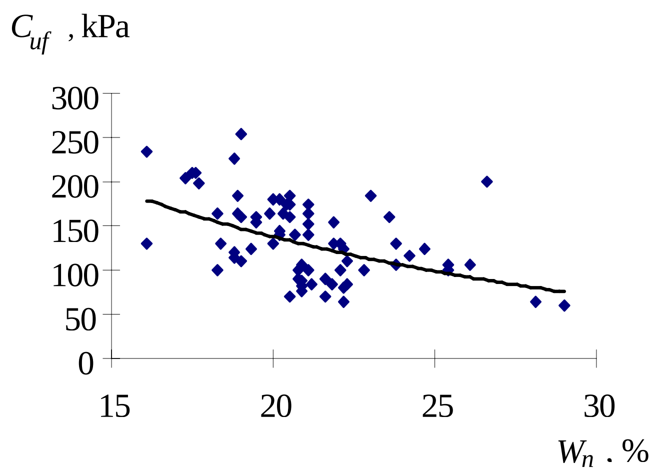

Fig. 3. Dependence between natural water content and shear strength of Cambrian clay's.

6.2.1. Slope processes

The stability of the dam was evaluated (in case of weak clays and ash layers and Cambrian clays) by minimum strength parameters that are in accordance with world practice. The basis of calculations of sands was the average of shear strength tests of lithological composition as well as mechanical properties, also corresponding to the results received at CPT tests.

In the course of work the stability factor was found on failure surfaces of more than 400 different forms. Hydrodynamic forces were not taken into account. They have practically no influence on the dam's stability now. If the failure surface passes through the dam's body, the stability factor is F=1.6...3.6.

Slide danger along the weak, soaked and strongly decomposed surface is generally small due to small inclination of clay's surface. The stability factor is F=1.3...1.6.

Stability calculations in the deeper layers of blue clay show that the factor of safety is *F*=1.05...1.3. It is less than it is required by the standards (*F*>1.5) and does not guarantee a stable slope.

6.2.2. Shore processes

The data of observations show that whole part of the shore is subject to very active sea effect. The natural condition of abrasion shores becomes worse from year to year. The abrasion is especially intense in front of the northern part of the waste depository's dam. The eastern shore of the waste depository is considerably well protected against destruction's at present by the belt of rocks

In connection with high activity of cyclonic activities and its probable further growth the active development of shores will go on also in the next decades, showing itself mainly in the expansion of abrasion areas and in the intensification of abrasion processes. It will impair essentially the power of resistance of the whole waste depository and the base of the bulwark (gravel terrace), seriously endangering the stability of the waste depository's dam.

6.2.3. Hydrodynamical situation

A rather stable hydrodynamical situation has been formed on the area of the waste depository. The depository works practically as an inverse filter. Permeability of nuclear waste and ash layers are small, remaining within the limits of *k*=0.01...0.1 m per day. Permeability of the material of the dam surrounding the waste is *k*=10 m per day, permeability of the natural gravel layer under the dam is *k*=40 m per day. The described hydrodynamical scheme guarantees practically the movement of vertical water in the waste and the outflow of the water into the sea through the gravel layer lying below. Hydrodynamical power to the dam's body is minimal.

7. GEOTECHNICAL MONITORING

7.1. Monitoring of shore processes

In calculating the stability of the dam and blue clay massif, the sea, sediments of the sea bottom and also the coastal sediments are the so-called counterbalance. They remain in failure surface footing area and improve the stress situation of the slope, expressed in the growth of the factor of safety in case of bigger counterbalance. Thus the intense shore erosion is very dangerous, because it makes counterbalance smaller. The described process may cause the landslide long before the waves could break the dam.

The monitoring of the shore in 1994 as well as in 1995 showed that erosion had become more speedy and the mass of gravel in the counterbalance body had considerably been reduced. Within the bounds of the town Sillamäe and in its closest vicinity there are no investigations and observations on shore processes.

7.2. Measurements of deformations in the dam of the waste depository

For measuring deformations in the dam of the waste depository and for evaluating its intensity, the network of benchmarks was founded in the summer of 1994.

The results show that on the seaside edge of the waste depository there are considerable deformations:

1. The speed of vertical deformations of the benchmarks above the depository, in its northern, eastern and north - western part grows relevantly 10-15...15-30 mm per year, the speeds of horizontal deformations has grown 3-12...20-30 mm per year. The summary values of deformations remain within the limits of 30...33 mm.
2. There are horizontal placements also at the benchmarks in front of the depository, having no vertical deformations. The size of these placements has also increased to a great extent, amounting to 25...54 mm.

The character of benchmarks movement allows to differentiate two kinds of slope processes. There is a deep creep of large measures involving the blue clay massif under the depository in the northern as well as in the eastern part of the depository. There are also local creeps inside the earth body of the dam of the depository and the movement of benchmarks under the slope connected with them.

7.3. Monitoring of pore pressure

In co-operation with Norwegian Geotechnical Institute in 1996 the piezometres were placed on the territory of the waste depository. The results of measurements are illustrated in the figure 9. The benchmarks as well as the changes of void pressure inform us of unstable situation in the layers under the dam. In deeper layers (in Cambrian clay) the pressure falls with a speed up to 5 kPa in a month, referring to the deformation of a failure surface. In upper soil layers (the upper part of Cambrian clay, moraine) there are no essential changes or there is unfixed tendency of it.

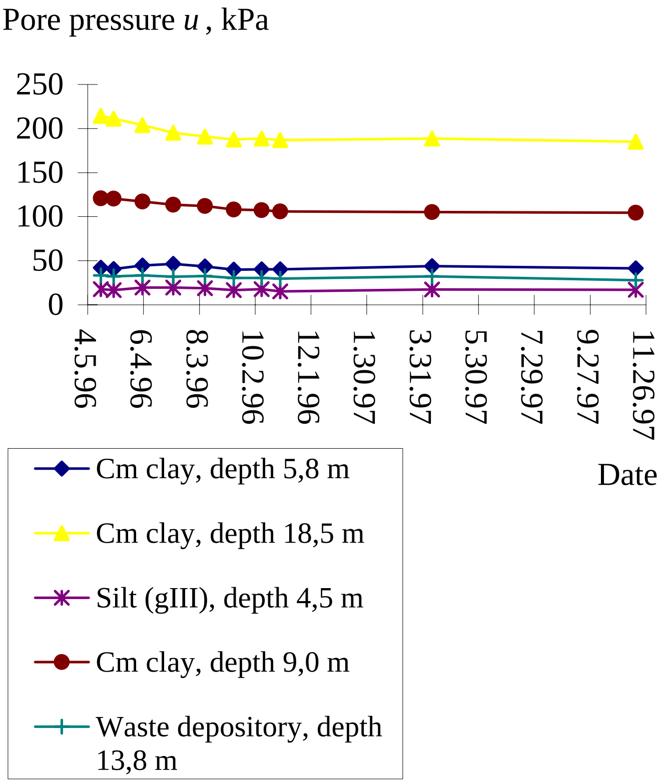

Figure 4. Results of monitoring of pore pressure

7.4. Environmental monitoring

Environmental monitoring gives information of the pollution of air, water and soil. As we have to deal with nuclear materials, the level of nuclear radiation should also be checked.

There is no monitoring of air pollution in Sillamäe, though it is known that in summer the waste depository dries, its surface becomes decomposed and it dusts. If the wind is strong, the fine fraction of the depository's soil will pollute the neighbourhood. As there is no data, the air pollution could not be evaluated.

Practically there is no hydrodynamic monitoring of soil and sea water level, the amount of flow and changes in chemical compounds. Only the department of environmental protection of the plant Silmet checks regularly the chemical composition of water percolating through the dam and measures the level of soil water in the pebble layer under the dam. This data has not been analysed.

Soil pollution and the influence of polluting materials on the soil, first of all on the strength of Cambrian clay, have not been investigated. On the basis of the existing data it cannot possibly be evaluated, because the problem needs special investigations.

Radiometric investigations made earlier showed that the intensity of gamma radiation on the ground fluctuates within the limits of 110...1700 μRh, here and there exceeds 3000μRh. The average radiation is 450 μRh. Gamma radiation at the foot of the dam is 100...200 μRh. Natural background is 14...20 μRh.

8. PROJECTS AIMED AT RAISING STABILITY OF WASTE DEPOSITORY

8.1. Factors having impact on deformations and drafting of measures guaranteeing stability

The analysis of geodynamic processes shows that the stability of the waste depository depends:

1. By the erosion due to shore processes and the reduction of counterbalance proceeding from it, owing to which the balance in the soil changes.
2. On the reduction of Cambrian clay's strength in time, lying under the dam, caused by the creep and the water percolating through the bottom of the dam into clay.
3. Hydrodynamic regime which change enlarges or reduces the hydrodynamic power having impact on deformations. Due to natural gravel layer the hydrodynamic power is minimum now as the depression curve does not permeate the dam's body.

Considering geodynamical processes it is necessary to enlarge counterbalance so that the formed hydrodynamic regime should be guaranteed and the shore erosion would be braked. In the future the problem of soil and water pollution should be solved.

8.2. Projects of countermeasures

Considering the geotechnical conditions of the area and economical possibilities, the decision has been made in favour of the filling method. The project has been made on the liquidation of the possible average situation (landslide). For raising the dam's stability, two principled solutions have been made.

In accordance with the first project the area between the dam and the sea will be filled evenly with the filling material. For banking the wave erosion the coastal defences will be founded on the water border.

In accordance with the second project the contra banquettes will be made from particular filling soil, locating perpendicularly towards the dam. Along the seashore on the area of landslide curves coming out the peripheral dam joining prisms will be built and at the same time it will also be the coastal defences. Between the contra banquettes and the two dams, the existing dam of the waste depository and the fundable peripheral dam will be blanks (honeycombs) that may be used for burying solid waste. It must be mentioned that the problem concerning the storing of dangerous waste has not been solved in Estonia. The area would be naturally protected, because blue clays exclude the pollution of the soil under them and the groundwater horizon. Sea pollution could be prevented by using special modern technologies and materials. At present the solution for environmentally safe storing place construction is under elaboration.

9. SUMMARY

1. Investigations show that the condition of the dam of the waste depository is unstable.
2. For observing the deformation process and preventing the landslide the surveillance system has been established. The existing monitoring system should be improved with inclinators.
3. The monitoring data confirm the occurrence of deformations and changes of stress condition in the soil.
4. The strength of blue clays and the impact of solutions filtrating from the depository on the geotechnical properties of the clay have not been ascertained.
5. Hydrodynamical situation has no influence on the dam’s stability, because the water flows freely into the sea. Without changing the formed stress condition, it is difficult to block the movement of water at the foot of the dam. For reducing the sea pollution, it is expedient to cover the waste depository with a watertight layer and to lead the precipitation water aside. On the basis of calculations in this case the pollution background falls to 1.6 % from the existing one.
6. The observation of coastal processes should be continued and the existing observation network should be improved.
7. For the evaluation of environmental danger, surveillance system should be established.
8. For the case of average the measures have been worked out for the liquidation of environmental damages.
9. For slope consolidation a project of level filling and contrabanquettes has been drawn up.
10. The project on level filling is technologically simpler, but the amounts of filling material are big.
11. The project on contrabanquettes is more complicated in technology, but it needs less filling material. At the same time it enables to found a storing place for dangerous waste to the place naturally the most suitable.

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Strength of Paleozoic clays

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ABSTRACT: The article deals with the last investigation results of the Paleozoic clays and the problems concurrent with them.

Estonian Paleozoic clays are represented in Estonia by Cambrian, Ordovician and Devonian deposits. The thickness of these deposits is very different; the thickness of Cambrian clays is 50...80 m, of Ordovician clays - 1...2 m and the total thickness of Devonian clays may come to some twenty or thirty metres, but it consists of layers of sand and sandstone with thickness of one to two metres. The Paleozoic clays belong to the overconsolidated varieties. They have become denser during a long period of time and certainly the glaciers have influenced the reaching of the present overlarge density. The natural density of these clays (e- void ratio - 0.25...0.4) is considerably greater than the one that we may gain making these clays denser by the optimum moisture (W_{opt} = 18...20%, e = 0.5...0.6). According to their consistency the majority of them are hard soils and on digging and driving they seem to be the materials the bearing capacity of which is beyond suspicion. Nevertheless there have been problems one after another concerning those soils - in slopes and under foundations. Under the foundations they have broken under pressure (the houses in Pavlovsk and Pushkino) that has been considerably smaller than their bearing capacity - on the ground of SNiP-2.02.01-83 (formula 7) and GOST 12 248-78 consolidated drained shear test.

The weathering processes have influenced the properties of them. These processes have influenced the properties of Palozoic clays to the depth of a couple of metres and have given rise to the net of microcracks that is decisive from the point of view of forming their activities. The formation of microcracks - weathering- has been evoked by the movement of glaciers above them or the rocks covering them. The changes of temperature and water content accompanied with it and the earth respiration and changes of temperature later. The annual temperature changes reach the depth of 10...15 m here and there.

Depending on the geomorphology the following varieties among the Paleozoic clays according to their weathering degree may be differentiated:

1. Clays that are deeper than 20...25 m. They are practically very strong varieties and the microcracks occur in them only in case of geological disorders. Their strength is rather accurately estimated by the drained test and usually their compressibility is evaluated in the laboratory much greater than it is in reality. The building of the underground in St. Peterburg and the foundation of tunnels in Tallinn have corroborated the last assertion. The water content of these clays is W_n = 8...12%.

2. The microcracked clays that are cropping out in the horizontal parts of the relief or are covered with a packet of Quaternary sediments with thickness of a few metres. The greater water content of them W_n = 14...18% is connected with the development of microcracks in them and due to the microcracks the strength of them is considerably smaller than that of the previous variety. Their strength has been influenced by the centuries - long changes of temperature and moisture regime and the shear deformations accompanied with the movement of a glacier (the majority of them had presumably elastic character initially). The surface of these clays (in case they crop out) has even more weathered in

the depth of 2...3 m and its water content is W_n = 18...20%. It is connected with annual temperature influences.

3. The microcracked clays that crop up on slopes and in changes of pre-glacial relief. Among them there are the clay massifs displaced in the course of old landslides. It is a cracked material which water content is 22...24% and its strength is considerably smaller than the previous ones have. These varieties have been influenced by the shear deformations with plastic character accompanied with the movement of glaciers and the rotational deformations accompanied with them later. Certainly they have also been influenced by the development of slope deformations, especially in the sea.

4. The fourth variety of clays occurs only in Cambrian clays on the sea shore - on the area that is incendated during the period of storms. Due to the salty water the Cambrian clays swell up with greater intensity, their microcracks widen and the water content increases W_n=28...30%. The strength of these clays regardless of their hard consistency does not differ from the strength of weak soils. The Devonian clays having been in the open hollow for a long time, also belong to these clays. These clays have strongly been weathered by cold and water and lost their bearing capacity.

At the first investigation stages of Paleozoic clays noone tried to find the general dependences between the soil strength and its physical properties. It was believed that together with the increase of the water content W_n the accompanying growth of the crack net is more undetermined than the growth of the water content in the weak soil without any cracks [1]. The increase of the water content W_n was considered to be only the indicator referring to the greater amount of cracks, but not fixing the influence of these cracks on the strength of the clayey soil. This cracking should be considered the only true in case if only the upper part of the cutting is investigated - the part that has most of all been the subject to the different weathering processes and which influence in different geomorphological and degenetic conditions has sporadically been rather different one.

To some extent this condition was favoured by a clear recommendation dominating in the former USSR to use a consolidated drained shear. Using the last - mentioned, the precompactness of the sample was accompanied with the diminishing of defects, the "improvement" of cracks and finally the growth of strength and at last, the levelling of strength properties of different clays [1].

Applying to use field tests showed the incompetence of such an approach. In the table 1 the results of plate load tests (10 tests with plates - 5000 cm^2) and laboratory investigations on the area of the former collective farm Kirov.

If to calculate the bearing capacity R and N using the formulas 7 and 3 of SNIP 2.02.02.83 by the undrained test - the results will be $R=q_y$ and $N=q_f$, but using drained parameters we shall get - in the first case - R=1000 kPa and N=3500 kPa, in the second case - R=450 kPa and N=1500 kPa, while fixing R the most suitable will be the use of C_{uy} $R=q_y=6\ C_{uy}+P_0$.

In general - C_{uy} characterizes the soil strength much better, because it does not depend on the test methodics and is constant for the overconsolidated clay.

C_{uf} depends on the speed of the test and its evaluation requires to consider the methodical shades.

The investigation of landslides [2] however showed that the indices of shear strength in overconsolidated clays gained by reciprocal calculations are equal precisely to C_{uy}.

4. Therefore the evaluation of the last index has become the basic one and it is recommended to use in the overconsolidated clays strength calculations.

The investigations made with different overconsolidated clays showed relatively good

Table 1.

W_n	W_L	W_p	q_y kPa	q_f kPa	φ' °	C' kPa	C_{uy} kPa	C_{uf} kPa	Number of tests
14	38	27	400	800	30	100	60	100	4
22	40	30	240	500	29	60	40	80	6

W_n - water content,
W_L - liquid limit,
W_p - plasticity limit,
q_y - proportionality limit at the plate test,
q_f - failure load,
φ' and C' - parametres of drained shear strength,
C_{uy} - proportionality limit at an undrained test,
C_{uf} - maximum shear strength at the undrained test.

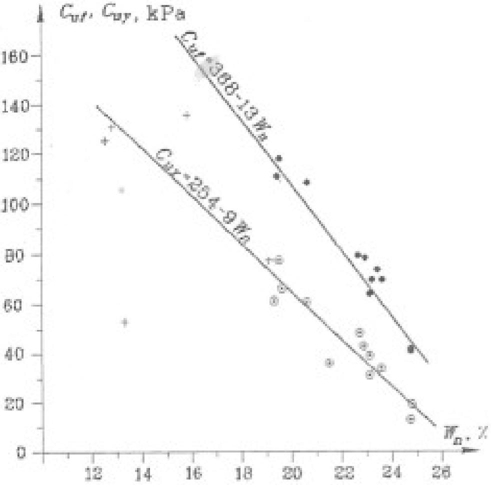

Figure 1. $C_{uy} = f(W_n)$, $C_{uf} = f(W_n)$, Karksi.

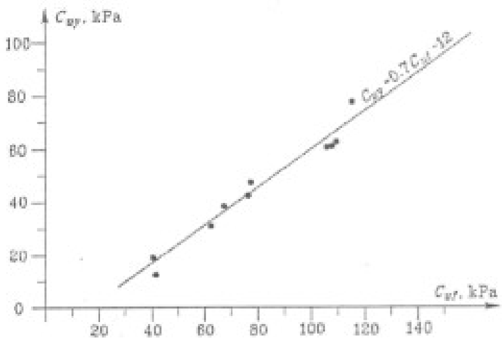

Figure 2. $C_{uy} = f(C_{uf})$.

dependences on single objects. For example, investigating the church of Karksi a very good correlation between C_{uy} and C_{uf} (maximum shear stregth) and the water content W_n (see fig.1) was noticed. At the same time a relatively good correlation between C_{uf} and C_{uy} ($C_{uy} \approx 0.7C_{uf}$ - 10 that is close to the classic dependence π/5.14). In general, the gained dependence harmonized with the investigation results of many other objects and it enabled to evaluate also the worsening of Devonian clays properties in the course of swelling and weathering.

The construction pit of the Tartu Private Bank was held open by archaeologists in connection with their investigations for two years and during that time the water content of the soil W_n increased 7 from 18 c/o to 27c/o and maximum shear strength

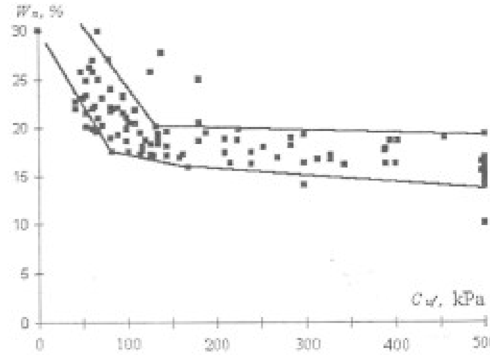

Figure 3. $C_{uf} = f(W_n)$, Aseri quarry.

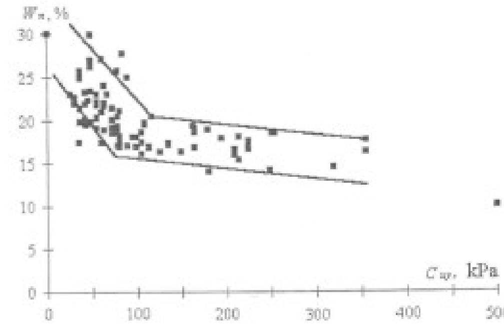

Figure 4. $C_{uy} = f(W_n)$, Aseri quarry.

decreased 1 from 25 kPa to 40 kPa and practically the soil with normal bearing capacity changed to weak soil. At the same time the remarkable fact has been the depth of swelling and weathering, reaching nearly 1 m.

The use of Cambrian clays as building materials raised the problem about old quarry slopes. The stability of these quarry slopes was evaluated by the central institutes of the Ministry of Building Materials of the USSR, basing on the drained consolidated test. The use of the stability factor - 2...3. Here and there it led to a very careless attitude and thus to the quarries (here and there 15 m from the shore) buildings, summer cottages and waste depositories had been founded. All that made GIB Ltd. to pay serious attention to that problem and the first investigations have already given interesting results.

The tests made in the quarry of Aseri are shown in the figures 3 and 4 - the dependence of the creep threshold C_{uy} fixed by the undrained test and the maximum shear strength C_{uf} on the water content W_n. As one can see two entirely different areas can

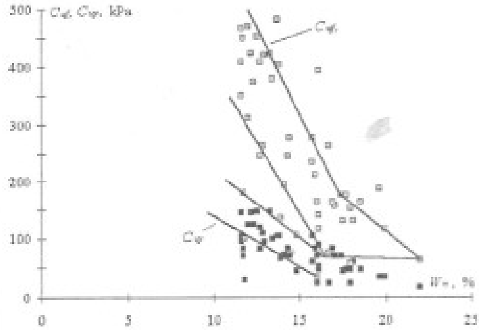

Figure 5. $C_{uy} = f(W_n)$, $C_{uf} = f(W_n)$, Kopli quarry.

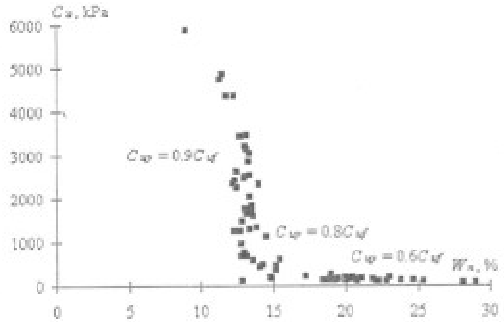

Figure 6. $C_{uf} = f(W_n)$.

be differentiated. The first one is characterized by the rapid decrease of the shear strength together with the growth of the water content (the beginning between 17...22%) and the other one - the non-dependence of shear strength on the water content. By the transition of zones, with the water content of 18...20%, the difference in shear strength may be tenfold. In the first zone the water content is the indicator of strength and fixes the soil strength together with crackedness. But the crackedness of the massif is decisive in the second zone that may not correlate with the water content.

The investigation of the Kopli quarry (see fig.5) gave the analogous result. Here the dependence of the creep threshold (C_{uy}) and maximum shear strength upon the water content can be seen in the figure. Here one can also see the two entirely different zones. The water content is over and beyond 16...17%, whereas in case of both zones the shear strength depends on the water content (W_n).

To evaluate anisotropy, a part of tests was made by the pressure increase along sample axis and the other part with pressure the increase of across sample axis. The tests showed no differences in strength.

Subsequently all the investigation points that were gained in the course of investigating different objects were carried over to the same graph, while the greater part of points are characterized by blue clay in deep oil - depositories of Viimsi. The graph in figure 6 shows a good correlation between C_{uf} and W_n, while by the same water content the difference in strength may be tenfold. The faulting point at the water content 16...18% is also noticeable here. There are not many investigation points of Devonian and Ordovician clays, but their investigation results concur relatively well with the arisen cloud of test results.

The most complicated problem is the following: how to fix the calculation parameters for making geotechnical calculations and which must be the factor of safety by that. The reciprocal calculations of the landslides taken place and the creep deformations have justified the use of minimum creep threshold (with probability 0.95). The deformations occurring in case of one waste depository (stable creep along the soil of blue clay) make us to have a more serious attitude to it. But to use at that the factor of safety 1.3, 1.5 or 1.8 is an economic problem - for the engineers to answer. Here one must also take into account the disturbing influencing, accompanying the sandstone layers in the clay massif that are sporadically working as armatures.

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Kambriumi savide omadustest

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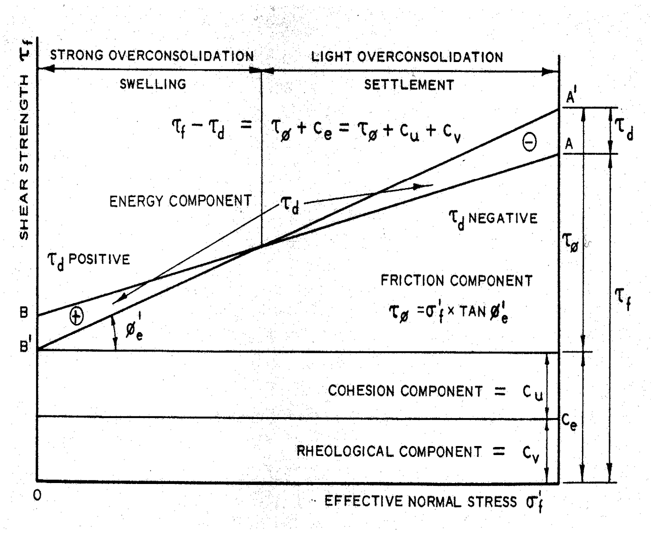
1. SAVIDE NIHKETUGEVUS

Savipinnaste tugevuse hindamiseks on põhiliselt kasutatud dreenimata stabilomeeterteime, üheteljelisi surveteime ning dreenitud nihketeime. Stabilomeeterteimide ja üheteljeliste surveteimide käigus määratakse dreenimata maksimaalne nihketugevus Cu_f ja roomeläve nihketugevus Cu_y. Nihketeimid võimaldavad määrata proovikeha nihketugevuse τ_f, mille kaudu leitakse maksimaalne sisehõõrdenurk ϕ' ja nidusus c'. Pinnase jääknihketugevuse τ_r määramiseks kasutatakse proovikeha tsüklilist purustamist. Kogemuslikult piisab jääknihketugevuse hindamiseks viiest tsüklist.

Pinnase nihketugevuse uuringutel on erinevatel aegadel arvutustes kasutatud kõiki eelnimetatud nihketugevuse näitajaid - Cu_f, Cu_y, τ_f ja τ_r.
L.Šuklje [1] ja S.Vjalovi [2] järgijad on soovitanud kasutada roomeläve näitajaid. Tuginedes seisukohale, et kui nihkepinged on väiksemad kui roomelävi, siis nihkedeformatsioone ei teki ning ehitiste stabiilsus on tagatud.

1.1. Dreenitud nihketugevus

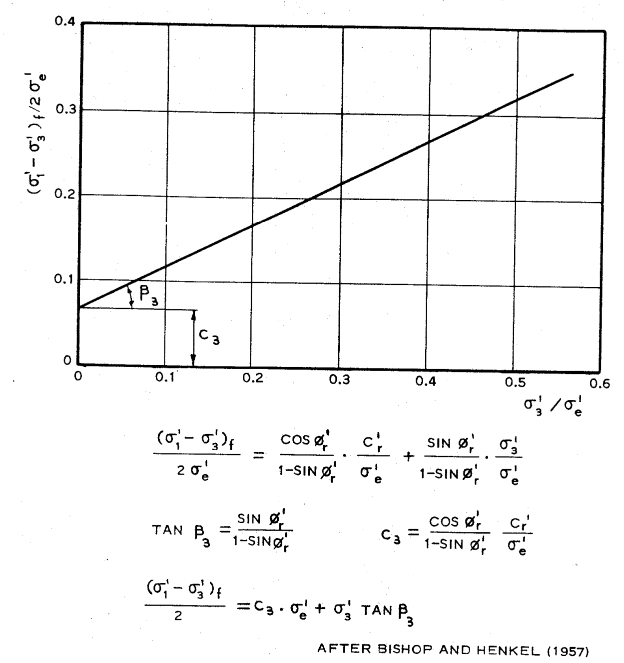
M.Hvorslev [3] , N.Maslov [4], A.W.Skempton [5] jt. on jaganud nihketugevuse erinevateks komponentideks, mis vastab Tiedemanni ja Hvorslevi poolt 1937.a. avaldatud põhimõtetele. Kokkuvõtlikult on veeküllastunud savipinnaste nihketugevuse füüsikalised komponendid avaldatud 1960.a. M.Hvorslevi poolt [3].
Põhimõtteliselt on kõik eelnimetatud autorid seisukohal, et nihketugevuse hindamisel jagatakse katse käigus määratud nihketugevus τ_f matemaatiliselt sisehõõrdeks ja nidususeks (joonis1).



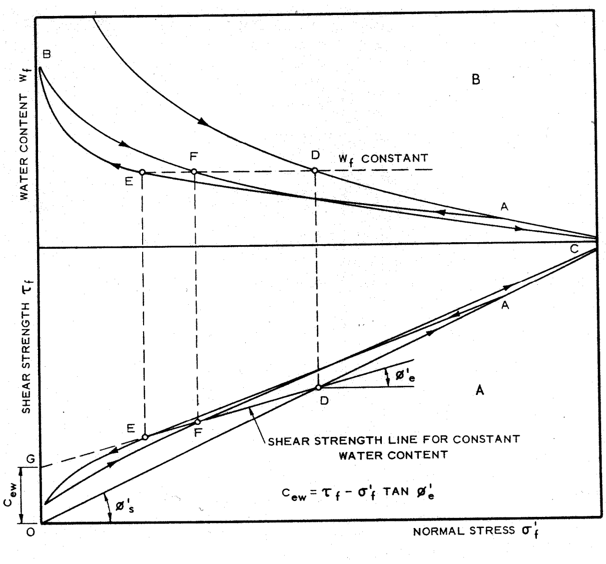
Joonis 1. Nihketugevuse komponendid konstantse poorsusteguri juures.

See jagamine tuleneb Coulombi seadusest ja sõltub pinnasest, teimimisel kasutatud seadmetest, tulemuste töötlemise metoodikast ning võib anda väga erinevaid tulemusi.
Maksimaalse nihketugevuse juures iseloomustab pinnast effektiivne sisehõõrdenurk ϕ_e, effektiivne nidusus c_e, mis jaguneb struktuurnidususe komponendiks c_u ja reoloogilise nidususe komponendiks c_v.

Sisuliselt samadele järeldustele jõudsid Bishop ja Henkel [6] stabilomeeterteimide tulemusi analüüsides (joonis 2 ja 3):

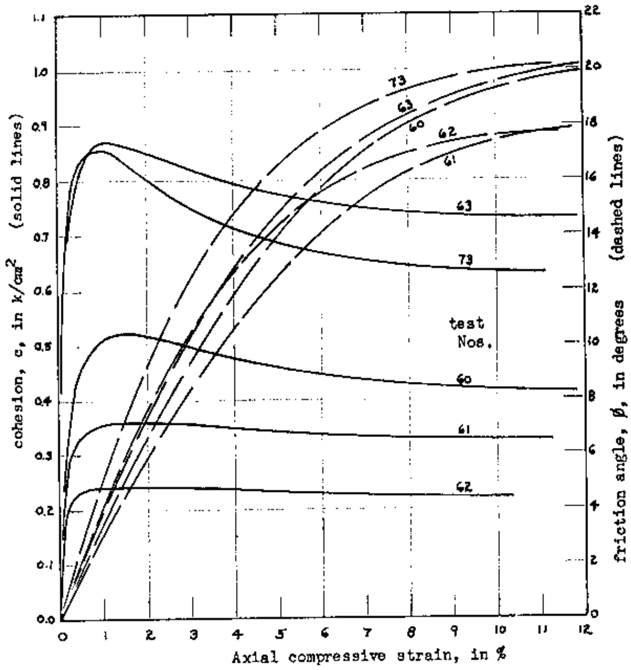


Joonis 2. Sisehõõrdenurga ja nidususe määramine kolmeteljeliste surveteimide tulemuste alusel.



Joonis 3. Sisehõõrdenurga ja nidususe componentide määramine.

H.Schmertmanni ja J.O.Osterbergi [7] poolt läbi viidud uuring näitab sisehõõrdenurga ja nidususe põhimõttelist mehhaanilise käitumise erinevust savipinnastes. Nihketugevuse nidususe komponent saavutab maksimumi suhteliselt väikeste pingete juures, sisehõõrdenurk vajab maksimumi rakendumiseks suuremat pinget (joonis 4). Nihketugevuse komponentide mehhaaniline sisu on selgelt erinev.



Joonis 4. Nidususe ja sisehõõrdenurga sõltuvus pingest, Bostoni (Cambridge) Sinisavi.

Pärast pinnase purustamist, jääknihketugevuse τ_r hindamise momendiks, on struktuurnidususe komponent c_u muutunud 0-ks. Effektiivne sisehõõrdenurk ϕ_e väheneb tänu mineraalide orientatsiooni muutumisele ja tekstuurilistele iseärasustele jääksisehõõrdenurgaks ϕ'_r ning on jäänud veel reoloogiline nidususe komponent c_v ehk jääknidusus c'_r mis sõltub füüsikalis-keemilistest protsessidest nihkepinnal, molekulaar-ja termodünaamilistest jõududest, savipinnase viskoossetest omadustes ning on väikeste deformatsioonide juures taastuva iseloomuga.

Praktikas kasutatakse normaal- ja ülekonsolideerunud savipinnaste püsivusarvutuste tegemisel dreenimata tingimustel ϕ'_r, c'_r=0 metoodikat või dreenitud tingimustel roomeläve C_{uy} parameetreid.

Samas annab jääknidususe c'_r ja jääksisehõõrdenurga ϕ'_r kasutamine Skemptoni [5] ja Maslovi [4] uuringute põhjal kõige parema tulemuse nõlvade püsivuse hindamisel. Skempton ja Hutchinson [5] uurisid erinevate maalihete arvutusparameetrite sobivust ning jõudsid järeldusele, et kasutatud ϕ'_r, c'_r=0 metoodika ei iseloomusta piisavalt täpselt tegelikkuses toimunud protsesse. Analüüs näitas, et jääknidususe lisamine minimaalse jääksisehõõrdenurga ϕ'_r juures annab nõlva püsivuse hindamisel täpseima ja reaalsetele protsessidele vastava tulemuse.

Seega on tähtis säilitada arvutustes laboris määratud jääknihketugevuse τ_r mõlemad komponendid ϕ'_r, c'_r.

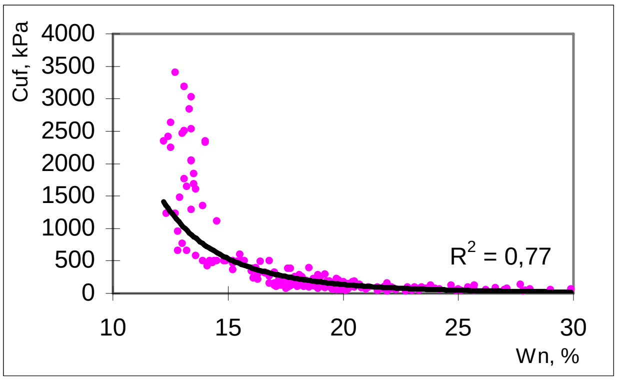
Kambriumi savides tehtud nihketeimide tulemused (95% tõenäosusega töötlusel) on toodud tabelis 1.

Tabel 1. Kambriumi savi dreenimata nihkeparameetrid

Murenenud Cm savi W_n=20…24%							
σ, kPa	50	100	150	ϕ'_f	c'_f, kPa	ϕ'_r	c_f, kPa
τ_f, kPa	75.7	93.6	124.3	26°	49		
τ_r, kPa	25.0	32.5	45.8			12°	10
Mikropraguline Cm savi W_n=17…20%							
σ, kPa	50	100	150	ϕ'_f	c'_f, kPa	ϕ'_r	c_f, kPa
τ_f, kPa	75.6	98.6	116.7	22°	56		
τ_r, kPa	25.7	39.6	54.5			16°	10

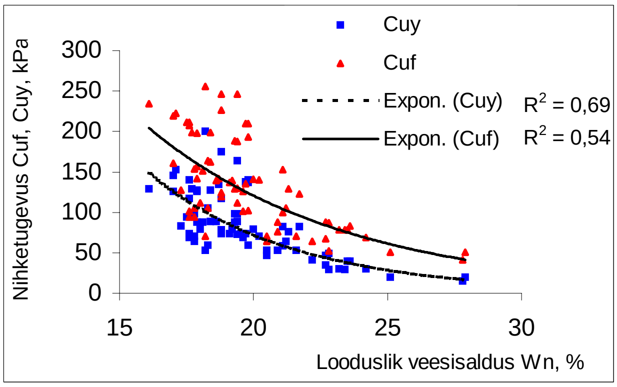
1.2. Dreenimata nihketugevus

Eestis levivad kambriumi savid on geotehniliste uuringute käigus jagatud neljaks kihiks, mida iseloomustab väga erinev tugevus, mis on põhiliselt tingitud savi ülemise osa murenemisest ja mikropragulisusest [8]. Uuringud näitavad ka head seost savi nihketugevuse ja loodusliku veesisalduse vahel ning viimast kasutatakse ühe mikropragulisuse hindamise kriteeriumina (joonis 5).

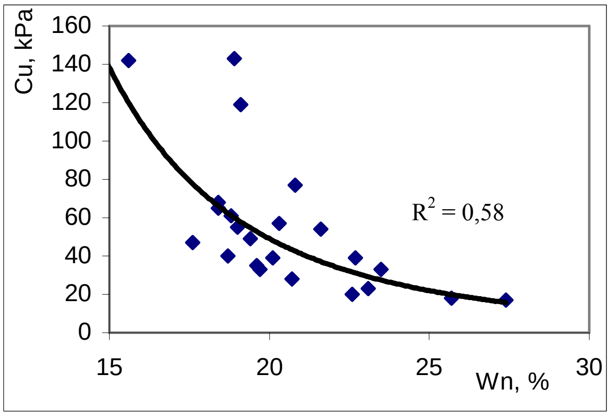


Joonis 5. Kambriumi savi dreenimata nihketugevuse sõltuvus looduslikust veesisaldusest.

Praktikas tuleb sagedamini kokku puutuda kambriumi savidega, mille veesisaldus muutub 15…27% piires. Siinkohal on oluline märkida, et normaalsete sõltuvuste ja usaldatavate arvutusparameetrite saamiseks ei piisa 5…6 proovikeha teimimisest. Üksikute proovikehade tugevus muutub küllaltki suurtes piirides ning sõltub proovi mõõtmetest (tavaliselt kasutatakse väikseid proove diameetriga 40 mm). Teimi tulemusi mõjutab oluliselt mikropragude hulk ja orentatsioon proovikehas (joonis 6). Kuus korda suurtemate proovide (S=78.5 cm^2) katsetamine stabilomeetris annab praktiliselt sama tulemuse, mis 1-teljeliste surveteimidega määratud roomelävi (joonis 7).



Joonis 6. Kambriumi savi murenenud osa maksimaalse ja roomeläve nihketugevuse sõltuvus looduslikust veesisaldusest, 1-teljeline surveteim ((proovikeha S=12.56 cm^2)

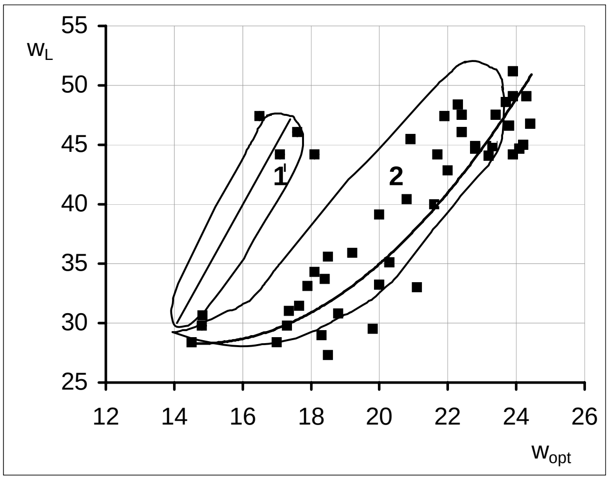


Joonis 7. Dreenimata nihketugevuse sõltuvus looduslikust veesisaldusest, stabilomeeterteim (proovikeha S=78.5 cm^2).

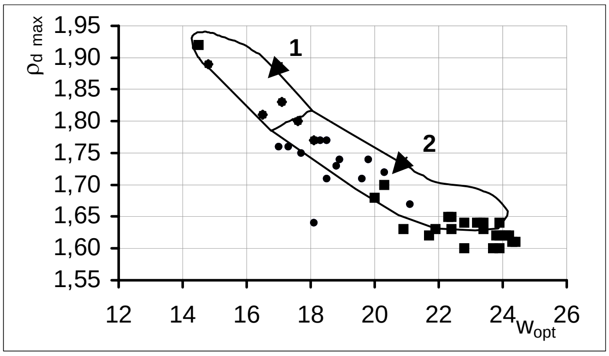
Seega tuleb kambriumi savide arvutusparameetrite valikul analüüsida nii teimimise metoodikat, proovikehade suurust ning tehtud teimide arvu. Väikeste proovikehade teimimise korral on soovitatav võtta arvutusparameetritena aluseks roomeläve nihkeparameetrid.

2. SAVIEKRAANID JA SAVI FILTRATSIOONIOMADUSED

Savide kasutamine ekraanidena on tän a muutunud väga aktuaalseks. Tänapäeva nõuded saviekraanidele on ranged ja tema veejuhtivus peab olema vähemalt 10^{-9} m/sek ning tihedusaste Proctori järgi on 0.95. Savide optimaalne veesisaldus ja maksimaalne tihedus sõltuvad tema voolavuspiirist ja kulutatud energiast. Joonisel 8 ja 9 on antud sõltuvused $W_{opt}=f(W_L)$ ja $W_{opt}=f(\rho_d)$ [10].

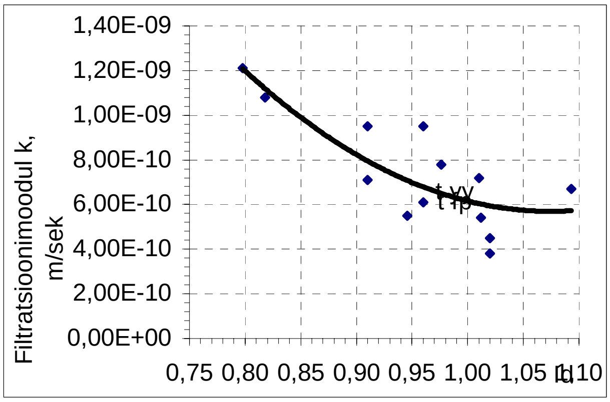


Joonis 8. Optimaalse veesisalduse ja voolavuspiiri vaheline sõltuvus.



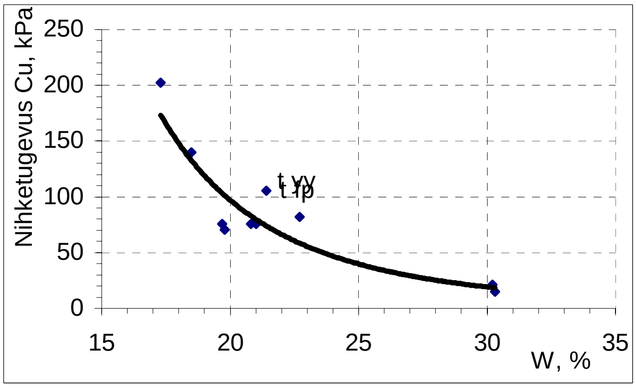
Joonis 9. Optimaalse veesisalduse ja maksimaalse tiheduse vaheline sõltuvus.

Joonistel väljatoodud ala 2 iseloomustab Proctori standardteimi ja ala 1 suurema energiakuluga moderniseeritud teimi.
Mõlemal teimil sõltub W_{opt} voolavuspiirist W_L ja väheneb voolavuspiiri vähenedes. W_{opt} vähenemisele kaasneb maksimaalse kuivmahu massi suurenemine ja pinnas tiheneb sama energia kulutuse puhul enam. Suurema energiakuluga on aga võimalik pinnast enam tihendada ja siis suureneb ρ_{dmax} ja väheneb W_{opt}.
Pinnase veejuhtivust ekraanis on hinnatud laboris kompressioonikatsete ja filtratsioonikatsete abil ning ehitusplatsil spetsiaalse filtratsioonikatsega (BAT) [10]. Laboris tehtud katsetulemused on esitatud joonisel 10.

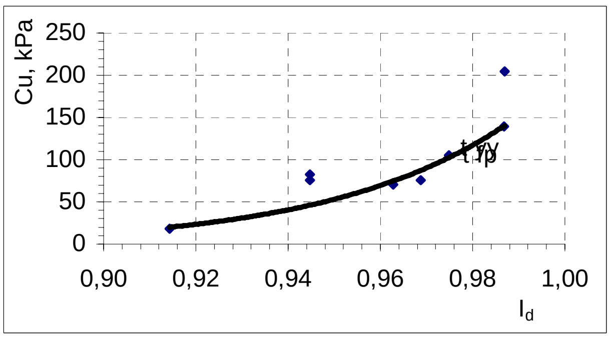


Joonis 10. Tihedusastme ja filtratsioonimooduli vaheline sõltuvus.

Kompressioonikatsed annavad mõnevõrra suuremad filtratsioonimooduli väärtused, kuid ka need vastavad normidele, kui tihedusaste on üle 0.85. Filtratsioonikatsetega saadud tulemused on ligi suurusjärk väiksemad. Kompressioonikatsed satuvad hästi kokku välimäärangutega (erinevused ±30 %).
Kokkuvõtteks võib öelda, et kambriumi savi sobib materjalina hästi ekraani rajamiseks ja tihedusastmel 0.90 garanteerib tema veepidavuse.
Saviekraani dreenimata nihketugevuse sõltuvused veesisaldusest ja tihedusastmest on toodud joonistel 11 ja 12.

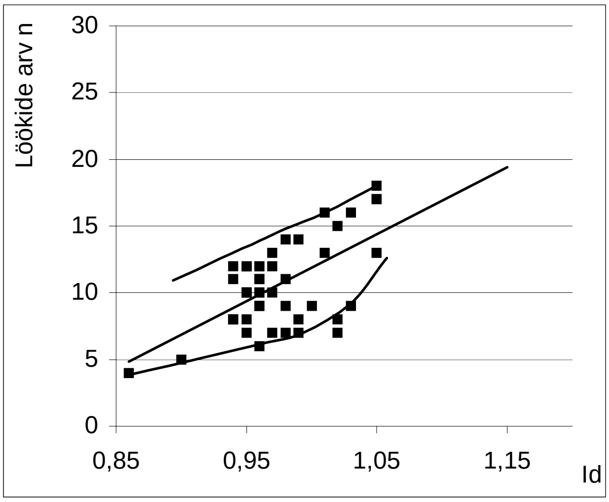


Joonis 11. Saviekraani dreenimata nihketugevuse sõltuvus veesisaldusest

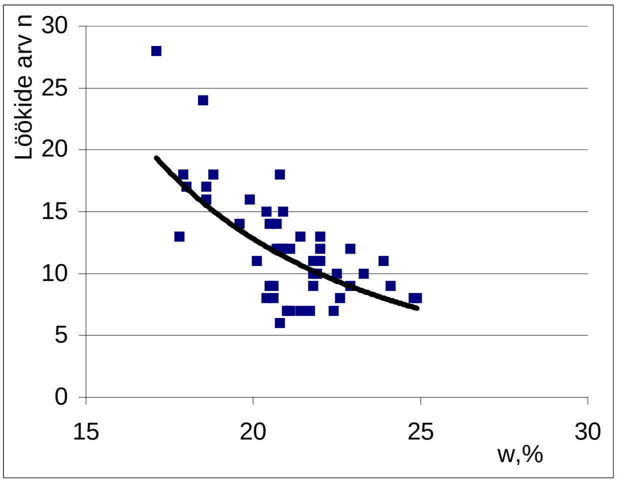


Joonis 12. Saviekraani dreenimata nihketugevuse sõltuvus tihedusastmest

Tihedusastmel I_d>0.95 ja veesisalduse W<23% on saviekraani kandevõime tagatud ka kõrgete hästi tihendatud prügimägede puhul.
Saviekraani tiheduse hindamiseks on kasutatud löökpenetromeetrit D-51 (joonised 13, 14).



Joonis 13. Löökide arvu n/0.1 m sõltuvus tihedusastmest



Joonis 14. Joonis 13. Löökide arvu n/0.1 m sõltuvus veesisaldusest.

Katsed näitavad, et kui löökide arv 10 cm läbimiseks on n>6 lööki/0.1 m, on saviekraani tihedus tagatud.

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