



New Insights into the Rheological Behavior of Soft Sediments: Integration of mechanical Testing and Numerical Modeling in Lake Urmia

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Abstract

Understanding the rheological behavior of soft marine and lacustrine sediments is crucial for the success of geotechnical and civil engineering projects. Coastal and offshore structures such as artificial islands, lake causeways, piers, and oil platforms directly interact with these sediments. Their safe and stable performance depends on accurate characterization of sediment behavior under complex loading conditions. This study investigates the rheological properties of soft sediments from Lake Urmia, Iran, through a combined experimental and numerical approach. Two key tests were performed: extrusion tests and unconfined compression tests. The extrusion tests were conducted on both undisturbed and remolded samples under various conditions, including different loading rates, moisture contents, and discharge orifice sizes. For the numerical simulation, the Bonded Particle Discrete Element Method (BPDEM) was employed, with the model's micro-parameters calibrated using experimental extrusion test data. The numerical results showed excellent agreement with experimental data: the force-displacement curve was replicated with less than 2% error. The calibrated model also successfully simulated the unconfined compression test, reproducing the stress-strain curve with less than 2% deviation from laboratory results. These findings demonstrate the accuracy of BPDEM in modeling soft sediment behavior. The results indicate that integrating laboratory methods with BPDEM modeling provides a powerful tool for analyzing soft sediments. This approach is particularly effective for Holocene and Late Pleistocene soft to ultra-soft sediments, offering reliable predictions of rheological and mechanical behavior in geotechnical applications.

1. Introduction

The development of civil offshore infrastructures such as artificial islands, traffic causeways, and oil/gas pipelines in seas and lakes provides clear examples of direct structure-sediment interaction. The accurate prediction of settlement during both construction and operation phases, along with comprehensive evaluation of long-term stability under static and dynamic

loading conditions, highlights the critical importance of understanding the mechanical behavior of soft marine and lacustrine sediments under complex loading scenarios. These factors fundamentally govern the safety, durability, and performance of coastal and offshore infrastructure projects throughout their service life.



Semi-consolidated or uncompleted consolidated sediments, often described as being in an underconsolidated state, are typically associated with Holocene sediments (less than 11,700 years old) and Late Pleistocene formations (less than 126,000 years old). Elevated pore water pressures are sometimes observed in these sediments. Regardless of the mechanism leading to underconsolidation, its effects remain consistent: reduced shear strength and significantly increased deformability of the soil [1]. Such subsoils do not undergo full consolidation under applied loads but instead experience slow, time-dependent creep deformations. In many cases, the actual response of soft cohesive soils deviates substantially from the generalized assumptions of classical soil rheomechanical models. When modeling these environments, the rheological flow properties that capture rate- and time-dependent behavior must be considered alongside their rheomechanical properties. Deformation in these materials generally follows a time-dependent function characterized by decreasing strain rates. However, in certain cases, the deformation rate may remain constant over extended periods. The rheological behavior of these soils sometimes resembles that of a non-Newtonian fluid with high viscosity and yield stress [1].

Accurate estimation of the behavior of soft and semi-solid lakebed sediments is of paramount importance in civil and geotechnical engineering, particularly in constructing offshore structures and sensitive infrastructure. Insufficient understanding of the rheological properties of these sediments can lead to significant errors in predicting settlements and dynamic responses, thereby increasing project risks. Moreover, the lack of standardized testing and modeling methods for such materials highlights the critical need for comprehensive and integrated laboratory and numerical investigations.

Studies on the rheological properties of clay soils in the early twentieth century initially focused on applying Newtonian viscous flow mechanisms. Temmann defined plasticity as the reverse of viscosity, equating it to fluidity. Maxwell described plastic materials as those capable of undergoing permanent deformation once a certain stress threshold is exceeded. Bingham introduced the concept of plastic flow

and distinguished between viscous and plastic flow based on the concentration of solid particles [2]. In decades, Terzaghi and Hvorslev conducted long-term creep tests on soils [3, 4], emphasizing the importance of post-elastic behavior. Based on these fundamentals, researchers including Haefeli and Schaerer, Casagrande and Wilson, and Geuze and Tan applied Bingham's viscoplastic laws to soil analysis [5-7].

Numerous studies have expanded classical consolidation theories and investigated the role of effective stresses and environmental factors, such as organic matter and salinity, in sediment behavior [8-10]. The orifice-extrusion apparatus is commonly used to determine rheological parameters of non-Newtonian and paste industrial materials, including notable studies by Benbow and Bridgwater [11]. Basterfield et al. developed an analytical model for the extrusion of viscoplastic pastes [12]. Engmann et al. applied squeeze flow to determine rheological properties [13]. Shao et al. reported pronounced rheological behavior in soft soils subjected to large strains [14]. Zhou et al. employed orifice extrusion to determine rheological parameters of fresh cement paste and mortars [15]. Widjaja and Lee developed a flow-box apparatus based on the Bingham model to measure soil viscosity [16]. Yang et al. investigated the shear-dependent rheology of naturally concentrated cohesive sediments and found that their behavior is well described by the Herschel-Bulkley and Casson models [17]. Ebrahimnezhad and Badv demonstrated that the flow behavior of soft sediments with a liquidity index from 0 to 1 is well characterized by the shear-thinning Herschel-Bulkley model, and their intrinsic rheological parameters can be determined using the reverse orifice extrusion test [18].

Despite considerable progress in understanding the rheological behavior of soft sediments, no unified or comprehensive standard yet exists for testing equipment, loading rates, or analytical procedures. Existing analytical models, such as that proposed by Basterfield, are useful but remain insufficient for fully capturing the complex behavior of these sediments. Furthermore, integration of laboratory data with numerical modeling in order to accurately reproduce the real behavior and dynamic

response of sediments continues to represent a major challenge.

Numerical methods based on the Particle Flow Code (PFC) have demonstrated their capability in simulating fracture mechanisms and crack propagation in hard and quasi-brittle materials [19-21]. The application of this approach to the rheological behavior of soft materials, which exhibit large deformations and nonlinear responses, has been scarcely investigated. This study employs an integrated experimental-numerical approach, using data from extrusion and uniaxial compressive tests, to model the rheology of soft sediments with the Particle Flow Code, enabling a more detailed analysis of deformation and fracture mechanisms in these materials.

The primary objective of this research is to investigate and analyze the rheological behavior of soft sediments in the bed of Lake Urmia using an integrated laboratory-numerical approach. The novelty of this study lies in the integration of experimental data from orifice extrusion tests to enhance numerical modeling and achieve more accurate predictions of viscoplastic behavior. The outcomes of this research are expected to significantly contribute to improving the design and safety of offshore structures while reducing associated geotechnical risks.

2. Theory and Fundamental Principles

2.1. Orifice Extrusion Test

Semi-solid paste-like materials exhibit complex behavior, including elastic, viscous, and

Figure

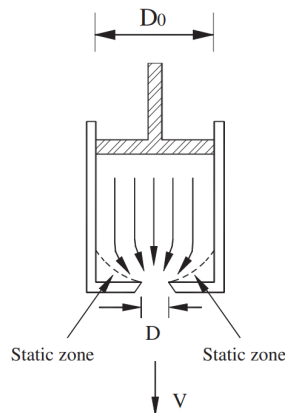


Figure 1. Mechanism of the orifice extrusion test [15]

plastic properties. Theoretically, the rheological behavior of these materials should be described as elasto-viscoplastic. Based on Herschel-Bulkley relationships, the shear stress of these materials with nonlinear viscosity under uniaxial flow is expressed as follows [22]:

$$s = \tau_0 + k_s \dot{\gamma}^n \quad \text{for } \tau \geq \tau_0 \quad (1)$$

$$\sigma = \sigma_0 + k_u (\epsilon^{vp})^n \quad \text{for } \sigma \geq \sigma_0 \quad (2)$$

where σ is the equivalent stress, σ_0 is the yield stress, k_u is the consistency coefficient, n is the uniaxial flow index, and ϵ^{vp} is the equivalent viscoplastic strain rate. These parameters are typically determined through rheometry and extrusion tests.

In the orifice extrusion process, due to the dominance of plastic strain over elastic strain, materials are modeled as rigid-viscoplastic (Figure 1). In the orifice entry zone, the material undergoes shear and plastic deformation, creating a viscoplastic flow. The flow can be described using theoretical analyses based on the Herschel-Bulkley equations. The primary objective of using an orifice extrusion device is to calculate the parameters of the viscous component.

Theoretical analyses of orifice extrusion are primarily based on classical plasticity theory, reflecting the rate-dependent response of materials subjected to large deformations. One notable analytical model was proposed by Basterfield et al. and is expressed by Equation 3 [12]. This model employs a spherical coordinate system (Figure 2) and makes the following assumptions:

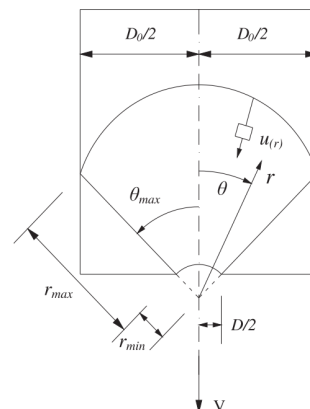


Figure 2. Orifice extrusion flow in polar coordinates [15]

$$P = -\sigma_{rr}(r_{max}) = 2\sigma_0 \ln \frac{D_0}{D} + Ak \left(\frac{V}{D} \right)^n \left(1 - \left(\frac{D}{D_0} \right)^{3n} \right) \quad (3)$$

$$A = \frac{2}{3n} (\sin \theta_{max} (1 + \cos \theta_{max}))^n \quad (4)$$

In the above relations, the parameters V , D , and D_0 represent the material extrusion velocity, orifice diameter, and reservoir diameter, respectively. The parameter (V/D) denotes the nominal extensional strain rate ($\dot{\epsilon}$). To calculate the yield shear stress from the uniaxial flow yield stress, Equation 5 is used, which is derived from the Von Mises criterion. For determining the shear stress and other deposition parameters, Equation 3 can be simplified into Equation 6, a three-parameter equation. Also, these parameters - yield stress, consistency, and flow index - are essential for proper curve fitting.

$$\tau_0 = \frac{\sigma_0}{\sqrt{3}}, \quad k_s = \frac{k_u}{\sqrt{3}^{n+1}} \quad (5)$$

$$p = a + c \left(\frac{V}{D} \right)^b \quad (6)$$

However, this analytical method has limited accuracy in fully predicting the complex behavior of semi-solid materials and cannot capture all real viscoplastic characteristics. Therefore, this study employs experimental data—particularly extrusion pressure versus displacement curves—as the primary input for numerical modeling. Numerical simulation enables more accurate modeling and greater flexibility in representing the actual behavior of soft sediments, effectively overcoming the limitations of the analytical approach.

2.2. Numerical Modeling of Discrete Elements with Bonded Particle

The Bonded Particle Method (BPM), an advanced extension of the Discrete Element Method (DEM), has been developed to simulate the mechanical behavior of granular, rock, and soil materials, particularly under discontinuous or quasi-continuous conditions [23-25]. In this

approach, the material is modeled as an assembly of rigid particles that can be mechanically bonded at their contact points. These particles may take the form of discs in 2D models or spheres in 3D models, with non-uniform size distributions. Particle interactions occur at contact points through normal and shear forces with finite stiffness. Mechanical bonds (e.g., parallel bonds) facilitate the transfer of forces and moments, as well as model bond failure under critical stresses. Consequently, the particle assembly can exhibit complex mechanical behaviors, including plastic deformation, failure, and time-dependent rheological responses a critical capability for modeling soft sediments, such as those found in Lake Urmia's bed sediments.

The motion of each particle is calculated independently based on Newton's laws. Forces and torques from particle contacts, boundary walls, and loading conditions are computed at each timestep, updating particle positions and velocities [26]. This dynamic approach enables the BPM to effectively simulate nonlinear behavior and initial condition dependency. For modeling the rheological behavior of soft sediments in extrusion tests, we employed BPM with parallel bonds that simultaneously transfer normal and shear forces as well as bending moments at contacts. These capabilities are crucial for accurately simulating saturated sediments with high moisture content. The model was calibrated using laboratory data from extrusion and unconfined compression strength (UCS) tests. This calibration established correlations between measurable macro-parameters and simulation micro-parameters, demonstrating excellent agreement between numerical and experimental results. Key BPM components including disk-shaped particles, bonds, boundary walls, forces, and boundary conditions are illustrated in Figure 3 [27].

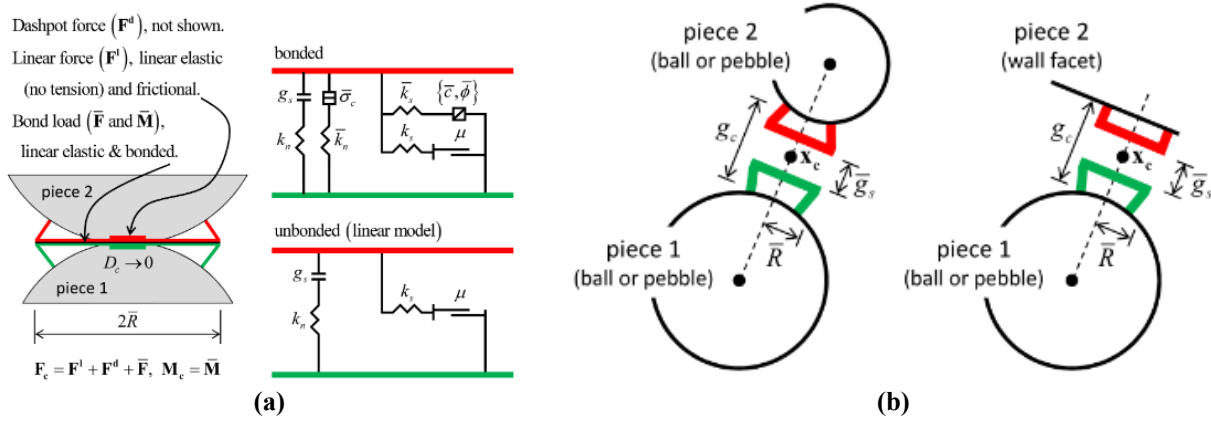


Figure 3. Components of the Bonded Particle Modeling approach: a) Various components of parallel bonds b) Disc-to-disc and disc-to-wall bonds [27]

3. Materials and Methodology

This study investigates the mechanical and rheological behavior of soft sediments from Lake Urmia through an integrated experimental and numerical approach. The research methodology encompasses field sampling, comprehensive laboratory testing (including physical, geochemical, mechanical, and rheological analyses), and numerical modeling of extrusion and UCS tests. For the numerical simulation of sediment behavior under loading, we employed the Discrete Element Method using bonded particles (BPM). The modeling process involves:

- Physical problem modeling based on laboratory conditions (sediment and apparatus).
- Micro-parameter calibration using macroscopic experimental parameters.
- Model validation and micro-parameter verification through UCS test simulation.

3.1. Materials and Study Area Introduction

Lake Urmia, Iran's most significant continental hypersaline environment, possesses distinctive geological characteristics. Over the past two decades, its water level has dropped by approximately 8 meters, with dissolved salt concentrations exceeding 300 g/L—more than eight times the salinity of ocean water [28]. The studied sediments in this hypersaline

environment have formed under extreme salinity conditions and are rich in evaporite minerals such as halite, exhibiting unique physical and mechanical properties. Radiocarbon (C-14) dating estimates the age of the upper 5 meters of sediments at 7,000 to 9,000 years, with a sedimentation rate of approximately 0.8 mm/year. Furthermore, sediments extending to 35 meters depth in the lake bed are estimated to be 70,000 to 117,000 years old, consisting primarily of allochthonous sediments of marine fauna origin [29].

Sampling of Holocene lakebed sediments was conducted at km 10+700 of the Urmia causeway, where materials had been upwelled during embankment construction. Both disturbed and undisturbed (monolith) samples were collected from 1-meter depth on the causeway's southern flank to preserve natural structural and environmental characteristics. All samples were stored in airtight containers protected from sunlight to prevent chemical and physical alterations (evaporation, oxidation, thermal changes) and to maintain anaerobic conditions according to **ASTM D1587**. As most mechanical and rheological tests required remolded samples, sediments were homogenized using mechanical mixing. Subsequently, samples were remolded under controlled moisture conditions (33, 35, 37.5, 40, 43.5, 45, and 50%) as shown in Figure 4.

Figure

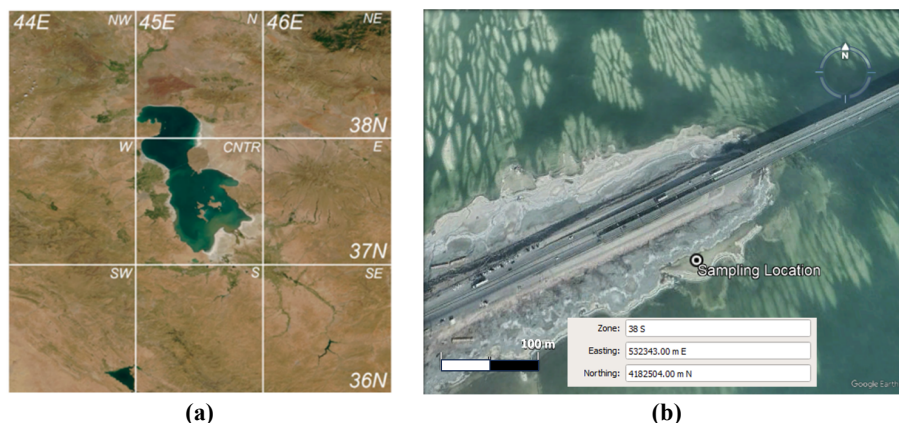


Figure 4. Case study site: a) Lake Urmia, b) Location of sampling

3.2. Geochemical and Physical Properties of Sediments

3.2.1. Geochemical Testing

Sediment mineralogy, chemical composition, and elemental analysis were characterized using scanning electron microscopy (SEM), X-ray diffraction (XRD), X-ray fluorescence spectroscopy (XRF), and inductively coupled plasma optical emission spectroscopy (ICP-OES). Seven major elements (Ca, Na, Al, Fe, K, S, and Ti) exhibited high concentrations (thousands of ppm). XRD and XRF analyses revealed that the lakebed sediments primarily originated from surrounding limestone and volcanic rocks, which underwent significant diagenesis and alteration over time. Periodic drought events and intense evaporation promoted salt precipitation across the lake surface. Clay minerals (illite, muscovite, and smectite) account for only 20% of the sediment composition, significantly less abundant than fine-grained particles ($<5 \mu\text{m}$). This indicates that physical

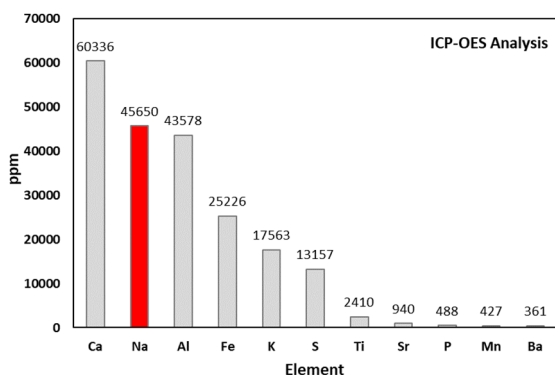


Figure 5. The major elements constituting the sediment

processes and comminution—or the primary fine-grained mineralogy of the rocks had a more dominant influence than hydrochemical weathering and rock decomposition. Climatic factors appear to have played a relatively minor role in rock weathering. The LOI (Loss on Ignition) index, commonly used as an estimate of organic matter content, accounts for approximately 21% of the sample's mass (see Figure 5-Figure 8).

3.2.2. Physical Tests

To evaluate the combined effects of organic matter and salt on the sediment's physical properties, systematic double hydrometer tests and Atterberg limits analyses were performed on four sample groups: 1) air-dried natural sample (reference), 2) oven-dried natural sample, 3) air-dried desalinated sample, and 4) oven-dried desalinated sample. Results are summarized in Table 1 [30].

Table 1

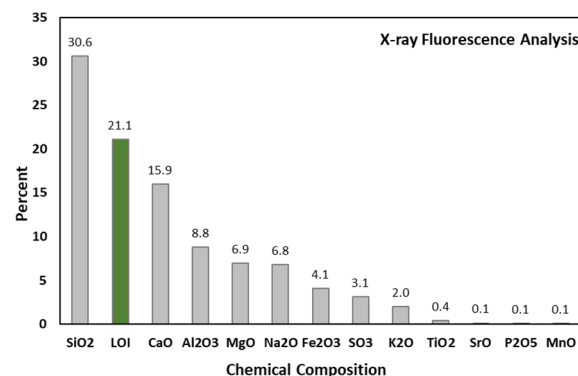


Figure 6. The chemical composition of the sediment.

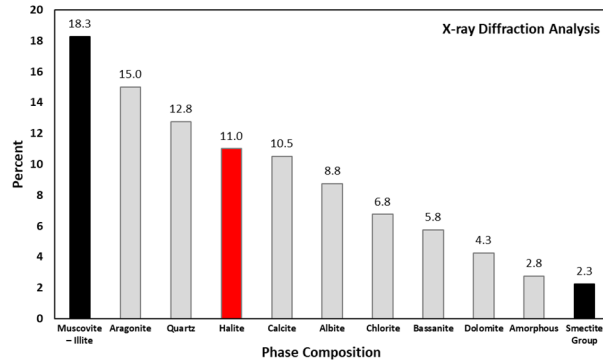


Figure 7. The mineralogical composition of the sediment

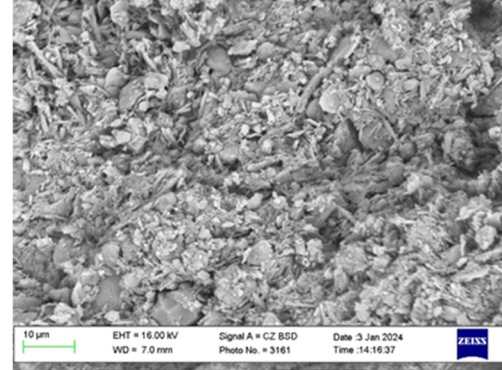


Figure 8. Scanning electron microscope (SEM) image of the sediment – magnification 2000×

Table 1. Physical properties of the reference and desalinated sediments.

Soil Sample	Specific Gravity	Percent Passing Finer, %			Atterberg Limits, %			Soil Classification	Activity Number	Flow Index	Toughness Index
	G_s	75µ	5µ	2µ	LL	PL	PI	USCS	A= PI/CF	If	IT=PI/If
Natural	2.58	90	51	15	57	31	26	MH	1.73	15.5	1.68
Desalinated	-	90	72	55	60	31	29	MH/CH	1.93	12.2	2.38

Figure 9 displays hydrometer test results in distilled water for both natural and desalinated sediments, before and after organic matter removal using hydrogen peroxide. The clarification of the mixture in the reference sample suggests that the final concentration can be attributed to soluble salts. Comparison of hydrometer curves between the reference and desalinated samples indicates approximately 8% salt content, which agrees well with the halite percentage measured by XRD analysis. Upon addition of hydrogen peroxide, vigorous gas evolution and organic matter oxidation were observed for several days. The measured mass loss during organic matter removal was 20.1%, consistent with the LOI (Loss on Ignition) value obtained from XRF analysis. Figure 10 presents the hydrometer test results in sodium hexametaphosphate solution for both reference and desalinated samples before and after organic matter removal with H_2O_2 . Organic-free desalinated samples have a coarser grain size than organic-rich ones—a key feature of hypersaline sediments. This likely stems from high polyvalent ion concentrations, acidic organic functional groups (e.g., sulfonate/carboxylate),

and unique EPS properties. Notably, salts act as soil electrolytes that neutralize particle charges - their removal increases surface charges, preventing fine particle approach and flocculation. This electrochemical stabilization mechanism explains the observed dispersion behavior in these hypersaline environments.

Figure 11 presents the flow curves of the samples along with their corresponding fitted equations. Based on the BS 5930 plasticity chart, the reference sample is classified as MH, while the desalinated sample falls under CH/MH classification (Figure 12).

The ratios of Atterberg limits, plasticity index (PI), flow index (If), and toughness index (IT) for different samples compared to the reference sample are presented in Figure 13. The plasticity index increases by 12% with desalination but decreases by 43% with heating. The liquidity index decreases by 21% with desalination but remains unchanged with heating. The toughness index increases by 43% with desalination and decreases by 43% with heating, indicating that sediment resistance to deformation increases with desalination but decreases with heating.

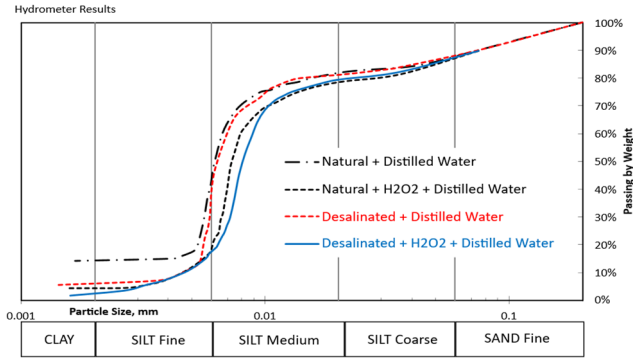


Figure 9. Hydrometer test results of the samples using distilled water

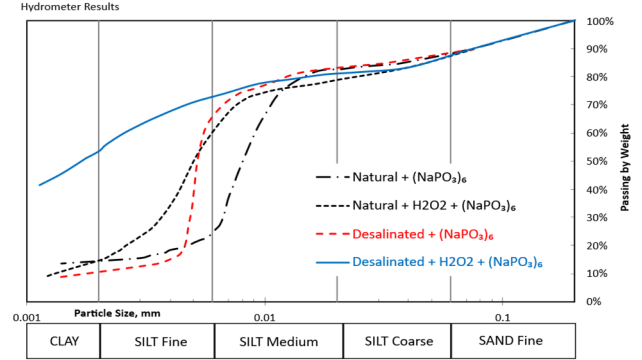


Figure 10. Hydrometer test results using Stokes' solution

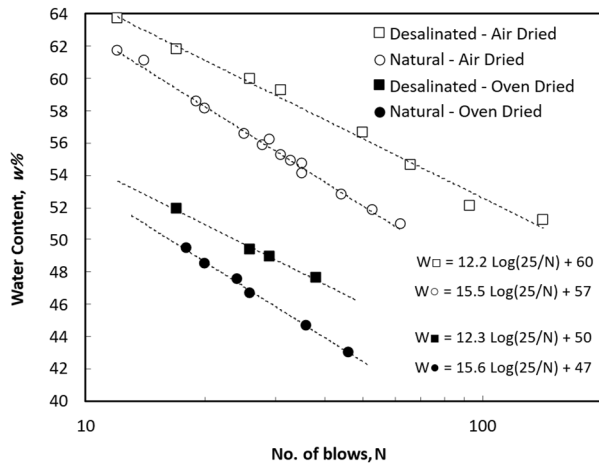


Figure 11. Flow curves of sediment samples

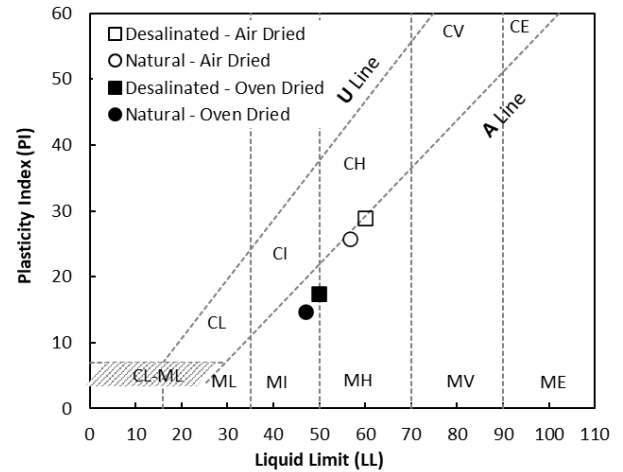


Figure 12. Plasticity characteristics of samples

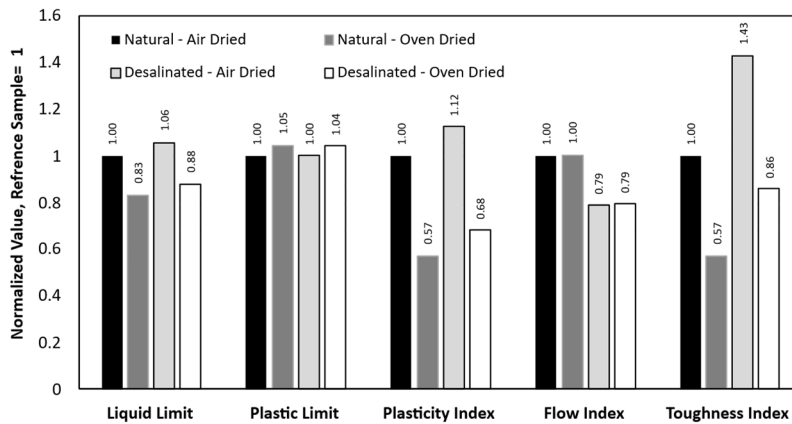


Figure 13. Comparison of normalized values relative to the reference sample

The Marsh funnel is a simple yet essential tool widely used in petroleum drilling and rheology laboratories to measure fluid flow time and apparent viscosity, particularly for drilling muds. Figures 14 and 15 present the density and apparent viscosity plots of the reference sediment

sample at different moisture contents, respectively. Since the sediment could not flow through the funnel at water contents below 135% (liquidity index > 4), testing was therefore limited to samples with water contents above 135% and lower densities (<1.38 g/cm³). It should be noted

that viscosity measurements obtained through this method are not absolute values but rather empirical indicators of fluid flow behavior. Furthermore, for non-Newtonian fluids, rheometer calibration data are required for proper interpretation of results.

Figure 16 presents the density of remolded sediment samples at varying moisture contents

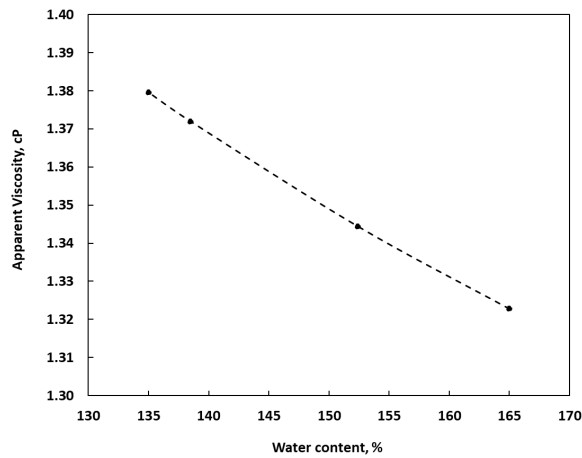


Figure 14. Density of the reference sediment sample at high water contents ($w > 135\%$)

for mechanical and rheological testing, while Figure 17 shows the corresponding calculated air void percentages. As demonstrated, when moisture content increases from the plastic limit to the liquid limit, the sediment density decreases from 1.86 g/cm^3 to 1.68 g/cm^3 , accompanied by a reduction in average air void content from 6% to 2%.

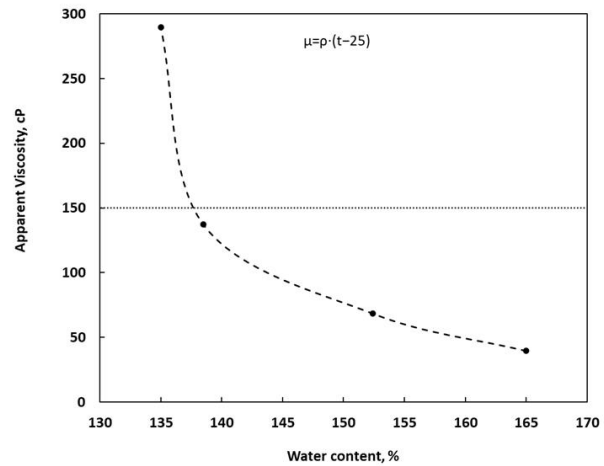


Figure 15. Marsh funnel apparent viscosity of the reference sediment sample

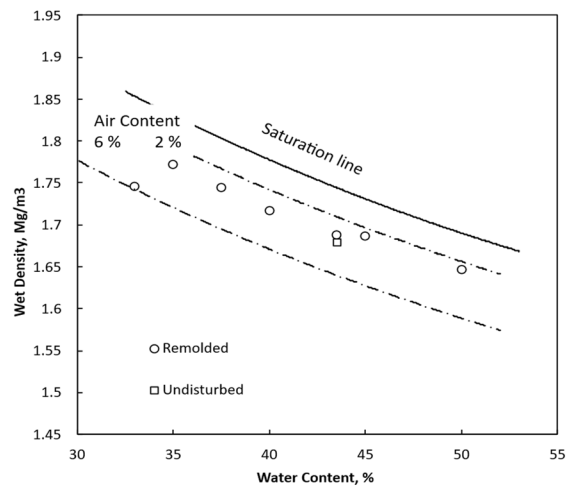


Figure 16. Density of sediment samples at different moisture contents

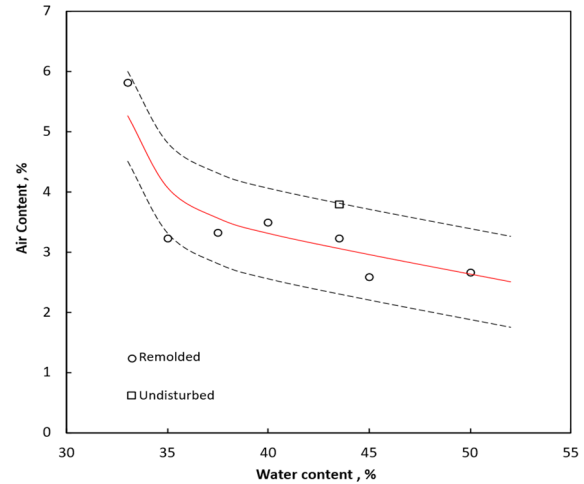


Figure 17. Air void content (%) of sediment samples at varying moisture contents

3.3. Mechanical and Rheological Properties of Sediments

3.3.1. Mechanical Testing

To investigate the effect of moisture content on the yield stress of sediments, remolded samples were prepared with moisture contents

ranging from 31% to 50% and subjected to three laboratory tests: unconfined compressive strength (ASTM D2166), undrained shear strength using a pocket penetrometer, and Torvane shear testing [31]. Figure 18-a illustrates the strength variations of the remolded sediment samples at different moisture contents, while Figure 18-b

presents the strength changes relative to the liquidity index (L_i). The *Plasticity Resistance Index* (m) is defined as Equation 7, where w is the water content, PL is the Plastic Limit, and I_f is the Flow Index obtained from Atterberg limits tests. Detailed analysis of the plots indicates that the average uniaxial yield stress (σ_0) of the remolded sediment under varying moisture conditions can be estimated using Equation 8. Where σ_p

represents the UCS of the remolded sample at the plastic limit moisture content. It should be noted that the validity of this relationship is confined to the plastic range.

$$m = IT.LI = \left(\frac{PI}{I_f}\right) \left(\frac{w - PL}{PI}\right) = \left(\frac{w - PL}{I_f}\right) \quad (7)$$

$$\sigma_0 = \sigma_p / 10^m \quad (8)$$

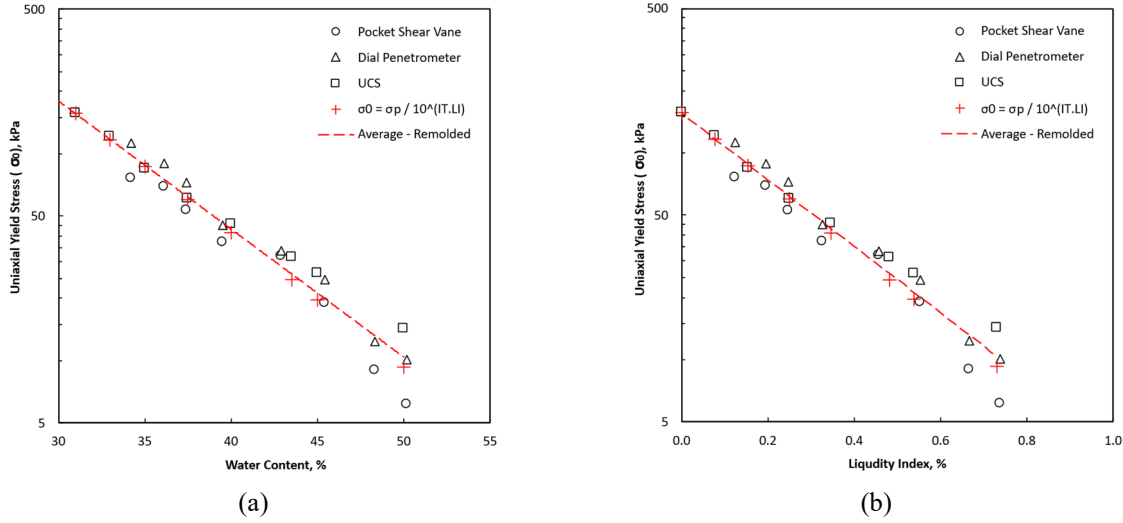


Figure 18. Yield stress of remolded samples versus a) moisture content and b) liquidity index

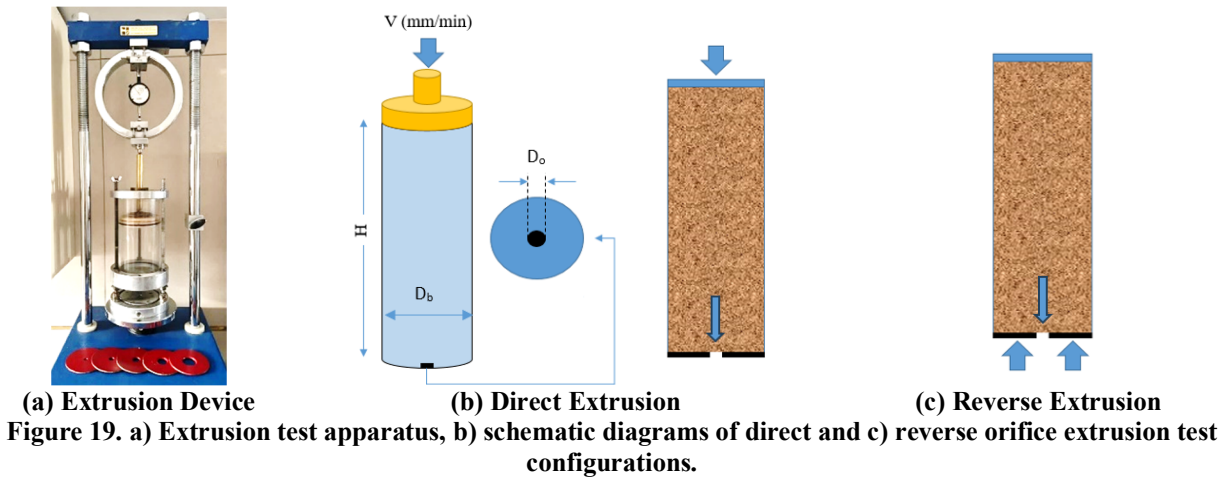
3.3.2. Reverse Extrusion Test

The orifice extrusion test is an effective laboratory method for evaluating the resistance of soft sediments to extrusion under constant loading rates. This test examines the flow behavior and rheological resistance of sediments in both saturated and partially saturated conditions while controlling the deformation rate.

The test apparatus (Figure 19-a) consists of a cylindrical chamber equipped with an upper piston and a lower end-cap featuring an orifice. Sediment samples with varying moisture contents are loaded into the chamber, and loading commences through relative movement between the piston and die. The test can be conducted in

either direct mode (force aligned with material outflow) or reverse mode (force opposing flow direction) as illustrated in Figure 19-b and Figure 19-c. Die moves at a constant rate, extruding a portion of sediment through the bottom orifice.

During testing, the discharge orifice remains open to allow immediate sediment extrusion upon loading. Force and displacement data are continuously recorded, generating force-displacement curves for rheological analysis of soft sediments. To minimize wall friction, the chamber's inner walls are polished and lubricated. The moisture content remains homogeneously distributed within the particle matrix, with no detectable water phase separation or preferential migration occurring during compressive loading.



Reverse extrusion tests were performed on both undisturbed Lake Urmia seabed sediments (43.5% moisture content) and remolded samples at 33% and 45% moisture contents. The test apparatus consisted of a plexiglass chamber (109 mm inner diameter $\times$ 200 mm height), metal plates with orifices (5–30 mm diameter), and an O-ring sealed piston. The orifices featured sharp edges to simulate zero-length entry conditions.

The tests were conducted using a displacement-controlled loading frame (adjustable speed: 1–50 mm/min, 50 kN capacity). The force was measured using 2, 5, and 10 kN load cells with an accuracy of 0.5% of full scale. To prepare homogeneous samples, the sediments were conditioned at the target moisture content, kneaded for 15 minutes, and cured in sealed containers for 24 hours prior to testing.

For each experiment, approximately 2 liters of sample were placed in the chamber and pre-compressed at 1 kg/cm² (98.1 kPa) for 5 minutes to ensure complete compaction and uniform initial conditions. After removing the load, the orifice was opened, and the sample was extruded at a constant displacement speed until the sediment was completely discharged through the orifice under stable conditions.

To account for the presence of agglomerated particles and salt crystals up to 2 mm in size within the sediment, extrusion tests were conducted using four different orifice diameters (10–30 mm) to minimize particle size effects. To prevent solid-liquid phase separation (consolidation) during testing, constant displacement rates of 2, 5, 15, 30, and 45 mm/min

were applied. This combination of variable orifice sizes and loading rates enabled testing across a V/D range of 0.01 to 10 sec⁻¹.

Each test consisted of two identical extrusion cycles at a constant speed up to 18 mm displacement to ensure the extruded sediment reached a stable, defect-free state. The average extrusion force measured during steady-state conditions was then taken as the representative extrusion load value.

3.4. Numerical Modeling of Extrusion Tests

Numerical modeling of the extrusion test was performed according to the process illustrated in Figure 20 using Particle Flow Code software (PFC2D 6.0). The simulation procedure sequentially included the following stages:

- Initialization physics of Problem
- Model execution to reach initial mechanical equilibrium
- Application of parallel bonds in disc–disc type particle bonds; disc–wall type bonds remain linear.
- The model was run until parallel bonds were applied and secondary mechanical equilibrium was achieved.
- Simulating extrusion loading (upward displacement-driven flow through bottom orifice).
- Model calibration through iterative microparameter adjustment until numerical force-displacement results match experimental data.

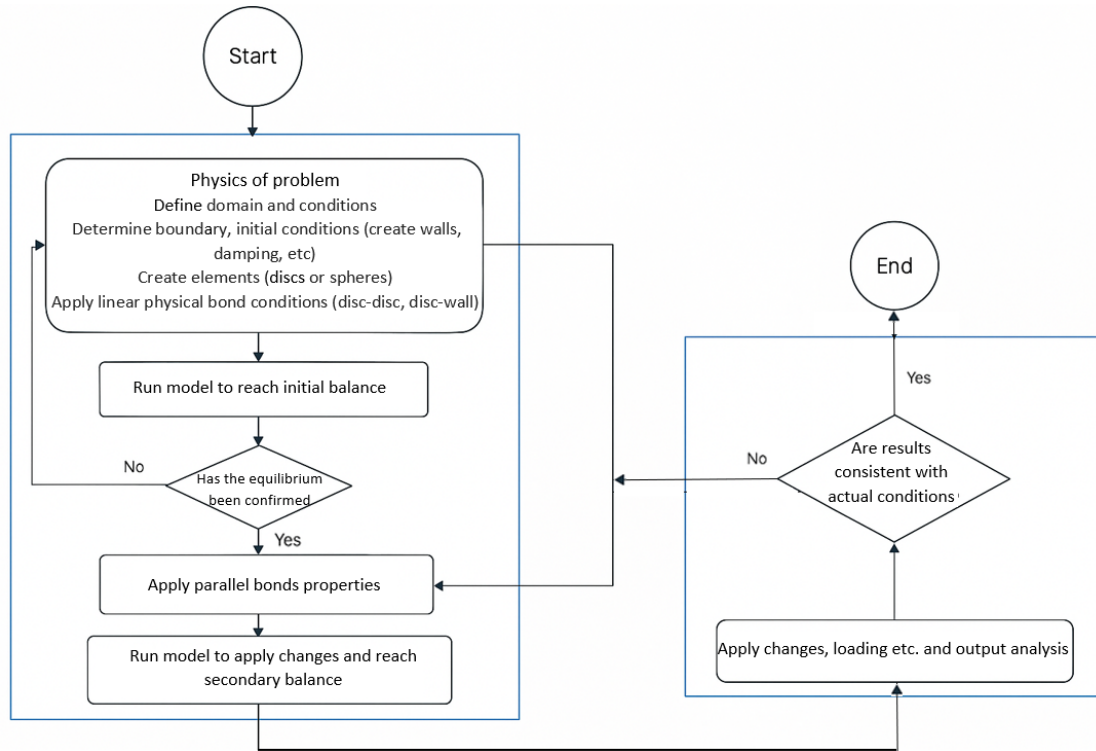


Figure 20. Modeling process using the bonded particle method [27]

3.4.1. Microparameters Calibration

After implementing the problem physics and achieving initial mechanical equilibrium (unbalanced forces < 0.00001 Newton), parallel bonds are activated, and the loading simulation begins. The loading phase replicates experimental conditions through controlled displacement of the bottom wall element at prescribed strain rates. Force-displacement curves are generated for direct comparison with laboratory data.

Following each loading process until stable discharge, numerical and experimental results are compared. If discrepancies persist without requiring modifications to initial conditions, an iterative trial-and-error adjustment of the microparameters of the disc-disc parallel bonds continues until the simulated force-displacement curve closely matches the experimental data. This process constitutes the parallel bond calibration phase. The primary challenge in bonded particle modeling is determining optimal microparameter values a time-consuming process heavily reliant on iterative refinement.

3.4.2. Validation of Behavioral Model and Microparameters

In this study, to evaluate the reliability of the parallel bond microparameters obtained from extrusion test modeling, unconfined compression (UCS) tests were simulated, and the results were compared with those of laboratory tests on actual sediment samples under loading. For this purpose, cylindrical samples with a diameter of 60 mm and a height of 124 mm were reconstructed from sediment with moisture content and unit weight similar to those of the extrusion test samples.

4. Discussion and Results

4.1. Laboratory Test Results Analysis

Figure 21 shows the complete pressure–time curve of the extrusion and relaxation test for a remolded sample with 33% moisture content, subjected to loading at a rate of 45 mm/min. During extrusion, the pressure initially increases as the sediment flows through the orifice until the system reaches equilibrium, after which it remains constant in the steady state. After the test is stopped, due to the viscous and plastic behavior

of the sediment, the pressure gradually decreases until it reaches the relaxation pressure. Figure 22 shows the force displacement curve of the extrusion test for an undisturbed sample with

43.5% moisture content, from the start of loading to stable extrusion. In both graphs, the boundaries of the three behavioral regions are clearly identifiable

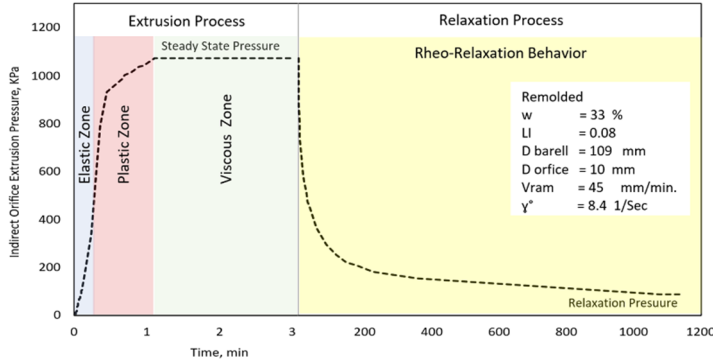


Figure 21. Pressure-time curve of the extrusion and relaxation process for remolded sediment with 33% moisture content.

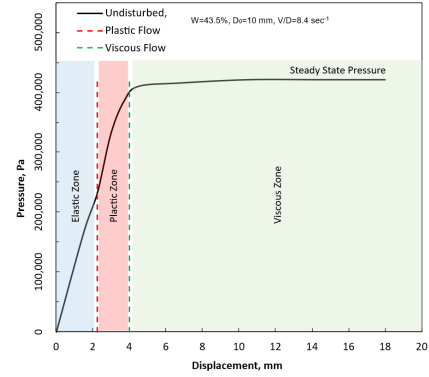


Figure 22. Pressure-displacement curve of the extrusion process for undisturbed sediment with 43.5% moisture content

Elastic Deformation Region (0-2 mm displacement): During initial compression, the sediment undergoes confined elastic deformation as pressure increases. The material resists flow, causing the required extrusion force to rise rapidly. This linear stress-strain behavior follows Hooke's law (Equation 9).

$$\tau = G\gamma \quad (9)$$

Plastic Flow Region (2-4 mm displacement): In this phase, pressure increases at a decreasing rate. Then, the internal structure fractures and shear stress reaches the yield strength; afterward, the material flows more easily. This plastic behavior is described by an appropriate yield function and flow rule (Equation 10).

$$F = \tau - \tau_y, \quad \dot{\gamma}_p = \lambda \frac{\partial F}{\partial \tau} \quad (10)$$

Viscous Flow Region (>4 mm displacement): Beyond 4 mm displacement, where pressure stabilizes, deformation continues, exhibiting creep-like behavior. As particle network breakdown progresses, the material approaches purely viscous flow. During this stable discharge phase, extrusion continues under a constant force.

This behavior is accurately modeled by the Herschel-Bulkley equation (Equation 11).

$$s = \tau_0 + k_s \dot{\gamma}^n \quad \text{for } \tau \geq \tau_0 \quad (11)$$

The sediment's relaxation behavior can be modeled using the linear standard solid model (Equation 12) for the viscoelastic component and the Pérezina-type viscoplastic flow model (Equation 13) for the viscoplastic zone.

$$\tau(t) = G_\infty \gamma_0 + (G_0 - G_\infty) \gamma_0 e^{-t/\tau} \quad (12)$$

$$\dot{\gamma}_p(t) = \frac{(\tau(t) - \tau_y)^n}{\eta_p} \quad (13)$$

The critical stage in extrusion testing is achieving stable ultimate resistance, as all rheological parameter calculations derive from this steady-state condition. Accordingly, this study's results focus exclusively on the stable zone where sediment behavior becomes reliably analyzable. Figure 23 presents pressure-displacement curves for both undisturbed and remolded samples across varying orifice diameters and loading rates, demonstrating consistent behavioral patterns regardless of test speed. **Figure**

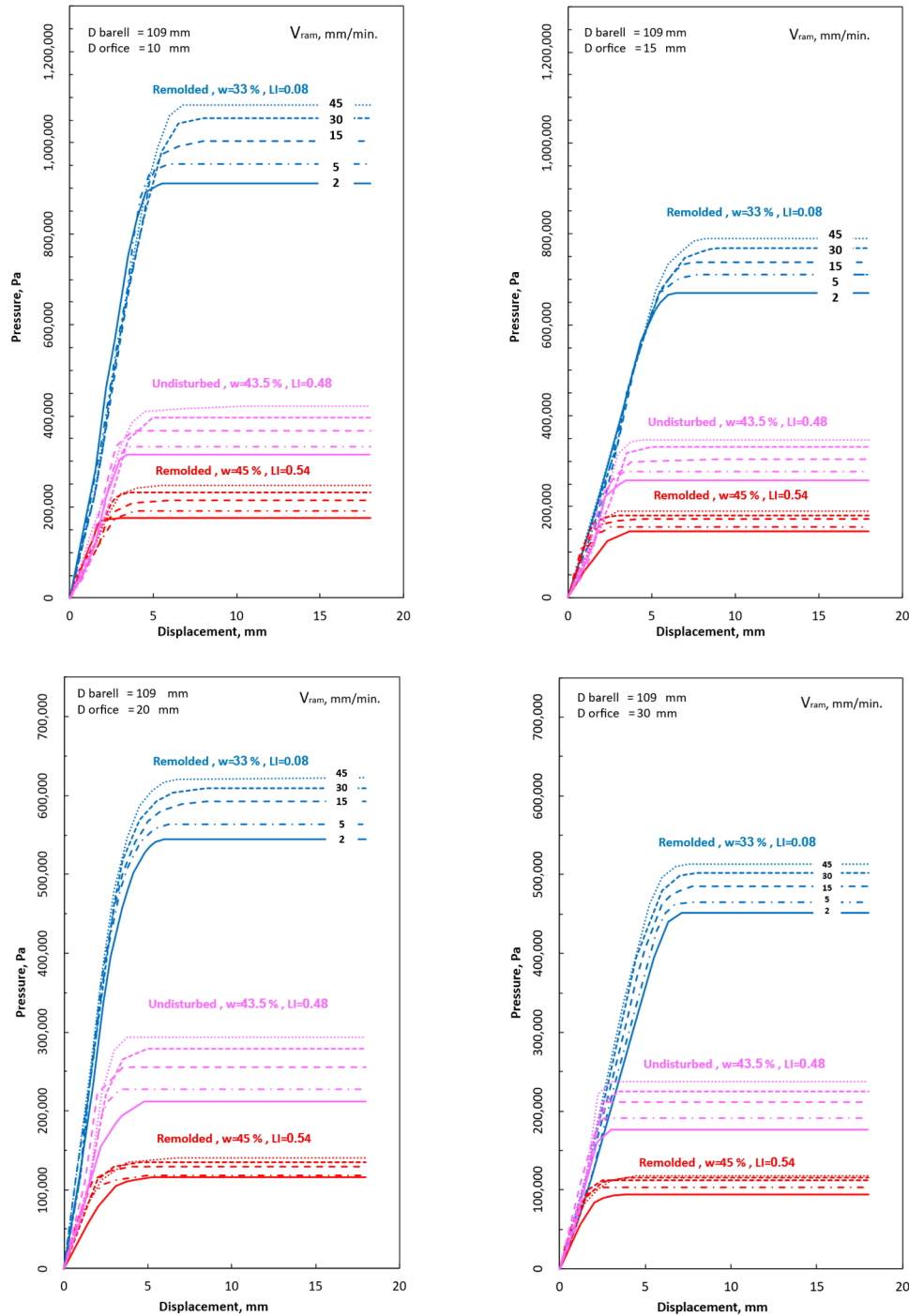


Figure 23. Pressure-displacement curves for both intact and remolded sediment samples at varying moisture contents, tested under loading velocities of 2-45 mm/min with orifice diameters ranging from 10-30 mm.

This section analyzes extrusion test results. The sediment paste flow velocity through the orifice was calculated assuming incompressible flow. The ratio V/D remains relatively independent of orifice diameter, while the

average flow velocity (v) depends on diameter. Therefore, plotting extrusion pressure versus V/D (rather than v) proves more meaningful, particularly when comparing data from different orifice sizes. The steady-state extrusion pressures

are plotted as functions of V/D values in Figure 24 for each orifice diameter. As shown in the figures, extrusion pressure grows proportionally with V/D . This proportional increase reveals strain-rate hardening behavior in the high-density semi-solid sediments. The normalized dimensionless viscous pressure can be calculated using Equation 14, after determining yield stress (σ_0) from Equation 8. Figure 25 displays normalized viscous pressure versus a reference

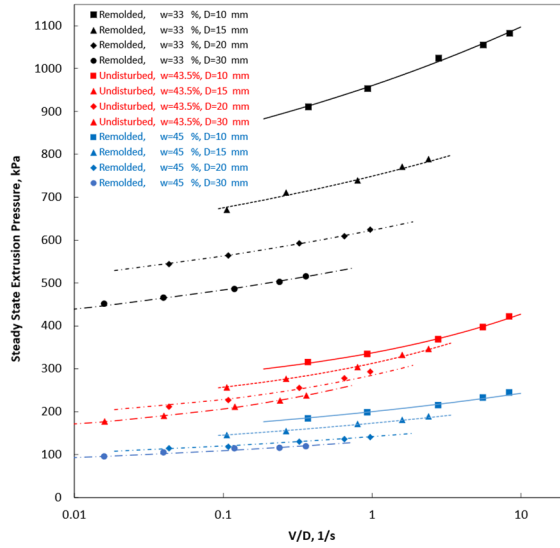


Figure 24. Extrusion pressure versus V/D for orifices with diameters ranging from 10 to 30 mm

The independent rheological parameters for sediment at varying moisture contents were determined using extrusion test data from a 10 mm orifice diameter ($D/D_0 \approx 0.1$), which provided a wider strain rate range. The results are summarized in Table 2.

4.2. Numerical Modeling of Extrusion Test

Based on field studies, sediment with a moisture content of 45% can be considered representative of sediment up to 35 meters depth in the lake bed. Therefore, the properties of sediment with 45% moisture were used for numerical modeling, to obtain the behavioral model, and to determine the microparameter values of the bonds between elements (2D discs). The following section outlines the details of the modeling of this sediment.

$V/D = 0.37$ (sec^{-1}) for different samples. All independent rheological parameters (σ_0 , n , k) were determined by fitting steady-state pressure data to the analytical model (Equation 3) through RMS error minimization.

$$P_v = \frac{(P - P_0)_{\dot{\epsilon}_i}}{(P - P_0)_{\dot{\epsilon}_{ref}}} \quad (14)$$

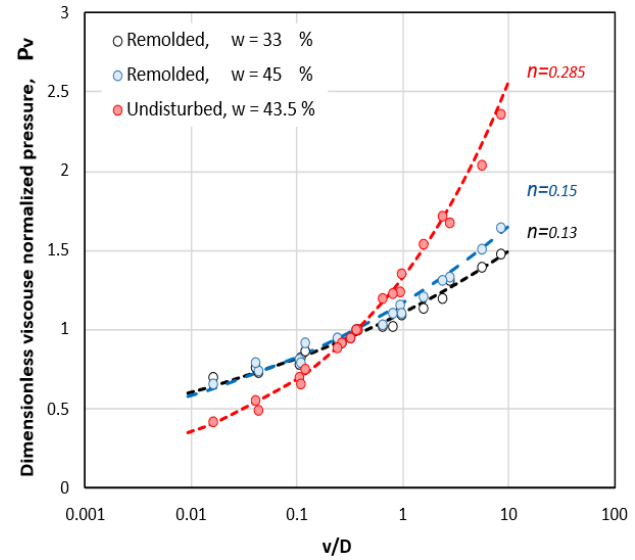


Figure 25. Dimensionless viscous pressure versus V/D (normalized to a reference rate of 0.37 sec^{-1})

Table 2. Rheological properties of undisturbed and remolded sediments from Lake Urmia

Sediment Sample	Remolded	Undisturbed
w , %	33	45
σ_0 , kPa	116	19
k_u , kPa. S^n	100	33
n , $R^2=0.98$	0.125	0.144
τ_0 , Kpa	67	11
k_s , kPa. S^n	54	18
RMS	0.81	1.51

4.2.1. Specification of Boundary and Initial Conditions

In this section, the model geometry including the computational domain and its boundary conditions—is first defined according to the problem requirements. A critical consideration in selecting the domain size is the computational cost. Hence, the computational solution time

increases proportionally with the number of discharged elements due to spatial gradient effects. To optimize efficiency, the domain geometry must be configured such that elements immediately contact the boundary upon exiting the extrusion chamber, enabling their prompt removal from the simulation.

In the subsequent modeling, wall elements are employed to confine the disc elements. A damping coefficient is incorporated to balance the model and dissipate unbalanced mechanical forces. Notably, due to the piston's unique relative movement conditions in this test and the requirement for frictionless chamber walls, the shear stiffness of disc-wall bonds (at bottom and side boundaries) is assigned a minimal value. This allows discs linearly bonded to boundary walls to detach effortlessly under shear forces induced by the motion.

According to the laboratory model dimensions, the model domain (10×21 cm) and wall elements (10×20 cm) were initially defined. An 'element removal' condition was applied to the domain to enable model execution with minimal unstable elements and an extended motion range. Finally, properly scaled disc elements were distributed throughout the model.

Due to limitations in the number of elements and the strong computational time dependence on this parameter, using the actual particle sizes (1–75 μm diameter) was not feasible. When determining these dimensions, another critical factor beyond computation time must be considered: the modeling requires adherence to the maximum-to-minimum diameter ratio

($R_{\text{max}}/R_{\text{min}}$), which is recommended to not exceed 1.66 in the software [27]. Thus, particle diameters of 0.5–0.75 mm ($R_{\text{max}}/R_{\text{min}} = 1.5$) were selected. Other properties were assigned based on sediment characteristics, as presented in Table 3.

The sediment moisture content was modeled by distributing disc elements with two distinct unit weights representing the solid sediment particles and the contained water. Specifically, during element generation, 45% volumetric ratio of the disc elements represented the solid particles, while 53% represented the water. This configuration resulted in 98% of the chamber being filled with water and soil, with the remaining 2% accounted for as air voids.

Assuming no moisture separation from the solid phase during modeling, each clay sediment particle and its contained water are treated as a unified element. The calibration process yields micro-parameters that effectively model the coupled behavior of sediment particles and their interstitial water. This approach enables large-scale modeling where sediment-structure interaction is critical, ensuring the mechanical behavior accounts for both sediment and its inherent moisture content.

Accordingly, as illustrated in Figure 26, a total of 69, 373 disc elements were generated in the model, maintaining dimensions consistent with the laboratory setup. Figure 27 displays the grouping of sediment and pore water elements. Following initial equilibrium establishment, parallel bonds were applied to the disc-to-disc contacts. The inter-element bonds are visualized in Figure 28.

Table 3. Physical properties of the numerical model corresponding to the actual laboratory test

Property	Unit	Value
Domain dimensions	m	0.21×0.11
Wall dimensions	m	0.2×0.11
Discharge orifice diameter	m	0.015
Particle diameter	m	5×10^{-4} to 7.5×10^{-4}
Specific weight of solid particles	kN/m ³	24.8
Specific weight of pore water	kN/m ³	9.8
Moisture content (weight %)	%	45
Cohesion	kPa	1.8
Porosity	%	2
Bottom plate velocity	m/sec	5×10^{-4}

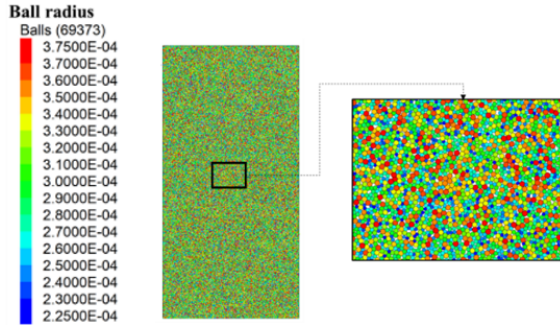


Figure 26. Particle dimensions in the model during initial equilibrium stage

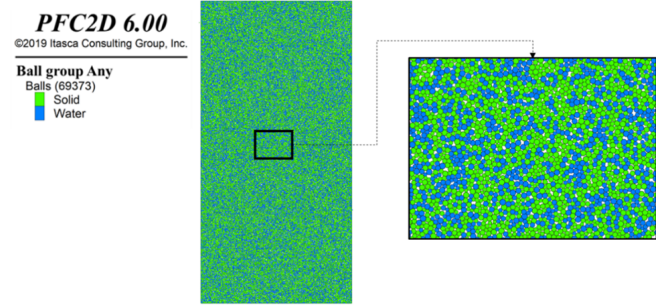


Figure 27. Grouped disc elements representing sediment components: solid soil particles and water elements

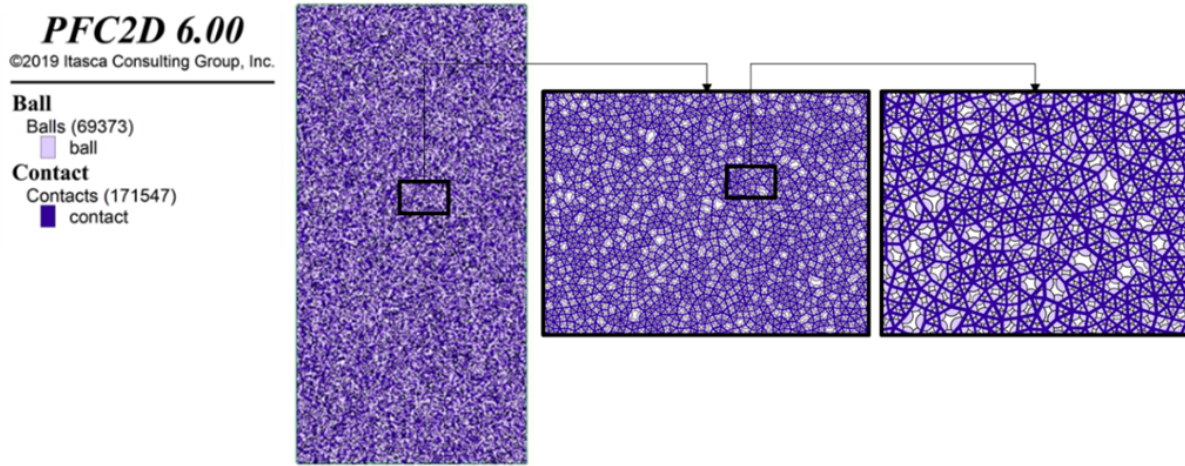


Figure 28. Established parallel bonds between disc-to-disc elements.

4.2.2. Calibration Process Results

Following parallel bond implementation, the calibration process was conducted to achieve force-displacement curves matching experimental results. Table 4 presents the calibrated micro-parameters for parallel bonds, while Figure 29 illustrates sediment displacement patterns at different loading stages

Figure 29-c and Figure 29-d displays the displacement contour of the model's disc elements after a 2 cm upward movement of the mold base and the subsequent discharge of sediment. Notably, during the calibration process, any additional evidence demonstrating agreement between experimental and numerical tests holds particular importance.

As shown in Figure 30, static zones form at a 45-degree angle in the side regions of the chamber, exhibiting complete agreement with experimental conditions in both volume and angle.

Figure 31 presents a comparative analysis of experimental and numerical force-displacement curves. Accordingly, the agreement of the model with real conditions is clearly observable. Therefore, the bonded-particle numerical model with parallel bonds demonstrates a high capability for simulating the behavior of soft sediments.

4.3. Numerical Modelling of Uniaxial Test for Microparameter Validation

As outlined in the methodology section, this study developed a uniaxial compressive strength test model to evaluate the reliability and generalizability of both the parallel bond constitutive behavior and the micro-parameters obtained from extrusion test modeling. Figure 32 displays the physical and mechanical properties (parallel bond micro-parameters) implemented in the constructed UCS specimen. The standard-dimensioned sample (60 mm diameter, 2:1

height-to-diameter ratio) comprised 3,602-disc elements. Two wall elements at the specimen ends move toward each other at a constant rate to simulate loading conditions. During simulation, the FISH scripting language converts the

measured contact forces (disc-wall interactions) and displacements into stress values by normalizing with cross-sectional area. Figure 33 presents the resulting element displacement contours.

Table 4. Calibrated micro-parameters of parallel bonds for soft sediments of Lake Urmia bed with 45% moisture content

Bond type	Micro parameters	Unit	Value
Linear	Elastic modulus	Pa	1.0e9
	k_n/k_s ratio	-	2
Contact	shear stiffness (K_s)	N	1.0e8
	Normal stiffness (K_n)	N	1.0e10
	Coefficient of internal friction angle (fric)	-	1.0
	damping ratio	%	50
	shear stiffness (K_s)	N	1.0e12
	Normal stiffness (K_n)	N	1.0e12
	Coefficient of internal friction angle (fric)	%	0.577
	damping ratio (dp_ratio)	%	50
Parallel	Elastic modulus (deform emod)	Pa	2.0e6
	k_n/k_s ratio (Krat)	-	1.0
	Elastic modulus (Pb_deform emod)	Pa	2.0e6
	k_n/k_s ratio (Krat)	-	1.0
	Normal Stiffness (Pb_kn)	N	5.0e4
	Shear Stiffness (Pb_ks)	N	5.0e4
	Cohesion (Pb_coh)	Pa	6.3e4
	Tension (Pb_ten)	Pa	6.3e4
	Coefficient of internal friction angle (Pb_fa)	%	10.0

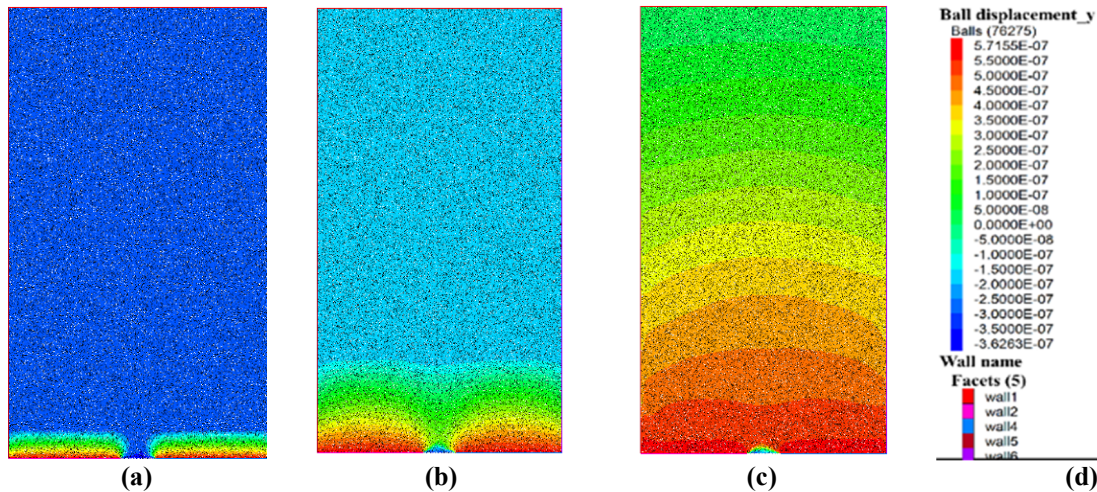


Figure 1. Displacement contour of the numerical extrusion test model during different loading and sediment discharge stages.

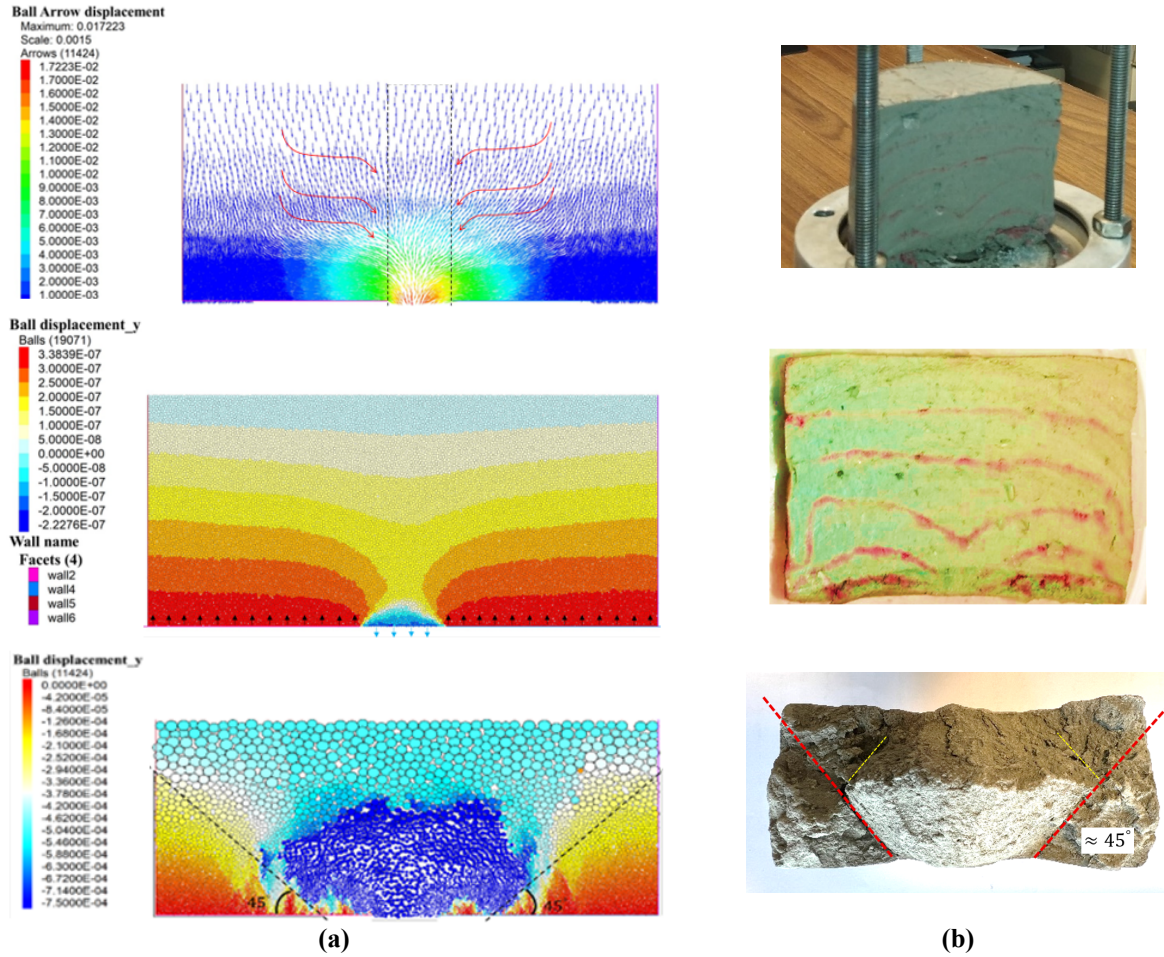


Figure 30. Sediment discharge from the chamber using calibrated parameters and static zone formation: a) numerical model, b) laboratory test results.

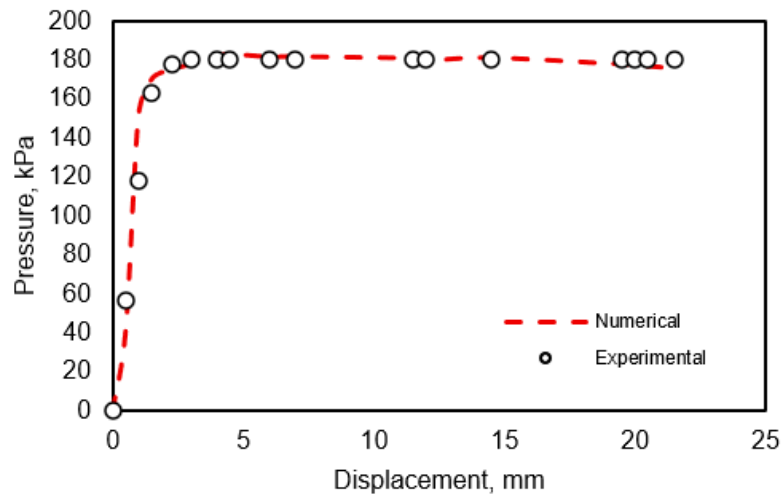


Figure 2. Comparison of numerical and experimental results from extrusion tests on remolded sediment samples with 45% moisture content.

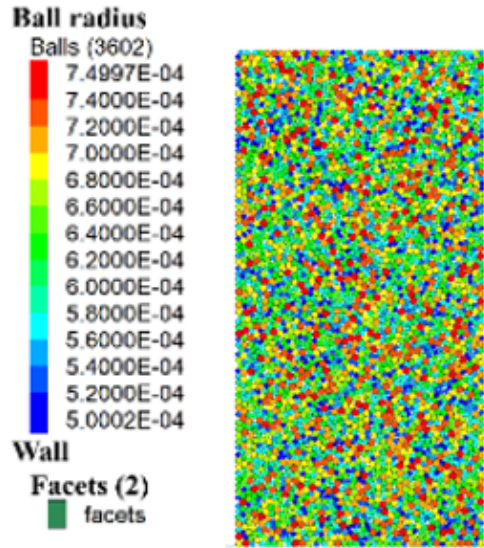


Figure 32. Modeled sediment specimen for uniaxial compressive loading

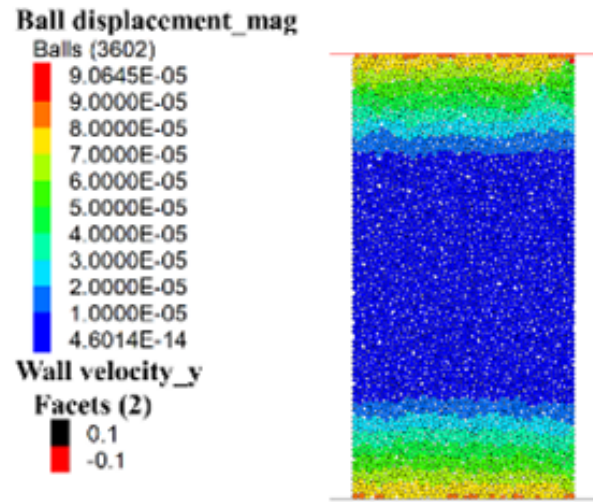


Figure 33. Start of uniaxial compression by wall element movement

Figure 34 compares the force-displacement curves of the numerical model (using extrusion-derived microparameters) and laboratory UCS test results. Figure 35 and Figure 36 respectively show post-loading conditions in both experimental and numerical specimens. The close

agreement between numerical (28.4 kPa) and experimental (28.7 kPa) strength values confirms that the parallel bond model with calibrated microparameters effectively simulates the lakebed sediment behavior.

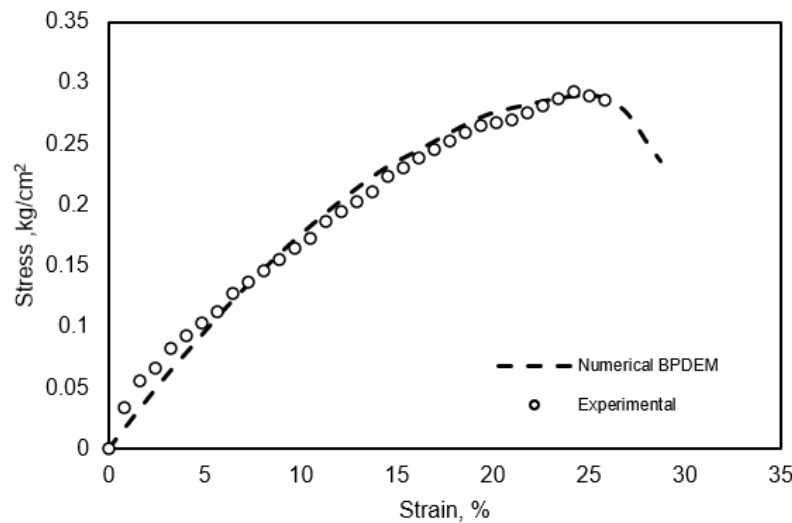


Figure 3. Comparison of force-displacement curves from numerical modeling and laboratory results for soft sediment under uniaxial compressive loading.



Figure 35. Actual specimen after uniaxial compression loading

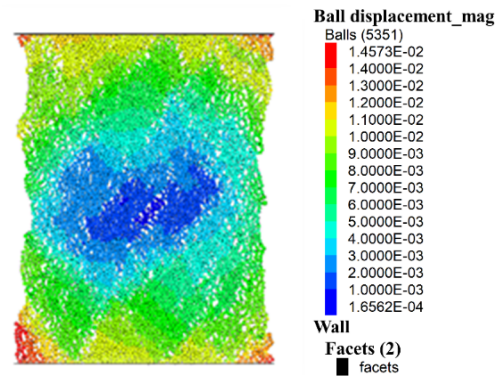


Figure 36. Modeled specimen after uniaxial compression loading

5. Conclusions

This study investigated the mechanical and rheological behavior of Lake Urmia's bed sediments through integrated experimental and numerical analyses. Extrusion tests were conducted on samples with varying moisture contents to characterize sediment response. Subsequently, a bonded-particle discrete element method (BPDEM) model was developed to simulate the behavior of soft sediments. Finally, a uniaxial compression test was numerically modeled to validate the parallel bond model and calibrated microparameters, with results showing strong agreement with experimental data. Key findings include:

- The reverse orifice extrusion test, along with index tests, serves as a simple and promising rheological method for investigating the complex rheological behavior of semi-solid, high-density cohesive clayey sediments and soils.
- The behavior of Lake Urmia sediments within the moisture range between the plastic and liquid limits depends on the yield stress and shear strain rate and can be described using a shear-thinning Herschel–Bulkley model.
- Intrinsic rheological parameters of the sediment, including yield stress (σ_0), flow consistency (k), and flow index (n), were determined. As the water content increases, both the yield stress and shear consistency decrease. The initial yield stress can be estimated using the relationship $\sigma_0 = \sigma_p / 10^{IT.LI}$.

- Remolded samples exhibited lower resistance to flow compared to undisturbed samples, reflecting the thixotropic behavior of the sediments.
- Although determining the parallel bond microparameters is time-consuming, trial-and-error based, and requires sufficient understanding of how multiple microparameters influence the macroscopic behavior of the sediment, the main advantage of such modeling lies in its ability to closely replicate the behavior of real materials without any prior assumptions regarding their constitutive model.
- The results of this study, including the parallel bond microparameters, can be highly useful for numerical modeling in projects involving structure–sediment interaction. Furthermore, given the performance of the bonded-particle numerical method in simulating sediment behavior, the application of this approach is recommended for modeling similar sediments.

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رویکردی نوین در مطالعه رفتار رئولوژیکی رسوبات نرم: تلفیق آزمون‌های مکانیکی و مدل‌سازی عددی در دریاچه ارومیه

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چکیده

درک رفتار رئولوژیکی رسوبات نرم دریایی و دریاچه‌ای برای تحلیل پروژه‌های ژئوتکنیکی، مهندسی عمران و معدن بسیار مهم است. سازه‌های ساحلی و فراساحلی مانند جزایر مصنوعی، گذرگاه‌های دریاچه‌ای، اسکله‌ها، سکوهای نفتی و سدهای باطله مستقیماً با این رسوبات در تعامل هستند. عملکرد ایمن و پایدار آنها به توصیف دقیق رفتار رسوبات تحت شرایط بارگذاری پیچیده بستگی دارد. این مطالعه خواص رئولوژیکی رسوبات نرم دریاچه ارومیه ایران را از طریق یک رویکرد ترکیبی آزمایشگاهی و عددی بررسی می‌کند. دو آزمایش کلیدی انجام شد: آزمایش‌های اکستروژن و مقاومت فشاری تک محوری. آزمایش‌های اکستروژن بر روی نمونه‌های دست‌نخورده و بازسازی‌شده تحت شرایط مختلف، از جمله نرخ‌های بارگذاری مختلف، میزان رطوبت و اندازه روزه‌های تخلیه، انجام شد. برای شبیه‌سازی عددی، از روش المان گسسته ذرات پیوندی (BPDEM) استفاده گردید و میکروپارامترهای مدل با استفاده از داده‌های آزمایش اکستروژن کالیبره شدند. نتایج عددی تطابق بسیار خوبی با داده‌های آزمایشگاهی نشان داد: منحنی نیرو-جابجایی با خطای کمتر از ۲٪ تکرار شد. مدل کالیبره شده همچنین با موفقیت آزمایش فشار تک محوری را شبیه‌سازی کرد و منحنی تنش-کرنش را با کمتر از ۲٪ انحراف از نتایج آزمایشگاهی بازتولید کرد. این نتایج، دقت BPDEM را در مدل‌سازی رسوبات نرم نشان می‌دهد. ادغام روش‌های آزمایشگاهی با مدل‌سازی BPDEM ابزاری قدرتمند برای تجزیه و تحلیل رفتار رسوبات نرم تا فوق‌العاده نرم هولوسن و رسوبات باطله فراهم می‌کند و پیش‌بینی‌های قابل اعتمادی از رفتار رئولوژیکی و مکانیکی در کاربردهای ژئوتکنیکی ارائه می‌دهد.

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