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Traffic-Light Framework for Early Liquefaction Assessment in Tailings Storage Facilities

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Abstract

This study presents an index-based classification framework for early liquefaction screening and laboratory test prioritization in Tailings Storage Facilities (TSFs), where strong material variability and limited access to advanced testing often constrain detailed analyses. A dataset of 391 tailings samples was evaluated using the Unified Soil Classification System (USCS), and a three-level traffic-light scheme (RED–YELLOW–GREEN) was established to classify materials according to their expected liquefaction behaviour. The RED class comprises sand-like materials that require full liquefaction evaluation and is subdivided into clean sands (R1), silty sands (R2), and low-plasticity silts (R3), reflecting increasing contractiveness, reduced drainage capacity, and lower post-liquefaction residual strength. The YELLOW class includes mixed-fines and borderline materials whose liquefaction susceptibility cannot be determined reliably from index properties alone and therefore requires additional in-situ or laboratory evidence. The GREEN class includes clay-like tailings that are not expected to undergo sand-type liquefaction, although cyclic softening under seismic loading remains possible. A practical procedure is proposed for selecting a minimal number of monotonic and cyclic laboratory tests when project constraints permit only limited advanced testing. Application of the framework shows that one representative silty sand material is sufficient to characterize the cyclic resistance of the dominant sand-like tailings, while low-plasticity silt must still be tested because of its highly contractive response and its disproportionate influence on static liquefaction initiation and post-failure mobility, even where it is not volumetrically dominant. The proposed classification supports preliminary liquefaction hazard zoning, defensible laboratory planning, and early identification of high-risk zones in TSFs.

Keywords

Tailings Storage Facilities, Flow Failure, Cyclic Mobility, Index-Based Classification, Liquefaction Screening.

1 Introduction

Liquefaction remains one of the governing mechanisms behind rapid loss of stability in tailings deposits (Carrier 1991; Rico et al. 2008). The main challenge in large TSFs is not simply that liquefaction may occur. It is that the deposit is too extensive and too variable to justify advanced laboratory testing of every material encountered in the field. Hydraulic deposition creates a population of related materials rather than a uniform tailings mass, and that variability must be treated explicitly during site characterization (Blight 2009). This problem is illustrated schematically in Fig. 1, which combines the generalized spatial variation of physical properties with the corresponding hydraulic segregation and material zonation in large TSFs. The figure shows why only part of a large TSF is likely to control liquefaction hazard.

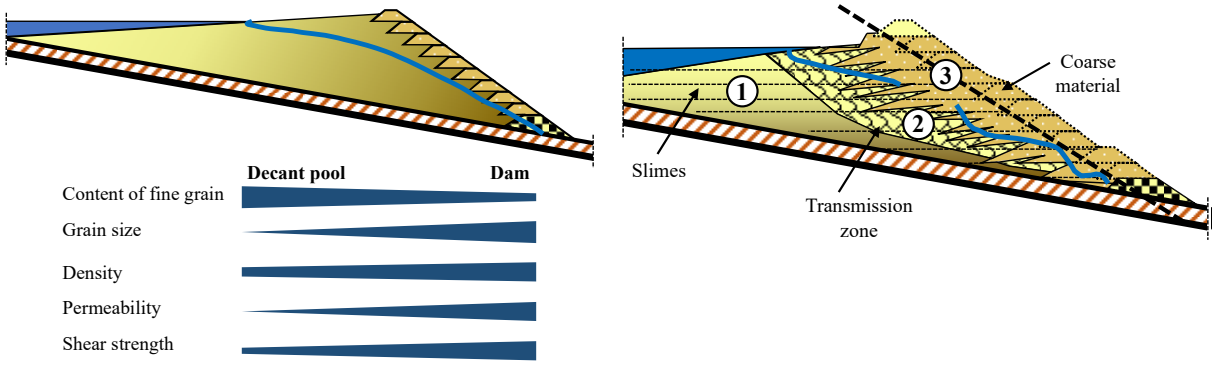


Fig. 1 Generalized spatial variation of physical properties, hydraulic segregation and material zonation in large TSFs.

Existing liquefaction assessment commonly relies on CPT/SPT triggering procedures (Seed and Idriss 1971; Boulanger and Idriss 2014), shear-wave-velocity-based methods (Andrus and Stokoe 2000; Kayen et al. 2013), and critical-state interpretation for contractive geomaterials (Jefferies and Been 2016). At the classification stage, sample-based systems such as USCS and CPT-based soil behaviour type frameworks are available (Robertson 2016), while Eurocode 8 (Part 5) provides code-based guidance for simplified liquefaction evaluation (CEN 2004). Recent studies also emphasize spatial variability and site-specific seismic characterization in liquefaction assessment (Guan et al. 2022; Geppetti et al. 2025). Against that background, the present traffic-light framework is proposed as a front-end material-screening step for large TSFs.

2 Basis of the proposed screening framework

2.1 Study context and investigation basis

The framework was developed using data from a large copper TSF in Bulgaria. The deposit was formed by long-term hydraulic placement and is characterized by marked spatial variability, thick saturated zones, and segregation between coarser and finer tailings. Seismic loading could not be ignored, so both static and dynamic liquefaction were considered within the broader project. The investigation programme combined borehole drilling and sampling, conventional laboratory classification, SPT, CPTu with dissipation tests, cross-hole seismic testing, and geophysical surveys. A key feature of the sampling strategy was the use of twin samples, with one portion used for index testing and the corresponding twin preserved for possible advanced laboratory investigation. This created a direct link between classification and later mechanical testing.

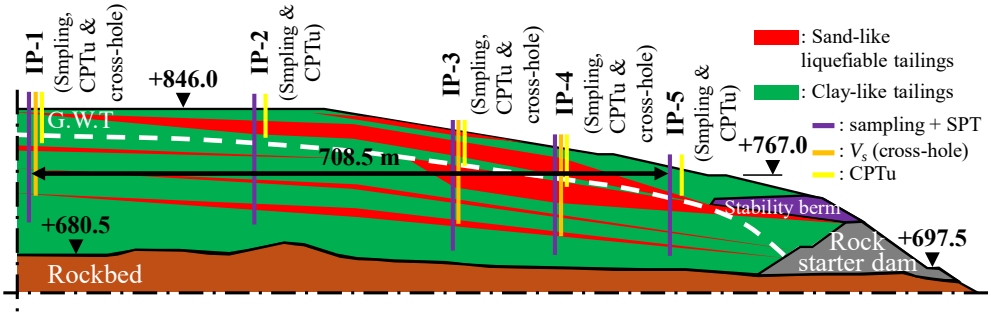


Fig. 2 Representative cross-section showing USCS-based stratigraphy and depths of investigation.

The field basis of the method is shown in Fig. 2, which schematically presents a representative section through the middle zone of the slope. The section is representative because it combines the main on-site investigation methods used in the study. Investigation points IP-1 to IP-5 mark locations where sampling with SPT, shear-wave velocity measurements, and CPTu testing were carried out. The resulting dataset was then used, following the procedure proposed in this paper, to distinguish between sand-like and clay-like tailings, as illustrated in the section. Fig. 2 therefore provides a direct link between the field investigation programme and the classification framework used for early liquefaction screening.

2.2 Why index-based screening is needed in large TSFs

Large TSFs do not justify indiscriminate advanced testing. Defining critical state lines, cyclic resistance curves, and stiffness-based interpretations for every tailings variety within a heterogeneous deposit is neither practical nor necessary. The first stage of investigation must therefore reduce complexity without distorting the problem.

This first stage is intentionally independent of local state. The immediate question is which material types require full liquefaction evaluation, which remain uncertain, and which can be screened out from sand-type liquefaction assessment.

That is where index properties are useful. Grain size distribution, fines content, and plasticity do not define liquefaction behaviour in full, but they provide a fast and standardized basis for first-stage screening. In the present study, all samples were classified according to USCS, following ASTM D2487-17 (ASTM 2020). That level of classification is sufficient for early screening and avoids premature interpretation of state or strength.

3 Traffic-light classification for early liquefaction screening

3.1 USCS-based grouping of tailings materials

All samples were classified according to USCS and then grouped into representative material families defined by grading and plasticity. This was the correct level at which to begin. USCS is not a constitutive model, but it clearly distinguishes between materials that behave fundamentally as granular tailings, materials that behave as clay-like tailings, and materials whose behaviour cannot be judged reliably from index properties alone.

The classified sample population was then reduced to three engineering categories: sand-like tailings, borderline or mixed-fines tailings, and clay-like tailings. This reduction is deliberate and differs from CPT-based soil behaviour type schemes, which infer in-situ behaviour from penetration response (Robertson 2016), because the present objective is sample-based screening and laboratory test prioritization.

3.2 Definition of the RED–YELLOW–GREEN classes

The RED class includes sand-like materials that require full liquefaction evaluation. These are the materials for which classical liquefaction mechanisms are credible under saturated undrained loading (Castro 1975; Seed and Idriss 1971). RED is subdivided as follows because sand-like tailings are not mechanically equivalent:

- R1 includes clean sands. These materials are unambiguously granular and belong in the liquefaction-focused part of the framework without qualification.
- R2 includes silty sands and poorly graded sands with non-plastic fines. These materials remain sand-like, but they are more representative of real tailings deposits than idealized clean sands. Their fines content modifies drainage conditions and tends to increase contractive response. In practice, R2 often dominates the relevant part of the sand-like tailings population.
- R3 includes low-plasticity silts. This class is critical. Low-plasticity silt tailings are easily underestimated if the screening is too crude. They are finer than the more obvious sand-like materials, but they may still be highly contractive and may exhibit very low residual strength once liquefaction is triggered. For that reason, they must remain visible as a RED-class material.

The YELLOW class includes mixed-fines and borderline tailings whose liquefaction susceptibility cannot be resolved from index properties alone. These materials lie in the transition between clearly granular and clearly cohesive response. Screening remains useful, but classification alone is not decisive. Additional field or laboratory evidence is needed before their role in the liquefaction problem can be judged with confidence.

The GREEN class includes clay-like tailings that are not expected to undergo sand-type liquefaction within the scope of the present method. This does not imply that these materials are dynamically safe or mechanically irrelevant. Under cyclic loading, they may still undergo cyclic softening, stiffness degradation, and deformation accumulation. These phenomena differ from classical sand-type liquefaction and therefore do not justify the same screening priority within the present framework.

The complete classification is summarized in Table 1 for the Bulgarian case study illustrated in Fig. 2. The table is the core of the paper because it converts raw USCS classification into a decision tool for investigation planning, while also showing the proportion of each material group within the investigated TSF. In this case, the classified sample population is dominated by RED and GREEN materials, with only marginal representation of the YELLOW class. Table 1 therefore shows that the proposed framework is not only conceptual, but directly grounded in the actual material distribution identified in the case study.

Table 1.Traffic-light classification of tailings materials based on USCS and relevance for liquefaction screening.

General classification	Project code	Material description	Percentage of all samples	Total percentage of all samples	USCS classifica-tion	USCS description
Sand-like liquefiable tailings	R1	Clean Sand Tailings	0.26	25.06	SP	Poorly graded sand
	R2	Silty Sand Tailings	23.02		SM	Silty sand
					SP-SM	Poorly graded sand w/ silt
	R3	Low-Plasticity Silt Tailings	1.79		ML	Low-plasticity silt
Borderline / mixed-fines tailings	Y1	Mixed Silty Clayey Sand Tailings	0.51	0.51	SM-SC	Silty to clayey sand
Clay-like tailings	G1	Low-Plasticity Clayey Tailings	25.32	74.42	CL	Low-plasticity clay
					CH	High-plasticity clay
	G2	High-Plasticity Clay or Silt	49.10		SC	Clayey sand

3.3 Engineering meaning of the classes and selection of representative materials

The traffic-light framework converts a large and heterogeneous sample population into a rational testing strategy. GREEN materials are not treated as the primary liquefaction problem, YELLOW materials remain under review, and RED materials become the immediate focus of advanced investigation. In the present case, this led to the selection of representative SP-SM and ML tailings for detailed liquefaction assessment by advanced monotonic and cyclic triaxial tests supplemented by shear-wave velocity measurements, with both materials later tested over a range of laboratory states.

This step also avoids a common mistake in large TSFs: the material occupying the greatest volume is not necessarily the one that controls the hazard. A relatively limited but highly contractive unit may govern liquefaction initiation or post-failure mobility if it occurs within a critical part of the deposit. That is why the distinction between R2 and R3 matters, and why low-plasticity silt cannot be screened out simply because it is finer or less abundant than the dominant silty sands.

The framework therefore supports the selection of a minimal but representative set of dangerous materials for detailed testing, rather than an attempt to test every material everywhere. It provides a practical basis for deciding which materials must be characterized properly before any later state-based analysis can be taken seriously.

4 From screening to representative advanced testing

4.1 Representative laboratory characterization

Once the dangerous classes have been identified, the next step is not to chase every local variation in density across the deposit. The next step is to characterize a minimal number of representative materials in sufficient detail to capture the range of relevant behaviour. That is where monotonic triaxial tests, cyclic triaxial tests, and bender-element measurements become necessary.

In the present study, one representative SP-SM material was selected because it was recurrent within the screened dataset, mechanically relevant, and directly linked to the classified sample population through the twin-sample procedure. Representative specimens of this material were obtained from multiple boreholes within the saturated interior of the deposit. The material was then tested across a controlled range of states rather than being tied to a single field density. In parallel, ML tailings were retained as a second key material because of their expected contractive response and potential significance for post-liquefaction behaviour.

4.2 Role of the representative results in later-stage assessment

The laboratory results are not the main contribution of this paper, but they are the necessary consequence of the screening strategy. Their function is shown in Fig. 3, where panel (a) presents the critical state line derived from monotonic testing and panel (b) presents the cyclic resistance curves obtained from cyclic triaxial testing. Together, the two panels show how the framework reduces a large and variable field problem to a manageable set of representative materials.

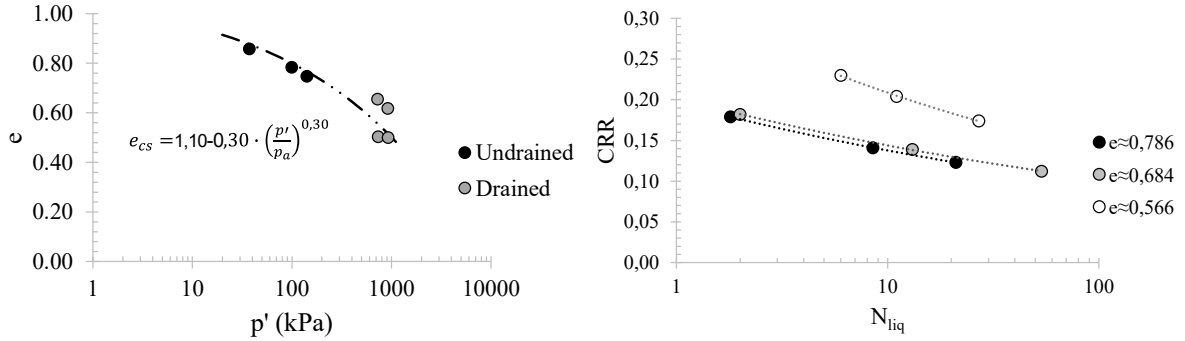


Fig. 3 Representative laboratory outcomes for the selected tailings material: left - critical state line from monotonic testing; right - cyclic resistance curves from cyclic triaxial testing.

For the purposes of this paper, the role of these results can be stated briefly. The critical state framework derived from the detailed laboratory tests provides the basis for later interpretation of whether the dangerous tailings are likely to behave in a loose and contractive or dense and dilative manner, consistent with a critical-state view of liquefaction and undrained behaviour (Jefferies and Been 2016). Once that framework is established for the representative materials, SPT- and CPT-based procedures can be used to interpret the state of the corresponding field zones and to judge whether they fall on the looser or denser side of the behaviour identified in the laboratory (Seed and Idriss 1971; Boulanger and Idriss 2014). The cyclic resistance curves provide the basis for later cyclic assessment.

Geophysical data add another layer of evidence because V_s constrains small-strain stiffness and reflects aspects of depositional soil fabric not captured by density alone, thereby supporting later liquefaction screening and interpretation (Andrus and Stokoe 2000; Kayen et al. 2013; Kiyota et al. 2019).

5 Discussion

The proposed framework is intentionally limited to what index properties can do reliably. It should be read as a preliminary screening step that sits ahead of established CPT/SPT, shear-wave-velocity-based, critical-state, and code-based liquefaction procedures, rather than as a replacement for them.

This distinction is important in large TSFs, where advanced laboratory testing is always selective. Here, testing priority is tied to material class and supported by a systematic field and laboratory dataset. GREEN does not mean dynamically safe. Clay-like tailings may still undergo cyclic softening and stiffness degradation, but these differ from classical sand-type liquefaction and therefore do not justify the same first-stage priority. The framework also avoids a common error in tailings engineering: the most abundant material is not necessarily the most dangerous. That is why low-plasticity silt must remain visible in the classification even where it forms only a limited part of the deposit.

6 Conclusions

A large TSF cannot be assessed efficiently by moving directly to advanced testing. The first step is to identify which material types matter for liquefaction assessment. The traffic-light framework proposed in this paper provides that step through a USCS-based screening procedure that separates sand-like, borderline, and clay-like tailings according to their relevance for liquefaction evaluation.

The main contribution of the method is the explicit definition of the RED, YELLOW, and GREEN classes and, within RED, the distinction between clean sands, silty sands, and low-plasticity silts. That distinction is essential because these materials do not carry the same implications for contractiveness, drainage, or post-liquefaction response. In particular, low-plasticity silt may remain critical even where it is not volumetrically dominant.

The framework also provides a defensible basis for selecting representative materials for advanced testing. Instead of dispersing effort across the full range of tailings variability, the method concentrates monotonic and cyclic laboratory work on the materials most likely to control instability. In that sense, the framework is not a substitute for detailed assessment. It is the necessary front end of a larger workflow that later incorporates critical-state interpretation, in-situ data, and geophysical evidence in a technically coherent way.

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