Optimizing Soft Clay Consolidation with Alternative Filter Materials- Study on Sand and Bottom Ash

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Abstract: This study evaluates the application of vertical drain systems using natural and synthetic clay (Kaolin) with sand and bottom ash as filter material for enhanced soil consolidation. This research seeks to evaluate the influence of varying vertical drain diameter and vertical spacing on clay subsoil consolidation. The experimental method used included consolidation tests that were carried out under laboratory-controlled environment with reference to the Indian Standards (I. S. 2720). Some of the highlighted findings is by comparing the consolidation rates of both sand and bottom ash drains through fulfilling the necessary conditions it was established that bottom ash can therefore be used as a replacement for sand to improve on the soil permeability and reduction of consolidation time. Finally, the results of the experiment were supported by Taylor's method numerical analysis of the consolidation coefficients and the volume variation. The findings provided in the study help to enhance the utilization of ground improvement techniques in an efficient manner with reference to soft clay soils.

Keywords: Ground improvement, soil consolidation, vertical drains, sand, bottom ash, Kaolin, hydraulic conductivity, Taylor's method, soil permeability, settlement analysis.

1. Introduction

There is a need for ground improvement techniques in civil engineering especially where there are issues of weak soil such as clayey soils which are characterized by low permeability and slow consolidation. Conventional methods such as sand drains are usually used to enhance consolidation by enhancing the permeability of the soil. That said, contemporary studies have analyzed some common replacements for sand, including industries waste like bottom ash in order to enhance the affordability and eco-friendliness of these techniques. The settlement of clayey soils depends on its consolidation rate and this is important when designing structures that will founded on such soils. Vertical drains, for instance, is widely used as a means of shortening the time required for settlement since they create shorter drain paths through which the excess pore water can drain. In these drains, sand is used as the filter material although research has proven that other materials such as the bottom ash which is by-product from thermal power plant could offer better performances in certain cases. This research focuses on the effect of vertical drains which are filled with sand and bottom ash on the consolidation behavior of natural clay and synthetic clay (Kaolin). Thus, changing the diameter and distance between the drains, the study will show the effectiveness of both materials in the process of soil compaction. The experimental procedure follows the Indian Standards (I. S. 2720) The analysis of the results shows the possibility of using bottom ash as a sustainable replacement of sand in vertical drainage construction. The findings of this research could contribute towards the development of sustainable and economic approaches for ground improvement methods particularly within infrastructure projects developed on soft clay subsoils.

2. Objective and Originality of This Research

This section outlines the primary objectives of the ongoing study. Ground improvement techniques have historically included the use of sand drains. It is well known that there is a strong correlation between the consolidation rate and hydraulic conductivity of clay soil. Sand drains may cause the nearby soils to become more permeable. Researchers from today, such as Nawagamuwa and Kumara [10], used a mix of waste materials in vertical drains, such as coir and sea sand, to improve the consolidation rate for soft clay. In sand drains, bottom ash was suggested by Kumar and Naresh [12] as a potential substitute for sand as the filter material. Additionally, according to the authors, bottom ash meets the filter specifications needed to be used in vertical drains. Most of the studies and evaluations about the -

(i) One important metric for comprehending the behavior of saturated fine-grained soil is the coefficient of consolidation. For settlement analysis as well as geotechnical and geo-environmental engineering, this is crucial.

(ii) Investigating the effects of vertical drain diameter and spacing on the settling behavior of kaolin and clay for both sand and bottom ash filters.

3. Methods of Research for The Experiment

Two kinds of soil (natural clay and synthetic clay, or Kaolin) and two kinds of filter materials (sand and bottom ash) were collected for the study. The engineering qualities of every specimen were evaluated in compliance with I.S. 2720. Some instances of the classification are given in the "material" chapter. Consolidation with sand drain was the main test for this thesis project. As a result, a table for the model consolidation test was created.

Table 1: Source of Material

Sl. No.	Materials	Collected From
1	Sand	Belkash & Zuzuty village, Damodar River, District Purba Bardhaman.
2	Clay	Morgra, District – Hooghly.
3	Kaolin	Open market at Bardhaman
4	Bottom Ash	Bandel Thermal Power Station (BTPS), Tribeni, Bandapara, Hooghly.

Table 2: Work plan for the test of Model Consolidation

SERIES	TYPE OF CLAY	TYPES OF FILTER MATERIALS	DIA.OF SAND/BOTTOM AS COLUMN	SPACING OF SAND/BOTTOMA SH COLUMN
A	CLAY (NATURAL CLAY)	SAND	13.5 mm	25 mm
			13.5 mm	31.25 mm
			13.5 mm	37.5 mm
			20 mm	40 mm
			20 mm	50 mm
			20 mm	60 mm
			25 mm	50 mm
			25 mm	62.5 mm
			25 mm	75 mm
		BOTTOM ASH	25 mm	50 mm
			25 mm	62.5 mm
			25 mm	75 mm
B	KAOLIN (ARTIFICIAL CLAY)	SAND	25 mm	50 mm
			25 mm	62.5 mm
			25 mm	75 mm
		BOTTOM ASH	25 mm	50 mm
			25 mm	62.5 mm
			25 mm	75 mm

4. Proposed Approach Along with The Experimental Process

Two kinds of filter materials and two types of consolidation materials were employed in this instance. This is shown in sequential order. For the investigation, two types of soil—natural clay and artificial clay (kaolin)—as well as two types of filter materials—sand and bottom ash—were gathered. All the specimens' engineering properties were assessed in accordance with I.S.:2720. The chapter on "material" provides examples of the classification.

1. Materials Preparation: - The collected sample (natural/artificial clay) has been oven-dried. To ensure that no spherical particles are visible, the necessary number of samples have been mixed with water at the L.L. of each test setup. Sand and bottom ash, the filter material, have been dried in an oven.

2. Mould preparation: Two pieces of filter paper with the requisite diameter, the same as the diameter of the porous stone—have been manufactured. For almost fifteen minutes, two porous stones were moistened. Next, remove extra water by wiping. A perforated PVC plate, secured with an aluminum tray and supported by a wooden platform, has been installed in the lowest section of the mold. At the bottom of the mold, a single porous stone has been placed, and filter paper has been adhered to it. Specific types of hollow circular steel/aluminum columns were then positioned over filter paper, with the upper part of the columns pierced at the necessary distance on two types of PVCC plates that were equipped with horizontal bars closed with supports. The mold has a sample for consolidation inside of it. Three layers of the sample have been compressed using a solid rod. One by one, filter material has been inserted into the empty space of the test sample in the mold through the upper section of the hollow circular column. Additionally, circular columns have been removed vertically one by one at the same time. The top of the mold has been leveled following the full installation of the filter materials. After applying filter paper to the upper part of the mold, another porous stone was added. A circular PVC load with another perforated plate has been placed atop a porous stone, acting as a sitting load. The load has been held until the dial gauge reading shows no change.

3. Consolidation Test: - Final dial gauge reading under the seated load has been loaded for the consolidation test. At the same time that the stopwatch began, the first load of intensity, 0.05 kg/sq.cm, was applied. The dial gauge has been loaded, and readings have been taken at different intervals. Up until a 90% consolidation point, the dial gauge readings were taken. Usually, within 24 hours, primary consolidation has been achieved. When the time and dial reading mentioned above have been taken at different intervals, almost double the load intensity is applied at the end of the prescribed period. Subsequent load increments have been made using this approach. There are three common loadings: 0.05 kg/sq.cm, 0.108 kg/sq.cm, and 0.182 kg/sq.cm.

Figure1: Applying 1st load @0.05 kg/sq.cm

Figure2: Applying 2nd load @0.11kg/sq.cm

5. Numerical Analysis

A consolidation test in one dimension was conducted on two types of soil specimens: kaolin and clay. An odometer ring with a standard diameter of 60 mm was used for this test. By utilizing Taylor's Method to calculate t_{90} values from the plots of square root time in minutes vs dial reading, C_V values were calculated. Using the "change of void ratio" method, the corresponding void ratios at various pressure increments were found, allowing for the computation of the coefficient of volume change (m_v).

Table 3: Results for one dimensional consolidation test

Type of Soil	m_v(cm²/kg)	Cc	Cv (cm2 /sec)	K(cm/sec.)
Clay	0.0179	0.347	1.034×10^{-4}	1.851×10^{-6}
Kaolin	0.0116	0.294	8.63×10^{-5}	1.001×10^{-5}

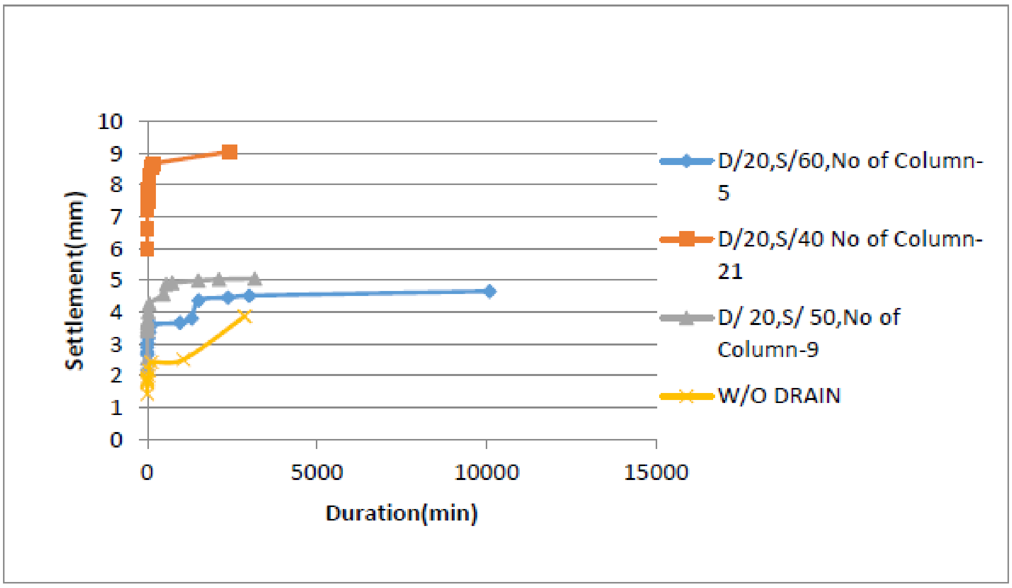

Figure 3: Comparison of Consolidation of Clay for w.o. Sand Drain to 20 mm dia.Sand column (Pr. Range 0.108 kg/sq.cm)

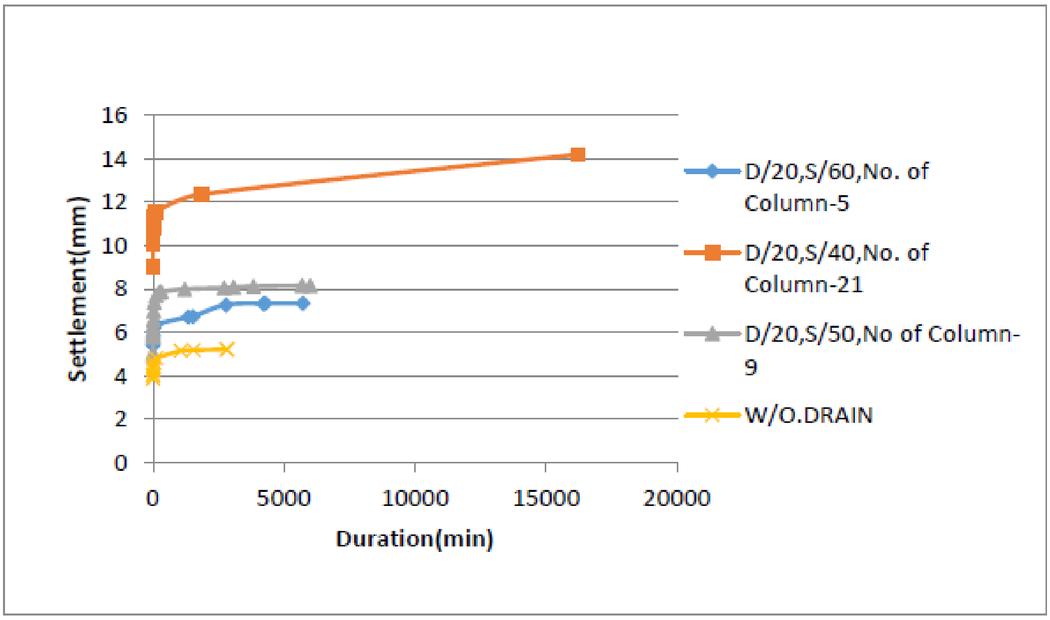

Figure 4: Comparison of Consolidation of Clay for w.o. Sand Drain to 20 mm dia. Sand column (Pr. Range 0.182 kg/sq.cm)

6. Results and Discussion:

The experimental study focused on assessing the effectiveness of sand and bottom ash as filter materials in vertical drains to improve the consolidation behavior of both natural clay and Kaolin. The following sections discuss the key findings from the experimental and numerical analyses.

A. Consolidation Behavior with Different Filter Materials

The one-dimensional consolidation tests showed significant differences in the consolidation rates between the two filter materials-sand and bottom ash. The primary metric for evaluating performance was the coefficient of consolidation (C_v), which reflects the soil's ability to expel excess pore water.

- For Natural Clay: The coefficient of consolidation (C_v), for natural clay with sand drains was calculated as $1.034 \times 10^{-4}\ cm^2/sec$, while for bottom ash, the C_v was slightly lower but still comparable at $8.63 \times 10^{-5}\ cm^2/sec$. Despite the marginal reduction in C_v, the results demonstrate that bottom ash can function effectively as a substitute for sand, offering adequate drainage to accelerate consolidation.

- For Kaolin (Artificial Clay): The C_v values for Kaolin also displayed similar trends, with sand yielding $1.851 \times 10^{-6}\ cm/sec$ and bottom ash showing a slightly lower permeability at $1.001 \times 10^{-6}\ cm/sec$. This difference is attributed to the finer particle size of bottom ash, which results in slower drainage but still achieves effective consolidation over time.

B. Effect of Vertical Drain Diameter and Spacing

- Drain Diameter: Increasing the diameter of the vertical drains led to a noticeable improvement in the rate of consolidation for both sand and bottom ash. The experimental tests confirmed that larger drain diameters (e.g., 20 mm or 25 mm) allowed for faster dissipation of pore water compared to smaller diameters (e.g., 13.5 mm). This behavior was consistent across both clay and Kaolin samples, with the larger drains reducing the consolidation time significantly.

- Spacing of Drains: The spacing of the vertical drains was found to have a substantial impact on the consolidation process. Closer spacing (25 mm to 50 mm) resulted in faster consolidation, as the drains provided more efficient pathways for water to escape. Conversely, larger spacing (up to 75 mm) slowed the consolidation rate. The tests demonstrated that optimal spacing is essential for maximizing the effectiveness of vertical drains, especially when using bottom ash, which benefits more from closer spacing due to its slightly lower permeability.

C. Comparative Performance of Sand and Bottom Ash

Bottom ash, though slightly less permeable than sand, still met the requirements for effective use in vertical drainage systems. The study confirms that bottom ash performs comparably to sand under various loading conditions, and its lower cost and environmental benefits make it a viable alternative. Sand showed a slightly faster consolidation rate overall, but the difference was minimal, especially when optimal drain diameter and spacing were selected.

D. Numerical Analysis and Validation

Taylor's method was employed to analyze the time-consolidation data. The results from the numerical analysis were consistent with the experimental findings, validating the calculated values of the coefficient of consolidation (C_v) and the coefficient of volume change (m_v). For natural clay, the coefficient of volume change (m_v) was $0.0179\ cm^2/kg$, while for Kaolin, it was $0.0116\ cm^2/kg$. The compression index (C_c) values were slightly higher for natural clay than Kaolin, indicating more significant volume reduction for natural clay under the same load.

7. Practical Implications

The findings have significant implications for ground improvement techniques in areas where sand is either expensive or unavailable. Bottom ash, being a waste product, offers a cost-effective and sustainable solution for vertical drains in soft clay soils. The optimal use of bottom ash, with careful attention to drain diameter and spacing, can reduce construction costs and contribute to more environmentally friendly engineering practices.

8. Conclusion

The experimental and numerical analyses demonstrate that bottom ash is a promising alternative to sand in vertical drains for soil consolidation. While sand performs slightly better in terms of permeability, bottom ash is a viable substitute, especially considering its environmental benefits and cost-effectiveness. The results provide a framework for optimizing vertical drain design, particularly in soft clay soils, by selecting appropriate drain diameters and spacing to enhance consolidation rates.

References

1. Hansbo, S. (1981). "Consolidation of fine-grained soils by prefabricated drains." Ground Engineering, 14(5), 16–25. https://www.issmge.org/publications/online-library
2. Huang, W. The use of bottom ash and fly ash in highway embankments, Subgrades, and Subbases. https://doi.org/10.5703/1288284313434
3. Taylor, D. W. (1948). Fundamentals of Soil Mechanics. Wiley.
4. Pandian, N. S. (2004). "Fly Ash Characterization with Reference to Geotechnical Applications." Journal of the Indian Institute of Science, 84(6), 189–216.
5. Indraratna, B., Bamunawita, C., Redana, I., & McIntosh, G. (2003). "Modelling of Prefabricated Vertical Drains in Soft Clay and Evaluation of Their Effectiveness in Practice." Proceedings of the Institution of Civil Engineers Ground Improvement 7(3) DOI:10.1680/grim.2003.7.3.127
6. Lee. et. al (2024). "Removal Efficiency of Bottom Ash and Sand Mixtures as Filter Layers for Fine Particulate Matter". Materials 2024, 17, 2749. https://doi.org/10.3390/ma17112749
7. Smith, D.R. Permeable Interlocking Concrete Pavements, 4th ed.; Interlocking Concrete Pavement Institute: Herndon, VA, USA, 2011.
8. Marto et. al (2014). "Shear Strength Parameters and Consolidation of Clay Reinforced with Single and Group Bottom Ash Columns". Arabian Journal for Science and Engineering. Volume 39, pages 2641–2654, (2014).
9. Moradi et. al. (2019). "Enhancement of Soft Soil Behaviour by Using Floating Bottom Ash Columns". KSCE Journal of Civil Engineering 23(2). DOI:10.1007/s12205-019-0617-x
10. Aparna, R. P. & Bindu, j. (2023). "Utilization of waste materials as a substitute for the sand drain in clayey soil". International Journal of Geo-Engineering. Volume 14, article number 2, (2023).
11. Bureau of Indian Standards. (Year). IS: 2720 - Methods of test for soils: Part 15 - Determination of consolidation properties. New Delhi, India.
12. Rangaswamy, K (2016). "Influence of burnt ash additives on stabilisation of soft clay soils". Innovative Infrastructure Solutions. Volume 1, article number 25, (2016). DOI 10.1007/s41062-016-0025-8
13. Mandal et. al. (2018). "Fluidized bed combustion bottom ash: A better and alternative geo-material resource for construction". Waste Management & Research: The Journal for a Sustainable Circular Economy. https://doi.org/10.1177/0734242X18761561.
14. Almuaythir et. al. (2024). "Sustainable soil stabilization using industrial waste ash: Enhancing expansive clay properties". Heliyon. Volume 10, Issue 20, 30 October 2024, e39124. https://doi.org/10.1016/j.heliyon.2024.e39124
15. Subramanian, S., Arumairaj, P.D., & Subramani, T. (2017). Experimental and modelling study of clay stabilized with bottom ash–eco sand slurry pile. Geomechanics and Engineering, 12(3), 523–537. https://doi.org/10.12989/gae.2017.12.3.523