Consolidation properties and structural alteration of Old Alluvium

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Received: 28 March 2021 / Accepted: 4 August 2021 / Published online: 19 August 2021
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Abstract
We present experimental observations and a conceptual model for understanding the compression and swelling characteristics of Old Alluvium (OA) from San Juan, Puerto Rico. Prior studies have classified OA as a transported, in situ weathered tropical soil whose intact macrostructure comprises a cemented, pseudo-silt with a mixture of quartz grains and aggregated clay particles. The aggregates include mixtures of kaolinite and smectite coated by Fe-oxides. The Fe-oxides also act as cementing agents between the particles. This study describes results from a series of high-pressure (up to 63 MPa) incremental consolidation tests. Breakdown of the clay aggregates and cemented structure is observed through changes in the compression properties, significant swelling during unloading, and an extraordinary reduction (i.e., by three orders of magnitude) in the coefficient of consolidation. These experimental observations are explained by a combination of mechanical processes, comminution and breakdown of cementing bonds, and physicochemical changes linking pore fluid in the intra- and inter-aggregate pore space. These processes alter the fundamental particle size distribution and macro-porosity of the soil and activate the swelling potential of the smectites concealed by the Fe-oxides coating in the intact material. The experimental observations provide the basis for the formulation of a constitutive model to describe macroscopic compression and swelling behavior of Old Alluvium and offer a framework to understand the response of piedmont transported residual soils found elsewhere.

Keywords Compressibility · Iron oxides · Old Alluvium · Swelling · Tropical soils · Weathering

1 Introduction

Large-scale construction projects in areas with tropical climates, such as Central and South America and Southeast Asia, have established the need to understand and model soils that are formed in situ through tropical weathering. Such soils may result directly from in situ weathering of parent rocks, or from in situ weathering of transported residual soils, following their deposition. The latter transported then in situ weathered soils are characterized by complex microstructures and diverse mineralogical compositions, which often include expansive clay minerals and pore systems at the macro- and microscales that are not initially interconnected.

The classic geotechnical literature has heavily focused on the behavior of sands, granular soils, and sedimentary clays (e.g., Jamilolowski et al. [22]; Ladd et al. [26]), with much less attention on the soils with other geological origins (e.g., residual, volcanic; Alonso et al. [2]; Leroueil and Vaughan [28]). The state of knowledge on properties of natural soils has been compiled in papers presented at two
Recent studies have investigated the compression behavior of weathered tropical soils (saprolite, laterite) from Hong Kong [34, 39, 49], Nigeria [4, 38], Brazil [17, 40], and China [61].

Old Alluvium (OA) covers most of North-Northeastern Puerto Rico and underlies major areas of the city of San Juan. It was deposited on the coastal floodplains by the surface runoff water from mountains in the south during the Early Pleistocene epoch and subsequently weathered from the surface downwards. As such, it can also be classified as a piedmont transported residual soil. The effect of weathering over the depth is evidenced in soil coloration transitioning from red and dark red near the surface to brown, yellowish-brown, and yellowish-green at depth. It is also reflected in profiles of the measured plasticity index and standard penetration testing blow count data (SPT N values; Fig. 1), and in the spatial variability observed during site investigations for underground construction of the Tren Urbano in Río Piedras [59]. For the purposes of engineering design and construction, the San Juan Old Alluvium was subdivided into three sub-units: Upper Clay, Middle Zone, and Lower Sand. The subdivision is based largely on the particle size distribution (PSD), coloration, and stratification of the otherwise highly spatially variable soil. However, clear horizontal boundaries between adjacent sub-units are usually absent, and the changes in coloration and PSD are progressive. The Upper Clay has undergone the heaviest weathering, while there is minimal alteration in the Lower Sand.

Before major engineering activities associated with the Tren Urbano in the late 1990s, there was no experience of underground construction in the OA formation, and very few foundation problems had been reported. However, earlier earthwork projects had traditionally been careful to control compaction procedures in order to avoid structural breakdown [59], indicating that some abnormal structure had been recognized by local engineers. During excavation for section 7 of Tren Urbano (by NATM/sequential excavation, earth pressure balance (EPB) tunnel boring machines, and stacked drift construction methods), measured ground movements greatly exceeded the initial predictions. This led to an extensive study of the behavior of Old Alluvium. Zhang et al. [63] reported on the effects of Fe-oxides cementation on the deformation properties of Old Alluvium, while Zhang et al. [64, 65] presented a detailed investigation to determine its mineralogy, microstructure, and index properties. In this paper, we discuss results from a subsequent, more extensive study on the compression and swelling behavior of Old Alluvium. The present study presents 4 new tests, including two high-pressure incremental consolidation tests up to 63 MPa (higher than previous studies), and includes a systematic study of swelling behavior with unload–reload cycles from multiple stress levels. These new experimental data provide a more complete understanding of structural degradation and its effects on mechanical properties, and the basis for the formulation of a constitutive model.

![Fig. 1 Engineering classification of Old Alluvium and index properties of intact material, after Whittle and Bernal [59] and Alba-Carbó [1]](image-url)
2 Nature and structure of the Old Alluvium

Table 1 summarizes results of quantitative mineralogical analyses reported by Zhang et al. [64] for representative samples of the Upper Clay and Middle Zone of the Old Alluvium. Both Upper Clay and Middle Zone contain significant fractions of quartz and orthoclase (K-feldspar), which are highly weathering-resistant primary minerals [16]. However, Middle Zone contains a much larger sand fraction than Upper Clay (45% vs. 10%). Both sub-units contain mixtures of two main clay minerals, kaolinite and nontronite (an Fe$^{3+}$-rich smectite). Upper Clay contains a higher fraction of clay minerals (45–55%, compared to 33–35% for Middle Zone) and a higher proportion of swelling minerals (nontronite). Two Fe-oxides, hematite ($\alpha$-Fe$_2$O$_3$) and goethite ($\alpha$-FeOOH), are present in the Upper Clay (3% and 6%, respectively), whereas only goethite is present in the Middle Zone. The different phases and mineral fractions reflect that Upper Clay is more weathered than Middle Zone. The presence of smectite indicates that Old Alluvium is not as well developed as other tropical residual soils that contain only kaolinite as the major clay mineral [18, 50], probably because of its deposition in the Early Pleistocene (0.8–2.6 Ma). Finally, it should be noted that in both layers, there is a substantial presence of adsorbed water in the air-dried soil (12.5 and 8.5 wt% for the Upper Clay and Middle Zone, respectively).

The microstructure of the Old Alluvium has been characterized through a combination of direct microscopic observations using the environmental scanning electron microscopy (ESEM) method and indirect examinations by slaking, cation exchange capacity (CEC) measurements, energy-dispersive X-ray spectroscopy (EDXS), selective chemical dissolution (SCD), and particle size analyses [64]. The ESEM micrographs show that the Old Alluvium has a dual-porosity microstructure, which is typical of many natural soils with aggregate formations [19, 33, 48]. The inter-aggregate pore diameter is roughly 50–80 µm, while intra-aggregate pores are smaller than 10 µm. The inter-aggregate pores are well connected to each other resulting in a high hydraulic conductivity for the intact soil ($10^{-5}$–$10^{-6}$ cm/s). Selective chemical dissolution using a sodium dithionite, sodium citrate, and sodium bicarbonate (DCB) solution [55] was effective in reducing or eliminating the cementing bonds between the silt-sized aggregates, but did not disperse the clays, since the salts in the DCB mixture act to suppress double-layer expansion [65]. However, the role of Fe-oxides in aggregating particles became apparent when glycerol was subsequently added causing rapid swelling and dispersion of the clay minerals [65].

These observations were synthesized into an initial conceptual model of the representative microstructure (Fig. 2), with the following key features:

- Particles of the two clay minerals, kaolinite and smectite, are associated in stacks with face–face configurations to form clay pellets of up to 10–20 µm, which are the elementary ‘units’ for the intact soil.
- The very fine crystals of Fe-oxides (e.g., the size of goethite and hematite is 0.05–0.1 µm and 0.02–0.05 µm, respectively) form a coating around the exterior surfaces of the clay pellets via precipitation and crystallization.
- A group of clay pellets are further connected together by Fe-oxides to form spherical or semi-spherical, relatively stiff aggregates, 50–100 µm in size (i.e., coarse-silt to fine-sand particle size range).
- Quartz and feldspar are present as silt- and sand-sized particles, which are also coated and connected to the clay aggregates by Fe-oxides. These silt and sand particles are distributed throughout the soil matrix and constitute approximately 25% of the particles in the size range 50–100 µm. Since the volume of the clay minerals approaches or exceeds that of quartz and

![Fig. 2 Schematic of the representative microstructure for Old Alluvium, based on the current study and Zhang et al. [65]](image-url)
feldspar, which are chemically inert, the overall behavior of the deposit is ultimately dominated by the chemically active clay minerals and Fe-oxides.

- Stiff aggregates, silt, and sand particles are again connected together by Fe-oxides to form the stiff intact soil matrix, within which all grains are bound together and form large interconnected, inter-aggregate pores of 50–80 μm in size.

Aggregates are often reported in the microstructure of weathered soils (e.g., Bello [4]; Ng et al. [34]; Okewale [38]; Otálvaro et al. [40]; Xu and Coop [61]). What distinguishes the Old Alluvium from previously studied materials is its two-level aggregate structure (Fig. 2), as well as the Fe-oxide coating around the exterior surfaces of the clay pellets.

3 Compression behavior

The original conceptual model proposed by Zhang et al. [65] was based on the discussed intact sample observations and on compression tests with limited unloading cycles from a maximum load-reversal stress of 30 MPa. These compression tests indicated that mechanical loading affects both compression and swelling behavior. The new experimental program presented here (Table 2) systematically studies the progressive effect of mechanical loading through unload–reload cycles at increasing levels of reversal stress (up to 63 MPa).

The new experimental program includes incremental, one-dimensional consolidation testing on hand-excavated intact block samples obtained during construction of the stacked drift cavern for the Rio Piedras station [59]. Large block samples (of up to 0.3–0.6 m) helped preserve the intact microstructure and the in situ water content during extraction and transportation. The X-ray radiography images of the block sample showed a relatively homogenous material with no discernible cracks and few of the white venations seen elsewhere on the Upper Clay (and attributed to weathering by organic acids, Zhang [62]). Test specimens were trimmed from the block sample using carbide tipped blades, due to the presence of highly abrasive quartz in the Old Alluvium [35]. Four compression tests (Fig. 3) were trimmed from the same block sample of the Old Alluvium Upper Clay unit (depth 6 m below ground surface). Low-pressure tests were performed in a conventional oedometer device (with stress limit of 3 MPa; Fig. 3a, b). High-pressure tests were conducted in a high-force universal loading frame (stress limit of 63 MPa; Fig. 3c, d), with feedback control and twin load cells to achieve high resolution control throughout the load range.

The partially saturated intact specimens were initially loaded to 200 kPa, sufficient to eliminate negative pore pressures and prevent swelling during the saturation phase. Specimens were then inundated with pore fluid and remained submerged in water for the test duration. Control on volume changes ensured minimized changes in the specimen’s micro-fabric during the saturation phase. Subsequent loading (with up to 7 cycles of unloading and reloading) was carried out using standard incremental oedometer procedures with a load increment ratio, LIR = 1.0, with each load maintained through the end of primary consolidation. Three of the four tests were inundated with distilled water, and the fourth (test 102, Fig. 3b) used glycerol solution as the pore fluid (with a 1:7 volumetric ratio of glycerol to water). Glycerol was used to investigate the swelling potential of the nontronite-rich Upper Clay.

### Table 2 Summary of new compression tests

| Test | Sample depth (m) | Initial density (kg/m³) | Initial water content, w₀ (%) | Initial void ratio, e₀ | Initial saturation S (%) | Test frame | Pore fluid | Unload–reload cycles at σ'₁₀₀ (MPa) |
|------|-----------------|-------------------------|-------------------------------|-----------------------|-------------------------|------------|-----------|----------------------------------|
| SJ1  | 6               | 1740                    | 32.55                         | 1.04                  | 83.6                    | Std Water  | 0.20      | 1.57                             |
| SJ2  | 6               | 1770                    | 33.95                         | 1.03                  | 88.2                    | HP Water   | 0.20      | 1.57                             |
|      |                 |                         |                               |                       |                         |            |           | 50.16 (9)                        |
| 101  | 6               | 1750                    | 38.62                         | 1.13                  | 91.8                    | HP Water   | 1.99      | 15.56 (3)                        |
|      |                 |                         |                               |                       |                         |            |           | 31.13 (62.25 (x 3))              |
| 102  | 6               | 1810                    | 40.23                         | 1.07                  | 100                     | Std Glycerol| 1.12      | 2.82 (4)                         |

HP high-pressure loading frame, Std. standard oedometer loading frame
because it solvates and expands the inter-layer spacing of smectitic minerals.

These results of the compression tests are presented in loge–logr'v plots of effective stress vs. void ratio (Figs. 3 and 4a), instead of the more typical e–logr'v (Fig. 4b). The loge–logr'v space corresponds to the Limiting Compression Curve (LCC) framework after Pestana and Whittle [42]. Whereas compression curves are nonlinear over large stress ranges in the e–logr'v space (Fig. 4b), the compression response at high pressures for a wide range of granular materials and clay–sand mixtures is found to be linear in the double-logarithmic loge–logr'v space [42]. This linearization is attributed to mechanisms of particle crushing: Irrecoverable plastic strains occur throughout first loading and represent mechanisms ranging from particle sliding and rolling at low stress levels to crushing which is the principal component of deformation in the LCC regime [42]. However, in the case of Old Alluvium, we find that the compression behavior does not linearize, even at the high-stress level of 63 MPa (Fig. 4a). In addition, the compression coefficient, \( \rho_c = \Delta \log e / \Delta \log r'v \), is not unique for the soil, as compilations of previous experimental work show [41]; instead, it varies with depth in the soil profile [Fig. 4a, 3 different depths of 1.2 m (blue), 6 m (red), and 10.7 m (green lines)]. The lowest value of \( \rho_c \) occurs for the most highly weathered Upper Clay material (1.2 m depth). The widely used \( C_c \) compressibility coefficient (Fig. 4b e–logr'v space; \( C_c = \rho_c e / 0.434 \)) also increases with sample depth for a given stress level. For a given sample depth, however, its value decreases with stress level.

In detail, the results show the following (Figs. 3 and 4):

1. The intact Upper Clay is very stiff and exhibits very small volume change, compared to the behavior post yield (\( \sigma'_y > \sigma'_v \)). The four specimens show well-defined yield points during the initial loading cycle, \( \sigma'_y = 0.5 \pm 0.3 \) MPa (obtained by conventional strain energy methods; Becker et al. [3]). Such yield stress values are also in accordance with stiff to very stiff clay classification [33].

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**Fig. 3** Compression and swelling behavior of Old Alluvium from Upper Clay unit. Dashed lines indicate missed measurements. Points omitted for scale: SJ1 (panel a), 3rd unload–reload cycle (green): sample unloaded to 0.1 kPa \((e = 0.88)\); 102 (panel b): initial stress at 6.66 kPa \((e = 1.074)\), 2nd unload–reload cycle (orange): sample unloaded to 6.66 kPa \((e = 1.034)\)
2. High-pressure tests (Fig. 3c, d) produce large compressive strains (up to 40%) but show no simple linearization of compression properties at pressures, $\sigma'_v \geq \sigma'_C$ (in either $e$–$\log \sigma'_v$ or $\log e$–$\log \sigma'_v$ space). The slope of the LCC, $q_c$, increases with the level of effective stress from, $q_c = 0.29$–$0.49$ for stresses in the range $\sigma'_v = 1$–$10$ MPa to $10$–$100$ MPa, respectively (Fig. 3c, d). In the $\sigma'_v = 1$–$10$ MPa range, the $\rho_c$ value is comparable to reported compressibility values for a number of $K_0$-normally consolidated clays resedimented from a slurry condition. (Reported $\rho_c$ varies from $0.14$ to $0.3$; Appendix 1, Fig. 10 and Table 4; Casey et al. [10].) However, the Upper Clay compressibility in the $10$–$100$ MPa range is significantly higher than resedimented clay values. (Reported $\rho_c$ values vary from $0.18$ to $0.32$; Appendix Fig. 10 and Table 4.) Corresponding values for the more familiar compression index, $C_c$, decrease from $0.46$ to $0.37$ over the same stress ranges (Fig. 4b) and are generally higher than compression indices of resedimented clays especially over the $10$–$100$ MPa range (where $C_c$ values of resedimented clays range from $0.17$ to $0.25$; Appendix Fig. 10 and Table 4).

3. There is a significant change in the swelling properties of the clay subjected to different stress levels prior to compression (Fig. 3, Table 3). At low load-reversal stresses ($\sigma'_{v,rev} = 0.2$ MPa), the equivalent swelling index $C_s = 0.02$, whereas swelling from $\sigma'_{v,rev} = 50$–$63$ MPa can be characterized by a significantly increased $C_s = 0.10$–$0.14$ (Appendix B, Fig. 11). Measurements of the recoverable vertical strain in the unloading phases of tests on Upper Clay specimens (Fig. 5a) highlight the marked increase in rebound strains for specimens previously compressed in the range, $\sigma'_{v,rev} = 0.2$, $1.5$–$3.0$, and $18$–$65$ MPa. At the higher load-reversal stresses, the recoverable vertical strain exceeds $20\%$ (test 101, red lines, Fig. 5a). Successive unloading–reloading cycles from the same reversal stress produce very similar strains (in unloading and reloading), strongly suggesting that the swelling potential is controlled by the level of maximum pre-compression stress (Fig. 5a).

4. Although the swelling properties are far outside the range of strains normally associated with sedimentary clays ($C/C_c = 0.1$–$0.2$; Table 3.3 in [24, 41]), reloading to the pre-consolidation stress generates only a small net change in void ratio (Fig. 3c), a result typically seen for all clays (i.e., memory of prior stress reversal; [33, 58]).

5. There is also very significant hysteresis in the unload–reload paths, especially at high load-reversal levels (Fig. 3c, d): A plot of the accumulated strain energy from the point of reversal in load direction for each of the four loading cycles of test 101 illustrates a notable hysteresis in unloading and reloading (Fig. 5b).

![Fig. 4 Effect of sample depth on compressibility properties of Old Alluvium a in $e$–$\log \sigma'_v$ space with slope of the Limiting Compression Curve, $\rho_c$, and b in $e$–$\log \sigma'_v$ space with compressibility $C_c$. ($q_c = 0.434 C_c / e$). SJ1, SJ2, 101 from this study (Fig. 3 and Table 2). Oed 7,11,13 (Upper Clay) and 8 (Middle Zone) from Zhang [62].](image-url)
6. In test 102, glycerol was used as a pore fluid. Glycerol is known to expand the double layer and cause macroscopic volume changes [37]. Old Alluvium in its natural state is not affected by the presence of glycerol [65], because the swelling potential is masked by the soil structure and the presence of iron oxides. The amount of swelling observed in test 102 is of comparable magnitude with the corresponding stress levels in the rest of the tests that are inundated with distilled water (Fig. 3), indicating that the maximum load applied to the sample (2.82 MPa) was not sufficient to destroy the structure protecting the expansive clay minerals.

The vertical coefficient of consolidation, $c_v$, was derived from each of the load increments using the conventional log-time method. Figure 6a shows a remarkable reduction in $c_v$ from $10^{-2}$ cm²/s in the initial intact state to $5 \times 10^{-6}$ cm²/sec at the end of test #101. One particular characteristic feature of the Old Alluvium is the large reduction in $c_v$ measured during each of the unloading branches. This feature is clearly linked to fundamental changes in the microstructure of the clay. The coefficient of consolidation, $c_v$, together with the 1-D compressibility, $m_v$, over each load increment are used to calculate the hydraulic conductivity, $k$, for the same test specimen (101; Fig. 6b). The hydraulic conductivity decreases with void ratio, and can be approximated by a linear correlation between $\log k$ and $e$, with a slope of permeability index $C_k = \Delta e/\Delta \log_{10}k = 0.25$. The hydraulic conductivity measured in unloading is typically 2–3 times smaller than in first loading at the same void ratio. Because of the presence of quartz grains, the hydraulic conductivity of Old Alluvium remains higher than reported values on resedimented clays over the same pressure ranges, despite the significant degradation of its microstructure (Fig. 6b; Casey [9]).

**4 Conceptual model**

We propose a conceptual framework to describe the effects of weathering on the consolidation behavior, compression and swelling properties within the Old Alluvium and capture the transition from the Lower Sand (‘unweathered’; Fig. 1) through the Middle Zone to the most heavily

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**Table 3** Swelling index, $C_s$, values for Old Alluvium, measured during the unload-reload cycles

| Test | $\sigma'_{c,rev}$(MPa) | $C_s$ | $\sigma'_{c,rev}$(MPa) | $C_s$ | $\sigma'_{c,rev}$(MPa) | $C_s$ | $\sigma'_{c,rev}$(MPa) | $C_s$ | $\sigma'_{c,rev}$(MPa) | $C_s$ |
|------|-----------------|------|-----------------|------|-----------------|------|-----------------|------|-----------------|------|
| SJ1  | 0.2             | 6.0  | 0.02            | 1.57 | 0.08            | 1.57 | 0.08            | 1.57 | 0.08            | 1.57 |
| SJ2  | 0.2             | 6.0  | 0.02            | 1.57 | 0.12            | 50.16| 0.13            | 50.16| 0.10            | 50.16|
| 101  | 1.99            | 6.0  | 0.09            | 15.56| 0.14            | 31.13| 0.14            | 62.25| 0.14            | 62.25|
| 102  | 1.12            | 6.0  | 0.05            | 2.82 | 0.07            | 2.82 | 0.06            | 2.82 | 0.06            | 2.82 |

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**Fig. 5 a** Recovered vertical strains during unloading cycles on Old Alluvium. SJ1, SJ2, 101, 102 from this study (Figs. 3 and 4 and Tables 2 and 3). Oed 7,11,13 (Upper Clay) and 8 (Middle Zone) from Zhang [62]. **b** Hysteresis during unloading and reloading for test 101 on Old Alluvium. Accumulated strain energy, $\Delta SE = \Sigma (\sigma'_{c,rev} \cdot \Delta \varepsilon_n)$ from point of reversal in load direction, where $\varepsilon_n$ is the natural strain [25]
weathered surficial Upper Clay layer. This framework offers a more detailed perspective on the original conceptual model proposed by Zhang et al. [65], which described the multi-scale particulate structure of the Old Alluvium (Fig. 2), and assumed that the Fe-oxides form a continuous, brittle shell around the clay pellets that is progressively broken down by the applied compressive stress, releasing the swelling potential of the encapsulated clay minerals. The updated framework links mechanical loading to physicochemical changes in the microstructure and is then used to formulate a constitutive model that relates these physicochemical properties of the clay aggregates to the macroscopic consolidation behavior of the material [36]:

1. The intact, weathered Old Alluvium most closely resembles a cemented sand or silt with high stiffness and high hydraulic conductivity. Approximately 90% of the particles in the Middle Zone are in the sand–silt size range, while only 55% in the Upper Clay [64]. The compression behavior of the Upper Clay specimens shows a characteristic yield stress ($\sigma''_y$, Fig. 3) that is linked to the shear strength of the inter-aggregate bonds (and not the stress history).

   - The average measured yield stress, $\sigma''_y = 0.5$ MPa (Figs. 3 and 4a) together with the apparent cohesion, $c' = 25$ kPa reported by Zhang et al. [63] from $K_0$-consolidated, drained stress–path triaxial shear tests are consistent with correlations between $\sigma''_y$ and $c'$ reported by Mesri and Abdel-Ghaffar [31] for a large database of tests on stiff clays and clayey shales.

   - The intact Middle Zone material has a much lower in situ void ratio and exhibits a much higher yield stress ($\sigma''_y \approx 3.4$ MPa; Fig. 4), but a similar cohesion to the Upper Clay [63]. In this case, yielding is more likely related to crushing/fracturing of silt-sized aggregates.

2. On average, 75% of the silt-sized particles in the Upper Clay are clay aggregates stably formed by Fe-oxides (Fig. 2), through electrostatic forces that mask the true physicochemical properties of the clay surfaces.

   - Iron oxides can associate with the clay mineral surfaces through processes of aggregation and cementation [50]. Whereas in the cementation process Fe-oxides fill portions of the pores between the original matrix particles, aggregation involves the association of the soil matrix particles into groups by minute particles of Fe-oxides. In the Old Alluvium, aggregates form primarily through an attraction between the positively charged Fe-oxide particles and the negatively charged clay minerals.

   - Zhang et al. [65] compare measurements of the cation exchange capacity for intact specimens and for specimens where Fe-oxides were removed by selective chemical dissolution with DCB. Of the
minerals present in the Old Alluvium, only the kaolinite and smectite have the capability to exchange cations with the solution. (Fe-oxides have zero CEC.) The measurements show that the CEC of the Upper Clay increases significantly from 29 to 52 meq/100 g (compared to measurements for nontronite, CEC = 79–108 meq/100 g; Köster et al. [23]). Similar measurements for the Middle Zone range from 36 to 45 meq/100 g. These results confirm that Fe-oxides suppress clay activity through aggregation, while the low CEC of the intact Upper Clay is indicative of a higher degree of aggregation than the Middle Zone, which has a lower clay content and hence a lower CEC when the clay minerals are fully dispersed.

- These electrostatic forces associated with aggregation by Fe-oxides contrast with the traditional definition of soil structure as the combination of fabric (arrangement and association of particles) and inter-particle bonding [27, 28, 33], but commonly control the behavior of expansive soils (e.g., Lin and Cerato [29]).
- Blackmore [6] suggests that aggregation is the result of cohesion between films, or parts of films of iron oxides formed on the clay surface (i.e., aggregation is fundamentally related to physico-chemical factors). Figure 7 shows the fraction of clay aggregates (obtained by an active hydrolysis procedure) as a function of the weight ratio of Fe-oxides to clay. The results show that bentonite requires a larger amount of Fe-oxides to achieve the same level of stable aggregation than kaolinite or illite, but the weight ratios for full aggregation (0.5%) are far less than that required to balance the total surface charge of the clay particles. Blackmore [6] also reports that the aggregates are very stable for all three clay minerals. More than 70% of the clay remained aggregated after 20 min treatment with dispersing agents. Based on the quantitative mineralogy for the Old Alluvium (Table 1), Blackmore’s results suggest that 60–80% of the clay mineral will form stable aggregates in the Upper Clay, reducing to 40–60% in the Middle Zone.

3. We believe the intra-aggregate porous system is generally interconnected, similar to inter-aggregate one (Fig. 2), but have no direct measurements to support this assumption. Within the clay pellets, the pore water is associated with the face-to-face smectitic mineral stacks, resulting in nanoscale pores. This fluid is likely to be rich in cations and hence have a different salinity to the inter-aggregate pore water. The stability (i.e., lack of volume change) of intact Old Alluvium when inundated with glycerol solution ([65], Fig. 3b) indicates that the nanoscale pore network is isolated from the inter-aggregate pore space.

4. Mechanical loading is able to disassociate the Fe-oxides and reveal the swelling capacity of the intra-aggregate clay minerals. This is evidenced by the progressive increase of swelling strains with increasing compression stress level (Fig. 3, Table 3). Regrettably, we do not have measurements of the CEC before and after the high-stress compression tests.

5. Uniaxial compression of the Upper Clay in the LCC regime (Fig. 4a: log $e$–log $r_0$ space, Pestana and Whittle [42]) is characterized by a progressive increase in the compressibility parameter from $\rho_c = 0.25$–0.49. This increase in compressibility contradicts the concept of a unique LCC assumed in previous frameworks [42] and indicates a transition from a sand–silt to a clay behavior:

- Prior studies by Pestana [41] found that $\rho_c$ is well correlated with clay activity ($A = I_p f_c$, where $I_p$ is the plasticity index and $f_c$ the volume fraction of clay). A large database of clays with low to medium activity were found with, $\rho_c = 0.22 \pm 0.03$, while for highly active, smectite-rich clays $\rho_c = 0.4$–0.6 [41]. In comparison, Pestana and Whittle [42] report that sand mineralogy has little influence on
\( \rho_c \), which is found to range from 0.37 to 0.43 for a wide range of sands.

- Studies on mixtures have shown that the introduction of clay minerals and plastic fines increases the compressibility of the mixture (e.g., Chu et al. [12]; Deng et al. [14]; Martins et al. [30]; Pitman et al. [47]; Tiwari and Ajmera [54]).
- These prior observations are consistent with the measured compression behavior of Upper Clay (Figs. 3 and 4) that can be associated with: (i) the breakdown/comminution of the silt-sized...
aggregates, (ii) the breakdown of clay aggregates and disassociation of the Fe-oxides coating from the clay minerals, and (iii) greater connectivity of the intra- and inter-aggregate pore space (which is linked to an increase in CEC).

- Differences in the compression properties of the Middle Zone (10.7 m depth) and Upper Clay materials (both at 1.2 and 6 m depth; Fig. 4) reflect a contrast in the mass fractions of quartz/feldspar and in the proportions of swelling clay minerals within the clay fraction (Table 1).

6. Swelling of the Upper Clay increases markedly with the level of compression stress within the LCC regime (Fig. 3, Table 3). We propose that pre-compression produces a breakdown in the aggregate structure, reduces pore sizes (at both inter- and intra-aggregate level), and increases the level of clay activity. Increases in the swelling potential are linked to: (i) the disaggregation of smectite within the clay pellets and (ii) the relative salt concentrations in the intra-aggregate and inter-aggregate pore fluid. Diffusion of cations from within the smectite layers (at the nanopore scale) after Fe-oxide disaggregation acts to increase the thickness of the diffuse double layer around the clay particles. Hence, the use of distilled water as the inundating pore fluid is expected to maximize swelling potential (e.g., Fig. 3c, d).

- Swelling of clays is usually characterized by the ratio of unloading to compression indices, $C/C_c$. For Old Alluvium, this ratio increases with the level of pre-consolidation stress up to a maximum value of $C/C_c \approx 0.5$ (for both Upper Clay and Middle Zone materials and with apparent OCR > 500; Appendix 2, Fig. 11). Bertuccioli and Lanzo [5] have reported similar increase in $C/C_c$ associated with mechanical disaggregation (measured in terms of clay size fraction) of several ‘structurally complex’ Italian clays.

- There are also examples where a change in salinity of the pore water has been shown to generate significant swelling. Picarelli et al. [46] describe the loading and swelling of reconstituted Bisaccia clay (with 30% smectite) that is initially consolidated with 1.0 M NaCl solution and later inundated with distilled water at different stages of unloading (Fig. 8a). Di Maio et al. [15] have also shown that there is a large decrease in the coefficient of consolidation of the reconstituted Bisaccia clay associated with unloading (Fig. 8b), similar to Old Alluvium measurements (Fig. 6a). These results (i.e., with no change in pore fluid chemistry) suggest that the reconstituted material was not fully disaggregated but underwent significant changes in microstructure during the prior compression phase.

7. Hysteresis is a very prominent feature of the unload–reload response of Upper Clay (Fig. 3). In fact, this is a common characteristic of clays. Following Pestana [41], the unloading response of clays can be attributed to: (i) recovery of elastic energy stored at particle contacts, a property shared with other cohesionless soils and (ii) a reduction in osmotic pressures due to changes in double-layer thickness, which can be affected by a variety of physicochemical factors (e.g., electrolyte concentration, exchangeable cations, valence of ionic species; Mesri et al. [32]). Hysteretic behavior is then attributed to a time lag between these reversible mechanisms, while the swelling potential relates to the prior compression-induced structural degradation.

The intact Old Alluvium exhibits compression properties similar to other cemented/bonded soils, including pronounced ‘yielding,’ progressive breakdown in structure and changes in compression indices for loading into the LCC stress regime. Studies for numerous cemented/bonds soils (e.g., Leroueil and Vaughan [28]) have noted a convergence of properties with respect to the intrinsic behavior of material that is reconstituted by thoroughly mixing the natural soil at a water content $w/w_L = 1.0–1.5$ (where $w_L$ is the liquid limit). For example, Burland [7] introduced the concept of an Intrinsic Compression Line (ICL; with compression index $C_c$) as a convenient reference condition. Depending on their microstructure, several weathered soils have a unique reference state [38, 40, 61], and modifications of the framework have been proposed to account for higher stress levels or ion concentration of the pore fluid (e.g., Horpibulsuk et al. [21]; Wang and Korkiala-Tanttu [56]). However, this framework is not useful for the Old Alluvium, as it is very difficult to achieve a fully disaggregated state (Fig. 9). Figure 9a compares the compression behavior of intact specimens of Upper Clay and Middle Zone with materials that were ‘reconstituted’ from bucket samples at $w/w_L = 1.5$ (usually achieved by thorough mixing). The aggregated state of the reconstituted materials is uncertain, and their compression behavior shows little resemblance to properties measured for intact specimens. This is further illustrated using Burland [7]’s void index, $I_v$ (Fig. 9b). The lack of a unique reference state has been reported for other tropical soils, well-graded soils, or soils with complex mineralogies (e.g., Ferreira and Bica [17]; Martins et al. [30]; Shipton and Coop [51]). It further highlights that Old Alluvium differs from bonded/cemented soils in that removal of bonds leads to physico-chemical changes in the microstructure and increase in clay...
activity, because bonding agents (iron oxides) do not only cement aggregates but also coat smectitic minerals and clay pellets (Fig. 2).

5 Discussion

The original depositional environment, post-depositional processes, and weathering products of the Old Alluvium are common to transported, in situ weathered soils in tropical environments. Deposits of Old Alluvia occur widely across Southeast Asia, because of the extinct drainage system of the South China Sea [20], in the major river basins of South Asia (Ganges, Brahmaputra, and Indus), sub-Saharan Africa (Niger, Congo), and South America (Orinoco), as well as Northern California (USGS maps). The Old Alluvium in Singapore has been studied in conjunction with major tunneling projects [11, 52]. Gupta et al. [20] record a significant proportion of smectites in some of the weathered mudstone beds with up to 50% of the clay fraction. However, most classification schemes show that this Old Alluvium has a high sand fraction (65–75% of quartz and feldspar). The studies note the presence of iron oxides (also clearly seen in photographs of excavated slopes) and some effects of cementation (from slaking tests), but there has been no systematic study of the microstructure of this material. Reported values for the compression index range from $C_c = 0.05–0.35$ at confining stresses up to 3 MPa [13, 60]. Limited compression data also indicate that Singapore OA behaves similar to this study’s Middle Zone material at low stress levels (Fig. 10; Chu et al. [13]).

The progressive breakdown of aggregates within the lightly cemented Old Alluvium closely resembles the behavior reported for other highly overconsolidated clays and clay shales. For example, Picarelli [45] shows that swelling properties of a saturated Laviano (scaly) clay shale increase with the imposed pre-consolidation stress, while Calabresi and Scarrelli [8] show a dramatic swelling of the highly fissured Todi clay following yielding of cementation bonds. (The clay contains more than 25% of CaCO$_3$ in the cementation.) Burland [7] also notes changes in the swelling properties of three stiff, highly overconsolidated clays, but these are referenced to the intrinsic compression of reconstituted materials ($C_C$). Picarelli [44, 45] appears to be the first to link disaggregation of ‘diagenetic bonds’ to changes in the swelling index of natural clay shales. The primary difference between these materials and the Old Alluvium relates to the specific nature of aggregation associated with Fe-oxides (and the formation of clay pellets) and the characteristic weathering profile-associated changes in engineering properties.

6 Conclusions

This paper presents a detailed interpretation of the compression and swelling behavior of the Old Alluvium in San Juan and their relation to alterations in the soil microstructure, particularly aggregation and cementation. Old Alluvium is a transported, deposited, and in situ weathered tropical soil, the intact macrostructure of which comprises a cemented, pseudo-silt with a mixture of quartz grains and aggregated clay particles. The aggregates include mixtures of kaolinite and smectite, coated by Fe-oxides that also act as cementing agents between the particles and aggregates. In the intact condition, the activity of the clay minerals is suppressed by aggregation with Fe-oxides. A series of uniaxial compression tests conducted to pressures up to 63 MPa show that compression initially causes yielding and breakdown of the bonds between the silt-sized aggregates, followed by progressive breakdown of the aggregates. The compression properties are closely related to the mineralogy, including the proportions of quartz and feldspar particles, the fraction of expansive clay mineral (nontronite), and the amount of Fe-oxides (and associated aggregation). Swelling behavior is observed during unloading and is linked to the pre-consolidation stress (which controls the level of disaggregation) and to the contrast in salinity between the fluid in the inter- and intra-aggregate pore space (that affects the diffuse double-layer thickness of the expansive clay minerals). Although very large swelling strains occur, the underlying osmotic pressures are reversible and exhibit very marked hysteresis.

Other researchers have described similar relations between the observed engineering properties and structural degradation of clay shales. It is likely that extensive deposits of Old Alluvium found elsewhere in the world with similar geological environments will have similar micro- and macrostructure and mineralogy. The proposed conceptual model offers a framework to understand the compression response of such materials. In addition, it provides the basis for a constitutive model that couples physicochemical and mechanical properties using cation exchange capacity as a state parameter to predict the macroscopic compression and swelling behavior of Old Alluvium [36].

Appendix 1

See Fig. 10 and Table 4.
Fig. 10. 1D compression data of several resedimented clays [9], Singapore Old Alluvium [13], and San Juan Old Alluvium (this study; Fig. 4), a in log–log space with slope of the Limiting Compression Curve, \( \rho_c \); and b in \( e-\log \sigma'_v \) space with compressibility \( C_c \). \( \rho_c = 0.434 \ C_c / e \). Summary of \( \rho_c \) and \( C_c \) values as well as soil information in Table 4

Table 4 \( \rho_c \) and \( C_c \) values for 2 compression levels (1–10 and 10–100 MPa), as well as liquid (\( w_L \)) and plastic (\( I_p \)) limits, clay fraction (CF), and mineralogy for several resedimented clays [9], Singapore Old Alluvium [13], and San Juan Old Alluvium (this study; Fig. 4). Detailed mineralogy for Old Alluvium in Table 1

| Resedimented clay          | \( \rho_c \) 1–10 MPa | \( \rho_c \) 10–100 MPa | \( C_c \) 1–10 MPa | \( C_c \) 10–100 MPa | \( w_L \) (%) | \( I_p \) (%) | CF (%) | Chlorite | Kaolinite | Illite | Illite–Smectite |
|----------------------------|-----------------------|------------------------|-------------------|-------------------|--------------|--------------|--------|----------|-----------|--------|----------------|
| Opalinus Shale             | 0.24                  | 0.23                   | 0.34              | 0.17              | –            | –            | 30     | 3        | 18        | –      | 44             |
| Presumpscot Clay (ME)      | 0.14                  | 0.28                   | 0.15              | 0.2               | 33.1         | 13.7         | 37     | 20       | 2         | 66     | 12             |
| Boston blue clay           | 0.21                  | 0.28                   | 0.29              | 0.24              | 46.5         | 22.7         | 56     | 5        | 2         | 65     | 28             |
| Ursa clay (GOM)            | 0.24                  | 0.31                   | 0.32              | 0.24              | 51.7         | 28.0         | 54     | 7        | 2         | 30     | 61             |
| San Francisco bay mud      | 0.29                  | 0.29                   | 0.43              | 0.25              | 60.2         | 28.6         | 63     | 6        | 2         | 11     | 81             |
| Ugnu clay (Alaska)         | 0.3                   | 0.32                   | 0.34              | 0.19              | 56.4         | 30.0         | 45     | 5        | 3         | 21     | 71             |
| London Clay (UK)           | 0.24                  | –                      | 0.38              | –                 | 73.8         | 48.4         | 63     | 1        | 5         | 7      | 87             |
| Eugene island (GOM)        | 0.25                  | 0.18                   | 0.42              | 0.2               | 85.8         | 62.9         | 63     | 1        | 4         | 8      | 87             |
| Singapore Old Alluvium     |                       |                        |                   |                   |              |              |        |          |           |        |                |
| Mazier 2                   | n/a                   | –                      | 0.05              | –                 | 50.9         | 25.9         |        |          |           |        |                |
| Mazier 3                   | n/a                   | –                      | 0.09              | –                 | 31.4         | 15.9         |        |          |           |        |                |
| Mazier 5                   | n/a                   | –                      | 0.09              | –                 | 37.8         | 20.3         |        |          |           |        |                |
| Old Alluvium               |                       |                        |                   |                   |              |              |        |          |           |        |                |
| Upper Clay (#101)          | 0.29                  | 0.49                   | 0.46              | 0.37              | 73–95        | 10–60        | 45–55  | –        | 33.64     | –      | 20.16          |
| Middle Zone (#8)           | 0.24                  | 0.47                   | 0.15              | 0.23              | 45–60        | 20–40        | 33–35  | –        | 22.93     | 3      | 13.08          |
Appendix 2

See Fig. 11.

Appendix 3

See Table 5.

Table 5 Nomenclature

| Symbol | Name                                      | Dimensions          |
|--------|-------------------------------------------|---------------------|
| $C'$   | Apparent cohesion                         | $L^{-1}M^0T^{-2}$   |
| $C_c$  | Compression index                         | $L^0M^0T^0$         |
| $C_{c0}$ | Compression index ICL [7]                  | $L^0M^0T^0$         |
| $C_k$  | Permeability index                        | $L^0M^0T^0$         |
| $C_s$  | Swelling index                            | $L^0M^0T^0$         |
| $C_u$  | Mean particle gradation                   | $L^0M^0T^0$         |
| $c_v$  | Coefficient of consolidation              | $L^0M^0T^{-1}$      |
| $D_{50}$ | Median particle size                      | $L^0M^0T^0$         |
| $e$    | Void ratio                                | $L^0M^0T^0$         |
| $f_c$  | Clay volume fraction                      | $L^0M^0T^0$         |
| $I_v$  | Void index                                | $L^0M^0T^0$         |
| $I_p$  | Plasticity index                          | $L^0M^0T^0$         |
| $k$    | Hydraulic conductivity                    | $L^0M^0T^{-1}$      |
| $K_o$  | Effective stress ratio, uniaxial conditions| $L^0M^0T^0$         |

Acknowledgements Research on the Old Alluvium was initially supported by a grant from GMAEC, Tren Urbano in San Juan, Puerto Rico. The authors are also grateful for support from the National Science Foundation through Grant No. CMS-008539. The lead author (MAN) also acknowledges the George and Marie Vergottis Fellowship for supporting her graduate studies at MIT. The authors thank 3 anonymous reviewers for their insightful comments and suggestions.

Authors’ contributions MN contributed to conceptualization, methodology, investigation, writing—original draft, and visualization. AW was involved in conceptualization, methodology, writing—review and editing, and supervision. JG contributed to methodology, investigation, and supervision. GZ was involved in conceptualization, methodology, and investigation.

Funding Funding was provided by GMAEC, Tren Urbano grant, San Juan, Puerto Rico, National Science Foundation Grant No. CMS-008539, and George and Marie Vergottis Fellowship (lead author).

Availability of data and material Data presented in this paper are available by request to the corresponding author.

Declarations

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

Code availability Not applicable.

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