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Research article

The relationship between sea-level change, soil formation and stress history of a very soft clay deposit

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Abstract: The paper addresses the relationship between sea-level change, soil formation and stress history of a very soft clay deposit close to the city of Rio de Janeiro (Sarapuí II), permitting some conclusions on hypotheses discussed over time. Dating samples throughout the very soft organic clay profile provided values between 8590 and 2300 cal. yr BP. The average rate of deposition is 0.9 mm/yr. The very soft clay overlies a yellow clayey silt soil of Pleistocene origin (12,630–12,240 cal. yr BP). The combination of geological and geotechnical data indicates that the paleo-sea-level highstand in the Rio de Janeiro area (and possibly in the region between 8°S and 26°S in the Southern Hemisphere along the Brazilian coast) occurred around 7000 cal. yr BP. These sets of data also indicate that the lower part of the Sarapuí II deposit was formed during transgression and the upper part during regression. The overconsolidation of the deposit, excluding the top 2.5 m, could be attributed to secondary consolidation.

Keywords: soft clay; sea-level change; soil formation; stress history; geological-geotechnical data

1. Introduction

The sea-level change in the Southern Hemisphere along the Brazilian coast in the Quaternary has been studied by numerous authors from different sources (e.g., [1–7]). Considerable discussion ensued regarding the existence of secondary oscillations and the date of sea-level highstand.

A comprehensive geological-geotechnical characterisation of a very soft clay deposit in the surroundings of Rio de Janeiro city has been conducted in recent years. The data have provided evidence supporting one of those hypotheses, as shown below.

The soil formation and cause of the overconsolidation of the deposit have also been discussed over the years. The available data have been examined and a clear explanation resulted from the analysis, as shown below.

2. Sea-level change, the hypotheses for the Brazilian coast

Flemming et al. [8] and Locat et al. [9] presented the eustatic sea-level that has varied over the last 25,000 years (Figure 1a, a magnification of the last 10,000 years in Figure 1b). These authors noted that the minimum sea-level may be about 120 m (last glacial maximum) below present sea-level, which corresponds to the maximum Wisconsinian glaciation. Also, most of the rise in eustatic sea-level due to ice melting during the Holocene was reached about 7000 years ago, and since then the sea-level has only risen approximately four metres. The insert in Figure 1a shows the variation of eustatic sea-levels during the last 500,000 yr, where a number of minimum sea-levels (corresponding to their maximum glacial periods) can be observed.

If the average trends of sea-level change are estimated from the figure, the values obtained are 11 mm/yr for the period 16,000–7000 yr BP (before present) and 0.4 mm/yr since 7000 yr BP. Masson-Delmotte et al. [10] reported average rates of global mean sea-level change of 10 to 15 mm/yr in the period 22,000–7000 yr BP. Reference must also be made to Lambeck et al. [11], Masson-Delmotte et al. [10] and Church et al. [12] for comprehensive studies on this matter, including rates in very recent years.

However, a steady rise might not have occurred in some places. In fact, a maximum (highstand) was reached, followed by a smooth decline in the Southern Hemisphere (e.g., [5]). According to Angulo et al. [7], Delibrias and Laborel [13] were the first to anticipate regional differences in sea-level history, indicating a highstand of at least one metre higher than at present in Brazil, unlike the Northern Hemisphere.

It is worth mentioning that at least one reference indicates a similar qualitative behaviour of a drop in sea-level after a highstand (around 6000 yr BP) in the Northern Hemisphere, which occurred in the Shanghai region (Ye et al. [14], quoting Wang and Wang [15]).

Concerning the Brazilian coast, the trend suggested by Suguio et al. [2] is that in around 6800 yr BP the present sea-level would have been reached, then rose to a maximum sea-level around 5100 yr BP. The continuous drop in sea-level to the present would have been interrupted twice, approximately 3900 yr BP and 2800 yr BP, when transgressions (or high-frequency sea-level oscillations) would have occurred. Angulo and Lessa [5] claimed that the trend suggested by them (illustrated in Figure 2) is more similar to the trends detected in other coastal regions of the Southern Hemisphere, where there has been a steady drop in sea-level.

Later, Angulo et al. [7] provided more arguments regarding the reliability of the indicators that they used, and after analysing a large number of vermetid (small to medium-sized sea snails, marine gastropod molluscs) samples, suggested the trend illustrated in Figure 3.

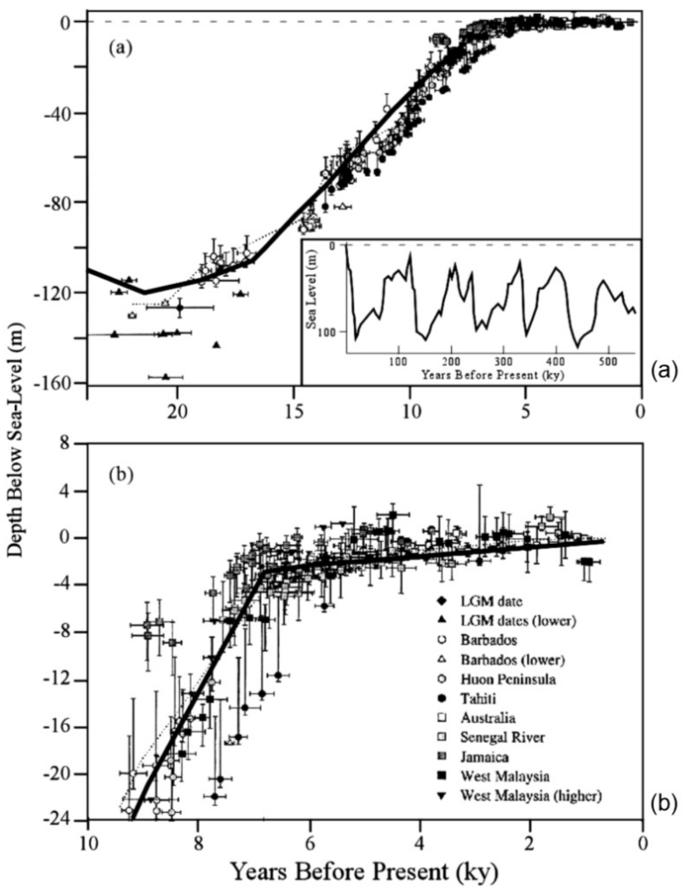

Figure 1. (a) Variations in eustatic sea-levels over the last 25,000 years; (b) magnification of the last 10,000 years (modified after Flemming et al. [8] by Locat et al. [9]).

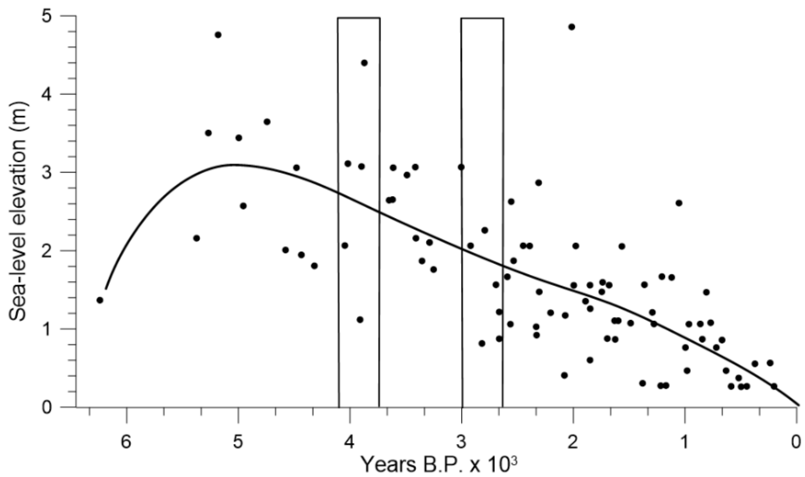

Figure 2. Paleo-sea-level indicators in Brazil from vermetid radiocarbon dates. Rectangular areas refer to suggested secondary oscillations (adapted from Angulo and Lessa [5]).

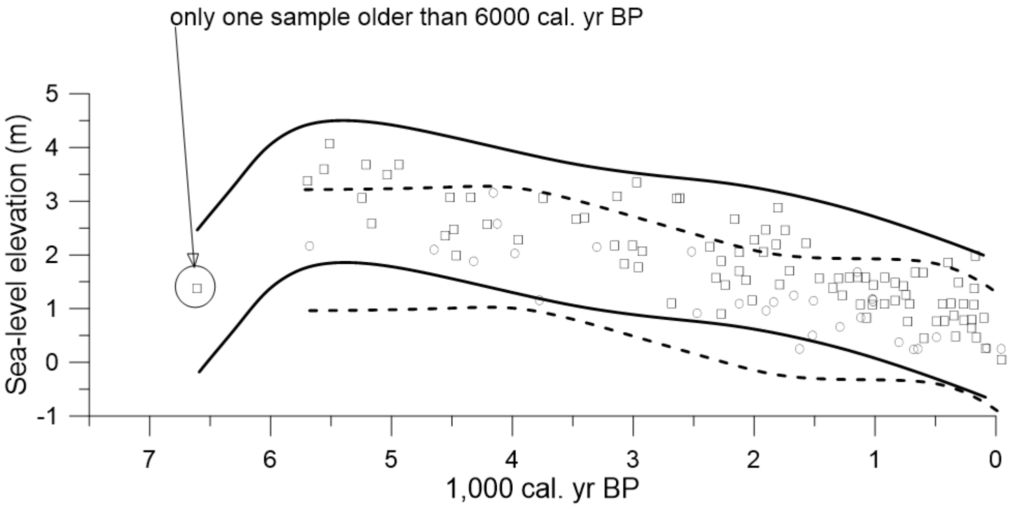

Figure 3. Paleo-sea-level for the Brazilian coast north of 28° (solid lines and squares) and south of 28° (dashed lines and circles), based on vermetid samples (adapted from Angulo et al. [7]).

These authors also compared the trend in Figure 3 with the predictions obtained from a geophysical model employed by Milne et al. [6], and found a difference in relation to the highstand date. Since the trend in Figure 3 was due to only one sample older than 6000 cal. yr BP (indicated in the figure), Angulo et al. [7] argued that if it was removed, the prediction by Milne et al. [6] for paleo-sea-levels older than 5800 cal. yr BP would represent an extension of the observed trend (Figure 4). There is, however, a difference between the predicted paleo-sea-level and the obtained trend, which seems to show a very gentle decline over time from 4000 to 2000 cal. yr BP (Figure 4).

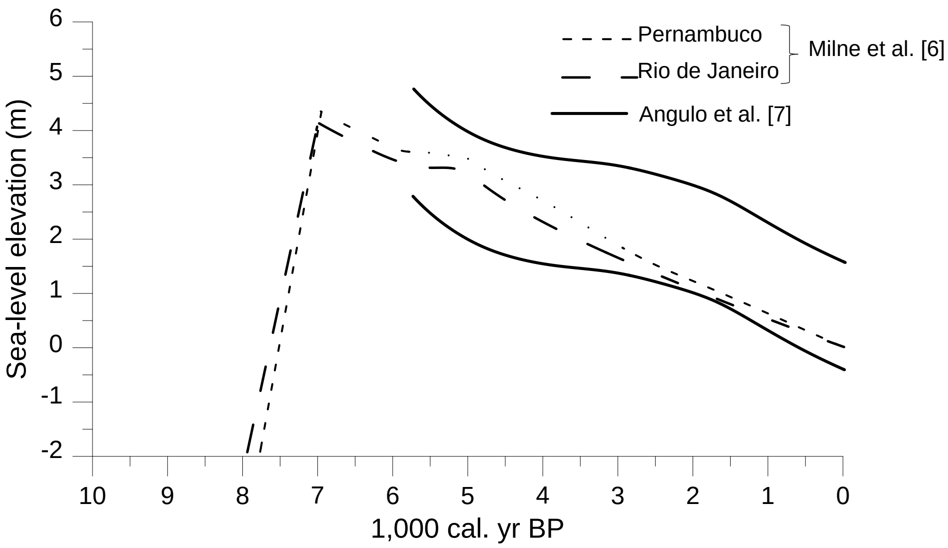

Figure 4. Sea-level envelopes for the region between 8°S and 26°S, plotted with the paleo-sea-level behaviour predicted by Milne et al. [6], from geophysical simulations (adapted from Angulo et al. [7]).

3. The test site

3.1. General

The Sarapuí II test site is situated on the left bank of the Sarapuí River, some 7 km from Rio de Janeiro city, with average coordinates 22°44′27″S and 43°16′49″W. The test site was established some fifteen years ago after deactivating the Sarapuí I test site (1.5 km from Sarapuí II, on the same bank), which was set up in the mid-1970s, after a significant number of studies (e.g., [16–21]).

The initial studies on the Sarapuí II test site were related to pile behaviour in soft clays [22–24]. Joint research projects between the Brazilian national oil company’s research centre (Petrobras-Cenpes) and the Alberto Luiz Coimbra Post-graduate and Engineering Research Institute of the Federal University of Rio de Janeiro (Coppe/UFRJ), have been undertaken on the test site since 2008. Those projects include the development of the torpedo-piezocone [25] and execution of load tests on model torpedo piles (e.g., [26]). Some of the geological-geotechnical characteristics of the deposit were presented elsewhere [27] and are summarised below.

3.2. Soil profile

The thickness of the very soft soil in the test site area ranges from 6.5 m to 10 m. An underlying layer of yellow clayey-silt has also been characterised. The water level varies in the range ± 0.3 m relating to ground level. The ground surface is covered by roughly 0.15 m of thick roots. The upper sample (Figure 5a) shows the top 15 cm consisting of thin roots mixed with the topsoil. Accordingly, the top of this layer, which corresponds to elevation 0.52 m, was assumed as the ground level. The transition between this layer and the underlying soil layer is reasonably well defined, as can be observed in Figure 5a. Figures 5b and 5c illustrate the presence of a significant number of wood fragments, between 1.38 m and 1.44 m in depth. Small shell fragments are present throughout the profile. However, between the depth of 1.0 m and 1.6 m and between 5.2 m and 6.0 m, a large quantity of larger fragments (in many cases closed and intact shells) is noticeable. Figures 5d to 5g illustrate an interesting feature of the profile. The top of a sample slice 12 cm in height (from 1.38 m to 1.50 m in depth) in Figure 5d shows brown-dark grey clay, with no shells. The bottom of the same slice is shown in Figure 5e where a large number of shells—some of them closed and intact—are being removed from the sampler. Figure 5f illustrates the bottom of the sampler after removing the shells, and Figure 5g shows the removed washed shells. Figure 5h depicts shells still inside a slice of the sampler (5.86–6.00 m depth), and in Figure 5i the removed washed shells. To the authors´ knowledge, it is the first time a quantity of shells in a soft clay was so significant that they were detected by the profile of cone resistance (q_t) from six piezocone tests [28] in the area, as shown in Figure 5j. The layer where the roots are mixed with the topsoil also shows an increase in q_t.

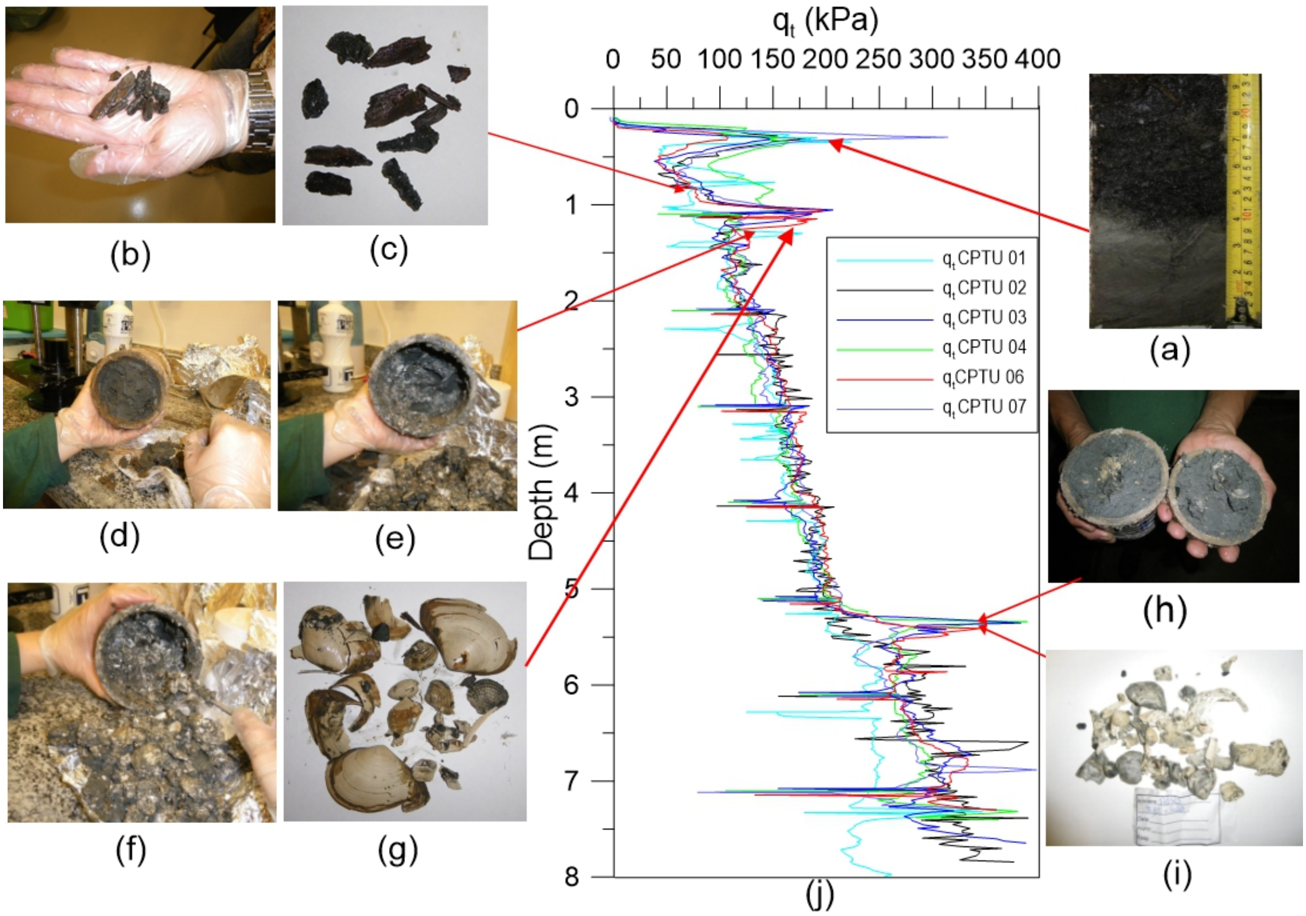

Figure 5. (a) Sample at the top of the profile, upper 15 cm of thin roots mixed with the topsoil; (b) and (c) wood fragments found between 1.38 m and 1.44 m depth; (d) top of slice 12 cm in height (1.38–1.50 m depth); (e) shells being removed; (f) bottom of slice, after removal of shells; (g) washed shells removed; (h) shells inside the sampler, sample slice 14 cm in height (5.86–6.00 m depth); (i) washed shells removed; (j) cone resistance from six piezocone tests.

3.3. Geological-geotechnical data

Geological-geotechnical data are summarised in Figures 6 and 7. The soil is silty clay, with 60% clay, 35–40% silt and 0–5% sand on average. It is a high plasticity soil (plasticity index in the range 60–170%), very soft, with organic content decreasing with depth, from 12–16% to 6%. The material is slightly overconsolidated (overconsolidation ratio of 2.0) from approximately 3 m in depth (this subject is discussed further in the paper). Sensitivity from vane tests is in the range 4–8 in most of the data. It should be pointed out that the values below the depth of 8.0 m correspond to the underlying layer of yellow clayey-silt. Further details about the soil deposit can be found in Jannuzzi [29] and Jannuzzi et al. [27].

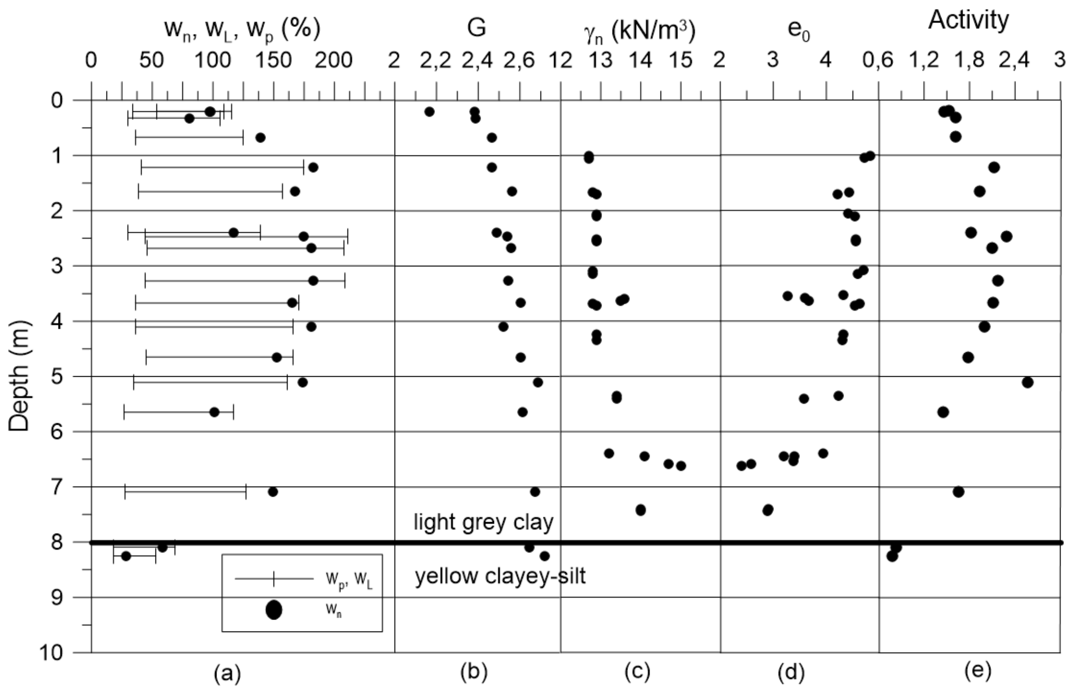

Figure 6. (a) Liquid limit, w_L, plastic limit, w_P, and natural water content, w_n; (b) specific gravity, G; (c) total unit weight, γ_n; (d) initial void ratio, e_o; (e) activity versus depth (adapted from Jannuzzi et al. [27]).

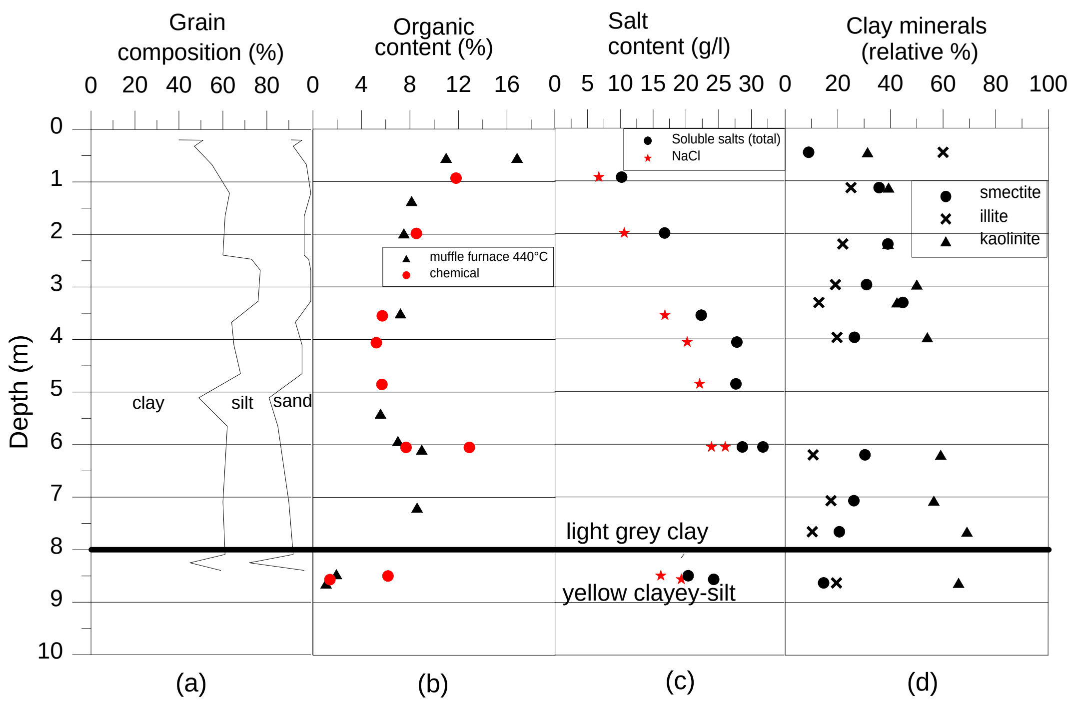

Figure 7. (a) Grain size distribution; (b) organic content; (c) total salt content and NaCl content; (d) relative percentage of clay minerals versus depth (adapted from Jannuzzi et al. [27]).

4. Age of deposit and rate of deposition and the relationship with change in sea-level

Almeida and Marques [21] quoted Antunes [30] to refer to the age of the Sarapuí deposit. In fact, the latter suggested that the sediments were formed in the last 6000 years. However, this suggestion was based on a literature survey—with available dating over a much broader region—and field observations, and no dating was available in the area where the Sarapuí deposit is located.

In the study reported herein, fifteen samples from radiocarbon analyses of the actual soil and the shells and wood (referred to as peat by Beta Analytic [31]) in the soil were dated by Beta Analytic [31], and a detailed picture of the age of the deposit could be obtained (Figure 8, see also Table 1). When shells or wood were present inside the sample they were dated in addition to the actual sediment. Both the conventional radiocarbon age and the calendar calibrated radiocarbon age (calibration is needed to convert radiocarbon age to calendar age) have been included in the table. The deposition rate was assessed based on the intercept of radiocarbon age in the calibration curve, also included in the table. The values obtained from the sediment and wood are found to be virtually the same for the samples at 6.10 m depth, but for the sample at 0.52 m depth the difference in values from the sediment and wood exceeded 1000 years. The difference between the values obtained from the sediment and shells was 660 years at a depth of 1.57 m and 2080 years at 4.40 m. This means that the shells came from the upper soil. Since the most reliable data are those obtained from the sediment, it can be said that the age of the deposit is in the range 12,630–2300 cal. yr BP (considering the first intercept of radiocarbon age from the calibration curve and including the very soft grey Holocene clay and the yellow Pleistocene clayey-silt, see Table 1). The general aspect of the data plotted in Figure 8 might suggest a linear variation of age versus depth, i.e. a deposition rate of 0.9 mm/yr. However, a closer look at the data in Figure 8, and especially in Table 1, shows some significant variations in the deposition rate between 6.4 mm/yr and 0.5 mm/yr. It is also noticeable that from roughly 1.5 m to 5.0 m in depth a reasonably uniform deposition rate of 0.9 mm/yr could be considered. This figure is similar to the deposition rates in shallow-water marine deposits reported by Skempton [32], as seen in Table 2, although these deposits are much thicker, and most of them have been deposited in the Pleistocene, not the Holocene, with the exception of the Oslofjord data. It is also 40–50% of the rate of estuarine deposits from the Holocene (see Table 2). The deposition rate of the depth interval 5.0–8.0 m (approximately) is very variable, 6.4, 0.6 and 6.4 mm/yr, with a general trend of higher deposition rates than the values discussed previously. The higher figure (6.4 mm/yr) is nearly three times as much as the deposition rates for the Holocene estuarine clays quoted by Skempton [32].

Locat and Lefebvre [33] also presented sedimentation rates for various deposits in different parts of the world, and found values between 25 mm/yr and 1 mm/yr, the smaller figures for more recent data, which is consistent with the data obtained herein.

Regarding Brazilian data, Bastos et al. [34], for example, obtained deposition rates between 0.4 and 0.8 mm/yr for Vitoria Bay sediments, dated between 7240 and 1010 cal. yr BP. These values are roughly 50% to 80% of the values obtained in the upper part of the Sarapuí II deposit, in the same age range.

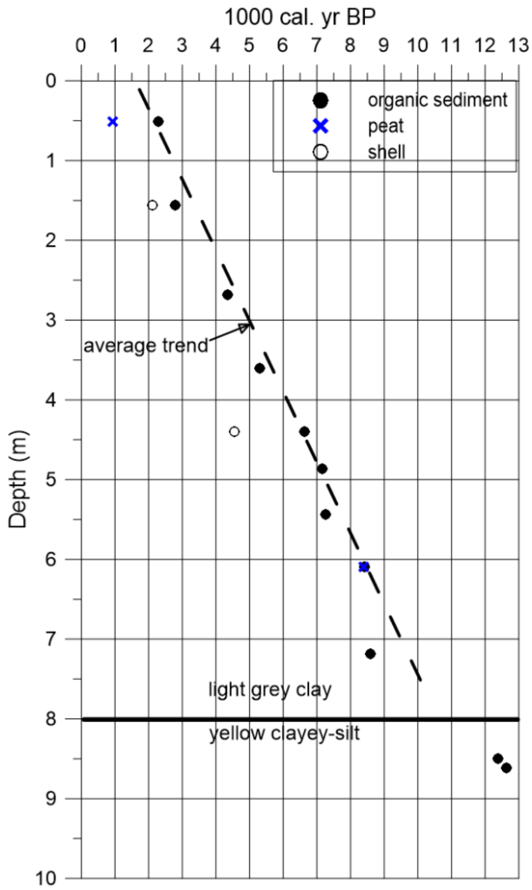

Figure 8. Age of Sarapuí II clay.

Concerning the correlation of the age of soil deposits with the sea-level elevation, it is worth mentioning, for example, Suguio and Martin [1], Suguio et al. [2], Martin et al. [3], Massad et al. [4], Angulo and Lessa [5], Milne et al. [6] and Angulo et al. [7] for Brazilian data. Figure 9 shows data from different authors: the trend suggested by Suguio et al. [2] for the city of Salvador, Bahia State (12°58′13.38″S), which has the largest set of data from those authors; the trend suggested by these authors for the town of Angra dos Reis, Rio de Janeiro State (23°00′36.18″S), which is nearer the Sarapuí II site; Angulo and Lessa's [5] suggestion for the Brazilian coast (see Figure 2); the prediction of Milne et al. [6] of paleo-sea-level for the Rio de Janeiro region (see Figure 4); Angulo et al. [7] envelopes (see Figure 4); variations in eustatic sea-levels over the last 25,000 years (modified after Flemming et al. [8], by Locat et al. [9], Figure 1); and elevations and corresponding ages of the dated samples of Sarapuí II site (from Figure 8).

It is worth noting that the reasonably uniform sedimentation rate (period 7000 cal. years BP to present) is consistent with a steady drop in the sea-level, as suggested by Angulo and Lessa [5], as well as with the geophysical model proposed by Milne et al. [6], supported by Angulo et al. [7]. In other words, the hypothesis of the two periods of high-frequency sea-level oscillations, also indicated in Figure 8, is not supported by the uniform sedimentation rate. Also, the highstand occurrence (around 7000 cal. years BP) is directly related to the change in the rate of sediment deposition, i.e., supporting the Milne et al.'s [6] model.

Table 1. Age of Sarapuí II clay.

Depth (m)	Elevation (m)	Sample Beta no.	Material	Conventional radiocarbon age (yr BP)	Calendar calibrated radiocarbon age, 95% probability (yr BP)	Interception of radiocarbon age at calibration curve (yr BP)	Rate of deposition (mm/yr)
0.52	0.00	311275	organic sediment	2220 ± 30	2340 to 2150	2300; 2240; 2180	
0.52	0.00	313034	peat	1030 ± 30	980 to 920	930	
							2.2
1.57	1.05	311276	organic sediment	2700 ± 30	2850 to 2750	2780	
1.57	1.05	313035	shell	2420 ± 30	2280 to 1990	2120	
							0.7
2.69	2.17	311277	organic sediment	3880 ± 30	4420 to 4230, 4200 to 4180, 4170 to 4160	4350; 4330; 4300	
							1.0
3.61	3.09	311278	organic sediment	4560 ± 30	5320 to 5280, 5170 to 5130, 5110 to 5070	5300	
							0.6
4.40	3.88	311279	organic sediment	5790 ± 40	6670 to 6490	6630; 6580; 6570	
4.40	3.88	315596	shell	4350 ± 30	4770 to 4720	4550	
							0.9
4.87	4.35	311280	organic sediment	6180 ± 40	7230 to 7230, 7170 to 6950	7160; 7100; 7090; 7080; 7070; 7040; 7030	
							6.4
5.44	4.92	316273	organic sediment	6300 ± 30	7270 to 7170	7250	
							0.6
6.10	5.58	316276	organic sediment	7650 ± 40	8540 to 8530, 8520 to 8390	8420	
6.10	5.58	316807	peat	7610 ± 40	8450 to 8370	8400	
							6.4

Continued on next page

Depth (m)	Elevation (m)	Sample Beta no.	Material	Conventional radiocarbon age (yr BP)	Calendar calibrated radiocarbon age, 95% probability (yr BP)	Interception of radiocarbon age at calibration curve (yr BP)	Rate of deposition (mm/yr)
7.19	6.67	316277	organic sediment	7800 ± 50	8650 to 8450	8590	
							-
8.50	7.98	316275	organic sediment[a]	10,420 ± 50	12,530 to 12,460; 12,440 to 12,090	12,390; 12,240; 12,240	
							0.5
8.62	8.10	316274	organic sediment[a]	10,740 ± 40	12,670 to 12,590	12,630	

Note: [a] Yellow clayey-silt.

Table 2. Deposition rate and thickness of some Quaternary and Pliocene argillaceous sediments (Skempton [32]).

	Thickness of deposit (m)	Rate of deposition (m/1000 yr)	Reference
Deltaic			
Mississippi, Holocene	55	120	McClelland (1967)
Rhone, Holocene	65	17	Lagaaij (1970)
Orinoco, Holocene	40	8	Kidwell & Hunt (1958)
Estuarine			
Avonmouth, Holocene	13	2.5	Skempton (1970)
Tilbury, Holocene	16	2	Skempton (1970)
Pisa, Holocene	10	2.5	Skempton (1970)
Marine, shallow water			
Oslofjord, Holocene	-	0.8	Richards (1970)
Po Valley, Pleistocene	2000	1.2	Skempton (1970)
Po Valley, Pliocene	3000	1.0	Skempton (1970)
Kambara, Pliocene	2600	0.9	Skempton (1970)
Marine, deep-sea			
Caribbean, Pleistocene	-	0.03	Rosholt et al. (1961)

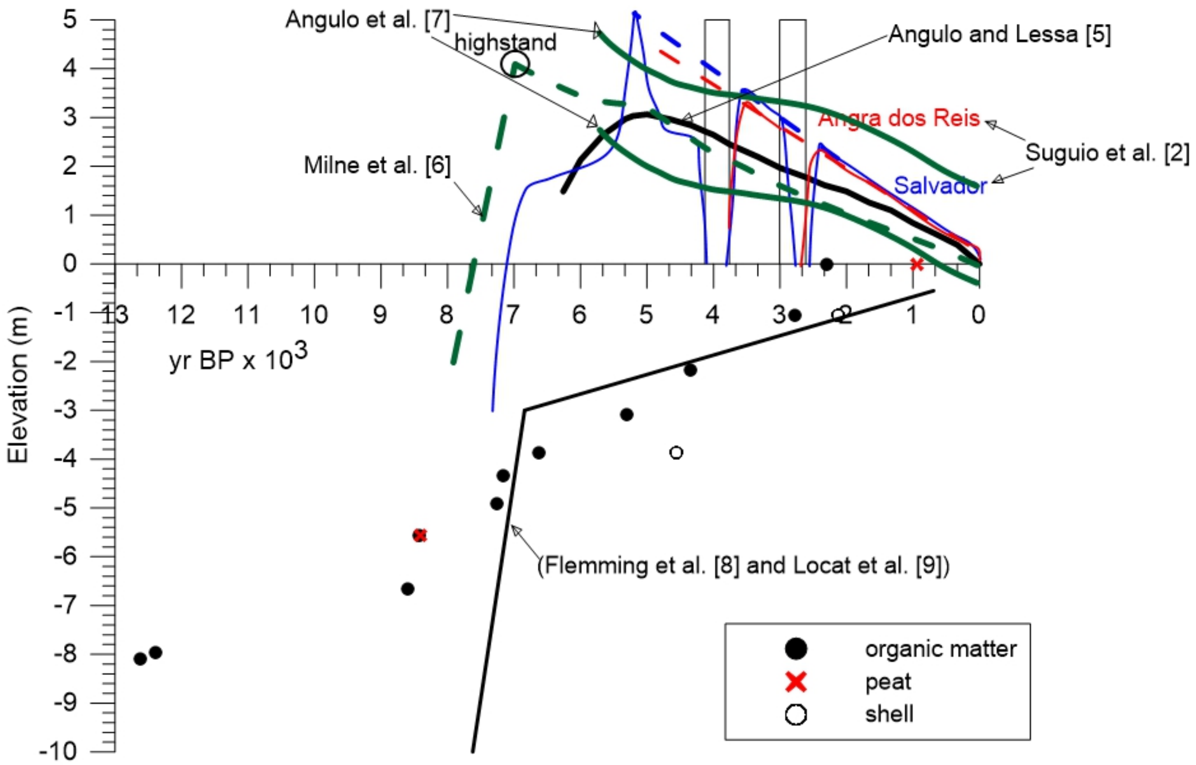

Figure 9. Data from Sarapuí II clay plotted together with different hypotheses for the sea-level change. Data from Sarapuí II, Milne et al. [6] and Angulo et al. [7] in cal. yr BP, the other data in yr BP.

5. Age of deposit and rate of deposition and the relationship to geological-geotechnical data

In the study herein, another interesting view of the previous discussion could be provided if the age versus depth of Sarapuí II clay were now to be plotted, together with cone resistance (Figures 10a,b,d). The cone resistance profile clearly indicates that, broadly considering, there are at least two layers of very soft soil (Holocene clay) in the profile, one from roughly 5.2 m to 7.5–8 m in depth, with cal. yr BP between 8590 and approximately 7200, which had probably been deposited during transgression, and the upper layer formed during regression. The top of the layer deposited during regression would be around 5.2 m in depth. If now considering the deposition rate, it is noticeable that the depth interval 4.87–5.44 m had a deposition rate of 6.4 mm/yr, while all other depth intervals above had a much lower rate, from 0.6 mm to 1.0 mm/yr (except the upper), which seems to be characteristic of the deposit formation's regression phase. Moreover, the depth interval between 6.10 m and 7.19 m (corresponding to the transgression phase) presented the same deposition rate of 6.4 mm/yr.

A similar comparison can be made between the deposition rate and grain size distribution (see Figure 10c). The higher rates are found to be related to a greater sand content, especially in the case of the depth interval 4.7–5.7 m, where there was a deposition rate of 6.4 mm/yr. In other words, the soil deposited during transgression has a greater sand content in the silty clay than during regression. The closer agreement in depth between deposition rate and grain size distribution could be attributed to a longer distance between samples and the piezocone tests. In fact, the same samples were used for both dating and grain size analysis, or samples from boreholes at intervals of 4.0 m or less were taken for this purpose, whereas the average distance between samples and the piezocone tests is 15 m. Also, a closer look at the geotechnical data shows that e_o and γ_n values also indicate two layers of the Holocene clay.

Therefore, the analysis of both geological and geotechnical data clearly indicates that the regression started indeed around 7000 cal. yr BP, as predicted by Milne et al. [6], and supported by Angulo et al. [7].

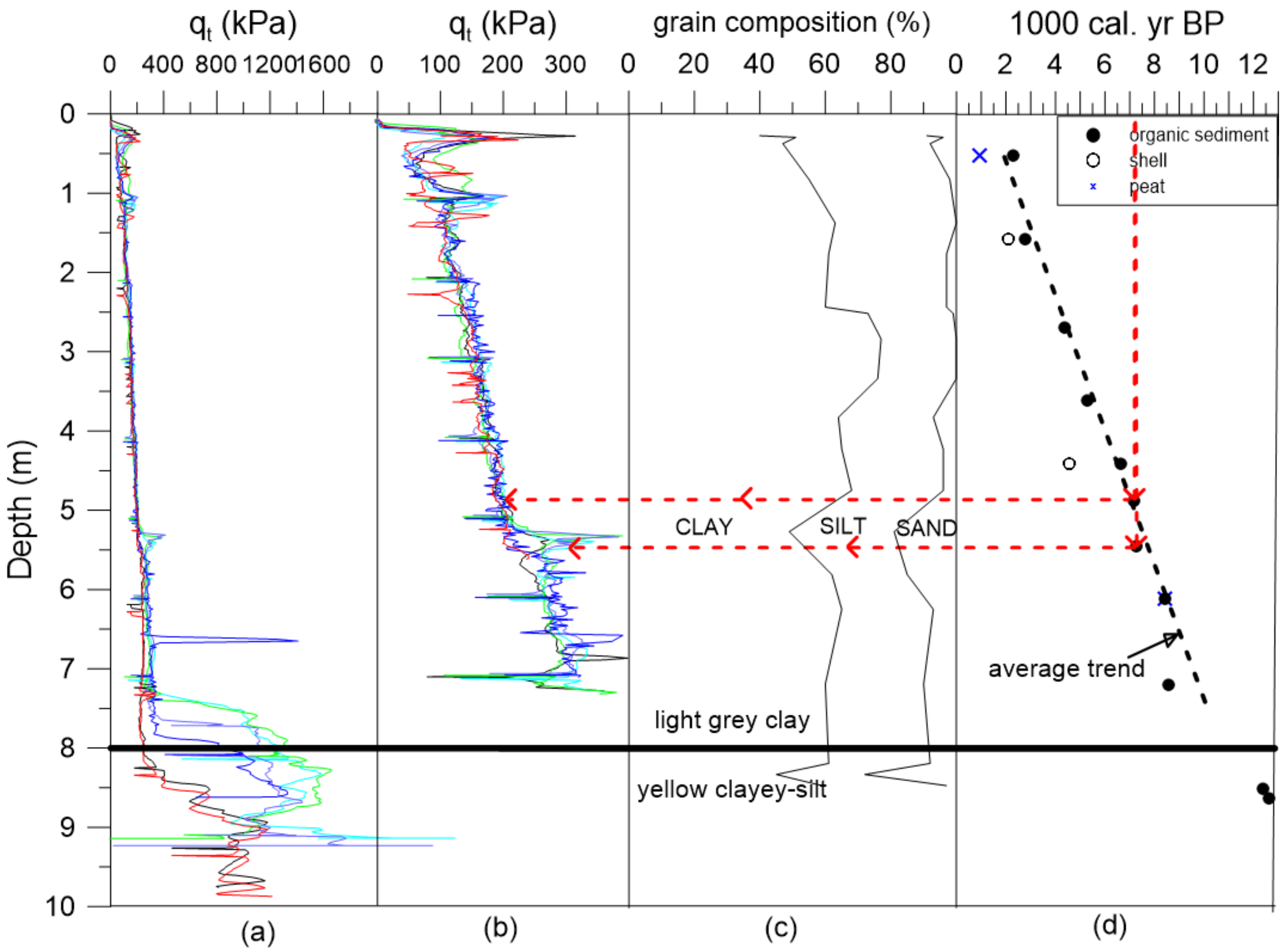

Figure 10. (a) and (b) cone resistance; (c) grain size distribution; (d) age of Sapuí II clay, versus depth.

6. Stress history

The proper evaluation of the stress history is a key issue in the design of embankments on soft clays. Therefore, the knowledge of the cause of overconsolidation plays a major role in the interpretation and accuracy of the measured values from in situ and laboratory testing.

Perret et al. [35] and Locat et al. [9] suggested the joint use of three parameters, OCR (overconsolidation ratio or yield stress ratio), OCD (overconsolidation difference, suggested by

Olsen et al. [36], according to Perret et al. [35]) and OCG (overconsolidation gradient), in equations 1, 2 and 3, respectively, to identify the consolidation state of a soil. The idealised marine soil profiles in Figure 11 represent secondary consolidation (a) to (d), erosion (e) to (h) and cementation and thixotropy (i) to (l). The less known OCG parameter, defined as the slope of the yield stress—vertical stress relationship, is not sensitive to erosion.

$$OCR = \frac{\sigma'_{vm}}{\sigma'_{vo}} \tag{1}$$

$$OCD = \sigma'_{vm} - \sigma'_{vo} \tag{2}$$

$$OCG = \Delta\sigma'_{vm} / \Delta\sigma'_{vo} \tag{3}$$

where, $\sigma'_{vm} = \sigma'_{p}$ = yield stress, σ'_{vo} = in situ vertical stress.

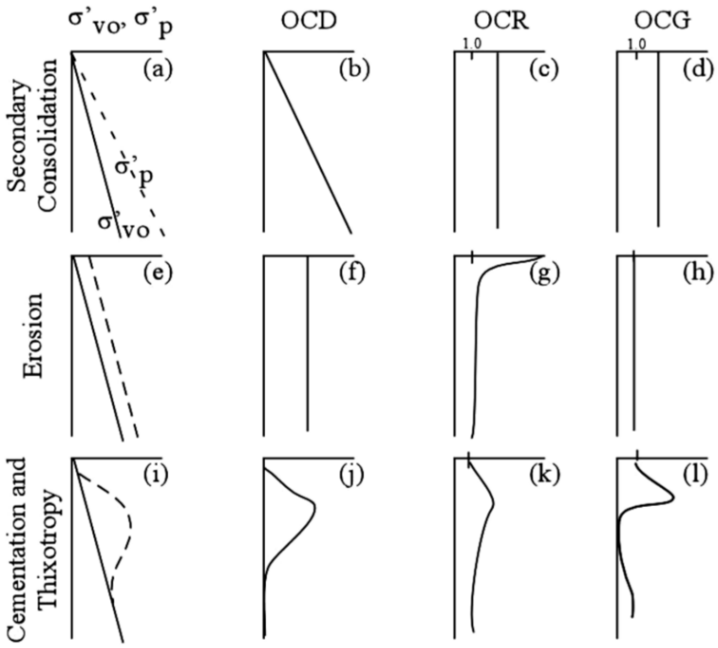

Figure 11. Idealized marine soil profiles (modified after Perret et al. [35] by Locat et al. [9]).

Figure 12 presents those values for the Sarapuí II deposit, obtained from incremental loading (IL) 24h-consolidation tests, where the yield stress was obtained from Pacheco Silva´s [37] method, which provides similar values to Casagrande´s method, but it is easier to apply. Values of OCG were obtained considering only the very good to excellent samples (see below for sample quality), and lines were drawn for the corresponding depth intervals from where the data were taken. The dashed lines represent general trends in the figures.

The samples were obtained from 100 mm in diameter thin wall tube samplers, and the specimens trimmed following the procedures suggested by Ladd and DeGroot [38]. The sample quality was assessed on the criterion of Lunne et al. [39] (see also Tanaka [40]; Lunne and Long [41]), based on the $\Delta e/e_o$ ratio (also included in the figure), where, $\Delta e = e_o - e$, e_o = initial void ratio, e = void ratio at the vertical effective stress in the field.

Almost all cases were classified as very good to excellent and good to fair. The few exceptions, classified as poor or very poor, correspond to the cases where shells inside the specimens had to be removed and replaced by disturbed soil.

The trend from around 2.5 m depth to the bottom of the very soft soil clearly indicates that secondary consolidation is the controlling process of the overconsolidation. The results obtained from the upper part of the profile seem to indicate a combination of secondary consolidation and erosion. However, there is no geological evidence for erosion, as discussed in previous sections. Also, no embankments were executed in the area where the samples were collected and piezocone tests performed. Thus, other causes may be investigated to provide a suitable explanation. The first is recent water level drawdown, or water level fluctuation during certain periods of the year, which would generate results similar to erosion. However, as aforementioned, there is no geological evidence indicating water level drawdown (or water level fluctuation) with a magnitude of more than 0.5 m, which would, therefore, be unable to generate the high OCR values obtained at a small depth (see also Parry [42,43]). Other possibilities to be investigated in the near future are desiccation/suction caused by the vegetation and bacterial action (see also Jennings [44]; Bjerrum [45]; Jamiolkowski et al. [46]; Ehlers et al. [47]).

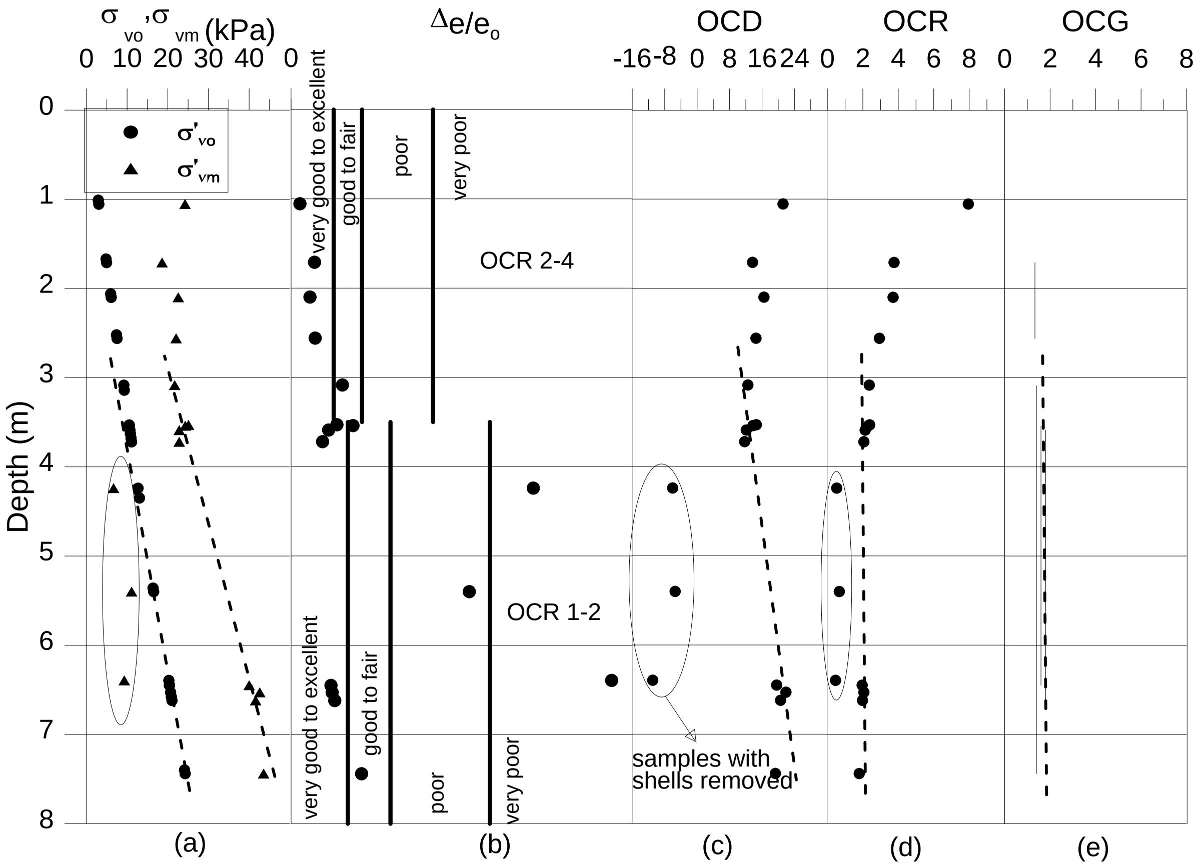

Figure 12. (a) σ'_{vm}, σ'_{vo}; (b) $\Delta e/e_o$; (c) OCD; (d) OCR; (e) OCG of Sarapuí II clay, versus depth.

7. Conclusions

The paper addresses the relationship between the sea-level change, soil formation and stress history of a very soft clay deposit near the city of Rio de Janeiro (Sarapuí II). Dating of the very soft organic clay throughout the profile provided values between 8590 and 2300 cal. yr BP. The average deposition rate is 0.9 mm/yr. The upper part of the deposit had a more uniform deposition rate (in the range 0.6–1.0 mm/yr) than the highly variable lower part (approximately 5–8 m depth interval). The fairly uniform sedimentation rate (period 7000 cal. years BP to present) is consistent with a steady drop in the sea-level. The very soft organic material overlies a yellow clayey-silt soil from Pleistocene origin (12,630–12,240 cal. yr BP). The combination of geological and geotechnical data with engineering properties of the deposit indicates that the paleo-sea-level highstand in the Rio de Janeiro area (and possibly in the region between 8°S and 26°S in the Southern Hemisphere, on the Brazilian coast), an issue under discussion for many years, occurred around 7000 cal. yr BP, as predicted by a geophysical model developed by Milne et al. [6] and supported by Angulo et al. [7]. Moreover, it also indicates that the lower part of the Sarapuí II deposit was formed during transgression and the upper part during regression. The overconsolidation of the soft clay deposit (excluding the top 2.5 m, which needs further investigation) could be attributed to secondary consolidation.

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Conflict of interest

The authors declare no conflict of interest in this paper.

References

1. Suguio K, Martin L (1978) Quaternary marine formations of the states of São Paulo and southern Rio de Janeiro. Special Publication 1. *International Symposium on Coastal Evolution in the Quaternary*, São Paulo, 55.
2. Suguio K, Martin L, Bittencourt ACSP, et al. (1985) Water level fluctuations during the Quaternary and implications on the sedimentation process (in Portuguese). *Braz J Geosci* 15: 273–286.

3. Martin L, Suguio K, Flexor JM (1987) Relative sea-level reconstruction during the last 7,000 years along the State of Paraná and Santa Catarina: additional information derived from shell middens. *Quat South Am Antarct Penins* 4: 219–236.
4. Massad F, Suguio K, Pérez FS (1996) Geotechnical characteristics of clay sediments as an evidence of relative water level variations in Santos (in Portuguese). *Proceedings 8th Brazilian Conference on Engineering Geology*, Rio de Janeiro, 1: 163–176.
5. Angulo RJ, Lessa GC (1997) The Brazilian sea-level curves: a critical review with emphasis on the curves from Paranaguá and Cananéia regions. *Mar Geol* 140: 141–166.
6. Milne GA, Long AJ, Bassetta SE (2005) Modelling Holocene relative sea-level observations from the Caribbean and South America. *Quat Sci Rev* 24: 1183–1202.
7. Angulo RJ, Lessa GC, de Souza MC (2006) A critical review of mid- to late-Holocene sea-level fluctuations on the eastern Brazilian coastline. *Quat Sci Rev* 25: 486–506.
8. Flemming K, Johnston P, Zwartz D, et al. (1998) Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth Planet Sci Lett* 163: 327–342.
9. Locat J, Tanaka H, Tan TS, et al. (2003) Natural soils: geotechnical behaviour and geological knowledge. Tan TS, Phoon KK, Hight DW, et al. (eds.), *Characterisation and Engineering Properties of Natural Soils*, Swets & Zeitlinger, Lisse, 1: 3–28.
10. Masson-Delmotte V, Schulz M, Abe-Ouchi A, et al. (2013) Information from Paleoclimate Archives. *In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker TF, Qin D, Plattner GK, et al. (eds.), Cambridge University Press, Cambridge, UK and New York, NY, USA.
11. Lambeck K, Woodroffe CD, Antonioli F, et al. (2010) Paleoenvironmental records, geophysical modelling, and reconstruction of sea level trends and variability on centennial and longer timescales. *In: Understanding Sea Level Rise and Variability*, Church JA, Woodworth PL, Aarup T, et al. (eds.), Wiley-Blackwell, Hoboken, NJ, USA, 61–121.
12. Church JA, Clark PU, Cazenave A, et al. (2013) Sea Level Change. *In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker TF, Qin D, Plattner GK, et al. (eds.), Cambridge University Press, Cambridge, UK and New York, NY, USA.
13. Delibrias C, Laborel J (1969) Recent variations of the sea-level along the Brazilian coast. *Quaternaria* 14: 45–49.
14. Ye GL, Lin N, Bao XH, et al. (2018) Effect of Quaternary transgression and regression on the engineering properties of Shanghai soft clays. *Eng Geol* 239: 321–329.
15. Wang JT, Wang PX (1980) Relationship between sea-level changes and climatic fluctuation in East China since late Pleistocene (in Chinese). *Acta Geogr Sin* 35: 299–312.
16. Lacerda WA, Costa Filho LM, Coutinho RQ, et al. (1977) Consolidation characteristics of Rio de Janeiro soft clay. *Proceedings Conference on Geotechnical Aspects of Soft Clays*, Bangkok, 231–243.
17. Werneck MLG, Costa Filho LM, França H (1977) In-situ permeability and hydraulic fracture tests in Guanabara Bay clay. *Proceedings Conference on Geotechnical Aspects of Soft Clays*, Bangkok, 399–416.

18. Ortigão JAR, Werneck MLG, Lacerda WA (1983) Embankment failure on clay near Rio de Janeiro. *J Geotech Eng* 109: 1460–1479.
19. Sayão ASJF (1980) *Laboratory tests on a soft clay from the experimental excavation at Sarapuí test site* (in Portuguese). M.Sc. thesis, PUC-Rio.
20. Danziger FAB, Almeida MSS, Sills GC (1997) The significance of the strain path analysis in the interpretation of piezocone dissipation data. *Géotechnique* 47: 901–914.
21. Almeida MSS, Marques MES (2003) The behaviour of Sarapuí soft clay, Tan TS, Phoon KK, Hight DW, et al. (eds.), *Characterisation and Engineering Properties of Natural Soils*, Swets & Zeitlinger, Lisse, 1: 477–504.
22. Alves AML (2004) *The influence of soil viscosity and time on the dynamic pile-soil interaction in clays* (in Portuguese). Ph.D. thesis, COPPE, Federal University of Rio de Janeiro.
23. Francisco GM (2004) *Time effect on piles in soft clay* (in Portuguese). Ph.D. thesis, COPPE, Federal University of Rio de Janeiro.
24. Alves AML, Lopes FR, Randolph MF, et al. (2009) Investigations on the dynamic behavior of a small-diameter pile driven in soft clay. *Can Geotech J* 46: 1418–1430.
25. Porto EC, Medeiros Jr CJ, Henriques Jr PRD, et al. (2010) The development of the torpedo-piezocone. *Proceedings of the 29th International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2010*, American Society of Mechanical Engineers, New York.
26. Guimarães GVM (2015) *Horizontal load test on instrumented model torpedo-pile in soft clay* (in Portuguese). Ph.D. thesis, COPPE, Federal University of Rio de Janeiro.
27. Jannuzzi GMF, Danziger FAB, Martins ISM (2015) Geological-geotechnical characterisation of Sarapuí II clay. *Eng Geology* 190: 77–86.
28. Jannuzzi GMF (2009) *The characterisation of Sarapuí II soft clay site by in-situ testing* (in Portuguese). M.Sc. thesis, COPPE, Federal University of Rio de Janeiro.
29. Jannuzzi GMF (2013) *Innovative and traditional methods to characterise the Sarapuí II soft clay* (in Portuguese). Ph.D. thesis, COPPE, Federal University of Rio de Janeiro.
30. Antunes F (1978) *Geological, pedological and mineralogical tests on Rio de Janeiro soft clay* (in Portuguese). IPR/DNER Report 2.019-02.02-2/10/42.
31. Beta Analytic (2012) *Reports on radiocarbon dating results dated 06 February 2012 and 26 February 2012*.
32. Skempton AW (1970) The consolidation of clays by gravitational compaction. *Q J Geol Soc* 125: 373–412.
33. Locat J, Lefebvre G (1985) The compressibility and sensitivity of an artificially sedimented clay soil: The Grande Baleine Marine Clay, Québec, Canada. *Mar Geotech* 6: 1–28.
34. Bastos AC, Vilela CG, Quaresma VS, et al. (2010) Mid- to Late-Holocene estuarine infilling processes studied by radiocarbon dates, high resolution seismic and biofacies at Vitoria Bay, Espirito Santo, Southeastern Brazil. *Ann Braz Acad Sci* 82: 761–770.
35. Perret D, Locat J, Leroueil S (1995) Strength development with burial in fine-grained sediments from the Saguenay Fjord, Québec. *Can Geotech J* 32: 247–262.
36. Olsen HW, Rice TL, Mayne PW, et al. (1986) Piston core properties and disturbance effects. *J Geotech Eng* 112 (6): 608–625.
37. Pacheco Silva F (1970) A new graphical procedure to determine the preconsolidation stress of a clay sample (in Portuguese). *Proceedings 4th Brazilian Conference on Soil Mechanics and Foundation Engineering*, Guanabara, 2: 219–223.

38. Ladd CC, DeGroot DJ (2003) Recommended practice for soft ground site characterization: Arthur Casagrande Lecture. *Proceedings 12th Pan-American Conference on Soil Mechanics and Geotechnical Engineering*, Boston, 1: 3–57.
39. Lunne T, Berre T, Strandvik S (1997) Sample disturbance effects in soft low plastic Norwegian clay. *Proceedings, Symposium on Recent Developments in Soil and Pavement Mechanics*, Rio de Janeiro, 81–102.
40. Tanaka H (2000) Sample quality of cohesive soils: lessons from three sites, Ariake, Bothkennar and Drammen. *Soils Found* 40: 57–74.
41. Lunne T, Long M (2006) Review of long seabed samplers and criteria for new sampler design. *Mar Geol* 226: 145–165.
42. Parry RHG (1968) Field and laboratory behaviour of a lightly overconsolidated clay. *Géotechnique* 18: 151–171.
43. Parry RHG (1972) Stability analysis for low embankments on soft clays. *Proceedings of the Roscoe Memorial Symposium*, Cambridge University, 643–668.
44. Jennings JE (1960) A revised effective stress law for use in the prediction of the behaviour of unsaturated soils. *Proceedings Conference on Pore Pressure and Suction in Soils*, Institution of Civil Engineers, London, 26–30.
45. Bjerrum L (1973) Problems of soil mechanics and construction on soft clays. State-of-the-art report. *Proceedings 8th International Conference on Soil Mechanics and Foundation Engineering*, Moscow, 3: 111–159.
46. Jamiolkowski M, Ladd CC, Germaine JT, et al. (1985) New developments in field and laboratory testing of soils. *Proceedings 11th International Conference on Soil Mechanics and Foundation Engineering*, San Francisco, 1: 57–153.
47. Ehlers CJ, Chen J, Roberts HH, et al. (2005) The origin of near-seafloor “crust zones” in deep water. *Proceedings Frontiers in Offshore Geotechnics*, Taylor and Francis Group, London, 927–933.

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