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On the probability of failure of tailings dams by flow liquefaction considering combined triggers

Lisandro Roldan, Florencia Spinazzola, Mauro Sottile, Alejo Sfriso
SRK Consulting, Buenos Aires, Argentina, lroldan@srk.com.ar
Universidad de Buenos Aires, Facultad de Ingenieria, Buenos Aires, Argentina

ABSTRACT: This paper presents a probabilistic framework that integrates the 2nd Generation of Eurocode 7 geotechnical design principles with advanced numerical modeling to assess the vulnerability of TSFs to flow liquefaction under combined actions. The procedure aims to support performance-based decision-making by accounting for spatial variability, uncertainty in strength parameters, and the probabilistic nature of external actions. The first component of the procedure addresses the statistical characterization of the undrained shear strength of tailings, using data from field and laboratory tests. A procedure is presented to derive a probability density function for the peak undrained strength ratio by combining CPTu and triaxial test data using reliability-based weighting. This characterization is then employed in the construction of a vulnerability surface—a continuous function in action-space that defines the limit state of the TSF under combinations of crest load, beach width, and toe contraction. The vulnerability surface is treated as fuzzy due to the uncertainty in input parameters. By performing a Monte Carlo simulation over both the vulnerability surface and the distributions of external actions, the procedure yields an annualized probability of failure for a representative cross section of the TSF. While this analysis focuses on a simplified configuration and a subset of uncertainties, it illustrates a path forward for incorporating reliability-based methods into TSF safety evaluations. The methodology is intended as a contribution to the evolving practice of tailings dam design, emphasizing transparency, rigor, and continuous improvement through collaboration and shared learning.

KEYWORDS: Tailings Storage Facilities (TSFs), Flow Liquefaction, Probabilistic Vulnerability Assessment, Eurocode 7, Performance-Based Design.

1 INTRODUCTION

Failures of upstream-raised tailings storage facilities (TSFs) in recent years highlighted the need for robust and transparent methods for the geotechnical characterization of tailings and for the assessment of dam vulnerability to flow liquefaction.

Regarding geotechnical characterization, industry practice largely relies on deterministic limit equilibrium analyses using conservative strength parameters, chosen to cover the underlying spatial variability inherent in TSFs. An opportunity for improvement is presented by the 2nd Generation of Eurocode 7 (EN 1997) (CEN, 2023; CEN/TC 250, 2023a; CEN/TC 250, 2023b; CEN/TC 250, 2023c) which provides a framework for an objective, statistically based selection of a "representative value", which is a design strength parameter determined by considering spatial variability and that is directly linked to the limit state in consideration, overall instability in the example provided in this paper.

Regarding the assessment of the vulnerability of TSFs to flow liquefaction, industry practice is to investigate "credible failure modes" and to assess their plausibility (ICOLD, 2025). Numerical modelling, when employed, simulates such credible failure modes and produces an estimate of the values of deteriorating actions that trigger flow failure. Sfriso et al. (2024) proposed a procedure for advancing vulnerability assessments towards performance-based, probabilistic frameworks aligned with reliability concepts, using the standardized actions proposed by Ledesma, Sfriso & Manzanal (2022). Sfriso & Sottile (2025) proposed the definition of PDFs for such standardized actions, and the use of a fuzzy limit state surface to compute the annual probability of failure of a TSF to flow liquefaction.

This paper presents a streamlined procedure that combines a Eurocode-based material characterization with probabilistic vulnerability assessments. This holistic approach enables for a performance-based and risk-informed analysis of TSF safety, ultimately supporting better decision-making and regulatory compliance in the mining industry. The procedure is applied to the same ideal TSF employed in previous contributions (e.g. Sottile, Cueto & Sfriso, 2020, Sfriso & Sottile, 2025), so the description of the TSF is not repeated here for brevity.

2 TAILINGS CHARACTERIZATION WITH EN 1997

2.1 *Overview of EN 1997 2nd Generation*

EN 1997 establishes a clear, stepwise procedure for geotechnical design that moves beyond subjective parameter selection by rigorously integrating statistical analysis, spatial variability, and limit states. Representative values of material properties—such as the undrained shear strength of tailings—are determined based on the consistency, quantity, and uncertainty of available data.

A key component of EN 1997 is that representative values depend on the limit state being analyzed. The scale of fluctuation θ of the ground property is compared to the extent of the potential failure surface L. If $\theta \ll L$, the representative value is close to the average value of the ground property; if $\theta \cong L$, a lower bound (close to the 5% fractile) is employed; JRC (2024a) presents a procedure for interpolating between these two extreme cases and a formula to estimate θ based on the number of crossings of the aleatory variable with respect to the property mean, as sketched in Figure 1.

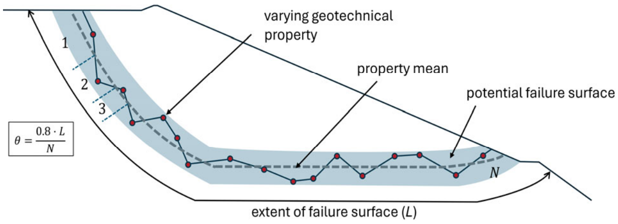

Figure 1. Scale of fluctuation θ compared to length of failure surface L (adapted from Spinazzola et al., 2025).

Weak layers, if they exist and are identified, must be treated as isolated geotechnical units (JRC, 2024a). This procedure ensures that the degree of conservatism employed in the selection of a design ground property is commensurate with the actual risk posed by its spatial variability. The advantage of applying this framework to tailings has been demonstrated by Spinazzola et al. (2025), where they presented that it can allow for a user-independent identification of weak layers and the selection of distinct ground properties to them.

EN 1997 procedure focuses on obtaining a representative value rather than providing a probability density function (PDF). In practical TSF engineering, data from several sources (such as CPTu, triaxial, DSS, and VST) must be combined; each set of data has its own uncertainty, and a consistent procedure to compute the PDF of strength parameters is required, if they were to be employed in probabilistic vulnerability assessments of flow liquefaction. JRC (2024b) provides guidance with respect to this goal.

2.2 *Uncertainty assessment*

Ground properties are random variables which are defined by their mean (μ_X), standard deviation (σ_X) and coefficient of variation ($V_X = \sigma_X/\mu_X$). Uncertainty comes from different sources, which can be categorized and combined as shown in Equation (1) (JRC 2024b)

$$V_{X,tot} = \sqrt{V_{X,i}^2 \Gamma^2 + V_{X,m}^2 + V_{X,s}^2 + V_{X,t}^2} \tag{1}$$

where $V_{X,i}$, $V_{X,m}$, $V_{X,s}$, $V_{X,t}$ are the coefficients of variation for inherent variability, measurement error, statistical uncertainty and transformation uncertainty, respectively, and Γ^2 is the sensitivity index, which accounts for spatial variability effects (JRC 2024b).

2.3 *Combining multiple data sources*

In practice, geotechnical characterization often relies on a range of testing methods, such as laboratory (triaxial, DSS) and in situ (CPTu, VST). Combining results from these sources is essential for building a comprehensive and reliable ground model. JRC (2024b) describes three main approaches for integrating data from different sources, with the choice depending on data availability, quality, and the consistency of measured properties.

The first approach involves merging values from different sources, and is only recommended when all data refer to the same property, are consistent, and have comparable quality.

The second approach, often preferred, is to determine characteristic values separately for each source, then combine them using weighting schemes that consider the reliability, representativeness, and the number of values in each set. Weightings can be assigned through engineering judgment or more structured methods, such as ordinary ranking or pairwise comparison, and should reflect factors like test applicability, data quality, and sample size.

The third approach is used when data is insufficient to allow for statistical combination; in this case, nominal values from individual sets are combined using expert judgment to yield a representative value.

Regardless of approach, careful data review is required: outliers or erroneous data should be excluded, and correlations between test types must be explicitly considered. When combining continuously measured data (e.g. CPTu profiles) with discrete values (e.g. laboratory strength tests at specific depths), the number of truly independent data points should be estimated based on the spatial scale of variability—typically, continuous data points within a certain depth, dependent on the soil type, are not statistically independent and should be accounted for accordingly.

2.4 *Application to tailings data*

The application of this procedure to real tailings data is presented to illustrate the procedure. The objective is to determine the PDF of the peak undrained shear strength ratio, $USR = s_u/\sigma'_{v0}$, employing ten CPTu soundings and four CK0UC triaxial tests. USR from the CPTu data were determined after Mayne & Peuchen (2022) while the USR values from the CK0UC tests were of direct interpretation.

Statistics (μ_X, σ_X) of the two sources and the observed coefficient of variation $V_{x,obs} = V_{X,i} + V_{X,m} = \sigma_X/\mu_X$, inclusive of inherent variability and measurement error, were obtained separately.

Measurement error in CPTu soundings $V_{X,m}^{CPT}$ is small compared to the inherent variability and is disregarded, resulting in $V_{X,obs}^{CPT} = V_{X,i}^{CPT} = 0.52$ for the data employed in the exercise. Statistical uncertainty is also be disregarded ($V_{X,s}^{CPT} = 0$) when the sample size is large ($n > 20$) (JRC, 2024b), as is the case in CPTu soundings. The transformation uncertainty of Mayne & Peuchen (2022) correlation is not available, so the value suggested for clays in JRC (2024b), $V_{X,t}^{CPT} = 0.50$, was adopted.

Regarding the triaxial tests, the observed coefficient of variation was $V_{X,obs}^{TX} = 0.34$. Values recommended in JRC (2024b) were adopted: $V_{X,m}^{TX} = 0.10$, resulting in $V_{X,i}^{TX} = V_{X,obs}^{TX} - V_{X,m}^{TX} = 0.24$; $V_{X,s}^{TX} = V_{X,i}^{TX} \cdot 1/n = 0.06$, where $n = 4$ is the sample size; and $V_{X,t} = 0$ because USR is a direct measurement, not a transformation, in the triaxial test.

The sensitivity index was obtained with the method outlined in Spinazzola et al. (2025), resulting in $\Gamma^2 = 0.20$. Thus, the total coefficients of variation are $V_{X,tot}^{CPT} = 0.55$ and $V_{X,tot}^{TX} = 0.19$. It is worth noting that the total coefficient of variation is higher than the observed value for the CPTu data and lower for the triaxial data. Lognormal distributions were employed for USR, as is customary in low strength materials.

The final statistics are:

$$USR^{CPT} \sim LN[\mu_{CPT} = -0.49, \sigma_{CPT} = 0.51] \tag{2}$$

$$USR^{TX} \sim LN[\mu_{TX} = -1.49, \sigma_{TX} = 0.19] \tag{3}$$

Combining the PDF of each data set was performed employing the second approach described in section 2.3 on the means and standard deviations separately. The following equations were applied, where ω_i are the weights assigned to each data set and ρ is the correlation between them.

$$\mathrm{E}[X_i] = e^{\mu_i + \sigma_i^2/2} \tag{4}$$

$$\mathrm{Var}[X_i] = \left(e^{\sigma_i^2} - 1\right) e^{2\mu_i + \sigma_i^2} \tag{5}$$

$$\mu_X = \omega_1 \mathrm{E}[X_1] + \omega_2 \mathrm{E}[X_2] \tag{6}$$

$$\sigma_X^2 = \omega_1^2 \mathrm{Var}[X_1] + \omega_2^2 \mathrm{Var}[X_2] + 2\omega_1\omega_2 \mathrm{CoV}[X_1, X_2] \tag{7}$$

$$\mathrm{CoV}[X_1, X_2] = e^{\mu_1 + \mu_2 + (\sigma_1^2 + \sigma_2^2)/2} \left(e^{\rho\sigma_1\sigma_2} - 1\right) \tag{8}$$

$$\sigma^{*2} = \ln[1 + \sigma_X^2/\mu_X^2] \tag{9}$$

$$\mu^* = \ln[\mu_X] - \sigma^{*2}/2 \tag{10}$$

Weights were adopted through a reduced pairwise comparison (JRC, 2024b), where the degree of importance of one data set over the other ranges from 1-equal importance to 9-extreme importance. A value of 7-very strong importance for the triaxial over the CPTu, since the USR is directly interpreted from the test and has lower dispersion, although the data size is smaller. Another two reasons are that: i) Mayne & Peuchen (2022) has been developed for clay materials: and ii) the peak USR interpretation can be strongly affected by partial drainage.

The choice of the relative importance is a decision that is subjected to considerable judgement, and heavily influences the outcome. The correlation between both data sets was considered moderate ($\rho = 0.50$) because CPTu data involves both sands and fine tailings while triaxial tests onl involved fine tailings. The corresponding weights result $\omega_{CPTu} = 0.125$ and $\omega_{TX} = 0.875$.

The heavy weight of the triaxial tests, for four samples only, compared to the CPTu soundings, for ten soundings providing thousands of data points, is the result of the large value of $V_{X,t}^{CPT}$. If the PDF of the CPTu data were capped by the drained shear strength, a smaller value $V_{X,tot}^{CPT} = 0.25$ would have been obtained, and the relative weights would have been $\omega_{CPTu} = 0.402$ and $\omega_{TX} = 0.598$. The resulting combined PDF for this latter weighting is plotted in Figure 2, together with the PDFs of the two individual sets (considering drained shear strength cap for CPTu data).

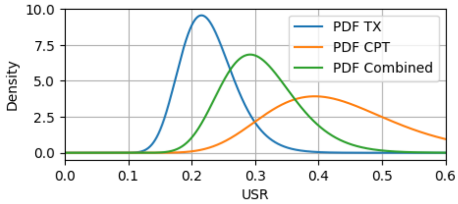

Figure 2. Triaxial, CPTu and combined PDFs.

3 PROBABILISTIC VULNERABILITY ASSESSMENT OF FLOW LIQUEFACTION

3.1 *Standard triggers vs combined actions*

The standard practice for assessing the vulnerability of tailings dams to flow liquefaction is based on trigger analyses of credible failure modes. Ledesma, Sfriso & Manzanal (2022) presented a procedure that considered three distinct perturbations irrespective of their credibility to analyze the robustness of the TSF as a system. In their work, a load at the crest, a rise in the phreatic surface due to a reduced beach width, and a toe displacement imposed by a contraction of the starter dam were analyzed as single-cause actions. While this approach provides valuable insight into the robustness of the TSF, it downplays the fact that deteriorating actions may occur simultaneously, each one of them with values below their alarm level but, when combined, can bring the dam to failure.

3.2 *The vulnerability surface*

Analyzing the dam's performance under combined actions offers a better insight and can be used to inform Trigger Action Response Plans. Sfriso et al (2024), and Sfriso & Sottile (2025) introduced the concept of a vulnerability surface, an analytic function computed by interpolation from a few FEM model runs. This vulnerability surface is formulated in the action-space (load at the beach q, toe contraction δ, beach width w), and defines the boundary between stable and unstable conditions of a TSF under any combination of the external actions.

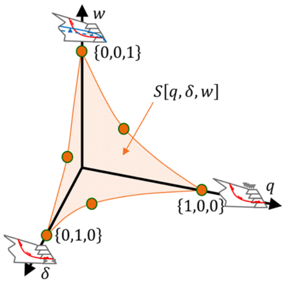

Figure 3. The vulnerability surface (adapted from Sfriso & Sottile, 2025). Actions are normalized to provide a non-dimensional plot.

In practice, the vulnerability surface is constructed by simulating combinations of these standardized triggers in a FEM model recording the critical values at which failure occurs and interpolating the results to delineate a continuous "failure envelope" within the action-space (Figure 3).

The vulnerability surface is itself fuzzy, because the strength parameters are themselves aleatory variables. This aspect is discussed later in this paper.

3.3 *How many model runs are required to define the vulnerability surface?*

This section examines how the quantity and distribution of the data points, obtained by running the FEM model, affects the determination of the vulnerability surface. Using the dataset assembled by Sfriso & Sottile (2025), several triplets which trigger failure $\{q, \delta, w\}$ were evaluated. Radial Basis Functions (RBF) with linear and multiquadric algorithms were tested over a set of 3, 4, 6, and 9 triplets, and a "true" reference surface was established employing all available triplets (26). Each surface resulting from the different number of triplets was compared in the action-space, as shown in Figure 4 for three of the cases studied.

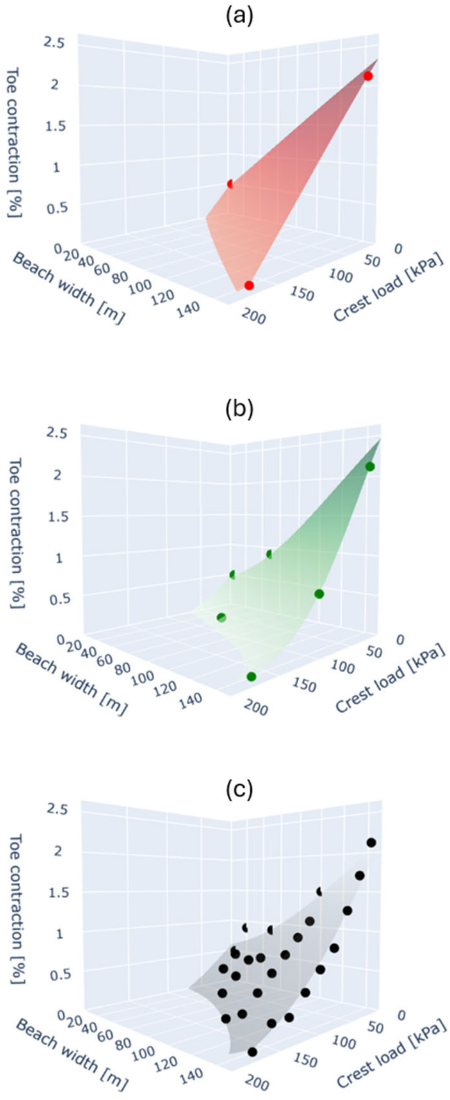

Figure 4. Vulnerability surface defined by (a) 3 triplets, (b) 6 triplets and (26 triplets), delimiting failure and safe action combinations.

A smooth and continuous vulnerability surface is obtained by calibrating the interpolation parameters of the Radial Basis Function —namely the function type, the epsilon value, and the smooth coefficient.

The function type determines the mathematical shape of the radial basis and thus the way each calibration point propagates data through the action-space, while epsilon controls the spatial scale of this influence, with smaller values producing more localized effects and larger values yielding broader, smoother transitions. The smooth coefficient governs how strictly the interpolated surface passes through the original data points, allowing the modeler to balance exact reproduction of FEM results with the need to suppress numerical artifacts or accommodate modelling inaccuracies.

Results shown in Figure 4 prove that six points suffice to provide a robust and fit-for-purpose interpolation which compares well with the full dataset of 520 runs. Adding more points beyond six offers minimal improvement, while fewer points may fail to capture the curvature of the vulnerability surface close to the corners shown in Figure 3.

3.4 *Uncertainty in strength and a fuzzy vulnerability surface*

To be fully probabilistic, the assessment must incorporate the uncertainty of USR into the analysis. To prove this statement, a series of USR values were selected at multiple confidence intervals (16%, 30%, 50%, 70%, and 84%).

For each selected value of USR, the NorSand constitutive model (Jefferies, 1993) was calibrated, and trigger analyses were performed across six combinations of the crest load and beach width, determining the toe contraction required to trigger flow liquefaction failure. Results are shown in Figure 5, where the vulnerability surface attached to each value of USR would be the result of interpolating dots of the same color.

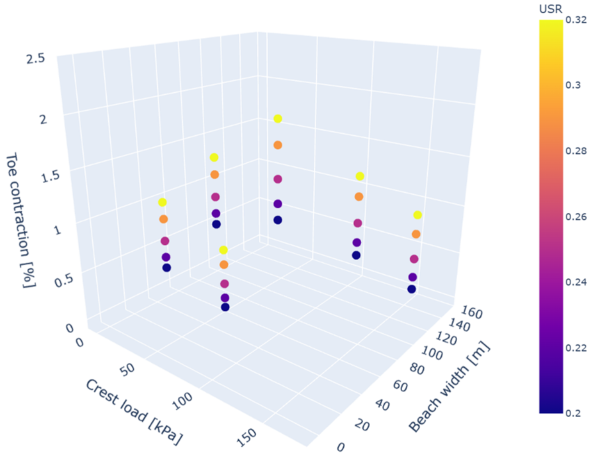

Figure 5. Points lying on the vulnerability surface for five values of USR. Each vulnerability surface would be the result of interpolating points of the same color.

To prove the smoothness of the vulnerability surface, a one-dimensional mapping between USR and the toe contraction δ required to initiate flow liquefaction failure was created. For each combination of crest load and beach width analyzed, a quasi-linear relationship between δ and USR was obtained as shown in Figure 6. While the exercise was not repeated for the other two actions acting as trigger, this linearity proves that the vulnerability surface is smooth, at least in the six tested locations.

The following procedure was employed to obtain the fuzzy vulnerability surface: i) triplets for six action combinations were found for the five selected USR values (Figure 5); ii) the mapping between USR and δ was defined for each action combination (Figure 6); iii) a Montecarlo sampling of USR was employed to generate a large number of triplets using said mapping; iv) for each set of mapped triplets a vulnerability surface is defined using a RBF, obtaining a large number of vulnerability surfaces, their density and location dictated by the statistics of USR, as shown in Figure 7.

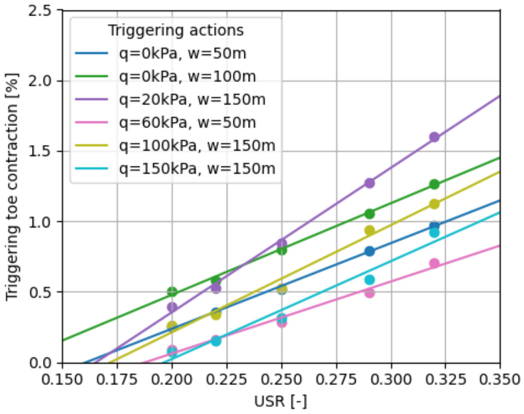

Figure 6. Mapping between USR and toe contraction δ triggering flow liquefaction failure for different values of q and w.

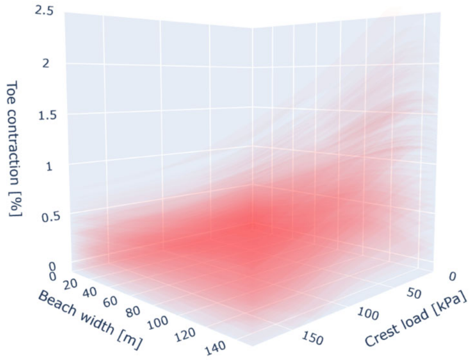

Figure 7. Fuzzy vulnerability surface obtained by statistical interpolation of the six surfaces.

The deterministic vulnerability surface producing an on-off failure assessment is thus replaced by a fuzzy envelope that captures the range of system responses arising from the uncertainty of the undrained shear strength ratio (Sfriso & Sottile, 2025). The characteristics of the TSF were purposedly chosen to be highly vulnerable to toe contraction (Sottile, Cueto & Sfriso, 2020). In this exercise, a large uncertainty is attributed to CPTu data and inherited by USR. These factors combined, the uncertainty of the vulnerability surface or, in other words, the span of the fuzzy surfaces is high, as shown in Figure 8.

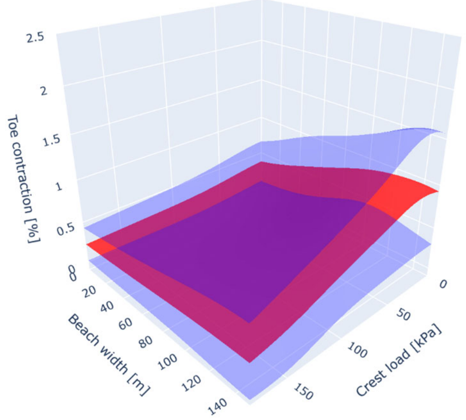

Figure 8. Uncertainty of the vulnerability surface: surface obtained with the mean (red) and one standard deviations (blue) of USR.

3.5 *Computing a probability of failure*

By combining this framework with probability distributions for the triggering actions, a comprehensive probabilistic assessment of dam vulnerability can be achieved. To prove this, a set of plausible PDFs for the three actions was selected (Figure 9).

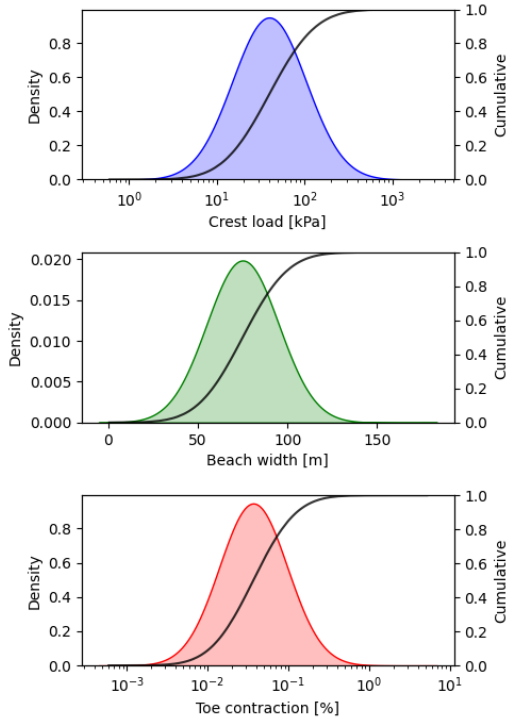

Figure 9. PDFs selected for the three deteriorating actions.

Sfriso & Sottile (2025) explain how to employ the return periods of the three actions to compute an annualized probability of failure. To keep this example simple, the PDFs presented in Figure 9 are not annualized, i.e. are representative of just one return period, say for instance 50 years. As explained by Sfriso & Sottile (2025), the estimation of the PDFs shown in Figure 9 must include all sources contributing to a specific hazard. For instance, changes in the beach width must include all events leading to an increase in pore water pressure within the tailings body, not covered by the other two actions, e.g. poor management of the pond location, a flood, etcetera.

The probability of failure is then computed by a second Montecarlo simulation (Sfriso & Sottile, 2025). A triplet $\{q, \delta, w\}$ is sampled and is compared to a sample of the vulnerability surface. If the triplet lies below the vulnerability surface, dam failure wasn't triggered; if the triplet lies above the surface, dam failure was assumed. Figure 10 shows the result of evaluating 100,000 triplets against the same number of vulnerability surfaces, resulting in $PoF = 9\%$. Note that the dots denoting failure and safe overlap as a result of the variability of the vulnerability surface.

It is important to highlight that the computed probability of failure is not that of the dam. It is just the probability of failure of one cross section, due to flow liquefaction only, and is only useful if employed in a full and comprehensive quantitative risk analysis of the dam.

It should also be emphasized that, for clarity and tractability, this study has focused on the uncertainty associated with USR of tailings. In practice, the probabilistic framework must be extended to capture a broader range of uncertainties, including delineation of geotechnical units, other material properties, etcetera.

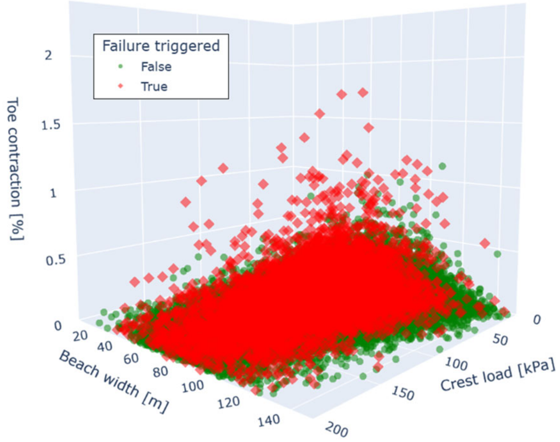

Figure 10. Result of probabilistic liquefaction dam safety analysis.

3.6 *Compliance with EN 1997*

In the nomenclature of the Eurocodes, the vulnerability surface derived in this work constitutes an explicit representation of a limit state—in this case, overall instability driven by flow liquefaction. The methodology described herein demonstrates that, for a representative TSF geometry, this limit state function can be determined with adequate accuracy using interpolation between a small set of targeted finite element analyses. Specifically, results confirm that six well-distributed model runs, covering the range of combined actions in the defined action-space, are sufficient to capture the curvature of the vulnerability surface for engineering purposes. This efficiency aligns with the intent of EN 1997 to enable reliability-based verification without excessive computational burden.

The procedure addresses a problem that fulfills the conditions outlined in JRC (2024b) where reliability-based methods are preferable over conventional design methods. These include: i) design of special structures for which the standard partial factors may not be appropriate; ii) design or assessment of structures with explicit reliability requirements (e.g. acceptable probability of failure) such as storage of hazardous substances; iii) assessment of existing structures for which the standard partial factors are not intended; iv) assessment of existing structures using performance information.

TSFs are critical infrastructures that typically meet all these conditions: they are large, complex, and spatially variable earth structures containing potentially hazardous materials, and their performance requirements extend far beyond typical geotechnical projects. By adopting a framework in which representative material properties are selected using the statistical and spatial variability concepts of EN 1997, and by defining a limit state surface amenable to probabilistic evaluation, the approach presented here demonstrates compliance with both the letter and the spirit of the standard.

Importantly, while the example presented is intentionally simplified, the framework is inherently scalable. As more comprehensive datasets, more refined geotechnical zoning, and additional load scenarios are incorporated, the reliability-based methodology remains valid and traceable to EN 1997 principles. Thus, the work contributes not only to the technical advancement of TSF safety assessment but also to fostering regulatory alignment and facilitating transparent, risk-informed decision-making.

4 CONCLUSIONS

This paper presents a stepwise methodology to integrate modern geotechnical characterization with probabilistic assessments of flow liquefaction in upstream-raised tailings storage facilities. By applying the framework of the 2nd Generation Eurocode 7 and coupling it with a probabilistic vulnerability analysis, the proposed approach facilitates a transition from traditional deterministic safety assessments toward a more rigorous, performance-based design philosophy.

The paper applies a method for selecting strength parameters that incorporates spatial variability and multiple data sources. Unlike traditional judgment-based approaches, it quantifies uncertainty transparently, following EN 1997 principles. By using real tailings data, the method combines CPTu and triaxial tests with reliability-based weighting to derive lognormal distributions for peak undrained shear strength ratio, providing a foundation for later probabilistic analysis.

Building upon this characterization, the concept of a vulnerability surface is employed to evaluate the system's response to combined external actions. Rather than focusing solely on single-event triggers, this approach acknowledges that failure may result from the concurrent influence of multiple deteriorating actions, each of which may remain below its individual threshold. The vulnerability surface thus defines a limit state in the action-space, where safe and unstable conditions are delineated. The study confirms that such surfaces can be accurately interpolated with relatively few finite element simulations, which makes the methodology practical for engineering application.

Uncertainty in material properties naturally introduces fuzziness to the vulnerability surface. This aspect is explicitly addressed by constructing a family of surfaces corresponding to different quantiles of the undrained shear strength distribution, ultimately leading to a fuzzy limit state function. When this fuzzy limit state is paired with assumed distributions for the triggering actions, a probability of failure due to flow liquefaction is obtained via Monte Carlo simulation.

It is important to recognize that this probability is not representative of the entire dam system but only of a specific cross section under idealized loading. Furthermore, the study deliberately focuses on a limited subset of uncertainties to ensure tractability and clarity. While these simplifications are necessary for early-stage implementation, they highlight the need for future work to broaden the framework, incorporating additional sources of uncertainty and extending the analysis to full three-dimensional representations of TSFs.

This paper represents an ongoing effort to advance the geotechnical design of TSFs through a performance-based, risk-informed lens. The procedures discussed herein are not definitive solutions, but contributions to a shared journey of improving safety and transparency in tailings dam engineering. Continued collaboration, testing, and refinement—across industry, academia, and regulatory bodies—will be essential as we collectively work toward more resilient and accountable TSF design practices.

5 ACKNOWLEDGEMENTS

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