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Review

Diatomaceous Soils and Advances in Geotechnical Engineering—Part II

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Abstract: In the geotechnical area, advances in diatomaceous soil research are laconic and mainly oriented towards understanding the primary soil response (typical characterization methods) considering observation and experience (failures in construction processes or unexpected laboratory results) more than following a scientific method. Coincident results have been evidenced in the correspondence between the content of frustules, the effective friction angle and the water retention capacity. However, the variables and processes that control some mechanical behaviors have yet to be documented in the literature, such as the level of fracturing of the frustules and its relation with interlocked behavior, compressibility and shear strength. In addition to the bibliographic background, SEM microscopy records are presented. These facilitate the understanding of the described phenomena. The images highlight the level of deterioration, the environment, the morphology and the pores present in diatoms of different origins. The morphology (as a function of the species) of intact or fractured frustules (depending on the stress record) affects the mechanical responses and volumetric variations of the diatomaceous deposits. Furthermore, this review presents some emerging research lines in diatomaceous soils, such as the subjection of structures to geotechnical centrifuge conditions, some constitutive models and the criteria for developing water retention curves.

Keywords: diatom frustule; fossil deterioration; interlocking; geotechnical centrifuge equipment; water retention curve

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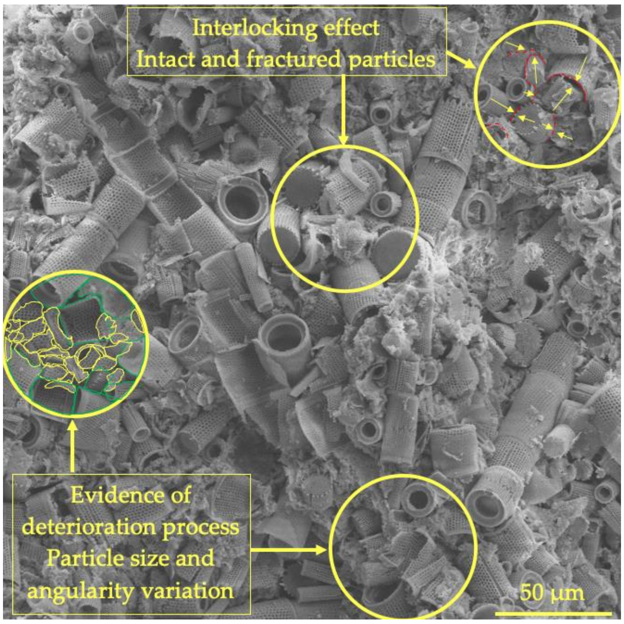
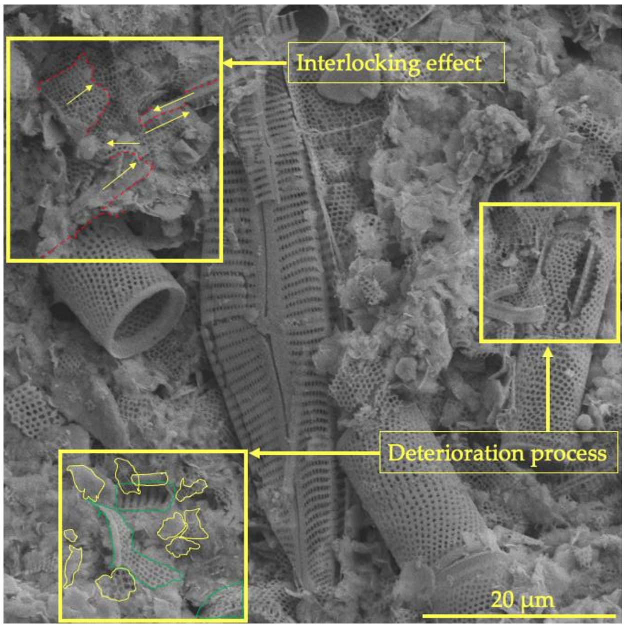
1. Introduction

Diatomaceous soils (DSs) and diatomites originate from sedimentation processes of the frustules, which fulfill a function similar to that of a shell, in this case covering the diatoms [1–3]. During stratified accumulation, the frustules are subject to deterioration due to total or partial dissolution [4], fracturing by friction due to transport (mostly in aqueous media), pH variation of the environment, crushing by loads transmitted from the upper strata, proximity to geological fault zones and even by interaction with predatory diatom species [5], among others. Therefore, the possibility of finding DS with frustules in different levels of deterioration is considerable (see Figure 1); this considers the evolution of their formation process, the stress history and the depth at which they are contained. The amount of diatomaceous skeletons that reach the seafloor without being dissolved is minimal, given the susceptibility of the amorphous silica that composes them to seawater [6].



(**a**)



(**b**)

Figure 1. Deterioration processes and frustule interlocking in undisturbed diatomite. DS from Boyacá (Colombia). (**a**) Centric monospecies; (**b**) Centric and pennate multispecies.

Most of the dissolution occurs in the most superficial part of the water column. This situation may result from taphonomic processes or ecological effects [4]. Individual diatoms or the chains formed by them and suspended in the upper part of the ocean are subjected to hydrodynamic shear stresses (breakage due to flow). The mechanical properties of chains and individual cells require understanding different nano-, meso- and microscales [7]. Despite all the deterioration factors, diatoms and their frustules present relevant mechanical properties, such as high elastic moduli, which give them restorative capabilities against the imposition of loads and deformations, with a high elastic modulus value of up to 22.4 GPa in some species [8,9].

The literature review has allowed us to identify recent lines of study regarding DS. In the first instance, the trend in the development of constitutive models that seek to explain the unconventional responses (high LL, high friction angle, unpredictable secondary compressibility) of this type of deposit is recognized; computational tools support this and include concepts such as "soft rocks", boundary surface, geomaterials and elastic–viscoplastic models, among others [10–14].

Another element identified within the state of the art pertains to evaluating the performance of different models of civil works (foundations and slopes) contained in artificial DS matrices, dosed with kaolin and subjected to centrifugal stresses. From the above, load and displacement records have been obtained that allow an understanding of the response of this type of work [15–19].

Research on diatomaceous soils in geotechnical engineering has mainly focused on analyzing index properties, compressibility and shear strength [20–24]. Consensus has been found on the effects of frustule content on the effective friction angle rather than on the mechanisms by which this effect occurs. There is some clarity on the water storage capacity, represented in the consistency limits. However, the yield stresses at which the volumetric reduction is enhanced by frustule breakage still need to be fully understood. The DS formation processes and the frustules' morphological conditions regarding the soil's mechanical performance as an engineering material have also been identified as essential aspects. More studies have yet to be developed to investigate the relationship between mechanical properties and the microstructure of microfossil deposits [25]. From the above, it is necessary to understand the effects of fracturing of the frustules and the interaction that the intact or fragmented particles may have, either between themselves or with the medium that contains them.

The high values of shear strength in DS have been partially explained through hypotheses of interlocking between particles, some of which are evidenced as fragments of the fossils [26], without being precise in the literature about the state of deterioration (fracturing) of the pieces, their representative form according to the species or the typology (single or multiple species). The relationship between diatoms and soil particles is partially characterized [27]. In addition to the level of deterioration, it is necessary to recognize a methodology to determine the concentration of frustules in a soil mass to relate these magnitudes to the geotechnical behavior [6].

The implications of frustule morphology on its mechanical strength have yet to be fully elucidated. The structure of pores, ribs, chambers and nodules appears to affect performance when particles are subjected to compressive stresses, either in a controlled laboratory condition or by predators when diatoms are in their natural habitat. Since the amount of energy required to generate a fracture increases with the surface area of the fracture, the characteristics of the frustule (thickness or pore size) theoretically should alter its mechanical strength at any scale [5].

This bibliographic review presents an information search methodology from whose results some topics, such as the effect of the deterioration of the frustules and the interlocking of particles on the behavior of the DS (compressibility and shearing), are delved. It is complemented with the presentation of SEM micrographs, allowing a better understanding of the exposed phenomena. In this case, fossil elements are presented with differences in origin and morphological characteristics. Generally, the literature is limited to presenting characterization results or the mechanical response of a single DS without allowing systematic comparison between types of frustules. Finally, a series of emerging topics of geotechnical research in DS are presented, such as water retention curves and the subjecting of models to geotechnical centrifuge conditions.

2. Methodology

The documents named "Diatomaceous Soils and Advances in Geotechnical Engineering" Part I and Part II are a sequence of articles that were structured from documentary sources dating back to the 1990s, taking into account that some representative authors such as Locat [6], Tanaka [28], Holler [29], Liao [30] and Antonides [31], among others, socialized several advances in characterization and mechanical responses in DS, and even an antecedent from 1973 prepared by Petrosyan [32] was included. These documentary sources to date continue to be cited quite frequently. However, to update the reader regarding a more recent state of the art (updated to 2023), a methodological search scheme was proposed considering the regular lines of study developed in geotechnical engineering applied to DS and likewise highlighting the emerging lines of analysis applied to this type of deposit.

Part I considered the evolution of concepts about DS, taphonomic processes, granulometric distribution, specific gravity, consistency and plasticity, artificial DS–kaolin soils, compressibility and shear strength. Part II concentrates on the effects of deterioration on geotechnical properties, fracturing and compressibility, fracturing and shearing, breakage and other research lines, effects of interlocking, emerging issues of DS in geotechnical research and geotechnical centrifuge modeling. Part II is complemented with a recording of SEM images so that the effects of frustule breaking and the accumulation of fragments could be more easily explained.

The main concept in this document is diatomaceous soil, shortened to "DS". Other denominations with technical affinities, like diatomaceous earth, diatom frustules or diatomite, were also considered. The study included bibliographic references if a specific relation with geotechnics or soil mechanics was recognized. Given that the research focuses on DS as a function of geographical and geological conditions, the review contemplated multilanguage literature. Nine research lines complemented the DS concept by applying the "AND" and "OR" operators. For searching, identification, filtering and selecting articles, ScienceDirect, Scopus and Web of Science databases were used.

Taking into account that diatomaceous soil research is a non-completely developed line in geotechnics, it was necessary to consult other alternative sources that are not available in open media or that present specific or restricted access, for example, university repositories or event proceedings (GeoCongress, International Conference on Physical Problems of Engineering, European Conference on Soil Mechanics and Geotechnical Engineering, International Conference on New Energy and Sustainable Development). ASCE, Taylor and Francis and Springer Nature were alternative databases that presented results from internet searches.

The selection process considered three steps, initial result, filters application and technical consistency. The "initial result" corresponds to the total number of outputs each database presented only by introducing the keywords "DS AND complement". The "filter application" considered the limitation by aspects like time frame (updated to 2023), document type (research article and case reports), journal classification criteria (engineering, Earth and planetary science, environmental science, material science, physics and astronomy, geotechnical engineering). "Technical consistency" covers the review of titles and abstracts. Finally, a comparison of documents and duplicate removal were carried out. From this, the entire reading of items proceeded. See Appendix A.

The "initial result" reached 3,606 bibliographic elements from the four consultation sources (103 from Scopus, 3420 from ScienceDirect, 71 from Web of Science and 12 from other databases). After "filter application", the documentary sample amounted to 160 items. The list was reduced to 144 as a result of technical consistency checking. In the end, with the duplicate removal step, the bibliographic sample consolidated into 53 articles for a full reading.

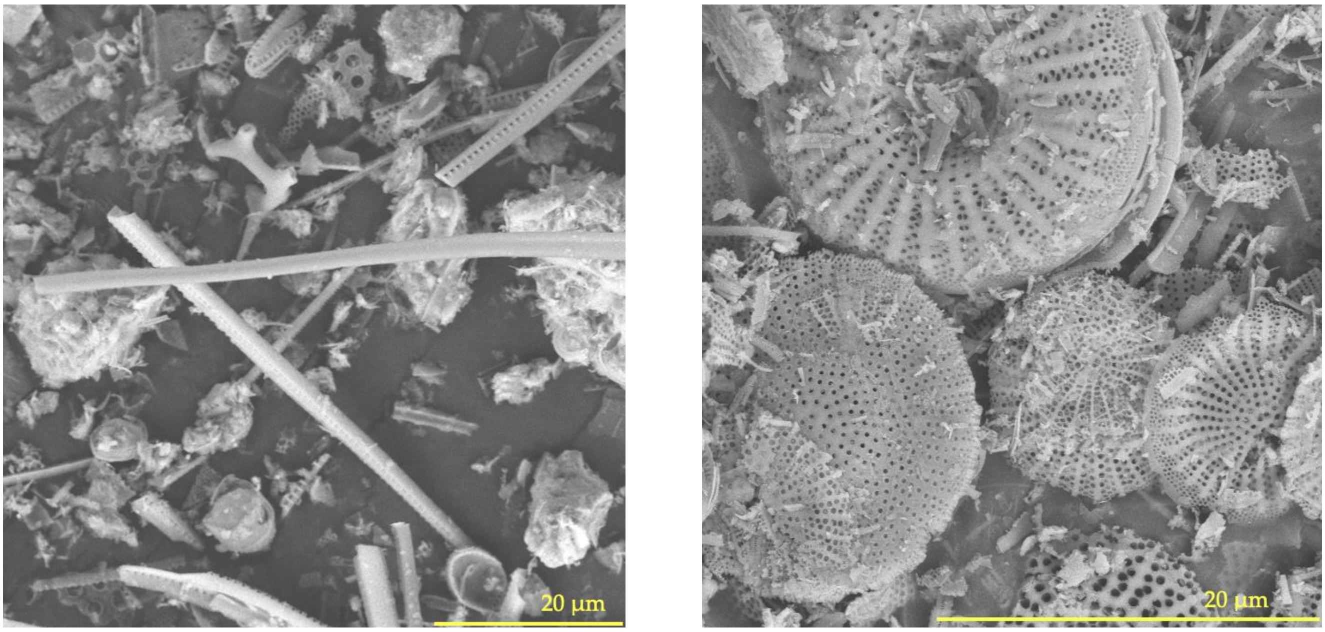
3. Effects of Deterioration on the Geotechnical Properties of Diatomaceous Soils

From the documentary consultation, the terms "crushing", "breakage", "fracture" and "fragmentation" were recognized as those that describe the states of deterioration or degradation presented by diatom frustules. This is because the terminology may vary according to the author.

Observations of fractured frustules revealed that the cracks travel mainly around and not through the spherical silica particles, considerably increasing the fracture surface and, thus, the energy required for fossil breakage. In porous materials, the restriction in crack propagation can collaborate in increasing the strength of the medium since the failure mechanism is distributed at the pore edges and avoids stress concentration [5,9,33].

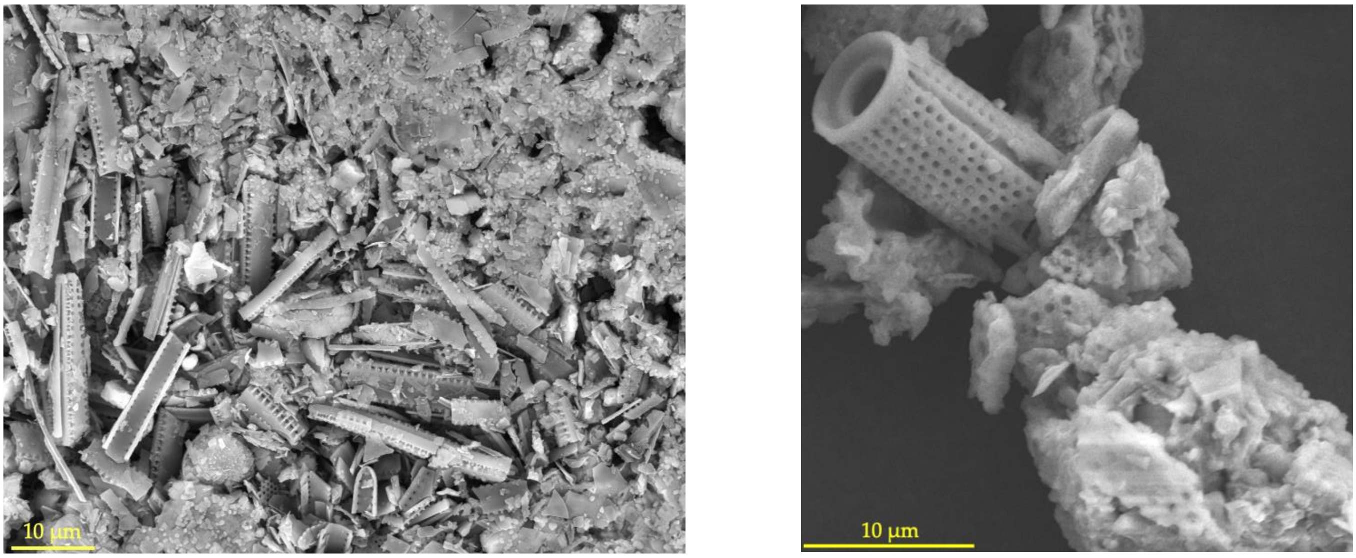
The shape of the particles (whole or fragmented frustules) influences the behavior of the soil (see Figure 2). Those containing elongated particles are more susceptible to breakage and increased compressibility compared to soils mainly composed of rounded particles [22].

Likewise, the shape, the state of preservation of the frustules, and the rates and environments of deposition determine the conditions of accommodation (fabric) within the soil mass. Studies on soils from Ariake (Japan), in samples obtained at 3 and 16 m depth, revealed very well-formed structured flocculates combined with abundant fossil remains, mostly diatoms. The fine component was mostly smectite, while the coarse fraction reported quartz grains and fossil fragments. Because most fossil remains were found fragmented, the observed intraskeletal pore families were minimal [34]. The agglomeration of particles (clays + fossil remains) in the DS affects the behavior of the soil mass, and its resistance is such that, even after exploitation and transport processes, the accumulation is preserved, possibly associated with cementation and interlocking phenomena (Figure 3a,b).



(**a**) (**b**)

Figure 2. Morphological variations in diatom frustules. (**a**) Elongated particle. DS Peruvian origin, species Thalassionema nitzschioides; (**b**) Centric particle. DS Mexican origin, species *Cyclostephanos tholiformis.*



(**a**) (**b**)

Figure 3. Formation of structures in the soil by fossil remains. (**a**) DS origin Ica (Peru) reorientation and interaction with clayey matrix; (**b**) DS origin Boyacá (Colombia) agglomerations after industrial exploitation processes.

Axial deformations are associated with pore-pressure dissipation and particle breakup in DS or with a high presence of diatom microfossils. However, the individual contribution of each mechanism proves challenging to quantify. For example, suppose the pore pressure inside the soil sample is not measured in an edometric test. In that case, it is not feasible to determine how much of the compression is associated with its primary consolidation. In the DS, particle breakage is expected to be enhanced when a certain loading level is exceeded, which will depend on the stress history and fossil content. Compression index

(Cc) values increase with higher frustule content, while recompression index (Cs) values are relatively small [35].

If small changes in diatom geometry are present at a given geostatic stress, the amount of water retained in the frustules will be almost constant. Representative variation will be evident with depth [6].

Water within skeletal and intraskeletal pores is retained by suction. The same could be said about the water in the intra-aggregate space, but this water is intimately bound with clay minerals and consequently can influence the index properties. On the other hand, with increasing stresses, the microfossils will fracture, and thus the intraskeletal pores will be drastically reduced. At this point, the overall effects of the index properties will have vanished [28].

3.1. Fracturing and Compressibility

Some DS show high degrees of compressibility due to the effect of fracture of the frustules, especially when the proportions of fossils are representative [32]. This phenomenon leads to considerable and irreversible deformations after applying some stress, for example, associated with edometric compression tests. This situation is intensified at stress levels higher than creep. At this point, the DS behaves similarly to a "crushable sand" in aspects such as the Cc/Cs ratio, of which magnitudes greater than twenty are reported [22].

Another proposal presented by Arenaldi and Ovalle [2], related to the high compressibility of the DS, details that the fracture of the frustules occurs when stresses higher than the pre-consolidation stress are applied. The record of large plastic deformations evidences that this is due to the collapse of the soil structure. Friction rupture is essential in vertical strain since it generates unrecoverable deformations even during the unloading period [35].

The geotechnical properties of sedimentary deposits are dependent on their microstructure and composition. Such is the case of the clayey soils of Mexico City, which present high compressibility, among other things, due to the abundant concentration of frustules. However, macromechanical and microstructural behavior changes during consolidation processes are still not fully understood [25].

Day [36] explains that diatomaceous fillers behave as dense granular material when subjected to effective stresses less than 50 kPa. This response occurs because diatoms can resist shear and compression, given their rough surface and interlocking characteristics. The fossils fracture at vertical stresses of 1600 kPa, significantly increasing their compressibility. Analyzing the settlement vs. time record in these soils is complex, as the boundary between primary and secondary settlement needs to be clarified. For the latter, the settlement rate is not linear in log-time space.

Ovalle and Arenaldi [37], apud Tanaka and Locat [28], and Shiwakoti et al. [38] explain that after yield stress, the microstructure of the DS is altered and becomes very compressible. This could be explained due to massive breakage of diatom frustules, loss of cementation by diagenesis and disturbance of microstructure [39]. The breakage of the frustules can result in collapsible behavior and lead to a rearrangement of the soil structure, which implies a higher densification for the same stress level [22]. Regarding this aspect, it is crucial to evaluate the collapse potential that a diatomaceous soil could eventually develop, not only by high loads but also by the wetting of the frustule in a marine environment of mineral salts that can degrade this material.

The deformations (plastic and total) obtained during edometric tests increase with the diatom content. The elastic deformation decreases as the skeletons are reorganized, and the particles are fractured into smaller pieces due to the imposition of a load. Unlike sand, diatoms are porous particles. The frustules are crushed into small fragments after compression, and these cannot recover their original shape during unloading [40].

Applying normal stresses that induce breakage causes a significant decrease in compressibility and decreases the friction angle of the DS. Gradual breakage of microfossil skeletons is responsible for the change in geotechnical behavior, particularly when subjected to considerable normal pressure [41].

Due to highly crushable particles, the compression ratio (Cc) increases continuously as the diatom content increases. The rearrangement of the soil skeleton and the breaking phenomenon decrease the swelling index (Cs) [40].

Wiemer and Kopf [42] apud Day [36] point out the effective particle breakup at consolidation stress thresholds above 1600 kPa. Similarly, they refer to Tanaka M, who, in his paper "Effects of diatom microfossil contents on engineering properties of soils", identified particle breakage factors at lower stresses, in the order of 196 kPa.

The fracturing of the frustules is a variable dependent on the diatom order, species, shape and age of the frustules. Consequently, Wiemer and Kopf [42] propose a detailed study of fracturing and its effects on excess pore pressure and slope stability.

One-dimensional consolidation tests carried out in DS show curvature in the "e vs. log σv" space, a phenomenon associated with a growing primary and secondary consolidation due to increased diatom content, vertical stress and frustule breakup. Loaded sand particles with normal stresses close to 10 MPa present well-marked yield points. Diatom particles begin to break at normal stresses of 500 kPa. This fracturing happens progressively; therefore, their yield point is poorly defined [20].

From the studies carried out on the undisturbed DS of Mejillones Bay (Chile), which stands out for presenting significant contents of frustules, it has been concluded that the high compressibility after yield stress can be attributed to the perturbation of the microstructure and the breakdown of diatoms [37].

The characteristics of the pores, of the surface of the frustules and thus of the structure of the soil containing them modify the trend of the compressibility curve [39]. This modification is more evident for diatoms with trapped water and higher angularity. It has been evidenced that the compressibility coefficient can reach high values when diatoms with high trapped water content are crushed. This deformation will depend on the type of diatom and the uniformity in particle sizes. However, this hypothesis needs to be confirmed by further research.

From results obtained in foraminiferal fossils (microfauna that stand out for having a calcareous cover) [6]. It has been explained that once specific compressive stresses are applied, the chambers rupture and the contained water is suddenly expelled, resulting in the sediment's pore pressure. For other types of microfossils, such as diatoms, the intraskeletal pore space is always connected to other voids in the containing soil. Two categories of intraskeletal pore spaces can be considered in microfossils, the "unconnected" and the "connected" ones. For the case of the Osaka Bay soil, it is clear that the correct classification is the "connected" type, an aspect that influences the compressibility of the medium [28].

In diatoms, the intraskeletal pore space can affect the compressibility of the soil. Microfossils can deform, which depends on composition, shape and orientation. During compaction, the arch effect may develop around the frustules (intact or fragmented), which could protect the diatom against any further deformation resulting from increased vertical stresses [41].

Similarly, Rajasekaran [41] developed tests on diatoms with concentric skeletons and sizable pores, applying normal stresses that caused individual particle breakage and permanently decreased water storage capacity. When compressive stress is applied, the chambers rupture and water is suddenly expelled, increasing pore pressure. After the expulsion, the pressure is drastically reduced.

Hong et al. [25] performed high-pressure edometric tests on unaltered and remolded diatomite samples extracted in Oita (Japan). Since the stiffness of a diatomite in its natural condition is high, the consolidation stresses were started at 100 kPa and scaled up to 9000 kPa. The yield stress in consolidation for one-dimensional compression in the unaltered sample reached 2100 kPa. The effective vertical field stress was estimated at 39.3 kPa. The cementation between the diatomaceous grains is the main factor in reaching a yield stress ratio higher than 53. It is concluded that the diatomaceous soil is highly structured.

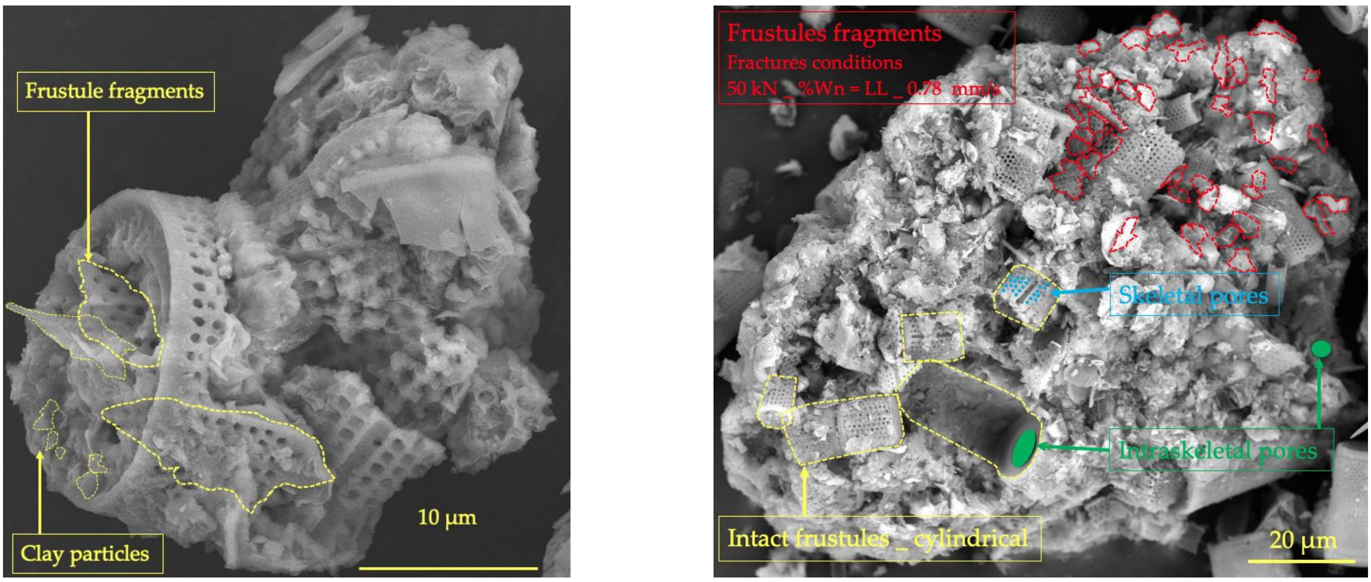
The Oita diatomaceous deposit is stiff before yield stress, indicating that the sampling process does not alter the soil structure due to its high cementation. Porosimetry analysis indicates that the highly structured Oita diatomite has significant changes in its microstructure near yield stress. However, the total volumetric change is negligible since the moisture content and mercury intrusion remain almost identical. Beyond the yield stress, the total pore volume is significantly reduced [25].

According to [22], in DS, creep deformations are usually representative of stresses higher than the yield stress (volumetric deformations up to 3%, with constant load in periods from 1 to 50 days). It also clarifies that, since no representative clay or organic matter contents are reported, a probable cause of such deformations may be the retarded breakage of the frustules, similar to the phenomenon of delayed breakage that occurs in crushable sands. The authors conclude that the physical source of creep deformation in DS remains unexplained and suggest that further research is needed.

The effects of geostatic stresses in DS (derived from depositional and post-depositional processes) may differ from the effects generated by laboratory consolidation tests [25]. Microfossils in clays may behave differently from diatomites, composed almost exclusively of frustules. Hong et al. [25] apud Tanaka [28] explain that centric microfossils found in Osaka Bay (Japan) remained intact even when high geostatic stresses (1200 kPa) were imposed. The volumetric changes recorded were instead associated with the fading of interparticle pores. Friction fracturing effects are reported for higher stresses up to 8000 kPa.

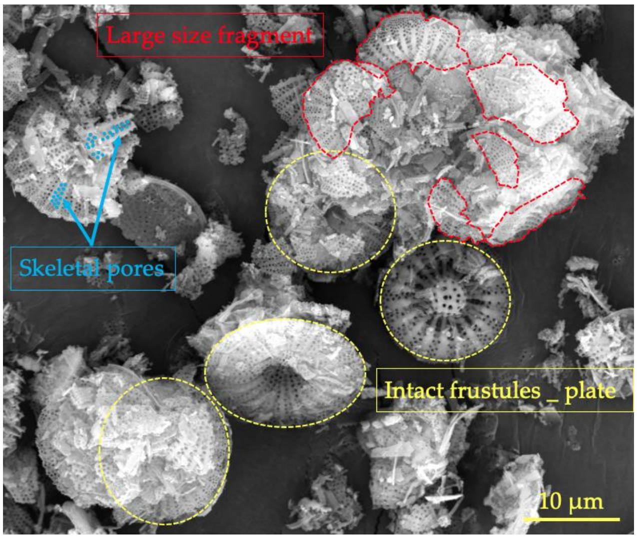
In addition to the magnitude of the applied load (vertical, that simulates the effects of geostatic stress), the moisture content and the rate of stress transmission influence the breaking process of the frustules. The morphology and accumulation capacity determine the rupture susceptibility (Figure 4).

The breakup of the diatom particles (DS from Oita—Japan) leads to the collapse of the tiny skeletal pores when the consolidation stress is greater than the yield stress (2100 kPa). This behavior is contrary to that recorded in Champlain clayey soils. When high confining stresses are imposed, the interaggregate macropores collapse first, and then the intra-aggregate pores are compressed. It has been proposed that the expulsion of water contained in skeletal pores significantly affects the compressibility of natural diatomites [25].



(a) (b)

Figure 4. *Cont.*



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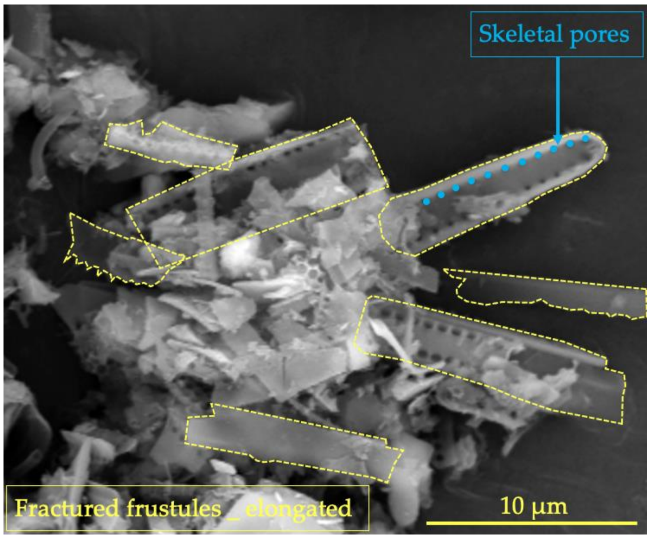


(d)

Figure 4. Deterioration of diatom frustules as a result of stress imposition (**a**) Partially fractured Diatom frustules. Colombian DS (**b**) Breakage of diatom particles (Colombian DS, 50 kN vertical stress, Low-Rate Application Stress LRAS 0.78 mm/s, Wn = LL) (**c**) Breakage Mexican DS (50 kN, LRAS, 100% LL) (**d**) Breakage Peruvian DS (50 kN, LRAS, 100% LL).

The pore size distribution of the diatom frustule walls depends on the species and its type; such is the case that the average pore area of monospecies samples (Colombian origin DS) is between 4 and 7 times greater than that calculated in multispecies samples (North American origin DS) (see Figure 5). The pore density (pores/μm^2) shows the opposite behavior.

Regarding the treatment of DS samples or the preparation of artificial specimens, it is noted that the remolded samples do not register such broad and sudden changes in terms of their compressibility since the previous manipulation process has most probably affected the structure and the original fabric, due to the breakage of a good fraction of the microfossils [22].

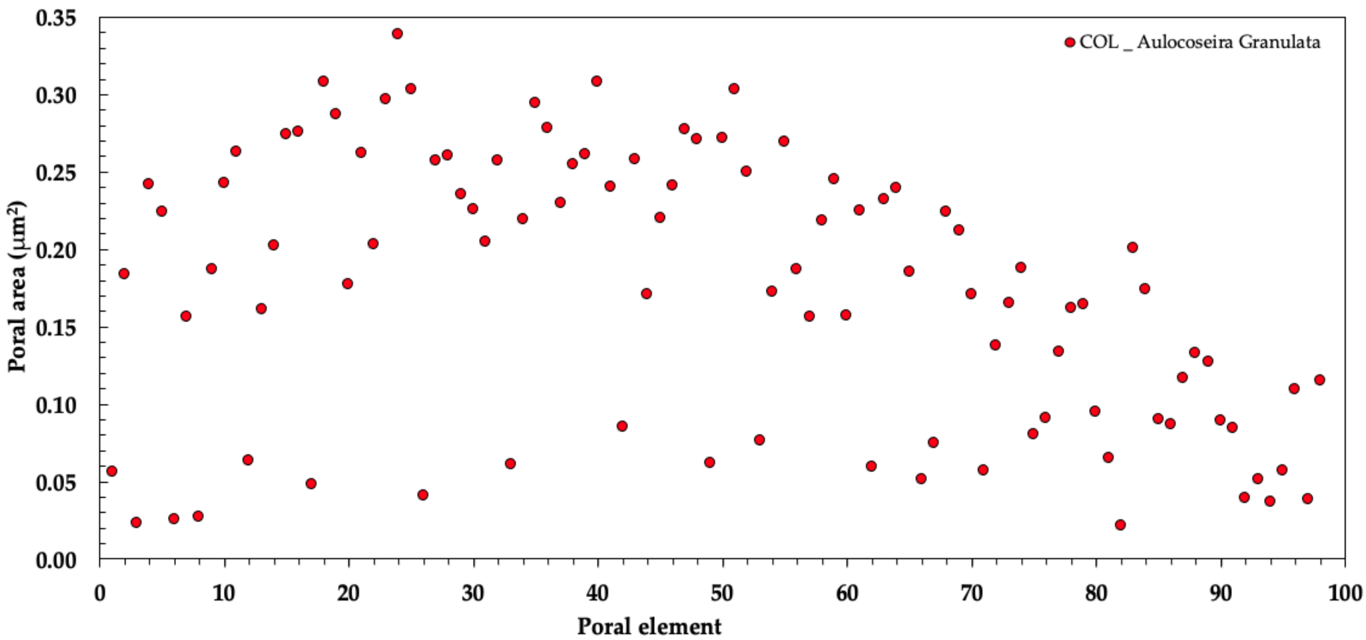


Figure 5. *Cont.*

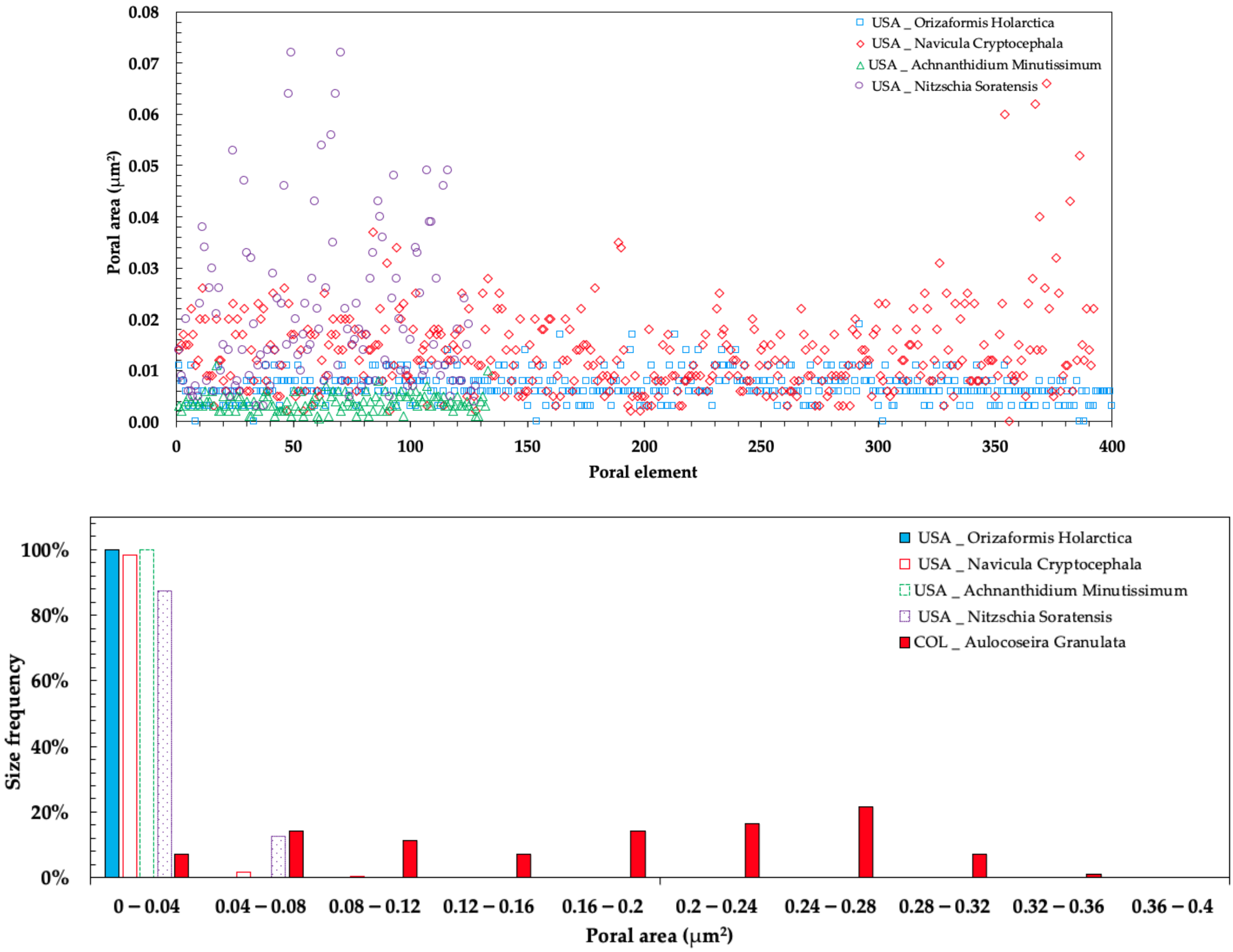


Figure 5. Pore size variation for different diatom species.

3.2. Fracturing and Shearing

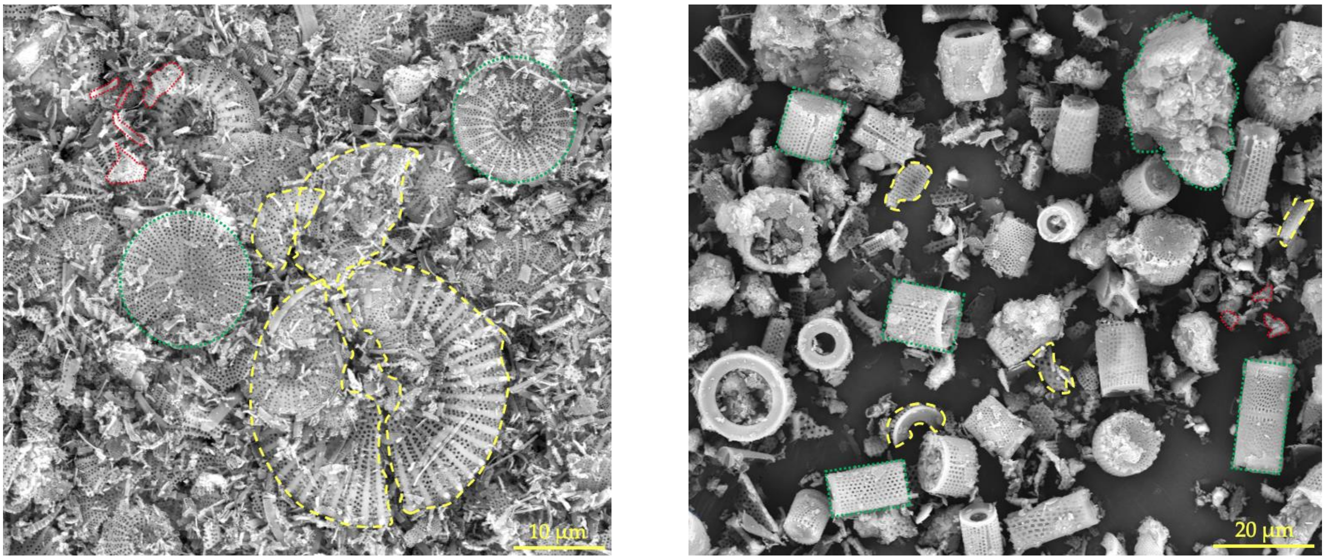
Although it has been proposed that the high values of shear strength in DS are caused by particle locking, the state of the art has not precisely defined the levels of fracturing, frustule concentration and species type (shape of the fossil) which have greater incidence in the unconventional responses of this type of soil.

Regarding shear strength, [36] reports an effective friction angle of DS of 44° and effective cohesion of 0. This calculation was determined with relatively low stresses < 50 kPa. The author points out that crushing the diatoms under higher normal stresses would tend to reduce the friction angle.

The level of deterioration in which the greatest angularity and the highest friction angle are obtained as a consequence of the rupture of the frustules is uncertain. The stress at which a more significant interlocking between the fragments is reported will depend on the shape of the fossil and its breaking pattern. This last factor depends on the nanostructural organization and concentration of the silica spheres and the arrangement and size of the pores of the frustule walls, characteristics that are unique for each species of diatom and that are influenced by environmental factors (mineral concentration in the water, hydraulic flow, sunlight amount, predatory activity, silica transporter efficiency, environmental temperature, among others) present at the moment of formation of the original algae.

The displacements associated with shear stresses imply an accumulated fracture of the frustules. Progressive deterioration will reach a point at which the angularity and contact of the fragments are such that friction increases. However, when applying a more significant shear displacement, the particles would reduce their sizes, lose the shapes that generate the interlocking effect and align along the plane of failure imposed by the loads, reducing the friction angle.

At low stresses, the strength of the DS is controlled by the microstructure, which can be disturbed by the reorganization and massive breakage of the frustules due to higher stresses, generating a transition towards frictional behavior [37]. The above has been supported by microscopic observations after the execution of different oedometric, compressive and triaxial tests (see Figure 6).



(**a**) (**b**)

Figure 6. Fragmentation of diatom frustules from laboratory tests. Vertical compressive stress (50 kN) and dry condition (**a**) DS origin Jalisco (Mexico) (**b**) DS origin Boyacá (Colombia).

Wiemer and Kopf [42] highlight the need for understanding the effects of diatom shattering with increasing geostatic stresses. They recognize the positive effect of increased microfossil content on shear strength and slope stability.

Research on marine geological processes has shown a relationship between DS porosity and the depth of some normally consolidated deposits. The primary explanation refers to a higher diatom content as strata deepen. Alternate variables such as water flow, accelerated sedimentation, seismic agitation and the presence of free gases have been considered to understand the phenomenon. These elements are associated with increased pore pressure and decreased stability of submarine slopes [20].

Although several works have been carried out on marine sediments, more progress has yet to be made on the impact of microfossils on the engineering behavior of this type of deposit. The presence of diatom microfossils exerts a significant influence on the index properties of soils. Such influence depends on the extent, state and type of microfossils present in the soil deposit and the ocean's depth at which these diatoms are located [41].

Shear strength increases with microfossil content, as does slope stability in marine sediments. However, more research is needed regarding the influence of sedimentation depth in geostatic stresses and its relationship with the potential increase in pore pressure as a function of particle crushing state [42].

Within this same line of analysis, [43] found that diatomaceous soils originating from lacustrine environments can be artificially reconstituted. Numerical simulations of elemental tests were carried out using the hardening soil model on this type of reconstituted sample. Likewise, [44] developed triaxial tests for different confining stresses, examining elastic wave signals at every 0.5% of the axial deformation. The authors evaluated the influence on the fabric, showing changes in the friction angle and the coordination number of this geomaterial.

Ref. [45] reported results related to reconstituted diatomaceous silts where the unaltered samples showed behaviors similar to the compressibility ratio and peak strength quantitatively lower than the remolded samples.

3.3. Breakage and Other Research Lines

As a result of scanning electron microscopy (SEM) tests and the application of an energy dispersive spectrometer (EDS), it has been concluded that DSs are primarily composed of pure biogenic opal (siliceous component generated by the metabolic activity of diatoms), with some level of mechanical alteration or fragmentation. Due to natural variations, changes in the proportions of fractured diatoms, intact diatoms, organic matter, sands [42], clay and silt are to be expected. Verification with microscopy techniques is the most direct way to validate the effective breakup of the frustules and the rearrangement of the frustules [22].

Dissolution of microfossils results in increased compressibility of the sediment. SEM observation shows that intact diatomite has a high degree of cementation and fabric, which is altered during remolding processes [41]. Tanaka et al. [34] report the scarce presence of fossils in the clayey soils of Bangkok. However, near the surface, some diatom fossils were found partially dissolved with apparent reprecipitation on the surrounding aggregates, which could contribute to the structural cementation of the soil.

Wiemer and Kopf [42] conducted investigations in DS based on the elaboration of artificial samples dosed in weight within a clay matrix and under a distilled water content equivalent to the liquid limit. The components were mixed to the point of being macroscopically homogeneous. As part of the methodology and sample treatment, the samples were used only once for shear testing to avoid potential cumulative particle breakage effects.

Tanaka and Locat [28] highlight a variable that has yet to be mentioned so far: the predominant orientation of the particles (intact or fractured), which will depend on the size of the frustules and the surrounding clay environments.

Hoang et al. [40] have investigated the influence of DS on S-wave and P-wave propagation and concluded that the presence of diatom particles, being porous and fillable, can soften the soil matrix and thus attenuate the propagation and reduce the shear stiffness at low deformations. Consequently, the reduction in the velocity of the "S" and "P" type waves is attributed to increased diatom content.

4. Effects of Interlocking on the Geotechnical Properties of DSs

Classical soil mechanics assumes that the greater the irregularity (roughness or fracturing) on the surface of the particles that make up a continuous medium, the greater the resistance to the differential displacement between them. Consequently, the greater the mechanical response of the whole. However, these phenomena are easy to understand and demonstrate at larger scales (sand sizes > 0.075 mm) [46]. They are less so at nano and micro sizes, where everything is regularly classified as fine soils, far from any high strength parameter, and even more so when liquid limits are reported to be high [47].

In DS, the increase in the content of frustules is associated with a simultaneous increase in the liquid limit and friction angle, reaching relatively high values of between 35° and 45°. Previous studies have explained this behavior as a result of particle locking, high frictional components at the diatom contacts and due to the surface roughness of the hard siliceous material [22].

Although DSs have a low dry density and high moisture contents, they behave as dense granular materials at effective stresses below 50 kPa, due to the frustules, which can resist shear and compression because of their interlocking characteristics and rough surface. At higher effective stresses, diatoms can fracture, significantly increasing the fillings' compressibility. In DS subjected to vertical compressive stresses of 50 kPa, the vertical deformation was less than 1% [36]. This author has reported effective friction angles of 44° and states the following reasons as the cause of such magnitude:

Diatoms have rough surfaces such as protrusions and indentations, which can increase the frictional resistance between the frustules.

Stress paths of DS in p-q space are characteristic of dense, interlocking granular particles. Even when diatomaceous fillers have low density, they can lock and generate highly effective friction angles.

The presence of predominantly hollow microfossil skeletons with rough, interlocking surfaces results in altered index properties and soil behavior. Increased diatomite content increases the DS compressibility and internal friction angle [41]. The degree of influence depends on the extent, state and type of diatom microfossils present in the deposit and the ocean depth at which the soil is located.

Cheng et al. [26] mention the relatively high friction angles (25°–40°) reported by [28] in reconstituted soil samples from Osaka Bay, in which high contents of diatom microfossils are identified. Likewise, this alludes to the effective friction angle of 44° obtained by [36] after evaluating a diatomaceous filler of low dry density and high moisture content. The arguments supporting these high results are mainly the interlocking effect and rough characteristics of the diatom surfaces at low stress levels.

Similar studies developed an experimental program that sought to define the strength and deformation of organic soils, with and without the presence of subhorizontal laminae, with the presence of microfossils, employing simple shear and edometric (Ko parameter) tests (op. cit. [26]). The authors propose that specific deformation mechanisms of these microfossils would make understandable the unusual geotechnical responses of the studied deposits, particularly the high friction angles (see Figure 7).

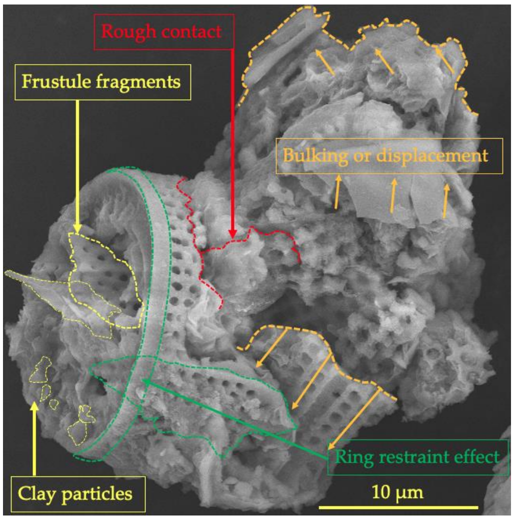


Figure 7. Deformation and interaction mechanisms for centric diatomaceous soils.

Medium-sized and coarse siliceous siltstones within the denser laminae and fine silica and carbonate-bearing siltstones outside them generate locking during deformation due to their angular, elongated and even lenticular shapes. Denser lamellae report a more significant opportunity for contact. However, this can also occur in loose material when the samples have undergone consolidation processes. The main siliceous silts in the organic soils analyzed correspond to broken diatoms. Some have densities (1.9–2.2 g/cm^3) lighter than quartz (2.65 g/cm^3), with very rough surfaces due to their nanopores. Although the micromechanical properties of lenticular elements deserve further study, it is possible to sustain a considerable amount of tensile rather than compressive stress [26].

Both cyclic and static shear strength increase with diatom content. For the static condition, the most representative increase is recorded for contents between 0% and 25%, while for the cyclic condition, it is reported for concentrations between 75% and 100%. Consequently, diatom microfossils in marine sediments contribute significantly to slope stability regardless of the loading mode. The increase is interpreted as a result of particle locking and surface roughness [42].

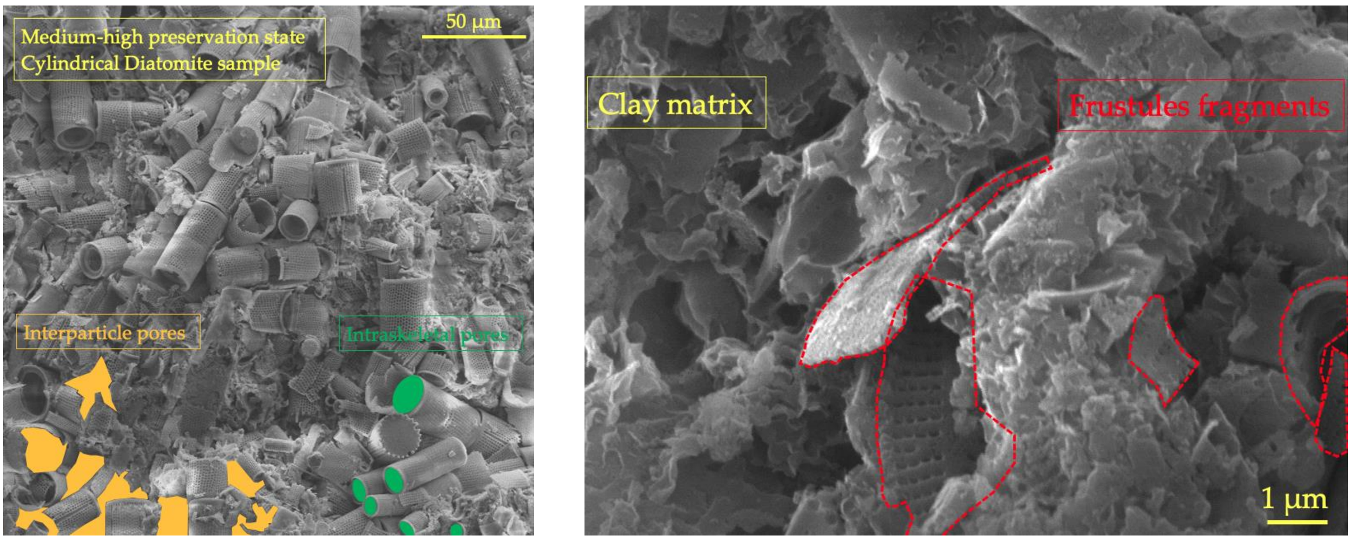
Particle locking, surface roughness and overlapping can be very efficient given the high variability in size and habit of species. High values of friction angle obtained from single shear tests may represent an underestimation of sediment strength at low normal stresses or an extreme overestimation at high normal stresses. Not surprisingly, the angle of pure DS internal friction is similar to the typical internal friction angles of silica sand since the mineralogy of diatoms is amorphous, mainly silica [42].

Liquefaction can occur in diatomaceous sediments. However, susceptibility to failure decreases with increasing diatomaceous earth content under a given earthquake load. This aspect can be interpreted as a result of interparticle locking, angularity, surface roughness and particle shape diversity. These aspects increase shear strength in static and cyclic conditions [42].

An apparent and systematic overconsolidation of surface diatomaceous sediments occurs due to particle locking, which is associated with high undrained shear strength, calculated by vane tests [20].

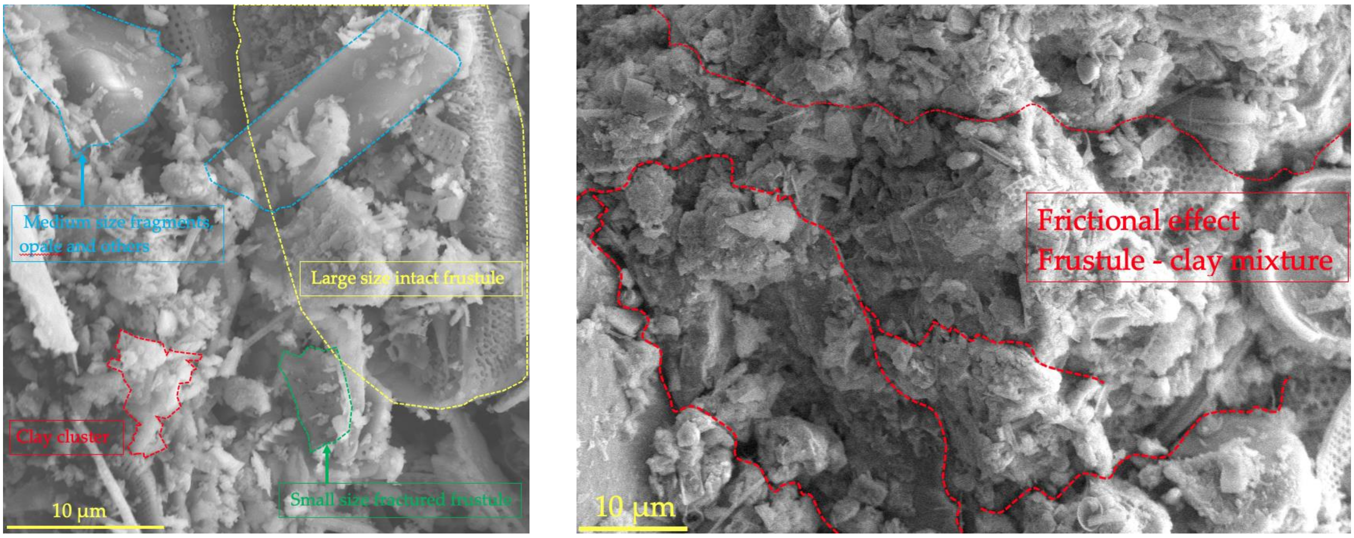
Ovalle and Arenaldi [37] apud Caicedo et al. [48] indicate that, concerning soils from Bogotá, it has been found that the angle of internal friction increases along with its liquid limit, which is counter-intuitive with conventional fine soils. This fact has been associated with the interlocking and high frictional component of the contacts between the particles and the high surface roughness of the siliceous material. Similarly, [40,49] state that the irregular shape of diatom frustules significantly influences the strength of the soil since it affects the surface roughness and induce interlocking between particles. The variation in the size of the fragments and, therefore, the size of the pores, the angularity of the fractured fossils and the alignment on some accommodation planes affect the frictional response of the soil mass (see Figure 8).

The interlocking effect has been identified even in artificial mixtures of DS and kaolin. After the dosing, mixing and pre-consolidation stages, the formation of clusters in which the clay particles fill the spaces left by the diatomite frustules has been observed by SEM, generating a structural and skeletal interlocking fabric. This situation is evident for a dry mass dosage of 40% kaolin–60% DS (Changbai, China) [50].



(**a**) (**b**)

Figure 8. *Cont.*



(**c**) (**d**)

Figure 8. Frictional behavior in DS due to multiple criteria (**a**) agglomeration of highly preserved and fractured frustules. (**b**) Frustule fragments in clay matrix; (**c**) Size and morphology variation (**d**) Rough accommodation planes.

5. Emergent Issues of DS in Geotechnical Research

The growing interest in the behavior of DS and diatomites has focused on determining their critical conditions and formulating constitutive models describing their response patterns [31–33,40]. In most cases, diatomite is a "soft rock" [11,12] or a "mudstone" [12,14]. In their composition, they show a considerable percentage of diatomaceous fossils simultaneously with other elements, predominantly clayey or volcanic.

In recent years, research has been conducted on the strength and stress–strain relationships in soft rock samples with well-defined failure planes. This particularity is mainly through triaxial compression tests for different drainage conditions. In reference [12], it is shown that the literature needs to exhibit models that correctly describe the behavior of this type of rock when it presents joint patterns. Consequently, they propose a constitutive model that considers, in addition to these planes, structural decay and overconsolidation. This research was developed on samples from the Noto peninsula (Ishikawa Prefecture—Japan).

Similarly, [13] formulated a boundary surface model for soft rocks in drained and undrained conditions. Experimental results showed that the overconsolidated samples' stress–strain relationships and stress path differ from those in normal consolidation; the same behavior is presented in the peak strength, residual strength and pore pressure. Comparisons between predictions and experimental results showed that the constitutive model adequately predicts the mechanical behavior of this type of rock under compressive conditions.

The DS is described by some authors [11] as geomaterials, and the models that attempt to describe them are analyzed by applying computational tools. Thus, some artificial intelligence methods have been implemented to solve the complexity of the mechanical behavior of this type of soil since traditional constitutive models do not adequately define them [11]. Some researchers have proposed applying genetic algorithms to determine the non-linear constitutive laws of the stress–strain–time relationship of DS. So, the strain-softening behavior under non-drained consolidated states can be described [10].

Lin et al. [14] propose a methodology that considers thermo-hydro-mechanical variables to facilitate theoretical modelers to refine their elastic–viscoplastic models. For this, volumetric and deflection data were calibrated from several sets of triaxial tests on samples of "diatomaceous mudstone" (1% sand, 66% silt, 33% clay) and "sandstone". For the case of the DS, the drained triaxial test records were evaluated, with whose stress–strain results the model was calibrated. From the background used by the authors, a correct fit with the failure envelope defined by the extended Cam-clay model was identified [14].

Another current line of research focuses on the determination of the water retention curves (WRCs) and the absorption potential reported by pure and sand-dosed DS [51]. This interest is growing, considering that DS is an example of a geomaterial whose fabric is not significantly modified by the wetting and drying processes. As a result, it has been possible to differentiate the retention curves generated by capillary processes from those generated by adsorption processes. This response is dependent on the soil structure. A parameter associated with this structure, known as the "contribution factor" and a "law of variation", is introduced, with which the effects of the retention capacity can be evaluated, depending on the changes induced by hydraulic, mechanical, thermal or chemical loads [51].

Ruge et al. [52] analyzed the influence of diatomaceous fossil content (5, 10, 20 and 40% by weight) on the WRC of kaolinitic soils. Several methods (dew-point hygrometer, filter paper, tensiometer and suction plate) were applied simultaneously. Maximum suction levels decrease with the addition of fossils. The WRC is restricted with the addition of diatoms, and the range of mobilized suction is low. In size, the frustules resemble fine sand and are located between the kaolin clusters, reducing the composite's suction potential. With a higher diatom content, a greater overlap between the filter paper and hygrometer techniques is identified. Therefore, using several methods to obtain the WRC in coarser soils would be adequate.

Geotechnical Centrifuge Modeling

Regarding studies using state-of-the-art physical modeling techniques, an investigation of the bearing capacity of a fine soil dosed with diatomaceous frustules from two origins (Colombia and Mexico) subjected to stresses transmitted by two types of foundations (footings and piles) was evaluated utilizing geotechnical centrifuge flights (50 gravities) [17]. For the deep foundation model, the piles were installed to be embedded within the soil mass at 50% of the total length. The footings were located just above the level ground surface. Three dosages were considered, 100% kaolin (C), 50% (C) + 50% DS of Colombian species, and 50% (C) + 50% DS of Mexican species. The actual and scaled geometric conditions are described in Table 1. Their determination considered the scaling factors applicable to this type of test [18,19].

Table 1. Real and scaled geometric conditions for different types of foundations.

Soil Proportion	Foundation Type	g	Real Geometry		Scaled Geometry	
			Diameter (m)	Length (m)	Diameter (m)	Length (m)
100% K	Pile	50	0.008	0.04	0.4	2
50% K–50% CDS	Pile	50	0.008	0.04	0.4	2
50% K–50% MDS	Pile	50	0.008	0.04	0.4	2
100% K	Rectangular footing	50	0.035	0.07	1.75	3.5
50% K–50% CDS	Rectangular footing	50	0.035	0.07	1.75	3.5
50% K–50% MDS	Rectangular footing	50	0.035	0.07	1.75	3.5

K: kaolin; CDS: Colombian diatomaceous soil; MDS: Mexican diatomaceous soil; g: gravities.

The failure criteria were 10% and 25% of the pile diameter and 10% of the smaller dimension for the rectangular footing. From the load–displacement records, the higher capacity of the soil mixtures containing Mexican diatoms was evident for both types of foundations.

Geotechnical centrifuge models supporting slope models with slopes of 45°, applying up to 200 gravities, were carried out [16]. The objective of the research was to determine the effect of the concentration of diatoms (0%, 25%, 50% and 100%), from Oicatá (Colombia), within a reconstituted soil mass based on kaolin, with which the slopes were formed. The analysis of results considered the comparison of images and photographs in order to recognize displacements and possible weak zones. In contrast, identifying failure surfaces of the different slopes was not possible, except in the sample formed only by kaolin. This effect was where more significant deformations were observed in the slope leg. It was recognized that, with the higher diatomaceous soil content in the different models, the cracking process in the slope leg was more evident, probably associated with tensile failures.

Similarly, Rodríguez et al. [53] established a new methodology for modeling soft soils using a geotechnical centrifuge machine, where specimens with diatomaceous soil content were used. The advantage of using this type of soil is highlighted in the research because it increases the consolidation coefficient, which consequently influences a reduction in the test duration without sacrificing the correct simulation of the deformable behavior of natural deposits, in this case of lacustrine soils.

6. Conclusions

From the bibliographic review and the analysis of the SEM micrographs, the following conclusions were generated:

- Frustules are subject to deterioration by multiple factors (taphonomic, ecological, geological), and the possibility of finding DS is considerable. Research on DS has focused on index properties, compressibility and shear strength rather than the mechanisms by which this effect occurs, the influence of the formation processes or the frustules' morphological conditions.
- Although some geotechnical variations due to the breaking of the particles can be foreseen, the mechanical response cannot be generalized since the rearrangement, the angularity of the fragments and the irregularity of the surfaces, among other factors, will depend on the morphology of the frustule. The pattern of breaking and accommodation of a cylindrical particle (e.g., *Aulacoseira granulata*) will not be the same as that of a plated one (e.g., *Cyclostephanos tholiformis*) or elongated one (e.g., *Thalassionema nitzschioides*). Elongated particles are more susceptible to fracture than rounded ones.
- The fracture's characteristics will depend on each fossil's micromechanics. It is not enough to determine that the main component of the frustules is opal; it is necessary to determine how the nanospheres that define the breaking routes are organized. The cracks travel around and not through the spherical silica particles, increasing the energy required for breakage. Consequently, the "strength–deformation" behavior of the frustules of each diatom species is different; therefore, their angularity and accommodation pattern vary when the yield stress is exceeded. It is necessary to understand the micromechanics of the frustules and motivate modeling through discrete elements.
- The interlocking phenomenon at the microscale is directly related to the frustules' quantity, shape and state of conservation. Interlocking will be effective as the fossils remain jointed or are sufficiently added to the medium containing them, so stress transmission is effective. There is a minimum number of fossils within a soil mass that ensures interconnectivity and explains the high values of friction angle. Simultaneously, there is a fragmentation state in which the frustules generate higher friction and, therefore, a better mechanical response.
- Frustule pores, ribs, chambers, nodules, surface area, thickness, fragment interaction and pore size could affect resistance when subjected to compressive or shearing stresses.
- Particle breakage enhances when specific stress is exceeded; consequently, the microfossils fracture and the intraskeletal pores reduce. Some DS show high compressibility due to the fracture of the frustules. After yield stress, the microstructure of the DS is altered and becomes very compressible due to massive breakage, loss of cementation and fabric disturbance. When frustules are reduced to small pieces, they cannot recover their original shape.
- The pending research lines in DS are the yield stresses at which the volumetric reduction is enhanced by frustule breakage, the relationship between soil mechanical

properties and the fossil microstructure, the micromechanical and microstructural behavior changes during consolidation and shearing processes, the boundary between primary and secondary settlement, the compressibility in DS with high trapped water content, the creep deformation, the suction effect in mechanical response and the most suitable constitutive model for DS.

- The information available regarding diatomaceous soils evaluated in a geotechnical centrifuge to determine their interaction with foundation structures and their performance on slopes or in water flows is minimal. Likewise, the absorption potential and suction stresses are not discriminated in the literature depending on the diatom species, the pores' geometric characteristics or the specific surface of the fossils.

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Appendix A

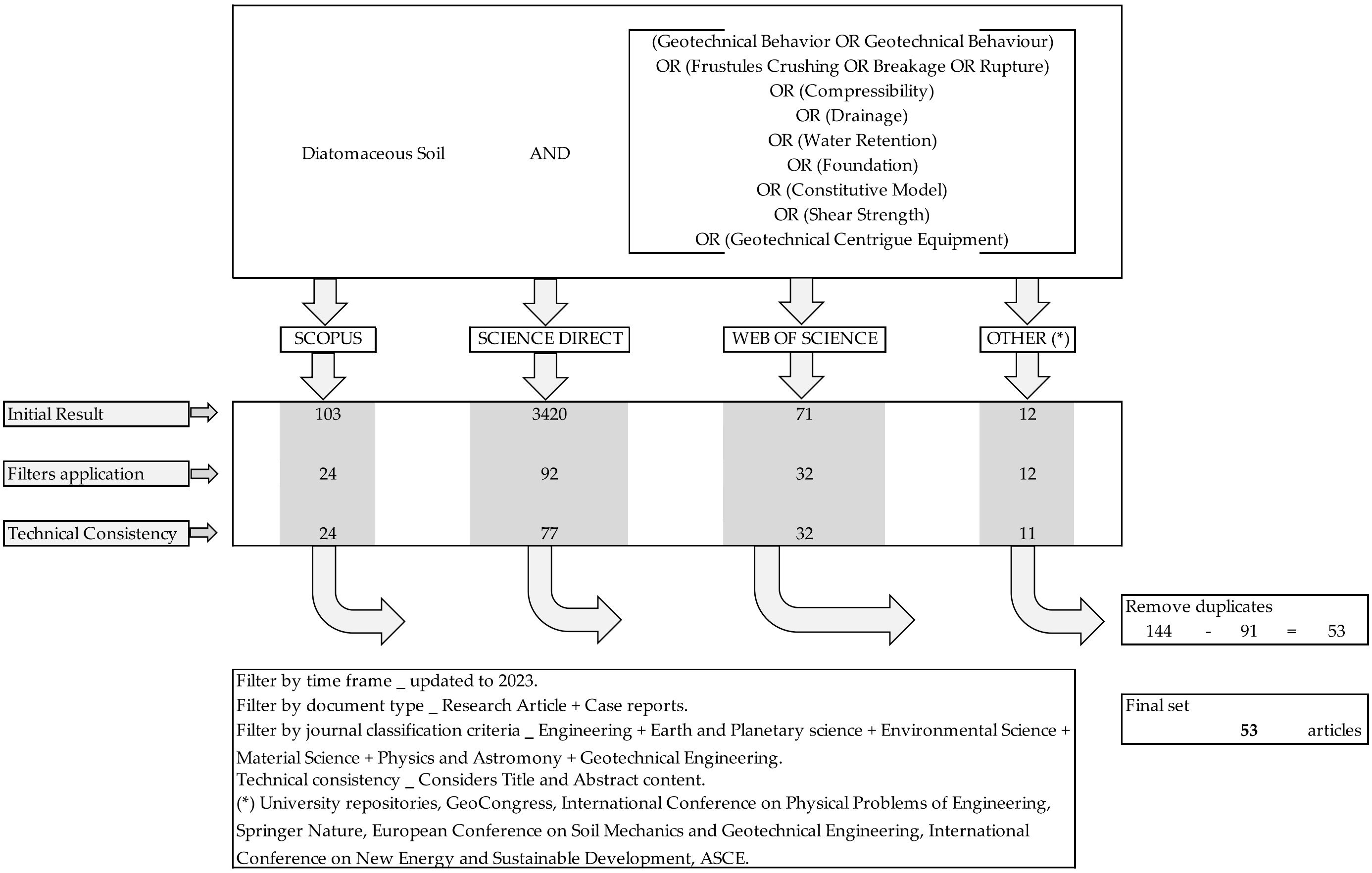

Figure A1. Flowchart of search criteria and selection of documents.

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