Composition, state and properties of the dikes’ technogenic soils of the Baikal PPM sludge collectors

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Abstract. The composition, state and properties of the dispersed technogenic soils of the sludge collectors’ dikes at the Baikal pulp and paper mill (BPPM) have been studied using standard and specific methods. As a result, a specific technogenic formation has been defined, i.e. clayey pulverescent sands. The sands have been studied for the first time, the study concerning the sands’ chemical and microelement composition and the toxicant pollution degree. It has been found that the sands are potentially running, have low plasticity due to the joint influence of the clayey and pulverescent fractions, and a capacity for physical-chemical activity. The examined wells have practically no dangerous zones of fluid consistency.

1. Introduction

The Innovation and Technological Center of Irkutsk National Research Technical University (INRTU) has considered the problem connected with the wastes of the Baikal pulp and paper mill (BPPM) that was closed down in 2013. As a result, the following project tasks were determined: neutralization of the lignin waste effluent; reclamation of the plant territory; disposal and neutralization of the sludge waters with special sorbents; production of technogenic low-toxic hard soil from the lignin waste effluent; obtaining a fertile soil layer by means of biotechnologies. The contractors for the federal-funded project are Rosgeologija and INRTU.

2. Materials

At the first stage of the above project, in November, 2017, there was a study done on the dispersed technogenic soils of the dikes surrounding the nine sludge collectors (1,500–2,000 m long, 100–200 m wide, 5–6 m deep) (Figure 1). For the research purposes, 15 wells of 6-10 m deep were drilled, and the damaged structure and natural humidity samples were taken at 2 m intervals. The aim was to study the composition, state and certain properties of the soils of the hydro-technical structures ‘guarding’ the dangerous wastes in the sludge collectors.

The research was implemented by the laboratory of rock composition and physical-mechanical properties, Scientific Research and Project Institute of Geology, Engineering Survey and Ecology, INRTU. As a result, the granulometric composition for 69 samples was defined; the natural humidity and plastic limits were defined for 34 (of 69) samples (material <1 mm); the yield indices were calculated. Based on the results of the soil granulometric analysis with the account of the plasticity indices, every object was designated according to the State Standard classification (GOST) 25100-2011 [12]. The other composition parameters were studied for 25 (of 34) air-dry samples (material...
<1mm) by the Laboratory of Engineering Geology and Geo-Ecology and by the Geodynamics and Geochronology Shared Center of The Earth Crust Institute, SO RAS (ECI SO RAS). The description of the objects, methods and research results is based on the data submitted by INRTU and ECI SO RAS.

3. Research methods and results
The soil granulometric composition, natural humidity and plasticity were defined at the INRTU test laboratory by standard methods [5].

Two methods were used in the granulometric analysis: screen test (with water-washing) and combined approach (34 samples) when after the separation of the coarse-grained debris and coarse sand fraction (200-1 mm), the rest of the material (<1 mm) was studied with a pipette method. In the first case, the content of the particles < 0.1 mm usually did not exceed 10% and the particles were not segregated into the fine-grained arenaceous, pulverescent and clayey types. In the second case, the particles <1 mm were represented by the arenaceous, pulverescent and clayey types making 100% in total, but after the recalculation for the sample’s total mass, their content changed. Note that it was the fraction <1 mm that the plastic limits were defined and the soil fluidity index was calculated for.

Based on the cumulative curves of the granulometric composition obtained with the screen analysis, the heterogeneity, grading and skewness coefficients were defined. The coefficients show that the soils are essentially heterogeneous (the heterogeneity coefficient’s minimum value is 5.5) and poor grading (the grading coefficient being 7.7 on the average). The value of the skewness coefficient is <1, which confirms the coarse grain fraction domination enhancing the permeability of the soils. This in turn affects the dikes’ stability in case of water-proofing failure [1].

The natural humidity, plastic limits and fluidity index were defined for 34 samples (material<1mm). The humidity varied from 4.0 to 25.8%, but it was only in two cases that the liquidity/fluidity index was >1 (1.24 for the humidity level of 25.8%, and 1.02 for the humidity level of 22.9% in the 2-4 m interval). In the other studied sections, the soils were in a hard state. It seems that with time, similar dangerous zones might appear in other zones.

The laboratory defined the yield and plastic limits and then, the plasticity index (Ip) which we call experimental (as later, the calculations by the predictive formulas were conducted). The statistical data processing by Ip (n=34) shows that the mean plasticity index is 2.9 % (which corresponds to suspension parameters), the variation coefficient (Vmp) being 42 %. The heterogeneity value is high due to the relatively wide range of the plasticity index (Ip = 1.1–5.8) with the general low plasticity. The mean yield point is 19.3 %, the variation coefficient going down to 17 %.
ECI SB RAS performed a visual analysis of 25 samples using the INRTU data on the granulometric composition. As a result, different zones were distinguished in the well sections according to the ratio of the arenaceous, pulverescent, clayey fractions (ps <1 mm) and the coarse-grained-debris and coarse-grained fractions (cr >1 mm). Further in the text, [ps] is designated as ‘sand’ phase and [cr], as ‘coarse-grained debris’ phase. Afterwards, every sample got a ‘double’ name: the standard one and the one including the correction based on the lithological parameters and certain properties of the sand and clay soils, as well as on the published guidelines on soil classification.

The following description of two samples is an example of the ‘double’ classification.

**841 – 0–2 m.** Grey sand, the content of gruss and gravel is 50.9% (by the screen method). Therefore, the content of the sand phase [ps] is practically equal to that of the coarse-grained debris [cr] phase [ps=cr]. The sand phase contains coarse (8.7%), big-size (9.6%), mid-size (14.0%) and small-size (11.9%) sand particles, as well as fine-grained arenaceous, pulverescent and clayey fractions (<0.1 mm), in total being 4.9%.

Standard name: gruss soil with mid-size sand particles.

**Correction name:** different-size-particle sand with an insignificant content of the material < 0.1 mm + gravel and gruss [ps=cr].

**842 – 2–4 m.** Grey pulverescent sand; the gruss and gravel content is 43.3% (by the combined method). Thus, the sand phase [ps] is a bigger part of the content of the technogenic formations, 56.7% (including the coarse sand particles content of 7.4%). By the granulometric analysis data for the fraction <1 mm (pipette method) it has been found that the content includes big-size (23.1%), mid-size (20.7) and small-size (20.9%) sand particles, as well as fine-grained arenaceous (11.0), pulverescent (20.1) and clayey (4.3%) fractions (in total being 35.4%). The pulverescent property is determined by the substantial admixture of the fine material (35.4%) and probably, by the fine-grain sand particles (20.9%) as well. The sample’s plastic limits and plasticity index have been defined (I_p=3.3). The plastic properties of the sands are most probably determined by the high content of the pulverescent fractions (20.1%) and by the presence of the clayey fractions (4.3%).

Standard name: sandy loam, rubble.

**Correction name:** clayey sand (the content of the particles <0.002 mm is 4.3%), different-size grain, pulverescent, low plasticity (I_p=3.3), admixture of gruss and gravel (43.3%) [ps].

Reviewing the data on all the wells resulted in defining three variants of sand and coarse-grained debris combinations: 1) ps=cr [ps=cr]; 2) ps>cr [ps]; 3) ps<cr [ps–filler]. Thus, any section can be represented as alternating zones, each having a specific combination of the said phases. There is a special type of the clayey pulverescent different-size-grain sands: grey quicksand, with no cohesion signs and low plasticity. 34 of 69 samples have been defined as the above sand type, and it was these particular samples for which the combined approach was used when doing the granulometric analysis. In accordance with the State standard system (GOST) 25100-2011, they are designated as ‘sandy-loam sands’ [12].

Let us consider some published research data to confirm the inconsistency of the term ‘sandy-loam sand’. Kashirsky V.I. states that ‘loamy sand’ has long existed in the soil classification accepted in the USSR and Russia, though in the standards of other countries it is absent [3]. In the former standards, the notion of ‘sandy-loam sands’ was absent, though there was a notion of light loamy sands (3–6%) and heavy loamy sands (6–10%) which were designated as ‘clayey sands’ in case of the pre-Quaternary sediments [2]. The engineering geological dictionary by V. D. Lomtadze gives the following definition of the term: “Loam sand is clayey Quaternary sediment with 3 to 10% clayey particle content; it is strong-clayey sand manifesting certain cohesion and plasticity [6].

The notion of ‘clayey sand’ is used abroad to denote a ‘transition type’ between clays and sandy clays, and ‘normal’ sand soils [13]. The Russian-English dictionary of terms used in construction engineering survey translates the Russian ‘supesj’ (‘sandy loam’) as ‘dust sand’ [8]. As for the southern territory of Eastern Siberia, the ‘transition’ types are represented by cohesive soils as loess lithogenesis products [9]. The technogenic clayey sands are not cohesive and thus do not belong to the above group; they are a special type with 3% content of the fraction <0.002 mm and certain plasticity.
Their chemical and microelement composition has been studied and some of their properties have been defined for the first time.

The chemical composition (rock-forming oxides content) has been defined by a silicate analysis for six samples; the data has been statistically processed; specific geochemical coefficients have been calculated. The obtained data allows us to conclude that the chemical composition of the sands is homogenous (variation coefficient is mostly < 10–15 %), the sands being concentrated with iron (average total content 7.60 %), calcium (4.98) and magnesium (4.09) oxides. No obvious anomaly signs have been registered.

The microelement composition of the six samples has been defined by an X-ray fluorescence method using S8 TIGER spectrometer (Bruker company, Germany). The contents of 23 microelements has been defined (ppm): V, Cr, Co, Ni, Cu, Zn, Pb, As, F, Sn, Ba, La, Ce, Nd, Sr, Y, Zr, Nb, Ga, U, Th, Rb, S. For the toxic component group (V, Cr, Co, Ni, Cu, Zn, Pb, As), the data has been statistically processed: vanadium, chromium and zinc are dominating, then fluorine (548 ppm on the average); the distribution is relatively homogenous (the variation coefficient being 9–23, for fluorine, 37). The group does not include tin as its contents is <4 ppm (ppm=0.0001 %).

A special index Zc has been calculated [7]; the index value (15–18, i.e. 17 on the average) shows that the pollution state of the clayey sand as the main constituent of the dikes’ technogenic soils is close to critical [11]. The concentration coefficient (Kс) has been defined; it shows the ratio of the component’s content (middle and maximal) and the Clarke value (by A.P. Vinogradov). Among the toxic microelements, V, Cr, Co and especially, As (4.71–5.29) exceed the Clarke value (Kс>1), the rest being close to it.

As for other microelements, barium (485–728 ppm), strontium (246–349 ppm) and sulfur (112–376 ppm) are dominating; zirconium concentration has a somewhat high value (79–134 ppm). La, Ce, Nd, Y, Nb, Ga, Rb are minor components (<10–50 ppm); the radioactive uranium is of no danger (<3 ppm); thorium content (4.7–7.5 ppm) is close to that of arsenic.

For 11 clayey sands samples, a standard chemical analysis of muriatic, water and alkaline extract has been conducted [4]. The obtained results are as follows: carbonate concentration with a wide-range content variation (6.3–23.1 %), dominance of ferrous and magnesium types; water-soluble salts <0.3 %, sulphates dominance, alkaline reaction of the medium, only one sample (865–10 m) showing anomaly salification (2.4 %) and sour medium (pH=4.0); the active (free) aluminum oxides’ content has positive and negative ‘peaks’ in the sections (the variation limits being 0.70–3.52 %). Similar ‘peaks’ have been registered in the humus content (by the I V Tjurin method): 0.0–2.0 %.

The cation-exchange capacity has been defined by the L.I. Kulchitsky method [4]; natural slope angle in the open air and underwater, sedimentation volume [5] and plasticity indices have been defined by three predictive formulas – Ір 1, Ір 2, Ір 3 [12]. Besides, the influence of the fractions on the target soils’ plasticity has been considered.

The cation exchange capacity (CEC, cmol (eq) kg⁻¹) has been measured for 10 samples, the parameter variation range being 10–62 cmol (eq) kg⁻¹ (35 as an average value). Therefore, besides plasticity, the clayey sands show some physical-chemical activity, which is not typical of normal sand soils.

The natural slope angles have been measured for 13 samples, and the following characteristic feature has been registered: underwater, there is a 7–13° lowering (Δф), which is a sign of the clayey sands being prone to running. The sedimentation volume (V, cm³) defined for 25 samples of the clayey sands is a classification parameter of potentially running soils. There are three types distinguished: I (V<3.3) – sands; II (V=3.3–10.0) – pulverescent clayey, including the loess sediments; III (V>10) – running clays. 21 of the 25 samples (84 %) belong to type I, thus belonging to running clayey sands. Moreover, they are characterized by abrupt lowering of the natural slope angle when underwater - most probably, because of the clayey and pulverescent particles’ presence.

Plasticity recalculation (n=34) has been done based on the yield point (Wm) by the predictive formulas suggested by B.F. Galay (Ір 1=0.75·Wm – 11; Ір 2=0.8·Wm – 14) as well as by the Eastern-
Siberian Trust of Engineering Survey (ESTES) \((I_p=0.599\cdot\text{Wm} – 0.079)\) [10]. The values calculated by formulas \(\#3\) and \(\#1\) show nearly complete match with the experimental data \((I_p)\).

In order to evaluate the fractions’ influence on the soil plasticity, a singular ‘experiment’ has been conducted using the R-type cluster analysis. Based on the data on the amount of the fine-grained arenaceous, pulverescent and clayey fractions and the plasticity index \((I_p)\), a few types of dendrograms have been charted, and the correlation coefficients \((r)\) have been defined. The parameters’ correlation degree is evaluated in the following way: with \(r>0.7\), the connection is essential; \(r<0.4\), negligible; \(r=0.4–0.7\), distinct (middle level). The parameter matrix includes the experimental plasticity index \((I_p)\), the fine-grained arenaceous particles content \((C_a)\), the pulverescent particles content \((C_d)\), the clayey particles content \((C_{cl})\) and the sum of the pulverescent and clayey \((C_d + C_{cl})\) particles \((n=34)\). The particles size: 0.01–0.05 mm for the fine-grained arenaceous particles; 0.05–0.002 mm for the pulverescent particles; <0.002 mm for the clayey particles. The first variant has shown a negative correlation between the plasticity and the fine-grained arenaceous fraction content \((r = -0.18)\). Thus, this fraction does not enhance the plasticity manifestation. The degree of the correlation between the plasticity and the clayey and pulverescent particle content has been defined separately, the correlation coefficient for the clayey fractions being 0.64, and for the pulverescent particles, 0.72. The aim of the final stage has been to evaluate the correlation between the plasticity and the total clayey and pulverescent particle content, the result being an increase of the coefficient value (0.73) (Figure 2).

![R-type cluster](image)

**Figure 2.** Correlation between the samples’ plasticity and the total content of the clayey \((C_{cl})\) and pulverescent \((C_d)\) particles.

Based on the obtained data, the research has confirmed the joint influence of the pulverescent and clayey fractions on the technogenic clayey sands plasticity, the pulverescent particles \((r=0.72)\) influencing the plasticity even more than the clayey particles \((r=0.64)\).

4. Conclusion

The granulometric composition study of the dispersed technogenic soils of the BPPM sludge collectors’ dikes has defined standard soil types and their properties.

Almost no dangerous high-fluidity sand zones have been found in the wells’ sections.

A specific type of the technogenic soils has been distinguished, i.e. pulverescent low-plasticity clayey sands (instead of the standard ‘sandy loam sands’) as a ‘transition type’ between clays and sandy clays, and ‘normal’ sands.

The analysis of the well sections based on the content ratio of the material <1 mm \([\text{ps}]\) and >1 mm \([\text{cr}]\) has revealed two different zones: the first one is designated as a ‘sandy phase’ zone, and the second, a ‘coarse-grained debris’ phase zone.

For the above technogenic soil type (pulverescent low-plasticity clayey sands), a complex study of the sand chemical and microelement composition has been performed for the first time. The study has shown: high concentration of iron, calcium and magnesium oxides; critical toxic microelement pollution with a high (compared to the clarke) arsenic concentration; high concentration of fluorine and sulfur; presence of radioactive thorium.


Along with the low plasticity, the clayey sands show certain physical-chemical activity which is not typical of ‘normal’ sand soils; therefore, there is a potential danger of running soil.

The study has confirmed the usefulness of the predictive calculations in defining the plasticity index by the yield point.

The joint influence of the pulverescent and clayey fractions on the technogenic clayey sands’ plasticity has been proven.

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