Influence of grain shape on the liquefaction susceptibility of natural sand soils – a methodological approach

Flora Feitosa Menezes[1*], *Gundula* Erdmann[1], and *Maike* Gröschke[1]

[1] Research and Development of Post Mining Areas, Federal Institute for Geosciences and Natural Resources, Cottbus, Germany

1 Introduction

KornELa is a research project aimed at characterizing the particle shapes of natural sand soils in order to better understand the interplay between grain morphology and the mechanical behaviour of soils - specifically for soils that are more prone to liquefaction.

The inspiration for this project emerged from the long-standing situation in the Lusatian mining area, where large post-mining areas have been restricted from public since 2010 due to the risk of spontaneous soil liquefaction. The dump soil in this region consists mainly of fine quartz sand, with a minor fraction of silt and lignite relics. Due to dredging and loose deposition, the soil is very porous and, with the ingress of groundwater and rainwater, remains loose and not fully saturated [1]. More recently, in January 2026, an area of approximately 19 ha around Angelteich was designated as a closed-off area by regional authorities [2]. The current extent of such closed-off areas in Lusatia is shown in red on the map below comprising a total area of approximately 30,000 ha (Figure 1).

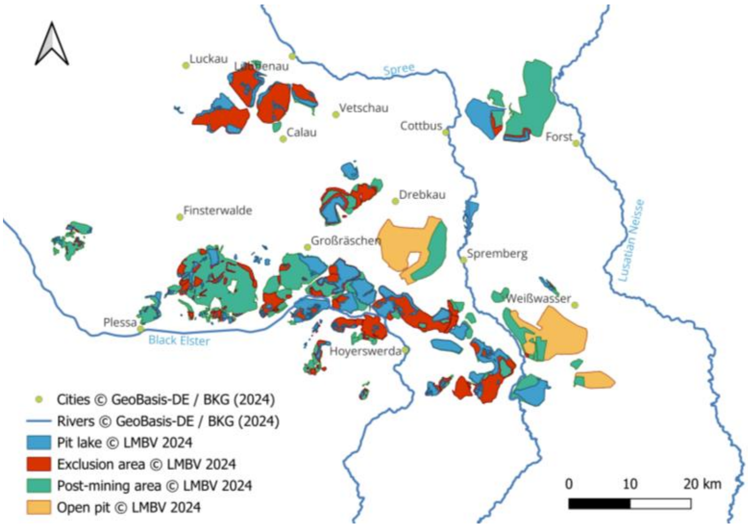


Figure 1. Map of the Lusatian mining district highlighting current mining-related areas. The district is located in eastern Germany, within the federal states of Brandenburg and Saxony, and extends to the Polish border. Lignite has been mined in this region since the early 19th century. Areas shown in red are permanently closed due to the potential risk of soil liquefaction.

Numerous studies have been conducted on either dump soils or related materials to investigate the interplay of factors influencing spontaneous liquefaction events. A common and widely used approach has been the conduction of triaxial stress tests, such as cyclic triaxial compression tests on fine sands under undrained conditions. These studies have concluded that the initial density of the fine sand plays a critical role in its ability to withstand additional load cycles during the cyclic mobility phase, until a defined failure criterion is reached [3].

Closer to the focus of this study, recent research using dynamic image analysis to determine the fundamental properties of sand grains has shown that reliable predictions of geotechnical properties can be made. For this purpose, a selection of natural sands was analysed using dynamic image analysis, and the geotechnical parameters—including different density levels and the angle of internal friction of the respective sands—were subsequently determined [4].

Our goal is to develop a comprehensive yet clear methodology for dealing with natural soils that takes into account aspects of their natural geological background, which are often neglected in purely engineering-based investigations. For this purpose, sand samples are collected from various depositional environments and subjected to a standard analytical program in our laboratories. Parallel to that, a sandy soil is to be selected for further microscopic analysis. Ideally, the selected sandy soil should resemble the fine sands naturally occurring in Brandenburg, which are used to fill the mining landscapes. Therefore, the present work focuses on the first step of this investigation: Characterising the sand samples and performing grain shape analysis using a dynamic image analysis.

* Corresponding author: flora.feitosamenezes@bgr.de

2 Methodology

The samples were subjected to a standardized analytical protocol in our laboratories, including the determination of grain size distribution and particle shape parameters and grain density. To obtain chemical insights into the possible mineralogy of the samples and the texture of individual grains, scanning electron microscopy (SEM) imaging combined with energy-dispersive X-ray (EDX) analysis was performed.

Grain size and particle parameters were determined by means of dynamic image analysis in 2D mode, where the number and dimensions of the particle fractions can be defined in beforehand by the user. This apparatus determines particle parameters such as the sphericity, symmetry and aspect ratio of individual particles, and outputs an average value for the given particle fractions. To obtain more precise data and to verify the validity of these averages, two set of analysis were carried out: a coarse one with 30 particle fractions and a finer one with 200. Due to the limited scope of this abstract, only aspect ratio is presented as a particle parameter for comparison purposes.

Beach sand, dune sand and fluviatile sand are natural sand deposits consisting mainly of quartz. Since sediments may have different genetic origins and therefore vary slightly in their mineralogical composition and quartz content, samples were subjected to energy-dispersive X-ray spectroscopy (EDX) as part of the standard analytical program. Minerals fracture and erode differently depending on their crystal structure, the resulting grain shape can be significantly influenced by the mineralogy of the respective sand grain. The aim here is to examine whether the samples are mineralogically comparable, whether there are characteristic differences and to what extent the observations on grain shape can be supported by mineralogy.

Grain density was determined by volumetric method using a helium pycnometer. Because the measurement is performed on the bulk sample, it provides an average density reflecting the mineralogical composition of the material. This allows an assessment of how much the sample deviates from a pure quartz sand. Further, grain density values higher than 2.65 g/cm³ may indicate the presence of minerals denser than quartz, such as plagioclase or clay minerals, while values exceedingly approximately 2.7 g/cm³ are commonly associated with an increasing carbonate content. Together with the results of the EDX analysis, it is possible to infer which mineralogical group the grain density reflects (e.g. carbonate or silicate).

In terms of microscopy, the most effective setup so far has been reflected-light dark-field imaging with a black-coated background to maximize contrast. The next steps involve addressing the remaining over- and under-segmentation issues in the microscopic images. Due to the scope of this abstract, no further details on the microscopy task will be provided. This ongoing research continues to reveal key challenges in configuring the dynamic image analyzer, which are currently the main focus, as they significantly influence the differences observed in the investigated soils.

3 Results

The following figure (Figure 2) shows the particle size distribution (PSD) through dynamic image analysis of the sands collected so far, along with their respective mean particle size (d_{50}), uniformity coefficient (c_u) and grain density (ρ)[1].

The sandy soils under investigation range from fine to coarse sand. Based on the c_u value, almost all samples can be described as poorly graded, uniform sandy soils, except for the one with $c_u = 3$ (dark green line). Taking into account the grain density in accordance with the chemical phases identified by the EDX analysis, only five samples can be classified as “typical sand,” as they match the grain density of quartz (2.65 g/cm³) and have a predominantly silica content. In contrast, most samples indicate an obvious influence of a second mineral or phase, for instance plagioclase (light yellow line, $\rho = 2.657$ g/cm³) or carbonate (purple line, $\rho = 2.726$ g/cm³).

Although the particle shape characteristics of the entire sand spectrum are of interest, particular attention should be paid to liquefaction-prone soils, which tend to be poorly graded, fine to medium sands. For instance, the dark red line, which represents a very poorly graded fine sand collected from the intertidal zone of a beach on the southern Atlantic coast. As seen in the SEM image (Figure 3), this sample consists of subrounded to rounded grains with polished edges and rather smooth surfaces. EDX analysis shows a chemical composition mainly dominated by Si and O and most likely corresponds to quartz (SiO_2). Noteworthy is the occurrence of iron–titanium oxides identified in the brighter areas, which are likely ilmenite or magnetite. Considering that ilmenite and magnetite have grain densities of around 5 g/cm³, it is apparent that this iron-titanium-oxide phase has a significant influence on the grain density of the sample, which is 2.698 g/cm³. It would mean that the visually more silica-dominated sand sample has a grain density significantly higher than that of pure quartz. However, it is recognized that the chemical evaluation through EDX is subject to uncertainties due to the quantity and randomness of measurement points, and therefore primarily serve a qualitative description. In this case further investigations must be carried out.

A key challenge when working with a dynamic image analysis is defining the grain diameter: Should one use the more favorable, minimum chord length (xc-min), thus resembling traditional sieve analysis, or should one determine the grain's projection area (x-area) and compare it to laser diffraction analysis? Indeed, the grain shape parameters vary depending on the chosen diameter. Since this study is primarily concerned with the geometric properties of sand grains, it is important to highlight the difference between the various methodological approaches.

[1] Since this is an ongoing investigation, the density has not yet been determined for all samples. In this case, the density value is missing from the legend.

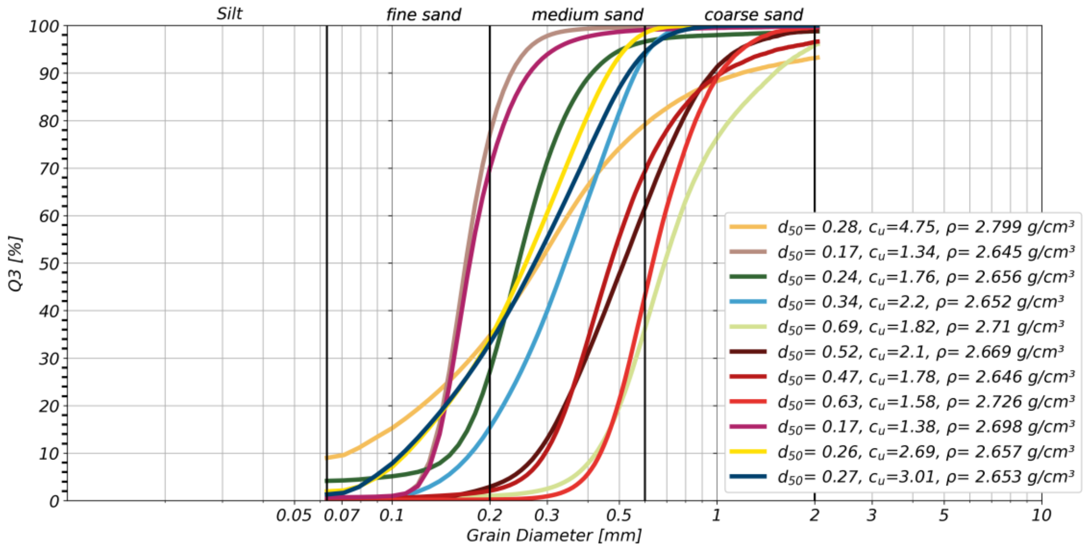


Figure 2. Particle size distribution for non-cohesive soils determined though dynamic image analysis, where the grain diameter was determined by the projection area of the particle (x-area). d_{50}: respective mean particle size, c_u: uniformity coefficient, ρ: grain density.

In this sense, the following figure (Figure 4) shows four PSD curves for the same sample, a fine beach sand consisting mainly of quartz. The pink dots represent the PSD determined by traditional sieve analysis (SA). The pink three lines represent the PSD obtained through dynamic particle analysis; either by using the area as diameter (solid line), or by using the minimum chord length (dashed and dot-dashed lines). It is undeniable that the sieve analysis curve and the PSD curve based on particle area (solid line) do not match. This is due to the fundamentally different approaches used to determine the quantity and the number of size fractions. Sieve analysis determines the mass per mesh, while dynamic image analysis uses statistical evaluation of the entire population. In dynamic image analysis, neither the mass nor the exact number of particles is known. However, the pattern from left to right: sieve analysis, xc_min and x_area, was observed nearly identical in all samples, suggesting a systematic error.

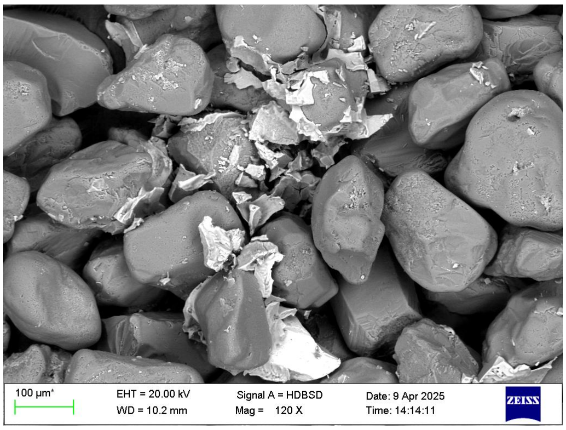


Figure 3. SEM-Imaging from a sandy soil from the intertidal zone of a beach on the southern Atlantic coast. This sample consists mainly of subrounded quartz grains. Brighter spots consist of an iron-titanium-oxide.

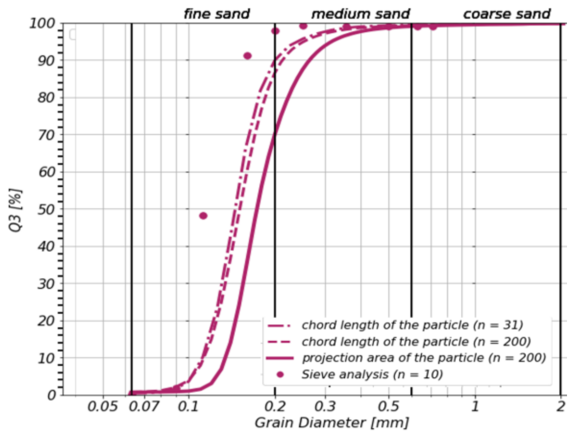
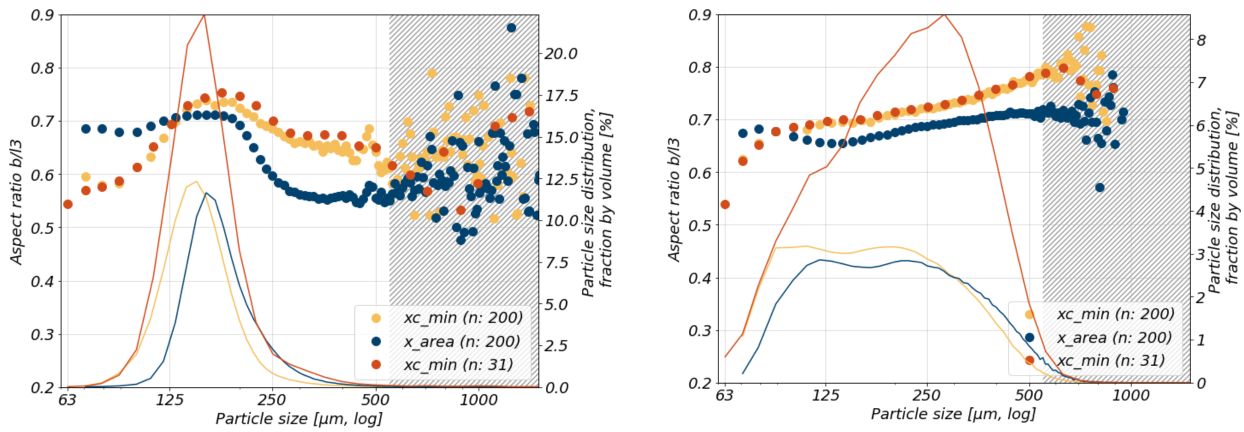


Figure 4. Particle size distribution curves for a sandy soil from the intertidal zone of a beach on the southern Atlantic coast, obtained through sieve analysis (SA) or though dynamic image analysis.

Two sandy soils from different depositional environments are compared in the graphics below using PSD and roundness: a fine sand from the intertidal zone of a beach on the southern Atlantic coast (Figure 5a), and a medium sand from an Algerian inland dune (Figure 5b). PSD is expressed as volume per size fraction. The blue and yellow lines correspond to evaluations based on 200 size fractions, while the red line is based on 31 fractions. The same applies to the evaluation of the particle parameter “aspect ratio”. Aspect ratio means the ratio between width (xc_min) and length (maximum Feret) of the particle, where values near 1 indicate circular particles. The results represent the average grain diameter (PSD) or aspect ratio for each size fraction. The shaded area in the graphics indicates the range in which grains are either too coarse to be fully detected or too few to form a statistically representative population, causing the values to become noisy.

The dune sand consists mainly of subangular grains with sharp edges and weathered surfaces; unlike the beach sand, plagioclase was frequently detected. Based on the values for aspect ratio derived from the xc-min in relation to the particle size fractions (shown in yellow for 200 fractions and in red for 31), the dune sand shows a general trend of increasing roundness with increasing grain size. However, when examining the blue circles (x_area), a small initial peak can be identified in the fine-sand fraction, followed by a slight decrease in ratio, after which ratio increases continuously toward the coarse-sand fraction. The presence of a bimodal pattern in the PSD curves supports this observation and indicates the need for further investigation.

On the other hand, the beach sand shows clearly higher aspect ratio values in the larger size fractions, coinciding with the peak of the PSD. Before and after this peak, roundness tends to be lower than for the most representative particle fractions. Similarly to the dune sand analysis, the red and yellow evaluations show good agreement in their particle parameter results, while the blue evaluation (x_area), although following the same overall trend as the other curves, yields lower values.



(a) (b)

Figure 5. PSD and aspect ratio of the beach sand (a) and dune sand (b) are shown based on the particle projection area (x_area) and the minimum chord length (xc_min), the latter evaluated for different particle size fractions (200 and 31).

4 Conclusion

This work deals with the initial steps towards the characterization of sandy soils by means of dynamic image analysis with focus on their grain shape. As this is an ongoing project aimed at building a geologically based geotechnical database for sandy soils, samples are continuously being added, previous tests are being refined, and new investigations are being included to better characterize non-cohesive soils. Using dynamic image analysis, it becomes evident that achieving high resolution and reliable grain-shape characterization strongly depends on the number of size fractions considered, as this directly affects the statistical representativeness of each fraction. Furthermore, the evaluation of PSD, mean particle size (d_{50}), uniformity coefficient (C_u), and particle parameters (here, aspect ratio) depends on whether particle size is defined by the approximate projected area of the particle or by its minimum chord length. The advantage of using xc-min as a measure of grain diameter is that it allows comparison with other studies, since sieve analysis—the standard, most widely used, and cost-effective method for determining PSD—is still the reference. However, due to the differences observed between the two methods when evaluating particle parameters (here, aspect ratio), the continued use of xc_min remains important. It is also important to consider the depositional environment of the sample, as well as its basic mineralogical composition.

References

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