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Evaluation of the usage of various capping materials in capping of contaminated sediments

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ABSTRACT

In this study, the beneficial reuse of alum sludge as a capping material in subaqueous contaminated sediment capping applications was investigated by finite element analysis. In the finite element analysis, the contaminated sediment was modeled on the bottom of a typical river bed geometry. The engineering behavior of alum sludge was compared with that of sand, which is a common capping material for contaminated sediments. The results of the analyses were evaluated in terms of settlement, excess pore water pressure generation, and factor of safety (FS) values. The results obtained from this study showed that the use of alum sludge capping resulted in lower settlement values compared with those of the sand capping, and FS values greater than 1.5 were obtained for all the capping systems studied, indicating that the capping systems modeled in this study were safe in terms of slope stability. Based on these results, and taking the advantage of alum sludge's ability to adsorb various contaminants into consideration, it can be concluded that the alum sludge examined in this study has physical and mechanical properties that are desirable for a capping material for use in subaqueous contaminated sediment capping applications.

Keywords: Alum sludge; Capping; Contaminated sediment; Finite element analysis

1. Introduction

Sediment is the mixture of various materials including soil particles such as silt, sand and gravel, fossil fragments, sewage, industrial wastes, chemical precipitates, and organic and inorganic materials that suspend in or accumulate on the bottom of a water body [1]. Due to various anthropogenic activities such as industrial or municipal discharges, petroleum spills, ship wastes, and seepage and erosion from surface mining, sediments can be contaminated by organic and inorganic pollutants [2].

Contaminated sediment is defined as soil, organic matter or other minerals that accumulate on the bottom of a water body and contain toxic or hazardous materials at levels that may adversely affect human health and the environment [3]. As can be seen from the definition, contaminated sediments may cause severe risks for human health and the ecosystem. Therefore, the management and treatment of contaminated sediments is a worldwide significant environmental concern [4].

To prevent unacceptable risks caused by the contaminated sediments, conventional treatment methods known as monitored natural recovery, in-situ containment, in-situ treatment, dredging, or excavation may be required [5,6]. However, as stated by Zhang et al. [7], due to the large volumes of the contaminated sediments, remediation techniques may often be economically unacceptable. On the other hand, in situ capping is reported to be a more economical, more durable, and less disruptive sediment remediation option [7].

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In-situ capping is the isolation of contaminated sediments from the environment by covering them with a layer of clean material [2,7]. The primary functions of in-situ capping are physical and chemical isolation of the contaminated sediments from the overlying water column and biota, stabilization and erosion protection, reduction of contaminant flux into the biologically active portion of the sediment, and new habitat creation for aquatic organisms [8–10].

In-situ capping of contaminated sediments is classified into two as passive and active capping. In passive capping, the contaminated sediment is covered by a clean neutral material such as clean sediment, gravel, sand, silt, and clay. In passive capping application, the cap acts as a physical barrier that does not chemically alter the contaminants [11]. However, in active capping application, chemically reactive materials such as activated carbon, apatite, zeolite and organoclay that can reduce the mobility, toxicity, and bioavailability of contaminants by changing their chemical speciation are used. With active capping, both containment and treatment of the contaminated sediment can be provided [12,13].

In the finite element analyses performed in this study, sand was used as the passive cap, and alum sludge was proposed as the active cap material. In a potable water treatment plant, while the raw water is purified through various processes such as chemical coagulation, flocculation, sedimentation, filtration, and disinfection, a byproduct known as water treatment sludge is produced. Water treatment sludges contain materials removed from raw water (sand, silt and clay particles, colloidal organic matter, and micro-organisms) and the products of chemical coagulation (coagulants, polyelectrolytes, and conditioners) that have been added to the raw water. If aluminum salts are used as the coagulant, this sludge is classified as alum sludge [14–18]. Alum sludge is a byproduct of the drinking water treatment industry which is produced in huge amounts worldwide, has low unit weight, low hydraulic conductivity, and high shear strength properties [19–21]. Alum sludges are also reported to be effective materials in the removal of several contaminants such as phosphorus [22], dye [23] copper, zinc, and lead [24] from wastewater.

In this study, two-dimensional finite element analyses were carried out to investigate the possible beneficial reuse of alum sludge as an active capping material in the remediation of subaqueous contaminated sediments. The geotechnical behaviors of alum sludge and sand, which is a conventional capping material for subaqueous contaminated sediments, were compared. The results of the analyses were evaluated in terms of stability, settlement and excess pore water pressure values, and reported in this study.

2. Materials and methods

2.1. Problem definition

When sand is used as a subaqueous capping material, its function is to physically cover the contaminated sediment without altering or removing the contaminants contained in the sediment [11]. However, it may not be an economical and easily accessible material for use in every subaqueous contaminated sediment capping applications. Besides, in some cases, reducing the mobility, toxicity, and bioavailability of contaminants in the sediment may be required in addition to the function of the capping as a physical barrier. Under such circumstances, active capping materials such as activated carbon, apatite, organoclay, and zeolite are used, as was mentioned before [12,13].

To the author's knowledge, there is no real field application reported in the literature studying the use of alum sludge as a subaqueous contaminated sediment capping material. However, in a study by Balkaya [21], the geotechnical properties of alum sludge, were investigated. The results of this study showed that alum sludge was a mechanically stable material with high internal friction angle and low hydraulic conductivity. Besides, various authors also reported that alum sludges have low hydraulic conductivities (on the order of 10^{-7} to 10^{-9} cm/s) [18–21,26], high shear strength ($\phi' = 39°–44°$) [19–21,26,29], and nonhazardous nature [27–29]. In the context of pollutant removal, alum sludges were reported to be effective materials for removing several contaminants (phosphorus, dye, heavy metals, etc) from wastewater. These properties of alum sludges make them a good alternative for use in various geotechnical and geoenvironmental applications. They are also easily available from water treatment plants at no cost. Therefore, in this study, alum sludge was proposed as a reactive capping material and an alternative material for sand in subaqueous capping applications.

In the present study, the reason for choosing the finite element analysis method is that this method has been proven to be a useful and advantageous tool for examining the effects of different parameters on the behavior of geotechnical materials. While performing finite element analyses, different parameters can be easily modified, and different configurations of the proposed system can be tried so that the feasibility of the proposed models can be evaluated before real field applications. However, the accuracy of the selected material properties and material models, as well as the interpretation of the obtained data, is of utmost importance for the quality of the analyses.

2.2. Modeling assumptions

In the analyses, half of the river and the soil profile including the contaminated sediment were modeled because of the symmetry of the system. The half system was assumed to be 50 m in length. This length was sufficient to minimize the boundary effects.

The side slopes of the contaminated river bed were assumed to be 3H:1V with H being the horizontal distance, and V being the vertical distance. The water table was assumed to be 1.0 m below the ground surface, and the sediment height was chosen as 2.0 m. In the analyses, two different capping materials with different cap configurations were investigated. The capping materials were chosen as sand and alum sludge. To evaluate the effect of a geotextile layer on the behavior of the proposed capping system, capping designs were performed with and without a geotextile layer between the contaminated sediment and the sand or alum sludge caps.

Since the modeled river bed geometry was not horizontal, gravity loading was applied for the generation of the initial effective stresses in the first step of the finite element analysis. After the equilibrium of in-situ stresses was reached, the construction of the capping system and the consolidation of the sediment layer after the placement of each capping layer were simulated.

The total capping layer was assumed to be 90 cm thick, consistent with Palermo et al. [30]. While designing the capping system, staged construction was used to simulate the application of the cap layers, which were applied in 3 layers of 30 cm. Each of the 30 cm capping layer application was assumed to take 1 d to complete, and the sediment layers were allowed to consolidate under each 30 cm cap load for 1 d. After the capping construction was completed, the consolidation of the contaminated sediment under the total cap load (90 cm) for 365 d was allowed, and the consolidation settlements under each load increments were obtained. The effects of hydraulic conditions were not considered in this study.

The details of the investigated contaminated sediment capping systems used in the finite element analyses are given in Fig. 1a. The selection of the capping system was consistent with the study of Palermo et al. [30], in which the capping layer for an actual contaminated sediment site was presented. The problem being analyzed is illustrated in Fig. 1b.

The stability of the contaminated sediment and the proposed capping systems against slope failure was computed by the ϕ-*c* reduction method of the PLAXIS finite element program [31]. This method is based on the principle of successively reducing the cohesion (*c*) and the internal friction angle (tan ϕ) of the soil layers until failure at the structure occurs. The factor of safety (FS) of the slopes of the investigated problem is determined as the ratio of the available strength to the strength at failure.

2.3. Finite element modeling

2.3.1. Generation of the finite element mesh

The effects of different cap designs and consolidation durations on the vertical displacements (U_y), FS values, and excess pore water pressure (P_{excess}) distributions of the contaminated sediment and the capping systems were modeled by finite element analyses. The finite element program PLAXIS Version 2019 [31] was used to perform the analyses. 15-node soil elements and 5-node geogrid elements were used for the generation of the finite element mesh. Due to the symmetric geometry of the studied problem, half of the river bed was modeled in the analyses (Fig. 2). The finite element mesh consisted of approximately 1049 elements. The mesh was refined around the contaminated sediment since stresses and strains were expected to vary around this region.

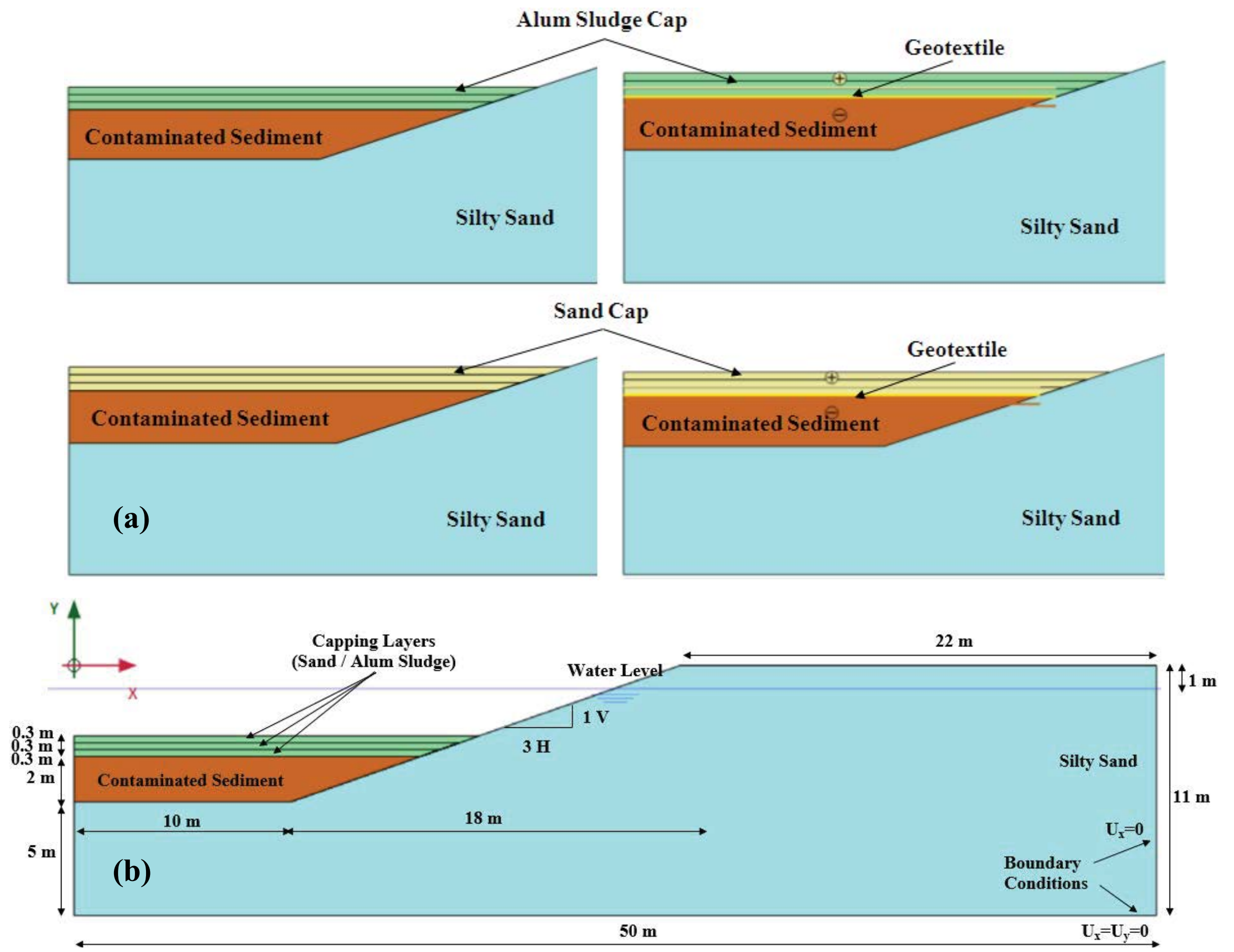

Fig. 1. (a) Details of the capping systems and (b) problem being analyzed.

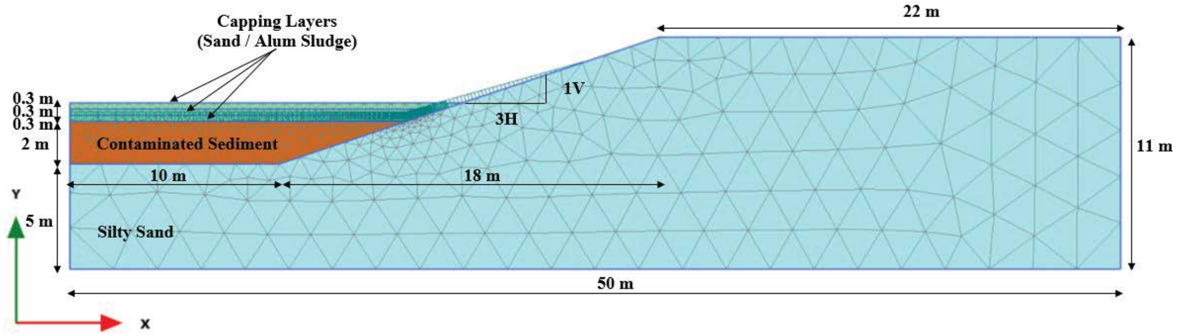

Fig. 2. Typical finite element mesh used to model the subaqueous contaminated sediment capping.

To determine the mesh density with a low computational cost but high accuracy, different mesh densities were studied for a control case. The highest difference obtained from the results of the models with different mesh densities was 1.39%, which showed that mesh refinement did not significantly affect the finite element analyses results. Hence, mesh having sufficient accuracy but the lowest computational cost was used in the analyses.

2.3.2. Material properties

The soil layers modeled in the finite element analyses were assumed to be uniform along the *z*-direction. Therefore, the plane strain model was used in the analyses. An elastic (LE) material modeling was used for the simulation of the geotextile (GT), while an elastoplastic material modeling was chosen for the sand (S), alum sludge (AS) and silty sand (SM) layers using the Mohr–Coulomb (MC) model, and soft soil creep (SSC) model was used to model the contaminated sediment (CS) layer investigated in this study. The material properties used in the analyses and their corresponding references are given in Table 1.

2.3.3. Boundary conditions

Due to the symmetry, half of the geometry was modeled in the finite element analyses. To determine the effect of the lateral and vertical dimensions on the finite element analyses results, sensitivity analyses were performed. The model dimensions were selected based on the numerous finite element analysis runs until the boundary effects became negligible. Sensitivity analyses showed that the results changed by less than 1% as the dimensions were increased, which was an indication of the negligible effects of the chosen dimensions on the analyses results. The two displacement boundary conditions were used in the finite element analyses such that the left and right boundaries of the studied model were constrained from horizontal movement ($U_x = 0$), and the bottom boundary was constrained from both horizontal and vertical movements ($U_x = U_y = 0$) (Fig. 1b).

Table 1
Material parameters used in the finite element analysis

	S	AS	SM	CS	GT
Material model	MC	MC	MC	SSC	LE
γ_{unsat} (kN/m^3)	18	3.6	17.7	16.5	–
γ_{sat} (kN/m^3)	21	11	21	18	–
E (kN/m^2)	50,000	5,400	60,000	–	–
ν	0.3	0.4	0.3	0.15	–
c' (kN/m^2)	0	0	2	1	–
ϕ' (°)	34	39	38	40	–
ψ (°)	4	9	8	10	–
K (m/d)	8.64×10^{-1}	8.64×10^{-5}	8.64×10^{-1}	8.64×10^{-2}	–
e_{init}	–	–	–	1.58	–
λ^*	–	–	–	0.0404	–
κ^*	–	–	–	0.006539	–
μ^*	–	–	–	0.00045285	–
EA (kN/m)	–	–	–	–	500
References	[32]	[19]	[33]	[34]	[35]

γ_{unsat}: unsaturated unit weight, γ_{sat}: saturated unit weight, E: Young's modulus, ν: Poisson's ratio, c': effective cohesion, ϕ': the effective internal friction angle, ψ: the dilation angle, k: permeability, e_{init}: initial void ratio, λ^*: modified compression index, κ^*: modified swelling index, μ^*: secondary compression index of the soil layers, EA: axial stiffness of the geotextile.

3. Results and discussion

3.1. Effect of capping system on the settlement of the contaminated sediment

Fig. 3 shows the consolidation settlement of the contaminated sediment 365 d after the completion of the capping systems composed of sand and alum sludge, with and without a geotextile layer. As stated by Palermo et al. [30], permeable geotextiles prevent the sediment to move along and mix with the cap but do not provide the isolation of the contaminated sediment. Besides, problems such as clogging, uniform cap placement over the geotextile and subaqueous placement of the geotextile can occur when geotextiles are used in subaqueous capping projects.

The results of the finite element analyses revealed that for each capping system, the sand capping resulted in higher settlement values compared with those of the alum sludge capping. This behavior is a consequence of the higher unit weight of the sand compared with that of the alum sludge, which consequently resulted in higher loads acting on the contaminated sediment.

As can be seen from the figure, for all the capping systems studied, the majority of the settlement occurred in the first 3 d (6.53 mm for the alum sludge cap, and 66 mm for the sand cap, at the end of the 3rd day) in which the constructions of the capping layers were completed, followed by a slight increase in the following days (15 mm for the alum sludge cap, and 75.2 mm for the sand cap, at the end of the 368th day). The results of the analyses also indicated that the geotextile layer used between the capping and the contaminated sediment layers did not have a significant effect on the settlement values.

3.2. Effect of capping system on the excess pore water pressure variation within the contaminated sediment

Fig. 4 shows the variation of the P_{excess} with time for the different capping configurations investigated. As can be seen from the figure, while a sharp decrease in the P_{excess} was observed in the first 3 d when sand was used as the capping material, a sharp increase in the P_{excess} was observed during this period when alum sludge was used as the capping material. This behavior can be attributed to the significantly lower hydraulic conductivity of the alum sludge used in this study compared with that of sand. As stated before, the 90 cm capping was constructed in 3 layers of 30 cm, and the construction of each capping layer was assumed to take 1 d. Since sand has a high hydraulic conductivity (8.64 × 10^{-1} m/d), the P_{excess} generated due to the application of the capping layers could dissipate quickly, and the P_{excess} decreased. However, the alum sludge has a low hydraulic conductivity (8.64 × 10^{-5} m/d). With the application of the alum sludge layers in the first 3 d, the P_{excess} could not dissipate in this short period, and increased. However, the P_{excess} decreased with time after the construction of the capping layers were completed, and became almost zero for all the investigated cases 365 d later. The geotextile layer used in the finite element analyses facilitated the dissipation of the P_{excess} for the sand capping but did not have a significant effect on the P_{excess} values of the alum sludge capping.

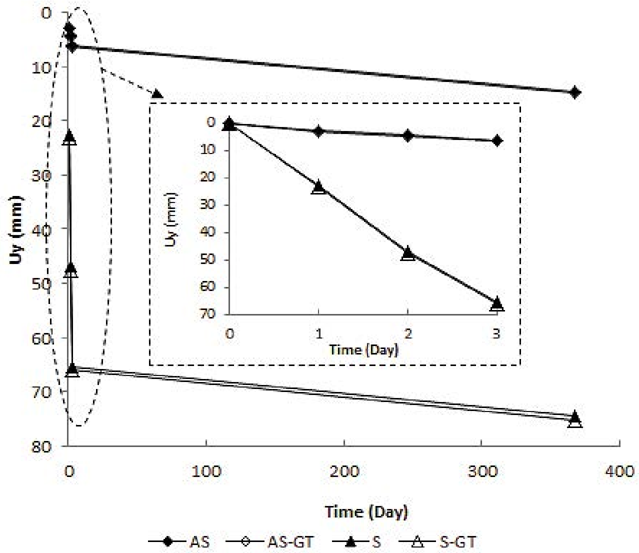

Fig. 3. U_y values of the contaminated sediment 365 d after the completion of the capping system.

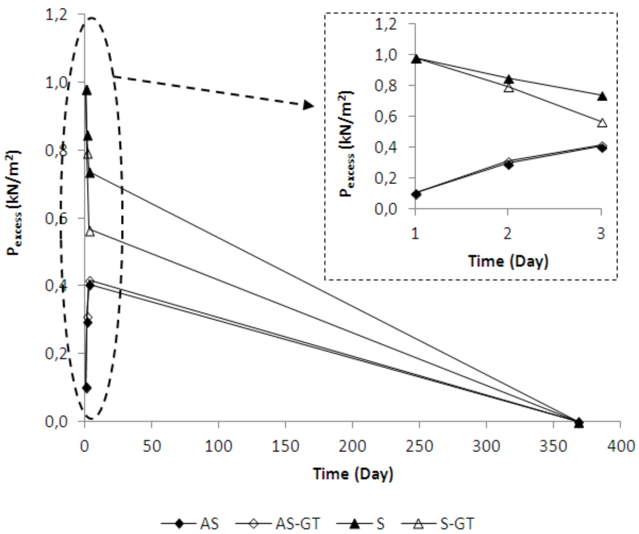

Fig. 4. Variation of the P_{excess} with time for different capping configurations.

3.3. Effect of capping system on the FS values

Typical shadings of the total displacement increments indicating the most applicable failure mechanism of the side slopes of the contaminated river bed are given in Fig. 5. Fig. 6 shows the variation of the FS values for the investigated capping systems. The FS for slope stability is commonly accepted as 1.5 [36]. As can be seen from the figure, although very close values were obtained for the sand and the alum sludge capping systems, slightly higher (<2%) FS values were obtained for the sand capping system. However, FS values higher than 1.5 (FS ≈ 3.1 for each case) were obtained for all the capping systems modeled, which indicated that the use of alum sludge in subaqueous contaminated

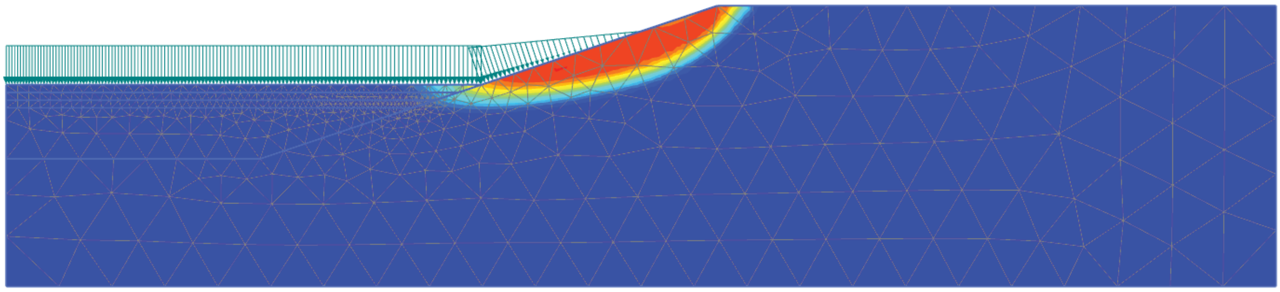

Fig. 5. Typical shadings of the total displacement increments indicating the most applicable failure mechanism of side slopes of the contaminated river bed.

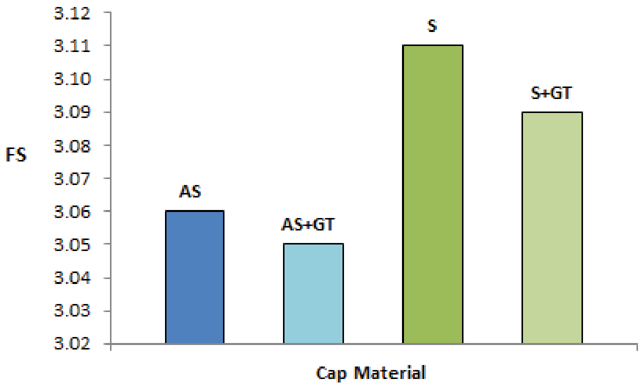

Fig. 6. FS values corresponding to different capping configurations.

sediment capping can result in comparable FS values with those of sand capping.

The results of this study showed that, although the alum sludge used in this study exhibited similar engineering behavior with sand, it was even superior in some respects in comparison to sand. Taking the advantage of alum sludge's cost-effectiveness, easy availability, low hydraulic conductivity, high shear strength properties, and effective contaminant removal abilities; it can be stated that the use alum sludge in subaqueous contaminant sediment capping applications may be an appropriate, economical, and environmentally friendly application. However, it should be kept in mind that the characteristics and compositions of alum sludges may vary depending on the characteristics of the raw water being treated, the type and amount of the coagulant used, and the dewatering method [18,24,26,29,37–40]. Therefore, some variations in the engineering properties of alum sludges obtained from different water treatment plants may be observed. Besides, although finite element analysis has been proven to be a useful tool for modeling geotechnical problems, and determining the possible problems before the field application, real field studies investigating the application of alum sludge in subaqueous contaminant sediment capping is recommended.

4. Conclusions

The results obtained from this study showed that a sharp increase in the U_y values occurred during the construction of the capping layers, and then the settlements increased slightly after the capping construction was completed. For all the cases studied, higher U_y values were obtained when sand was used as the capping material. The results also indicated that the use of a geotextile layer did not have a significant effect on U_y values. FS values greater than 1.5 were obtained for all the sand and alum sludge capping systems, which revealed that the capping systems modeled in this study were safe in terms of slope stability. Within the limitations of this study, it can be concluded that the alum sludge examined in this study has physical and mechanical properties that are desirable for a capping material for use in a typical subaqueous contaminated sediment capping application. It can also be stated that the use of alum sludge as a capping material for contaminated sediments would possibly help in eliminating certain contaminants from the sediment, and pose an economic solution to subaqueous contaminated sediment capping systems.

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