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Physical Modeling in Geotechnical Centrifuge of Foundations Supported on Diatomaceous Soils

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Abstract Diatomaceous soil deposits have been found in different parts of the world. However, until recently, its applications only existed in the field of agricultural engineering and agronomy. Within geotechnical engineering, there are still few studies on the subject. In this context, the advances found in the literature highlight that these materials are characterized by presenting geotechnical responses different from those dictated by traditional soil mechanics. One of the points of interest is related to the high values of resistance to shear that they can present, even when they are within clay matrices. Therefore, it is necessary to investigate the behavior of these deposits so that the physical and mechanical responses can be known in detail when subjected to stresses transmitted by a foundation structure. Thus, this study employs reduced-scale models installed in a small diameter geotechnical centrifuge. The load and displacement trajectories of shallow and deep foundations in artificial soils built from a kaolin base with different dosages diatomaceous soils of different genesis are presented.

Keywords Geotechnical centrifuge · Diatomaceous soils · Foundations

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Background

Foundations and Unusual Behavior of Diatomaceous Soils

Implementing deep and shallow foundations on soft soils tends to be complex, both in its design stages and in the construction process. Even during the useful life, pathologies associated with the foundation soils can occur, either due to intrinsic or extrinsic conditions, potential excessive settlements, and the absence of simple models for calculating bearing capacity. The stated factors generate uncertainty, prioritizing conservative criteria when sizing the foundation structures and assigning mechanical resistance properties to the surrounding soils.

The presence of diatom frustules (microscopic skeleton of algae and dead plankton) in soft soils and sediments of lake origin leads to the measurement of mechanical characteristics in magnitudes that contradict the behaviors defined in conventional geotechnics [1]. Diatomaceous soils are characterized because they can conserve high water content inside their frustules [2, 3] and simultaneously register high values of friction angle and high soil shear strength [4]. Therefore, diatomaceous soils have broad potential to be applied in geotechnical and geoenvironmental engineering projects, as it would be the case of the formation of mechanically stable hydraulic fillings, and in the redefinition of the criteria of bearing capacity of the

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soils that support foundation structures (footings or piles). The unusual response of soils with diatoms concerning traditional soil mechanics [5] is not only evidenced in ex situ laboratory tests but has also been reported in actual construction processes.

In the diatomaceous silt deposit that supports the Buck Creek Bridge (OR, USA), laboratory tests indicated high values of liquid limit, shear strength, and over-consolidation ratio (OCR) [6]. However, during pile driving, rejection was observed at a depth of 4.9 m, and external elastic rebound in the conservative pile area after exposure to cyclic loads [7]. On the other hand, the secondary consolidation of diatom lake materials in the "La Pine" basin triggered significant settlements after the construction of the foundation embankment in Wickiup Junction (OR, USA), in response to the deformation and crushing of the skeletal particles by the imposition of new charges [8].

A similar case with underwater diatom deposits in Lake Villa-Rica (south-central Chile) prompted the failure mechanism of the foundation infrastructure of on-shore and offshore exploration platforms [9]. From the preceding, it is evident that the conventional characterization criteria are not sufficient to describe this type of soil. Also, the typical tests of mechanical response evaluation are inadequate to quantify the resistance parameters in diatomaceous soils properly. According to observed in these antecedents, they are given as a function of the frustule's properties their rupture potential. Most of these foundation structures (footings and piles) depend significantly on the underlying soil's shear strength, which is conditioned by the inherent spatial variability [10]. For this reason, the behavior and constitutive parameters of soft and diatomaceous soils have received diverse attention in recent decades in order to interpret their response framework [11].

Characteristics of Diatomaceous Soils

Diatomites are sedimentary rocks composed primarily of fossilized remains of unicellular photosynthetic algae of fresh and saltwater with silica skeletons, known as diatoms [12, 13] the same origin describes diatomaceous soils, which are derived from the progressive sedimentation of soil layers with the presence of microfossils. Soils formed from diatoms have been identified all over the globe: Mexico [14], Japan [15, 16], Australia [17], Equatorial Pacific [18], United States [19], China [20], and Colombia [21, 22]. The intrinsic morphology of diatomites can link extreme plastic characteristics (absorbent capacity), high void ratio values [14–16], low density, and a variable surface area between 40 and 350 m^2/g [23, 24]. As a result of its unique physicochemical properties, diatomite has been evaluated to understand residual shear strength in fine-grained soils by the ring shear strength test.

The tests carried out by Shiwakoti et al. [1] indicate significant increases in the coefficient of permeability and compressibility of soils with diatom microfossil contents. Wiemer and Kopf [9], through triaxial cyclical tests on clay-silty soils, established the diatom content that induces the soil to change from a cyclical softening behavior to a liquefaction one. Additionally, several scale laboratories studies have been carried out to investigate both the intrinsic framework of the water retention curve of diatomites [25] and the potential of the diatom at the Atterberg limits, with increases attributed to the enormous water retention capacity of the internal structure of diatomites [14, 26].

The physicomechanical response of diatomaceous soils is closely related to the effective stresses applied [27, 28], which indicates that shear strength, the particle size distribution, and textural arrangement of the soils of diatoms change with the stresses-history. Therefore, the standard geotechnical requirements and correlations for foundation design are not entirely suitable for soils containing diatom particles, especially in concentrations greater than 40% by weight. From this magnitude, some soils with the presence of diatoms register considerable increases in the liquid limit and the void ratio, mostly at low-stress levels (12.5–100 kPa). In situ studies are scarce, related to the behavior of soils with algal microfossilization contents type *Diatomeae*, the results of which can be used in geotechnical design procedures and construction methods [29]. Recently, deep foundations in diatomaceous soils have resulted in the shallow rejection of piles and excessive differential settlements after driving [6].

Geotechnical Centrifuge Modeling (GCM)

Since the mid-1980s, the full-scale simulation technique has been implemented to evaluate the potential response in the field of different problems associated with civil engineering, within which the effects of foundation structures, through the construction of prototypes or models that can be evaluated in geotechnical centrifuge equipment [30]. The centrifugal test examines the cooperative behavior (soil and foundation structure) through the imposition of forces derived from high-intensity rotary movements. By increasing the force of gravity, the centrifuge allows replicating the stress and strain fields perceived by the prototype under study, but in a condition comparable to the scale of in situ structures [31], taking into account that the constitutive behavior of soils is dependent on the level of stress to which it is subjected.

Some of the fields of application of the centrifuge for replicating geotechnical phenomena are caissons, landslides, and slope stability, dams, fillings, shallow and deep foundations, tunnels, vegetation interaction, dynamic effects, subsidence surfaces, among others [32]. Taylor [30] and Garnier et al. [33] analyze the main aspects of geotechnical centrifuge-gas modeling at a theoretical level. In general, the tendency to increase the size of centrifuge devices generates high testing costs, so that, for geotechnical problems of different nature, it is possible to carry out practical tests on geotechnical centrifuge equipment of smaller magnitude. Small-scale centrifuges have been developed to model slope stability problems, to know the response of the soil located below surface foundations [34–36], to assess the global stability of dikes in soft soils [37], and to know the hydraulic properties of unsaturated soils [38]. In particular, geotechnical centrifuge tests have been developed for educational purposes [39–42]. Aiban and Znidarčić [43] studied the effects of eccentricity and inclination on the load capacity of continuous footing through simulations in centrifuges with radius equal to 1.36 m. Centrifugation systems with a similar rotary radius for foundation modeling were used by Li et al. [32] and Wang et al. [44]. Table 1 reports some studies of dimensionally modified geotechnical centrifuges at rotational diameters less than 2.15 m used for foundation simulation.

Material and Methods

Geotechnical Centrifuge Models

Centrifugal modeling allows to understand the response mechanisms of the soil before the imposition of forces, thanks to the instrumentation that can be implemented within the prototypes, which are 1:1 scale, structure and which are subsequently subjected to an acceleration N times greater than the force of gravity. For the analysis of results, the model's initial state, the properties of the materials, and the boundary conditions must be defined [49]. It is essential to properly handle the scaling rules as well as the edge conditions so that the information obtained corresponds precisely to the situation under investigation (e.g., [50, 51]). For the case of the deep foundation model, the piles were embedded within the soil mass at a depth of 2 cm (50% of total length). In the case of footings, their location occurred just above the level ground surface (Fig. 1). The dimensions of the centrifuge used are presented in Table 2.

The installation of the piles was done in condition 1 g. Initially, a lower soil layer was preconsolidated under a stress of 50 kPa, verifying that its final height, counted from the bottom of the container, was close to 6 cm. The tip of the pile rested on the surface of this first layer. At a 9 cm height from the bottom of the container, a perforated sheet was temporarily fixed to allow the pile to be inserted, ensuring its verticality. Simultaneously, and through the other perforations of the sheet, an additional soil layer was placed in the total area of the container. Then, 50% of the entire length of the pile was embedded in the second layer of soil. This layer was pre-consolidated at 50 kPa, and the load was transmitted through the lateral supports of the perforated sheet. The final soil height was close to 8 cm. Once the soil was pre-consolidated, the perforated sheet was removed, and the instrumentation and preparation phase for the centrifuge flights began.

For evaluating the mechanical response of clayey matrices with the presence of diatomaceous soils under stresses induced by a condition of 50 gravities, the research considered the construction of six models of soil, which were pre-consolidated under a stress of 50 kPa. An electro-pneumatic oedometer was used. Three types of dosage (100% Kaolin, 50% Diatoms of Colombian Species, 50% Diatoms of Mexican Species) were considered, always taking kaolin as the base material. The main object of using the GCM is to determine if the variation of species influences the load capacity of a diatom added to the soil when it is submitted into a strength test based on different foundation types, footing, and pile.

Three of the models considered incorporating a scaled structure that simulates a rectangular surface-type foundation (footing). The other three were elaborated, including a structure that reproduces a deep pile foundation. The material use for footing and pile was non-friction surface

Table 1 Summary of previous researches of foundation modelling on small-centrifuges

Reference	Capacity	Radius (m)	Foundation	Complementary devices for testing
Ketcham et al. [45]	100 g	0.250	Circular footing	Heave cell within a cylindrical container
Borghei et al. [46]	5 g-ton	1.000	Square footing	In-flight shake table
Borghei and Ghayoomi [47]	5 g-ton	1.000	Square footing	Accelerometers connected to a single data acquisition system
Black et al. [41]	2 g-ton	0.500	Square footing	2 port hydraulic rotary union
Quin et al. [48]	20 g-ton	1.070	Square and circular footing	Electro-Hydraulic Shaker (EHS)
Caicedo [42]	500 g	0.300	Strip footing and pile	Stress and displacement sensors

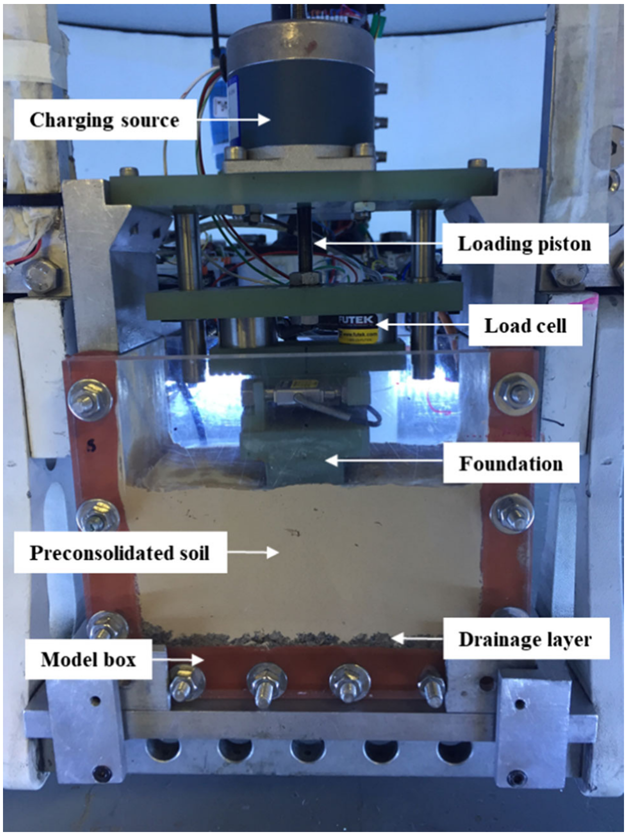

Fig. 1 Assembly of models in geotechnical centrifuge

Table 2 Details of the centrifuge

Dimensions	Value
Platform axis distance (cm)	56.6
Rotor length (cm)	1.50
Centrifuge room diameter (cm)	1.70
Centrifugation room height (cm)	70.0
Platform length (cm)	17.5
platform length (cm)	13.5
Free height (cm)	10.0
Model mass (g)	4000
Internal dimensions of the container	
Height (cm)	11.5
Width (cm)	14.0
Depth (cm)	7.4

aluminum. The in situ and scaled geometric conditions of the different models are described in Table 3. Their determination considered the scale rules defined by Muir Wood [52]. For the models of both types of foundations (footing and pile), the assembly considered installing a load cell located in the upper part, which would record the force transmitted vertically from a hydropneumatic piston or actuator. In this case, strain gauges were not used. The actuator drove at a controlled speed and, in turn, measured the strain. For this investigation, displacements were verified but not unitary strain.

The footing was located in the center of the soil sample seen from the front face. In-depth, the container registers about 7.4 cm, while the footing measures 7.0 cm, which means that it was ensured that no type of effective friction was generated between the wall of the container and the side walls of the footing. In this case, the deformation effect caused by the footing is the same in any axes, thus being a symmetrical condition, variable in depth. The axial (E.A) and flexural (E.I) stiffness of the piles were obtained, revealing the following values of 3.25 MN and 416 MN/m^2, respectively. Similarly, the scaling law for each of these properties is (1/n2) and (1/n4), where n is the number of gravities imposed on the model.

Kaolin Matrix and Diatomaceous Soils

The fine clay type soil (Kaolin) and those of the silty order (diatomaceous soils with species of Colombian and Mexican origin), which were dosed and implemented in the elaboration of the models for flight in Geotechnical Centrifuge, were characterized under the tests and laboratory tests described in Table 4. The different current imaging techniques allow a dimensional and spatial approach to the processes that occur in the microstructure of the clay body. The identification of the particles of the diatomaceous soils and the kaolin used in the research was carried out through observations in a Scanning Electron Microscope. Under a microdimensional approach, each soil matrix is presented in Fig. 2, as well as its mineral construction. Large sheet-like particles stacked together in agglomerates make up the microstructural tissue of kaolin. For diatom species, in diametral spectra of 5–10 µm, digital mapping indicates cylindrical and circular geometry particles with a significant surface arrangement of voids.

Once the soil was consolidated to the desired level and the piles embedded in the kaolin and the footing disposed on the surface, the vertical displacement sensor and the load cell were activated, respectively. In the centrifuge, all the equipment and instrumentation were correctly verified. The loading speed of the actuator during flights was kept constant at a speed rate of 0.05 mm/min. The maximum displacement reached in the prototype model was 5 mm, equivalent to a displacement of 250 mm in the real scale model. The duration of each centrifuge test was approximately 100 min, including the period of preloading and conditioning of the system, which consisted of progressive increases in gravities until reaching the regime of 50 g.

Table 3 Model and prototype geometric conditions for different types of foundations

Soil proportion	Foundation type	Gravities	Real geometry		Scaled geometry	
			Diameter (m)	Length (m)	Diameter (m)	Length (m)
100% K	Pile	50	0.008	0.040	0.4	2.0
50% K–50% CD	Pile	50	0.008	0.040	0.4	2.0
50% K–50% MD	Pile	50	0.008	0.040	0.4	2.0
Soil proportion	Foundation type	Gravities	Real geometry		Scaled geometry	
			Wide (m)	Length (m)	Wide (m)	Length (m)
100% K	Rectangular Footing	50	0.035	0.070	1.75	3.5
50% K–50% CD	Rectangular Footing	50	0.035	0.070	1.75	3.5
50% K–50% MD	Rectangular Footing	50	0.035	0.070	1.75	3.5

K Kaolin, *CD* Colombian Diatom, *MD* Mexican Diatom

Table 4 Characterization results of kaolin and diatomaceous soils

	Kaolin	Diatomaceous soil	
		Colombian species	Mexican species
Specific Gravity	2.69	2.55	2.34
Liquid Limit	44	99	131.7
Plastic Limit	24	48	60
Plasticity Index	20	51	71.7
Liquid Limit (50% Kaolin)	–	63	67.6
Plastic Limit (50% Kaolin)	–	35	39.5
Particles < 2 um (%)	29.07	22.48	0.72
Activity	0.69	2.27	99.58
e_{max} (50% Kaolin–12.5 kPa)	–	1.65	2.80
e_{min} (50% Kaolin–800 kPa)	–	1.20	1.79
Effective friction angle (50% Kaolin)	–	33.38	49.65

Some features of the centrifuge model: (1) it was built in 1994, (2) electronic speed variator, (3) steel framed shaft, (4) 3 HP alternating current motor, (5) two arms, one for the model and one for the counterweight, (6) maximum acceleration of 200 g, (7) platform radius: 75 cm, (8) maximum load: 5 kg/g, and (9) electric ring. The piston is very light to avoid mass and weight effects during the test. For its adaptation to the model, a raft section was implemented that properly facilitated the union of the mini-displacement transducer (piston) with the ground. Displacement transducer reported: Delrin bearings, infinite resolution, and precision linear variable differential transformer (LVDT). The model used was the OMEGA LD400-5.

Results and Discussion

The GCM measured the vertical displacement (mm) and the load required (kN) to achieve that distance. In all cases, the maximum distance allowed to be registered is 250 mm. Failure criteria were established for pile and footing foundations to determine the variation in load capacity according to the Diatom species added. Although codes define no criteria, this research adopts the criterion where settlement is limited relative to 10% of the diameter of the pile [53]. For rectangular footing foundations, according to Vesic [54], a versatile criterion based on the definition of the slope of the load-settlement curve is zero or a stable minimum value. For this study, it is considered appropriate to adopt a standard value of 5% of the smallest dimension of the footing.

Figure 3 presents the load response for pile testing. In this case, the result evident the significant load capacity of Mexican Diatom Soil Mixture (D 50% added) compared with Colombian Species (D 50% added) and Kaolin Sample (100% K). The behavior of Kaolin and Colombian Diatom added samples is similar in the load–displacement space, particularly in the magnitude of slope in the linear part of the curve. This means that the more significant amount of load that the kaolin base supports due to the presence of Colombian Diatoms (D 50%) is not very substantial (< 15.88%). The Mexican species sample presents a less steep slope, which means shorter displacements for higher load ranges. The results from the load capacity test and gained load proportions (a significant amount of load for a determined failure criteria) for pile foundation according to evaluated species are described in Table 5.

Figure 4 presents the load and vertical displacement response for a rectangular footing. The Mexican Diatom added sample reports the highest value of load (> 18,000

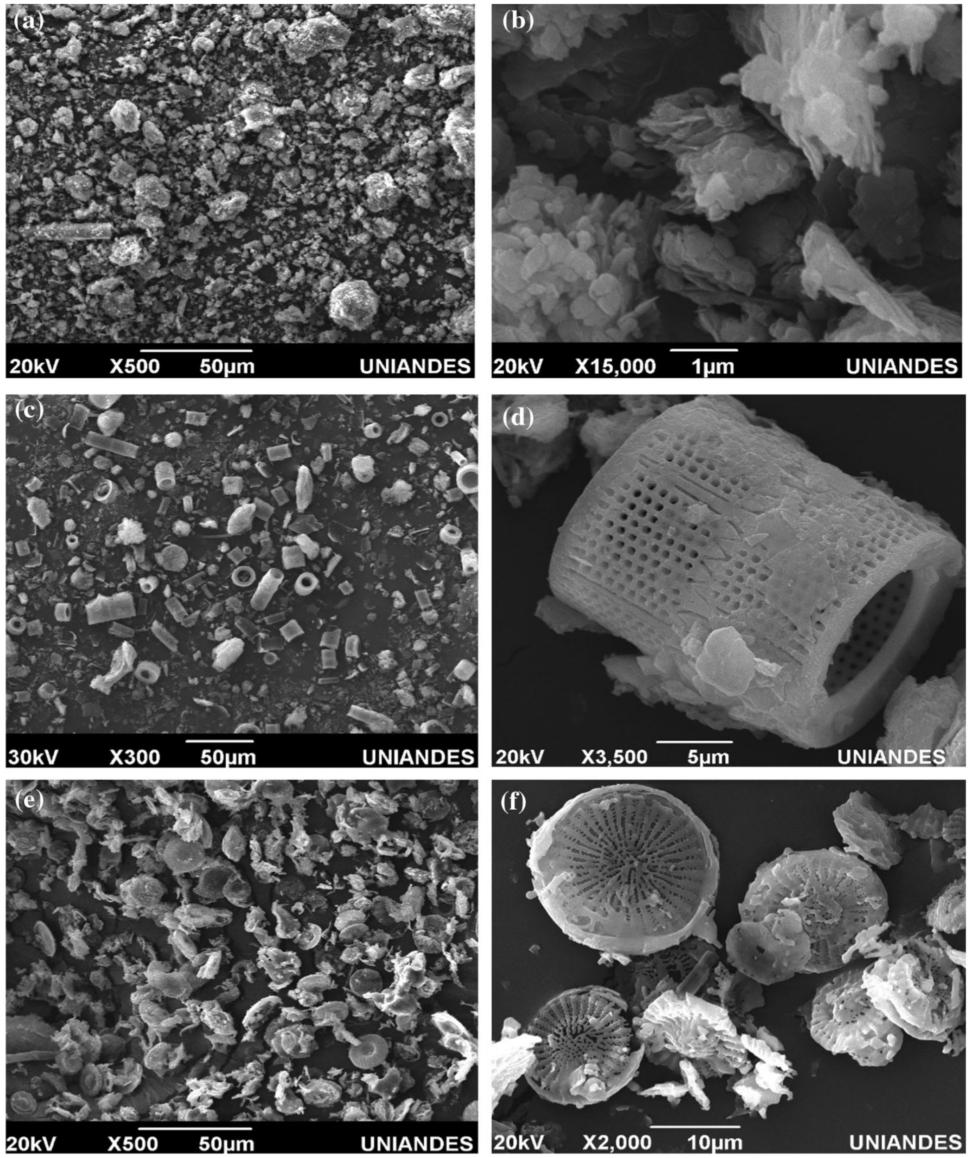

Fig. 2 Observation with a scanning electron microscope. Kaolin (**a**, **b**), Diatomaceous soils species of Colombian origin (**c**, **d**), and Diatomaceous soils species of Mexican origin (**e**, **f**)

kN) for the vertical displacement failure criteria (10% of the smallest dimension). The Kaolin and Colombian species added sample report similar behavior, particularly in the straight part of the curve, the same as the pile foundation response. Nevertheless, the gained load capacity resulted in quite representative (48%). The Mexican species added sample presents an almost perfect linear trend in the load–displacement space, with no evidence of change in slope, at least in failure criterion distance. The results from the load capacity test and gain load proportions for rectangular foundations depending on species are described in Table 6.

One of the explanations that can appropriately clarify the increase in load capacity in composite soils added with diatoms is the microstructural configuration of each of them. Due to their morphology, the cylindrical frustules do not offer a great interlock in the arrangement of the skeleton that they could form (Fig. 2). The microdisks of the Mexican diatom, on the other hand, could have better contact between their particles and increase the friction angle of the soil, as it is also shown in Table 4.

Figure 5 presents the physical models after the gradual application of the load by an actuator during centrifugal flight. It is possible to appreciate the deformations caused by the stress, both of the pile and the footing. The clear case of failure surface in the shallow foundation model (Fig. 5b) is derived from the state of frontal displacement and coating movements for the prototype. In comparison, surface settlements and casing movements were marginal for the driven pile model (Fig. 5a).

The error is understood as a variation of the gravitational effect due to the distance counted from the turning

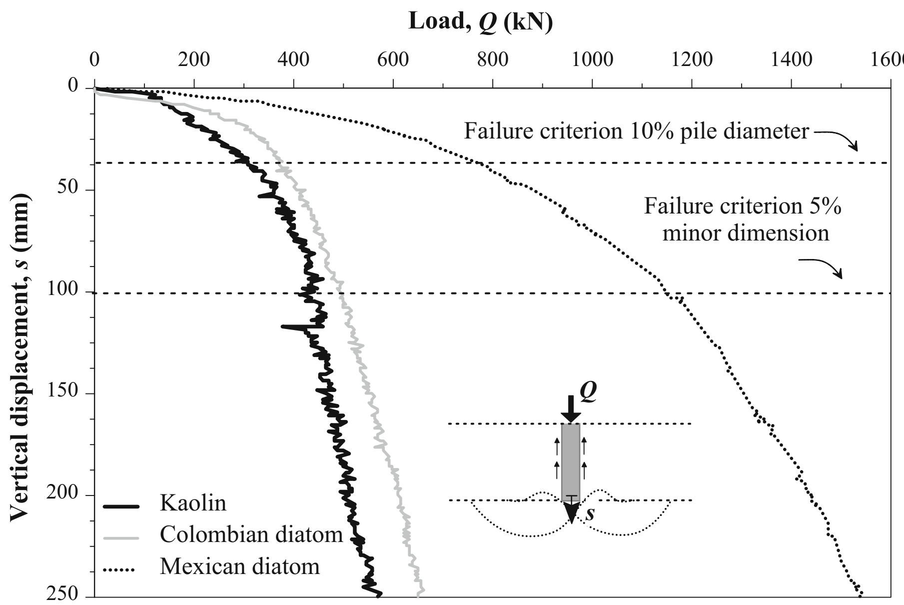

Fig. 3 Load–displacement space for pile foundation, GCM test

Table 5 Results of load capacity test for pile foundation and gained load capacity according to species

Failure criterion (% pile φ)	Kaolin load (kN)	Colombian species load (kN)	Gained load capacity (%)	Mexican species load (kN)	Gained load capacity (%)
10	325.22	376.88	15.88	795.28	144.54
25	441.36	493.02	11.70	1155.13	161.72

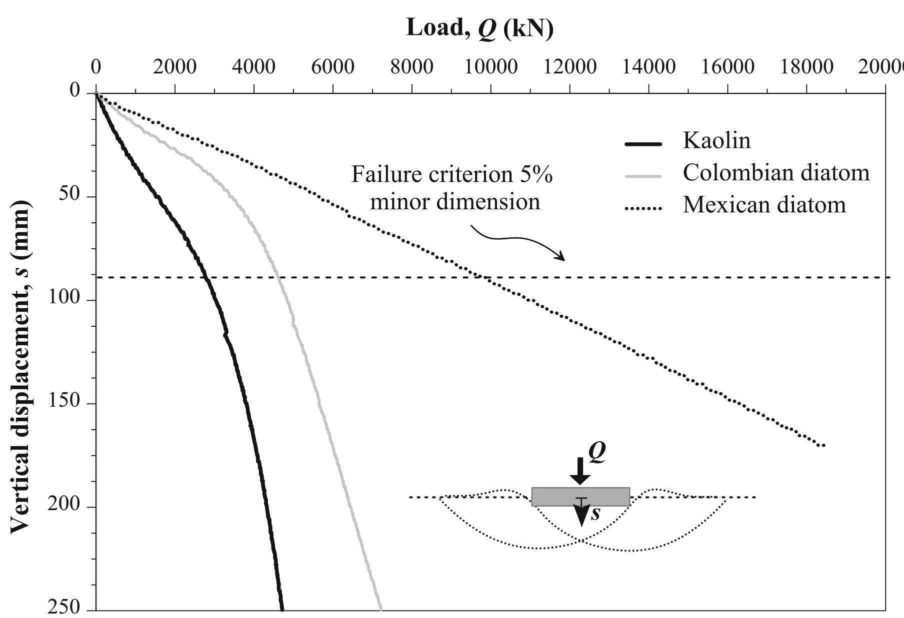

Fig. 4 Load–displacement space for footing foundation, GCE test

point to any sample point. Therefore, the centrifugal effect of the upper part of the sample (floor + pile) when it is in flight will not be the same as the one presented at the base of the container. For this case, the variation implies a radius difference of 8 cm (55.5–47.5 cm). According to Caicedo [55], the artificial gravity induced in the model is not

Table 6 Results of load capacity test for footing foundation and gained load capacity according to species

Failure criteria (minor dimensión %)	Kaolin load (kN)	Colombian species load (kN)	Gained load capacity (%)	Mexican species load (kN)	Gained load capacity (%)
5	4079.48	6040.01	48.06	18,533.29	354.31

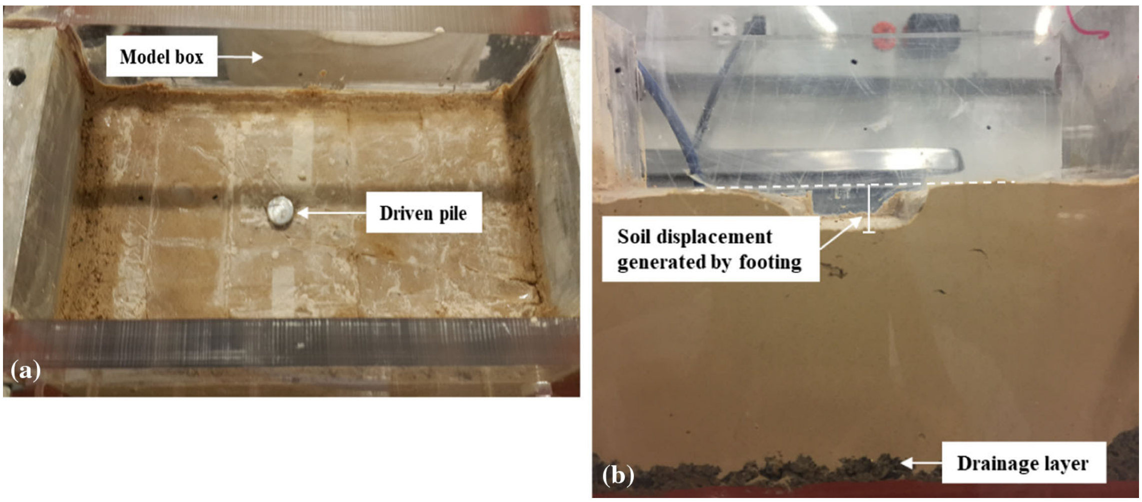

Fig. 5 Models after centrifuged in 50% kaolin and 50% Colombian diatom soil for **a** driven pile and **b** footing

uniform but varies from one point to another depending on the distance to the rotation axis. This difficulty decreases the larger the average radius of the model path. If H represents the height of the model placed in the container and R is the radius of the path of the model base, the maximum relative difference between the stresses in the model and the geostatic profile is equal to $H/(2R)$. For this case, the $H/(2R)$ value is 0.07.

Conclusions

In this case, the use of composite materials improved soils with diatoms is an emerging option in this field that has not been explored previously. This possibility, validated by the promising results shown in this study, will allow further research to be carried out by varying the range of parameters under analysis. The addition of diatoms significantly increases the bearing capacity of clay soil. Possibly, the interlock offered at the microstructural level by the interaction between frustules of Mexican diatoms due to their disk shape is greater than the frustules originating in Colombia that have cylindrical microforms, which are characterized mainly by their water retention.

The applications in geotechnical centrifuges are handy to solve problems in complex soils or pathologies that classical soil mechanics cannot explain. Reduced-scale physical modeling should be a topic of more frequent use in practical engineering for geotechnical structures' design, performance, and even maintenance. Although they were developed under the precepts of traditional techniques, the characterization of the diatomaceous samples allowed to capture the primary response of the materials against this conceptual framework, being key to the subsequent understanding of the load–displacement results measured in the small geotechnical centrifuge.

Undoubtedly, the mechanical response of the Mexican species presents better benefits than the Colombian species, both in the deep and superficial foundations. In the criteria adopted, taken from the literature for load-settlement curves, this species always performed better. It is observed that the Colombian species only has a slightly higher response than the sample with 100% kaolin. It is recommended that future work induces samples with different proportions to know the intermediate results of the load-settlement curves and thus has higher reliability of the results.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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