Geotechnical Assessment of Clay Material Exibiting Double Porosity Type

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Abstract

This study investigates the mechanical behavior of dump clay from northern Bohemia through compression and undrained triaxial tests. The material, originating from embankments over altered claystone to coal mining levels, shows potential static liquefaction and structural collapse under high confinement stress, with sudden drops in deviatoric and mean effective stresses. These soils pose notable safety risks, emphasizing the need for cautious foundation design. Using such materials as foundation soils requires additional investment, which must be reflected in project costs.

Keywords: *clay dump, triaxial test, static liquefaction, compressibility, coal-contaminated soil, double porosity, foundation risk,*

1. Introduction

Previous studies [1–4] have laid the groundwork for understanding the fundamental mechanics of sands and clays through triaxial and oedometer testing, demonstrating characteristic stress-strain behaviours within simplified frameworks. Building on this knowledge, the present study focuses on the mechanical behaviour of dump clay from northern Bohemia, aiming to improve understanding of these challenging materials.

The investigated material originates from mine landfills, where numerous slopes were constructed without strict control over compaction, raising significant concerns regarding slope stability and the potential for liquefaction. Static liquefaction and slope instability exhibit similar effective stress paths, both associated with rapid increases in pore water pressure that can trigger strain-softening mechanisms [6].

To explore these behaviours, a series of undrained triaxial compression tests (CU) were conducted under isotropic consolidation stresses ranging from 50 to 350 kPa, complemented by oedometer tests to determine compressibility parameters and to assess stress-strain and strength-rupture responses. Testing was performed on two types of samples: remoulded and intact/stabilized specimens, derived from compacted mine dumping. The soils demonstrate low permeability $\left(\boldsymbol{k \approx 10^{-9}\, m/s}\right)$, resulting in immediate pore pressure responses under loading that nearly cancel the effective stress — a condition recognized as static liquefaction. Assessment of preconsolidation stress and strength parameters further highlighted the potential for static liquefaction. Additionally, the liquefaction potential index proposed by Charles et al. (2004) [5] was applied as a preliminary design tool to evaluate slope stability.

The specific behaviour of the dump material is influenced by changes experienced by individual clay lumps, such as stress variations dependent on material thickness, potential water saturation, and time-dependent processes.

2. Geology and Stratigraphy

The Most Basin represents the largest of the four basins within the so-called Ohře Rift, part of the European Cenozoic rift system. It constitutes a graben structure that was initiated in the late Eocene and continued into the early Miocene [14]. Subsequent lateral extension was limited, and local faults matured into well-developed structures with reoriented fault planes (Fig. 1). From the Middle Miocene onward, progressive basin uplift occurred [19], resulting in erosion of the upper and marginal parts of the basin fill.

Sediment accumulation in the basin began with heterogeneous lithological sequences, including volcanic rocks, weathering products, localized fluvial systems, and marsh deposits. This phase was followed by extensive peat-forming wetlands and ultimately culminated in widespread lacustrine sedimentation throughout the basin [15-17].

Sedimentation in the Most Basin was episodic rather than continuous. Three main depositional phases, separated by two significant hiatuses, can be distinguished. The initial phase, represented by the Staré Sedlo Formation, began in the Middle Eocene (Priabonian) and continued into the Upper Oligocene. This was followed by the Střezov Formation, characterized by dominant volcanic activity throughout most of the Oligocene. The youngest stratigraphic unit is the Most Formation, spanning the Upper Oligocene to Lower Miocene (Chattian–Burdigalian). During this interval, all major lithofacies of the basin fill—including peripheral deposits—were deposited. The Most Formation includes, in stratigraphic order, the Duchcov, Holešice, Libkovice, Lom, and Osek Members [16].

The specific mechanical behaviour of the dumped clay material is governed by transformations affecting individual clay aggregates, including stress variations related to material thickness, potential water saturation, and time-dependent processes. These properties have direct implications for geotechnical design, as they influence slope stability, settlement behaviours, and the risk of static liquefaction, highlighting the need for careful laboratory characterization and design considerations in construction projects (see Fig. 1 for structural and lithological context).

The thickness of Tertiary sediments in the North Bohemian lignite region averages approximately 150 meters. Apart from the coal seams, the sedimentary succession is predominantly composed of clays and claystones, which can be characterized as overconsolidated and fragmented materials. Minor fractions of the deposits include sands, coal-bearing clays and claystones, as well as silty clays and claystones.

The mechanical properties of these sediments—particularly the overconsolidation, fragmentation, and variability in lithology—have direct implications for geotechnical engineering. Their heterogeneity affects compressibility, shear strength, and permeability, and consequently influences slope stability, foundation design, and the assessment of potential static liquefaction. Understanding the detailed composition and behaviour of these Tertiary deposits is therefore essential for reliable design and safe construction in the region.

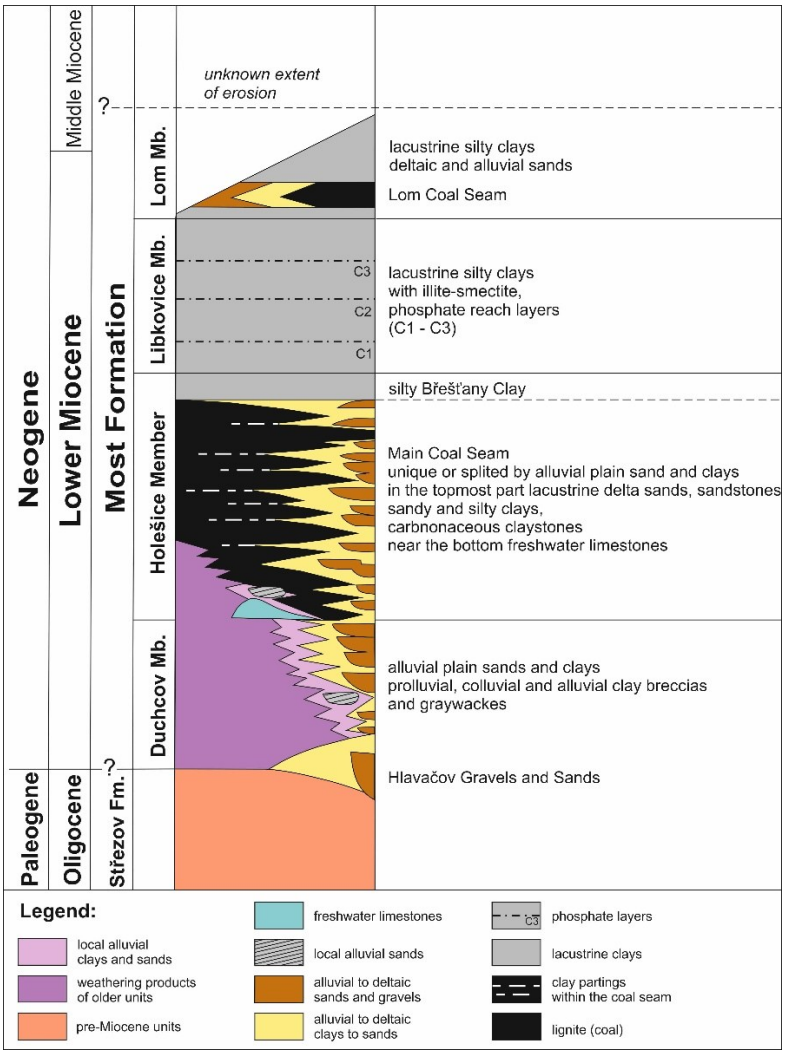

Fig. 1. Stratigraphy of Most Basin sedimentary fill (Mach et al. 2014, modified).

3. Soil Category

The clays forming the overburden of coal seams, and subsequently giving rise to clay dumps (spoil heaps), can be classified according to ČSN 731001 as clays of high to very high plasticity, designated CH to CV, and predominantly of firm to stiff consistency [11]. From a mineralogical perspective, they are generally kaolinite–illite clays with a variable minor content of montmorillonite. Other engineering parameters, particularly those relevant for stability analyses, are strongly depth-dependent:

- **bulk density** increases with depth, from approximately 1800 kg/m³ near the surface to about 2100 kg/m³ at depths of 70–100 m.
- **unconfined compressive strength** also increases with depth, ranging from 1.0 to 3.0 MPa at depths of 40–80 m.
- **degree of saturation** is close to unity, most commonly in the range 0.95–1.0. This corresponds to:
    - **decreasing porosity**, from roughly 45 % near the surface to 30–37 % at depths of 60–100 m,
    - **moisture content** decreasing from 20–45 % in the upper 30 m to 13–32 % at depths of 30–60 m.

These depth-dependent variations in physical and mechanical properties are critical for geotechnical assessments of overburden and dump materials, influencing settlement, stability, and potential liquefaction behaviour in both in-situ and re-deposited conditions.

Three samples of the Holešice Member were collected, both in their original in-situ position and from the dump: 1 – dump clay, 2 – Holešice Member – clay in-situ, and 3 – Holešice Member – silt in-situ, collected from the 4th overburden cut K99, section 2, northern part of Bílina coal mine.

3.1 Particle size distribution

Grain-size curves of the clay dump samples S2 and S3 are reported in the literature [10]. In this study, these curves have been supplemented with the original (intact) materials, taken from the locations from which the overburden was originally transported. These correspond to samples 1, 2, and 3. The sediments were dispersed in water and manually stirred for several minutes. The resulting suspension was then poured into the ultrasonic bath of the FRITSCH Analysette 22 MicroTec Plus laser granulometer. The measurement of each sample lasted approximately one minute. This granulometer is capable of measuring particle size fractions in the range of 0.0008–2 mm [20], within which it can define up to 102 particle size categories.

The laser granulometer operates on the principle of detecting the diffraction pattern of fine particles present in the measured sample as they pass through a laser beam. The intensity of the transmitted light and the interference pattern created by the scattering of the laser beam on the particles is captured by a photodetector. The signal from the detector is transferred to a computer for processing. The analysis evaluates the cumulative particle size distribution curve [20].

The instrument outputs data as cumulative percentages of the identified size classes. The resulting percentages were subsequently converted to weight percentages. From the granulometric parameters, the mean particle size and the percentage representation of individual size fractions (clay, silt, sand) were determined.

Figure 2 presents all analysed samples in a single ternary diagram. It can be observed that the original clays contain very low amounts of coarse particles and are therefore positioned in the lower part of the diagram. In contrast, the spoil material is contaminated with coarse fractions larger than 0.063 mm, reaching relatively high proportions of 28 % and 10 % for samples S3 and S2, respectively. The most likely cause of this contamination is the admixture of other fractions during transport and deposition.

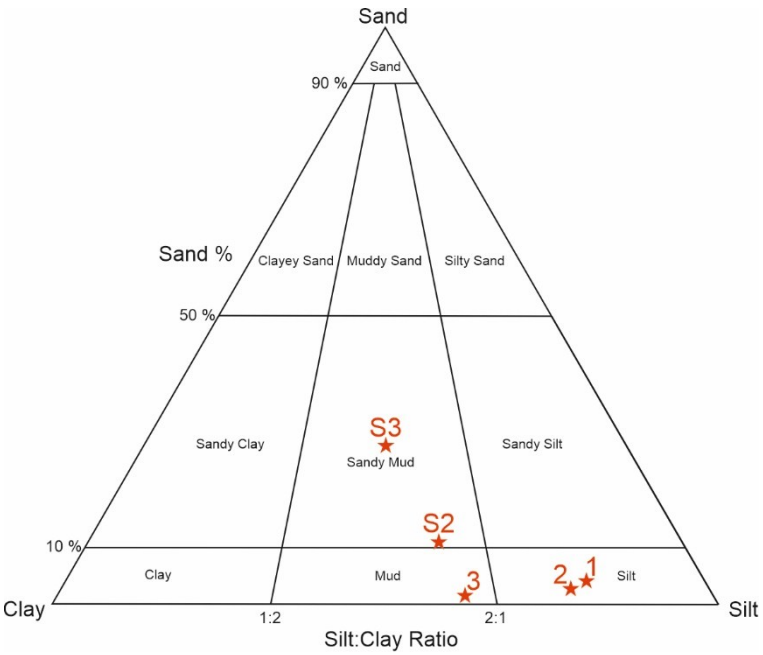

Fig. 2. Ternary diagram Sa-Si-Cl of the collected samples.

3.2 X-ray Fluorescence (XRF)

The elemental composition of all samples was determined using energy-dispersive X-ray fluorescence (EDXRF) spectrometry. Powdered samples were placed into plastic cuvettes with a volume of approximately 5 cm³, sealed with a 4 µm-thick polypropylene (Mylar) foil. The samples were analysed using an EDXRF method on a pre-calibrated handheld DELTA PREMIUM Olympus Innov-X X-ray fluorescence spectrometer mounted in a docking unit [18].

Measurements were carried out in the extended GEOCHEM mode, which allows a complete geochemical analysis of the rock, providing concentrations of the following trace elements: Si, Al, K, Ca, P, Cl, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Y, Zr, Mo, Ag, Au, Hg, Pb, Bi, Th, U, and LE. Elements with concentrations below the instrument detection limit were not considered in this study. Each sample was measured for 240 seconds at acceleration voltages of 15 kV and 40 kV [21].

The measured elemental concentrations were converted to weight percentages (wt. %), from which the weight percentages of the oxides commonly expected in natural materials were calculated, namely: SiO_2, Al_2O_3, MgO, K_2O, CaO, TiO_2, MnO, and FeO (Table X). The elements detected by the instrument and suitable for further analysis include Mg, Al, Si, P, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Rb, Sr, and Zr.

In Tab.1 we can see mass percent of chemical oxides provided XRF method for a new samples (1, 2, and 3) with compare old samples (S2 and S3) which were done by scanning electron microscope (SEM) in the literature [10].

Tab. 1. Mass percent (%) of chemical oxides in sample of intact (1,2,3) and dump clay (S2, S3) from Bohemia.

Sample	MgO	Al_2O_3	SiO_2	K_2O	TiO_2	Fe_2O_3
S2	1,460176	26,86517	58,13053	4,222983	1,73856	7,582585
S3	1,63252	26,81454	55,72307	3,551319	2,045119	10,23344
1	5,52145	15,81146	66,11054	3,074483	1,957615	7,524459
2	8,221524	23,35829	52,95031	3,138962	1,618499	10,71241
3	5,705993	15,0916	65,96012	3,522625	1,678239	8,04143

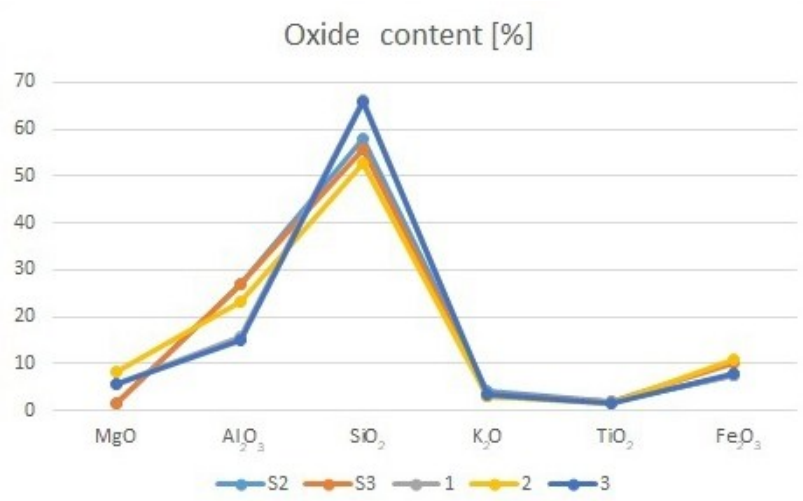

Fig. 3. Oxide content from XRF method.

Figure 3 shows a graphical representation of the values presented in Table 1. The original dump samples and the new intact clay samples do not exhibit significant changes in oxide composition. Only an increase in manganese oxides of approximately 6 % and a decrease in aluminum oxides of about 10 % are observed for the new samples 1, 2, and 3 compared to the dump samples (S2 and S3).

3.3 Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

ICP-MS measurements were also carried out at the laboratories of the Geological Institutes at the Faculty of Science, Charles University in Prague. The measurements were conducted in the Plasma Spectrometry Laboratory (LAPS).

ICP-MS (Inductively Coupled Plasma Mass Spectrometer) is an analytical instrument capable of detecting trace concentrations and isotopic compositions of elements present in a sample. The Plasma Spectrometry Laboratory is equipped with a Thermo Scientific XSeries II quadrupole ICP-MS (2008) with an AS 520 Cetac autosampler. The mass spectrometer is fitted with a simultaneous (PC/AN) single SEM detector, allowing measurements over a wide range of concentrations in an automatic mode. Data are processed using Thermo PlasmaLab software [13]. Solution-mode ICP-MS is used for trace element analysis of geological and environmental samples and for precise isotopic ratio measurements. Detection limits vary depending on the sample matrix and the analysed elements, ranging from low ppt to several tens of ppb. Analytical precision for most elements ranges from 0.5 to 2 % RSD (Relative Standard Deviation; RSD = [standard deviation/mean value] × 100). Isotopic ratio measurements can achieve a precision of up to 0.3 % RSD, depending on isotope abundance and sample matrix [8].

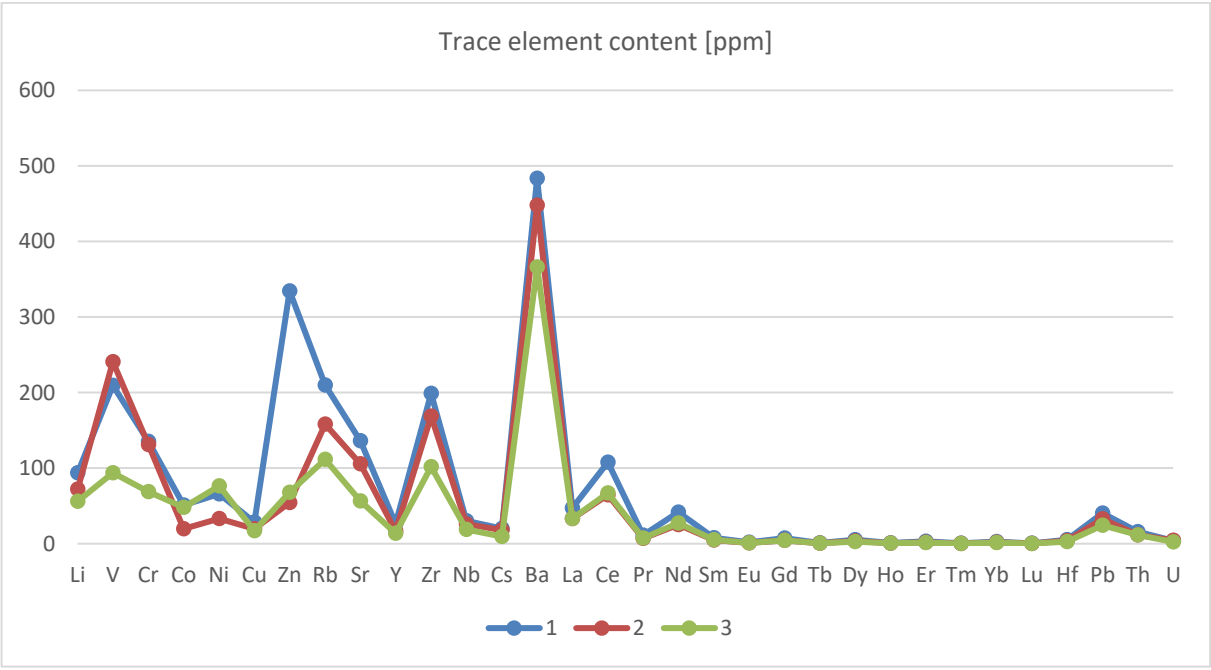

Fig. 4. Trace element content by ICP-MS method.

Trace elements measured by ICP-MS in all three samples included Li, V, Cr, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Cs, Ba, Hf, Pb, U, and Th. Rare Earth Elements (REEs) analyzed included La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, and Hf. As shown in Figure 4, the measured element concentrations did not change significantly. Zinc, however, exhibited a notable difference: in intact samples, its concentration was 54.21 and 67.90 ppm, while in redeposited materials it reached 334.29 ppm (mg/kg).

In the environment, zinc binds to soil and dust particles. These particles may enter water or soil via atmospheric deposition. Zinc is a common component of rocks, soils, and sediments; for example, clays typically contain around 100 mg/kg of zinc. Background

concentrations in soils are approximately 80 mg/kg. Most zinc in soil is particle-bound and insoluble in water, resulting in low concentrations in waters. Dissolved zinc (as Zn^{2+}) is sorbed onto clays and humic colloids [22].

In the Czech Republic, zinc limits for soils are set at 310,000 mg/kg dry matter for industrial areas and 23,000 mg/kg dry matter for other areas, according to the Ministry of Environment guideline for soil contamination [23]. In the Bílina region, the most probable source of elevated zinc in landfill clays is coal combustion, or the use of mining machinery with anti-corrosion treatments.

4. Test and procedures

In this chapter, we aim to summarize the conclusions of research conducted in previous years and published in [9, 10]. The main findings regarding the strength-deformation properties of the dump material are presented in Tables 2 and 3.

Table 2 is dedicated to the development of the LPI index, calculated according to the formula:

$$LPI = \frac{q_{max} - q_{min}}{q_{max}} \tag{1}$$

It can be observed that at triaxial stress levels of 350 kPa, the probability of plastic flow occurrence is 47 %. This represents a very high likelihood of material plasticization for the future development of dump bodies approximately 220 m in height.

Table 3 presents the strength parameters, including both peak and residual values. These parameters are critical for the design of spoil slope inclinations and for the planning of future structures and facilities that will be constructed on these bodies.

Tab. 2. Liquefaction potential index (LPI) results of Bohemia clay dump (S2–S3) [10].

Specimen	p'₀ (kPa)	LPI
S2I-CU50	50	0
S3I-CU50	50	0
S3R-CU150	150	0.16
S3-CU200	200	0.17
S3R2-CU350	350	0.47

Tab. 3. Failure strength parameters for two criteria used of the Bohemia clay dump (S2–S3) [10].

Shear Parameters			
Sample	**S2:S3 (I and R)**		
Failure Criteria	**ϕ' (°)**	**c' (kPa)**	**R^2**
$(\sigma_1-\sigma_3)_{peak}$	25	4.2	0.983
$(\sigma_1-\sigma_3)_{residual}$	14	0.0	0.995

These generally low strength parameters are a consequence of the processes accompanying the formation of these clay dumps [11]. The original relatively stiff tertiary clays and claystones in the overburden sections are excavated by bucket-wheel excavators, transported on conveyor belts (up to 8 km), and deposited using walking-frame stackers. During all these technological stages, the original stiff clay mass is transformed into clods or lumps initially angular, which become rounded during transport and can absorb water from atmospheric precipitation. The stackers (mechanical machinery) then deposit this material from heights of up to 30 m, although the deposition height varies from a few meters to approximately 30 m.

The fundamental difference between these clay dumps and conventionally compacted earth structures lies in the relatively loose placement of the material, resulting in high void ratios between individual clods. Free fall partially crushes and compacts the clods, but the achieved bulk density reaches only 1500–1600 kg/m³, and the void ratio can be around 30 % (maximum 37.5 %). The resulting macropores between clods are sufficiently interconnected to allow continuous air flow, resulting in high air permeability of the dumped material. The clod material itself is mostly of firm to stiff consistency. These clods readily absorb water because a negative pore pressure is generated inside the pores due to stress relief (essentially reduced to zero in situ). The outer shell of the clod may already be wetter due to water uptake during transport. Occasionally, water infiltrates cracks in the originally disrupted, overconsolidated clays, which expand due to stress relief, marking the first signs of initial disintegration.

Vertical heterogeneity is caused by the impact of clods from different heights and the movements of the stacker and bulldozer (used to level the surface of each deposition layer). This interface heterogeneity can be further enhanced by the time lapse between leveling a layer and depositing the next one, sometimes occurring after complete surface weathering and the development of a vegetative cover. Additional complications arise from the variability of the deposited material; for instance, when sandy material from an overburden section is excavated, the sands may create easy infiltration paths for surface water to penetrate the dump body.

In general, the initial characteristics of the dumped material resemble those of a coarse rock fill. It exhibits a high internal friction angle, allowing slopes of 1:2 to reach heights of 20–25 m. However, these properties can deteriorate significantly depending on the conditions under which the material is deposited. In extreme cases, the deposited material may **transform** into clay with soft or liquid consistency with susceptibility to liquefaction, as demonstrated by our research.

The overall issue of dumps can be divided into two main aspects. The **first concerns** the stability of the dump itself, both during the active mining phase and during its subsequent reclamation and use as an open area. This stability is primarily influenced by the goal of constructing the dump with the smallest possible footprint—that is, achieving the largest possible mass at the greatest height and steepest slope. This approach introduces key differences compared to the construction of conventional compacted embankments:

- extreme heights of the dumps,
- reduction of strength due to increasing moisture content,
- the possibility of local zones with particularly reduced strength.

As a result, modern dump slopes are relatively gentle. For example, in the so-called Ervěnický Corridor, an embankment with an average height of 110 meters was constructed with a general slope of 1:6.5 on one side and 1:7.7 on the other (slope angles of 7.5° to 9°). However, dumps with slopes of 1:12 (i.e., **5°**) are also known, which proved to be **unstable**.

The **second aspect** concerns the stability and deformation (behaviour) of structures built on the dump. This moves us into the realm of geotechnical engineering and construction. The main and general considerations for shallow foundations on dumps are as follows:

- finding an appropriate compromise between the choice of site, subsoil improvement, type of superstructure, and the design of foundation structures.
- typically, a reinforced and homogenized layer is constructed; proper drainage solutions must be implemented (choice of slope ratios).
- definition of warning levels for deformations (requiring construction monitoring), which may necessitate rectification or remedial measures.

For deep foundation methods, displacement techniques and Franki pile technologies are most commonly employed. It is essential to account for negative skin friction.

The overall complexity of using a dump as foundation soil is highlighted in the literature [12]. An illustrative case is the residential development project on the Kateřina dump near Modlany, Teplice. The preliminary design proposals submitted for the competition did not include additional calculations, which are essential for decision-making regarding construction feasibility. Based on the conducted site investigations, costs and risks for the construction of buildings, roads, and utility networks were assessed. Following this analysis, the investor withdrew due to excessive financial demands.

Construction is possible, but under entirely different (higher) costs, which include:

- subsoil improvement and structural reinforcement of buildings;
- utility networks and road infrastructure, which disproportionately increase the investment costs.
- the definition of the public interest of the state in construction on dumps is related to support for the developer, for example, through reduced land prices for sites located on these materials.

5. Conclusion

This examination of data from physical, triaxial (by [7]), and oedometer tests on the Bohemia clay dump (S2–S3) samples, also sample (1, 2 and 3) of intact clay tertiary material revealed that the test results show:

- particle size and consistency tests classified the clay dump as CL group, with S2 as silty clay and S3 as sandy clay, representing low to medium plasticity inorganic clays with low to normal clay activity. Electronic analyses suggest a high probability of kaolinitic clay presence.
- recent investigations of tertiary clay samples, conducted using particle size analysis, X-ray fluorescence (XRF), and inductively coupled plasma mass spectrometry (ICP-MS), confirmed that there are no significant differences in oxide composition, trace element content, or classification within the ternary diagram.
- laboratory testing indicated that artificial lateral stress and suction increased the virtual preconsolidation stress, which is depth-dependent and influenced by K_0 in the embankment. The critical state line derived from triaxial testing does not pass through the origin at 20% axial strain, though stress paths at $p'_0 = 350$ kPa approached structural collapse near peak strength.
- comparison of the Isotropic State Line (ISL) and the Critical State Line (CSL) suggests convergence at higher effective stresses, indicating reduced dilatancy due to particle crushing and rearrangement. This defines a compressible zone susceptible to softening and liquefaction.
- static liquefaction tests revealed substantial post-peak softening, with liquefaction potential decreasing as confining pressure increases. These findings highlight the critical role of understanding dump properties for predicting mechanical behaviour under higher loads and for ensuring safe design of structures, including linear and bridge foundations, constructed on these materials.
- a thorough understanding of the physical, mechanical, and hydraulic properties of dump materials is essential to reliably predict their behavior under increased or concentrated loads. Without such knowledge, any assessment of stability, settlement, or potential for liquefaction remains highly uncertain.
- detailed characterization of dump materials contributes directly to the design of safer structures built on these deposits. This is particularly critical for linear infrastructure (e.g., roads, railways) and bridge foundations, where differential settlements, local instabilities, or unexpected softening could compromise structural integrity. Incorporating appropriate geotechnical investigations, reinforcement strategies, and monitoring protocols ensures that constructions are adapted to the unique and heterogeneous nature of the dumped soils.

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