

Microstructural Characterization of Post-Liquefaction Soil Using Scanning Electron Microscope (SEM) and Its Implications for Geotechnical Disaster Mitigation: A Case Study of Jono Oge

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Abstract: Liquefaction induced by the 2018 Palu Earthquake caused changes in geotechnical conditions in Jono Oge Village, Sigi Regency, while the microstructural characteristics of post-liquefaction soil at the particle scale remain limitedly investigated. This study aims to identify and compare the microstructural characteristics of liquefaction-affected and unaffected soils and to interpret their relationship with soil shear strength. Five samples were investigated, namely BH01 as the reference sample and BH02–BH05 as liquefaction-affected samples, using grain-size analysis, direct shear testing, and Scanning Electron Microscope (SEM) observations. The results show that liquefaction did not alter the basic morphology of the grains, which were predominantly angular to sub-angular, but variations occurred in microstructural organization, particularly in pore configuration, interparticle contacts, interlocking, microcracks, and fabric structure. These microstructural variations occurred together with differences in shear strength, with apparent cohesion of 0.19–0.31 kg/cm² (19.4–30.7 kPa in the direct-shear results) and internal friction angles of 24.70–42.77°. The findings indicate that microstructural organization, particularly contact networks, pores, and interlocking, is associated with variations in the mechanical behavior of post-liquefaction soil. However, this relationship cannot be directly attributed to liquefaction because of material heterogeneity and the limitations of the research design. SEM can be used as supporting information for integrated geotechnical evaluation together with field investigation and other geotechnical tests.

Keywords: Post-Liquefaction Soil, Soil Microstructure, Scanning Electron Microscope (SEM), Shear Strength, Jono Oge.

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I. INTRODUCTION

Liquefaction is the response of saturated soil, particularly loose granular materials, to cyclic loading that can increase pore-water pressure and reduce effective stress. Its effects may include loss of shear strength, permanent deformation, lateral spreading, ground settlement, and disruption of infrastructure. The 28 September 2018 Palu Earthquake is an important example because it produced large-scale ground deformation in several areas of Central Sulawesi. In Jono Oge, a flow-slide phenomenon was recorded with very long-distance soil-mass displacement despite the relatively gentle terrain slope (Hazarika et al., 2021). This condition makes the post-event soil characteristics important to investigate not only at the field scale but also at the particle scale.

Previous studies in the Palu area indicate that liquefaction mechanisms are associated with a combination of sediment conditions, groundwater level, layer characteristics, and earthquake loading. Jalil et al. (2021) emphasized the role of loose materials, groundwater conditions, and sediment characteristics in the occurrence of mudflows, while Andiny et al. (2021) showed that the Jono Oge affected area remains relevant for assessing re-liquefaction potential. These studies provide important information on macro-geotechnical conditions, but they do not specifically explain how particles and pore spaces are organized after liquefaction.

In granular materials, particle arrangement, grain shape, surface texture, interparticle contacts, and pore systems form the fabric that contributes to force transfer. Image-based analysis has been used to relate particle

characteristics to the mechanical response of granular materials (Fonseca et al., 2016). Changes in contact networks may also be associated with the evolution of material response during loading (Cheng & Wang, 2018), while particle-shape variations are known to affect packing, stiffness, and strength of granular materials (Hatefi et al., 2024). Therefore, microstructural observations can complement the interpretation of variations that cannot always be identified from macroscopic physical parameters.

Scanning Electron Microscope (SEM) provides high-resolution images for observing surface morphology and particle arrangement at the micrometer scale. In soil research, SEM has been used to identify pores, surface texture, interparticle relationships, aggregation, and fabric characteristics (Goldstein et al., 2018). Studies of soils subjected to cyclic loading have also shown that deformation can be accompanied by changes in contact configuration, pore structure, and micro-damage (Xiu et al., 2020). For post-liquefaction soils, Wang et al. (2025) reported microstructural changes associated with particle and pore-system reorganization following an earthquake. These findings demonstrate the potential of the microstructural approach, although the characteristics of each deposit remain dependent on local materials and geological conditions.

This study focuses on seven aspects of microstructure: particle shape, surface texture, micro-pores, interparticle contacts, interlocking, microcracks, and fabric structure. BH01 was used as the reference location unaffected by liquefaction, whereas BH02–BH05 were obtained from affected zones. SEM data were interpreted together with grain-size distribution and direct shear test results. The approach was not intended to directly determine residual strength or to prove a single causal relationship between liquefaction and one microstructural feature, but rather to identify configurations that may help explain variations in the mechanical behavior of post-event soils. The objective was to identify and compare microstructural characteristics among site conditions and interpret their relationship with shear-strength parameters as supporting information for an initial geotechnical evaluation.

II. EXPERIMENTAL PROCEDURE

2.1 Study Area and Sample Design

The research was conducted in Jono Oge Village, Sigi Regency, Central Sulawesi, Indonesia, in deposits associated with the 2018 Palu Earthquake liquefaction event. Five borehole locations were used. BH01 represents the reference location unaffected by liquefaction, while BH02, BH03, BH04, and BH05 are located in the affected zone. Undisturbed samples from the lower layer at approximately 3 m depth were used for SEM and direct shear testing, whereas disturbed samples representing the material condition were used for grain-size distribution analysis.

The grouping of BH01 and BH02–BH05 was used as the basis for comparison, rather than as a before-and-after comparison of the same soil at the same location. Therefore, differences among samples were treated as variations in the material and microstructure observed at the study locations. Sediment heterogeneity was an important consideration in the interpretation.

2.2 Testing and Analysis

Grain-size distribution was determined using sieve analysis in accordance with ASTM D6913/D6913M-17 (ASTM International, 2017). Parameters D₁₀, D₃₀, D₆₀, Cu, Cc, and the percentage passing No. 200 sieve were calculated when the required data were available. Because hydrometer analysis was not performed, samples with D₁₀ below 0.075 mm were not forced to obtain Cu and Cc. The results were used primarily to describe material characteristics and support the microstructural interpretation.

Direct shear tests were conducted on undisturbed samples at three levels of normal stress: 10.4, 20.8, and 31.2 kPa. The Mohr–Coulomb failure envelope was determined from peak shear stress. The parameters used in this article are apparent cohesion and internal friction angle. Apparent cohesion was treated as the regression intercept, rather than as true cohesion or residual strength.

SEM observations were performed on BH01–BH05 samples at image magnifications of approximately 500–3000×. Seven parameters were qualitatively observed: particle shape, surface texture, micro-pore, particle contact, interlocking, microcracks, and fabric structure. Identification was based on features visible in two-dimensional images. Terms such as apparent connected pore and cementation-like feature were not used to claim three-dimensional pore connectivity or confirmed mineral cementation. Microcracks were also interpreted cautiously because some cracks may have been influenced by sample preparation.

Final analysis was conducted integratively. Grain-size distribution was used to understand material characteristics; SEM was used to describe internal organization; and direct shear testing was used as supporting data for interpreting variations in mechanical response. No statistical correlation was performed between SEM variables and shear strength.

Table 1. Summary of the research sample design

Sample	Site condition	Main sample depth	Main analyses
BH01	Unaffected by liquefaction	±3 m	SEM, direct shear, gradation
BH02	Liquefaction-affected zone	±3 m	SEM, direct shear, gradation
BH03	Liquefaction-affected zone	±3 m	SEM, direct shear, gradation
BH04	Liquefaction-affected zone	±3 m	SEM, direct shear, gradation
BH05	Liquefaction-affected zone	±3 m	SEM, direct shear, gradation

III. RESULTS AND DISCUSSIONS

3.1 Material Characteristics and Shear Strength

Based on sieve analysis, all study locations were generally dominated by sand fractions, with different fines contents among layers. BH01 showed 17.70% and 12.38% passing No. 200 sieve for L1 and L2, respectively, whereas samples from the affected zone contained approximately 0.36–6.31% fines. Most post-liquefaction samples were classified as poorly graded sand (SP), while BH04L2 was treated as a tentative classification. BH01 was not classified using C_u and C_c because D_{10} could not be determined from the sieve range used. These differences in fines content indicate material heterogeneity and should be considered when comparing microstructures.

Direct shear testing showed variations in shear-strength parameters among the sampling points. Apparent cohesion ranged from 19.4 to 30.7 kPa, while internal friction angle ranged from 24.70° to 42.77° . BH02 had the highest internal friction angle at 42.77° , BH04 had the lowest at 24.70° , and BH05 produced an apparent cohesion of 30.7 kPa with $\phi = 37.72^\circ$. These ranges show that the affected-zone samples did not exhibit uniform mechanical responses. Because direct shear testing was performed under laboratory conditions and only three normal-stress levels were used, these values are treated as test parameters for the samples rather than representations of field residual strength.

Table 2. Shear-strength parameters from direct shear testing

Sample	C_a (kPa)	ϕ ($^\circ$)	R^2
BH01	19.4	36.99	0.80
BH02	22.8	42.77	0.94
BH03	29.1	37.78	0.94
BH04	24.2	24.70	0.97
BH05	30.7	37.72	0.97

Figure 1. Variation in apparent cohesion (C_a) among the study samples

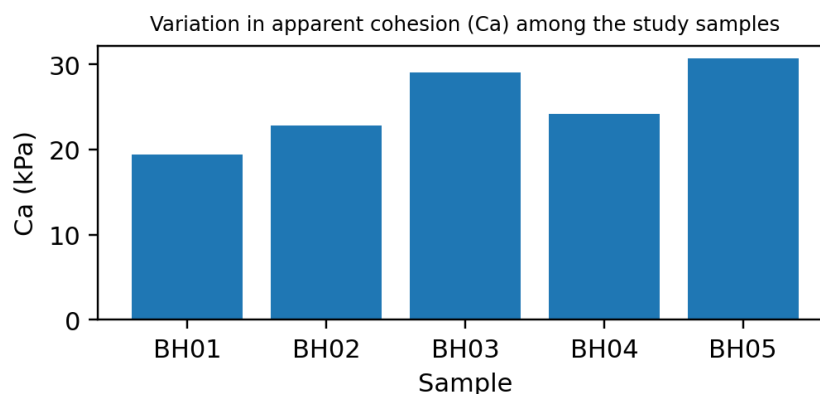
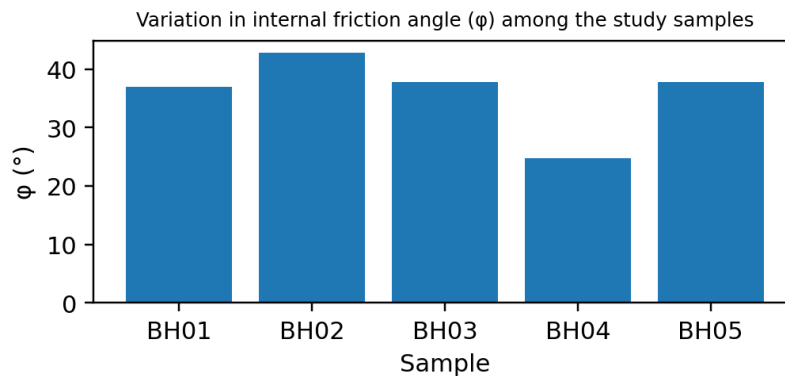
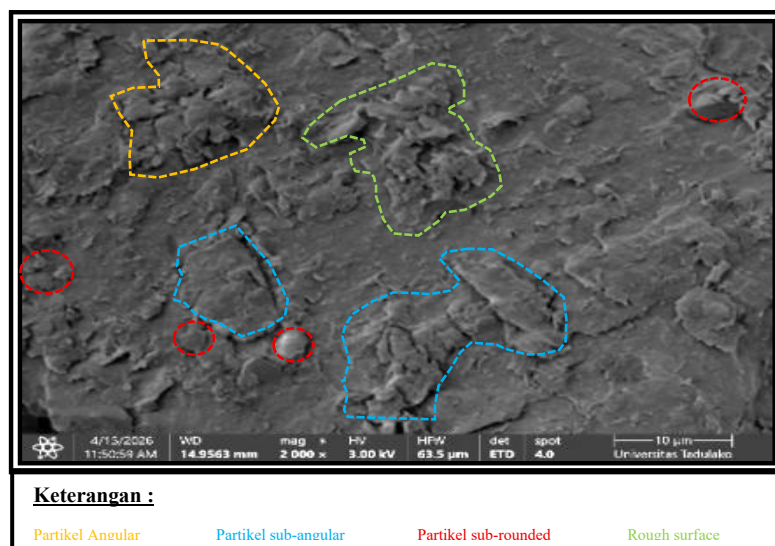


Figure 2. Variation in internal friction angle (ϕ) among the study samples

3.2 Microstructural Characteristics Based on SEM

SEM observations show that particle shapes in BH01–BH04 were generally angular to sub-angular. Sub-rounded particles occurred locally in BH02 and BH03, while BH05 showed aggregates with more distinct platy morphology. Thus, the basic particle morphology was relatively similar across most samples and did not form a pattern that could be directly attributed to liquefaction. Particle shape is more appropriately treated as a material characteristic that provides context for interpreting contacts and interlocking. This limitation is important because SEM images represent only two-dimensional planes and do not quantitatively measure roundness or sphericity.

Surface texture in all samples was dominated by rough surfaces characterized by irregular micro-relief, asperities, and fractured planes. BH01–BH04 showed combinations of rough surfaces with local variations including smooth surfaces and granular coatings, while BH04 showed portions of surfaces covered by fine matrix. In BH05, layered and flaky textures were more evident on platy aggregates. Surface roughness may mechanically influence contact characteristics and shear interaction, but in this study the texture differences were treated as local morphological variations because their frequency was not quantified across the entire soil mass.

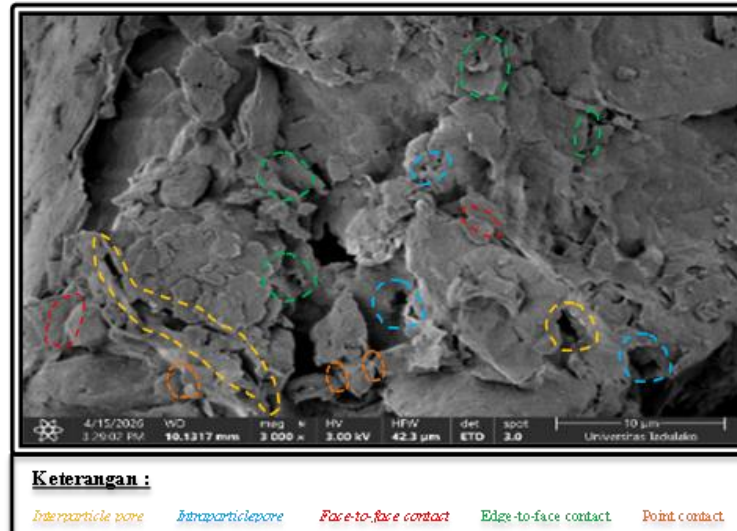
Figure 3. Variation in particle shape and surface texture based on SEM images of the soil samples.

The pore system showed interparticle pores in all samples, accompanied by intraparticle pores, intra-aggregate pores, inter-aggregate pores, and open pores. In some image fields, voids appeared to be connected and were therefore described as apparent connected pores. These observations indicate the configuration of void space within the observed plane, but they cannot confirm three-dimensional pore connectivity. Variations in pore type and arrangement are more informative than changes in grain shape because they are directly associated with packing patterns and the available void space.

Identified interparticle contacts included face-to-face contact, edge-to-face contact, point contact, aggregated contact, matrix-mediated contact, and cementation-like features. BH01 tended to show direct

interparticle contacts, whereas BH02–BH05 showed more diverse contact configurations and, in some fields, involvement of fine material. Cementation-like features were identified only from SEM morphology and cannot be considered evidence of mineral cementation because the study was not complemented by EDS or XRD.

Figure 4. Variation in micro-pores and interparticle contacts based on SEM images of the soil samples



Interlocking configurations included mechanical interlocking, geometrical interlocking, matrix-supported interlocking, flake-to-flake interlocking, and particle-bridging-like features. The observed fabrics included porous/open fabric and random orientation in BH01; aggregated and matrix-supported fabric in BH02; aggregated and dense interlocked fabric in BH03; matrix-supported and massive fabric in BH04; and aggregated fabric with stacked orientation in BH05. These variations indicate that microstructural response is not controlled by a single parameter. Fabric results from the combined effects of particle shape, pores, contacts, interlocking, aggregation, and fine material.

Microcracks were observed as intraparticle and interparticle cracks, branching cracks, linear discontinuities, crack openings, and microspalling in certain image fields. These cracks provide information on micro-scale discontinuities, but not all can be considered to have formed as a result of liquefaction. Sample preparation, drying, and cutting may generate or enlarge cracks at the micro scale. Therefore, microcracks were used as descriptive indicators rather than as sole evidence of earthquake-induced damage.

Figure 5. Variation in interlocking, microcracks, and fabric based on SEM images of the soil samples.

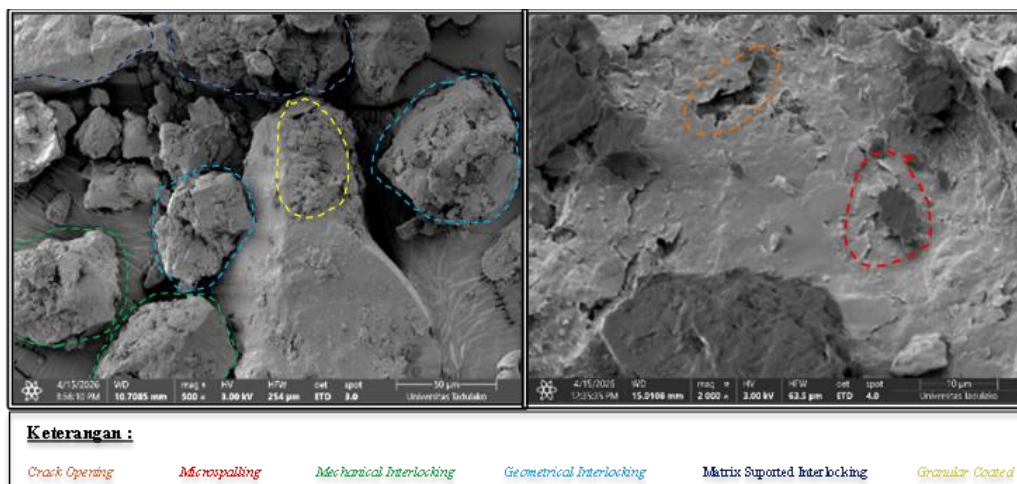


Table 3. Synthesis of the main microstructural characteristics

Aspect	BH01	BH02–BH05	Interpretation
Particle shape	Angular–sub-angular	Angular–sub-angular; local sub-rounded; clearer platy morphology in BH05	No consistent change in basic morphology
Surface texture	Predominantly rough	Predominantly rough with local layered/flaky/granular coating	Local variation in surface topography
Micro-pores	Predominantly interparticle	Interparticle, intra-/inter-aggregate, intraparticle, open and apparent connected	Variation in 2D pore-space configuration
Contact	Predominantly surface point contact	More diverse direct and matrix-mediated contacts	Contact networks vary among image fields
Interlocking	Predominantly mechanical interlocking	Mechanical, geometrical, matrix-supported, flake-to-flake	Different local interlocking geometries
Fabric	Porous/open, random orientation	Aggregated, matrix-supported, dense interlocked, massive	Fabric results from combined microstructural parameters

3.3 Relationship Between Microstructure and Mechanical Behavior

Comparison of SEM observations and direct shear results shows that variations in mechanical response can be interpreted more meaningfully when contact networks, interlocking, pores, and fabric are considered together. BH02, for example, showed visually denser contact and interlocking configurations in several image fields and had an internal friction angle of 42.77° . In contrast, BH04 showed the presence of fine matrix and local discontinuities in several fields and produced $\phi = 24.70^\circ$. This descriptive agreement indicates that microstructural organization may be associated with shear response, but it is insufficient to establish a causal relationship because density, water content, fines fraction, specimen condition, and sediment heterogeneity were not quantitatively controlled.

BH03 and BH05 demonstrate that different microstructures do not necessarily produce substantially different shear-strength parameters. BH03 had $\phi = 37.78^\circ$ and $\text{Ca} = 29.1 \text{ kPa}$, whereas BH05 had $\phi = 37.72^\circ$ and $\text{Ca} = 30.7 \text{ kPa}$. This supports the interpretation that no single microstructural feature independently controls shear strength. In granular materials, mechanical response is more appropriately understood as the result of interactions among contact networks, particle shape and texture, pore configuration, interlocking, and fabric.

The findings also show that liquefaction-affected status did not produce a uniform pattern of shear-strength parameters. The ϕ value of BH02 was relatively high, whereas BH04 was relatively low; at the same time, Ca increased from BH01 toward several affected samples. These variations cannot be interpreted as evidence that liquefaction directly increases or decreases shear strength. The differences may reflect post-disaster material conditions, local reorganization, and deposit heterogeneity. Therefore, direct shear testing in this study serves as supporting evidence for interpreting mechanical response rather than as a direct measure of post-liquefaction residual strength.

3.4 Implications for Geotechnical Evaluation and Mitigation

Integration of the data shows that SEM can provide additional information about the internal condition of soil that cannot be obtained from grain-size distribution alone. Information on pore configuration, contacts, interlocking, microcracks, and fabric can help identify variations in particle organization in post-liquefaction soil. In an initial evaluation context, this information can be used together with field data and conventional testing to determine the need for further investigation, particularly at locations with a history of deformation or liquefaction.

However, SEM results should not be used as the sole basis for selecting soil-improvement methods. Mitigation decisions require CPT/SPT data, the depth of susceptible layers, groundwater level, fines and plasticity, relative density, soil-structure conditions, and evaluation of liquefaction or re-liquefaction potential. Methods such as densification, drainage, stone columns, or soil mixing may be considered under appropriate conditions, but their selection must be based on site-specific investigation and technical analysis.

The main contribution of this study is to provide a description of post-liquefaction microstructure in Jono Oge and to show that differences in mechanical behavior cannot be explained by grain morphology alone. Interpretation is more appropriately focused on internal organization, particularly the relationships among pores,

contacts, interlocking, and fabric, while recognizing the limitations that SEM images are two-dimensional and that the analysis is qualitative.

IV. CONCLUSION

The soils at the study locations were generally dominated by sand materials with variations in fines and gradation, while the microstructure showed combinations of angular–sub-angular particle shapes, rough surfaces, various pore and contact configurations, interlocking, microcracks, and fabric. Differences between BH01 and BH02–BH05 did not show a consistent change in basic grain morphology; therefore, the post-liquefaction condition is more informatively examined through internal particle organization than through grain shape alone.

Direct shear parameters varied, with apparent cohesion of 19.4–30.7 kPa and internal friction angles of 24.70–42.77°, but the variations did not form a single pattern based on liquefaction-affected status. The agreement between microstructural configurations and shear response is interpretive and does not establish causality. Thus, SEM can serve as supporting information in the evaluation of post-liquefaction soil conditions when integrated with field investigation, grain-size distribution, and conventional geotechnical testing.

Conflict of interest

There is no conflict to disclose.

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