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A parametric study on numerical simulation of crude oil contaminated site capping

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ABSTRACT

This study aimed to investigate whether alum sludge, a material that is normally disposed of in landfills as waste, could be used as capping material in crude oil contaminated soil capping applications. The remediation of a crude oil-contaminated site by in-situ capping was investigated by a parametric study using two-dimensional finite element analyses. In the finite element analyses, different crude oil contents (0%, 4%, 8%, 12%, and 16%), contaminated soil depths (0, 1, 3, 5, and 10 m), capping materials (alum sludge and compacted clay), and uniform surface loadings (2.0 and 5.0 kPa) were modeled, and the results of the analyses were evaluated in terms of displacement and factor of safety (FS) values. The results of this study showed that settlement increased with increasing crude oil content, contaminated soil depth, and surface loading conditions. However, the use of alum sludge as the capping material resulted in a lower settlement and lateral displacement, but higher FS values in comparison to those of the compacted clay for all the crude oil contents, contaminated soil depths, and surface loading conditions investigated. For all the cases studied, FS values greater than 1.5 were obtained for slope stability. Based on these results, it was concluded that alum sludge has favorable mechanical properties, and can be used as a comparable alternative to compacted clay for use in crude oil-contaminated site capping applications.

Keywords: Alum sludge; Capping; Crude oil contaminated soil; Finite element analysis

1. Introduction

One of the most common soil pollution in the world is the contamination of soils by petroleum hydrocarbons. Contamination by petroleum hydrocarbons in the soil can occur due to various reasons such as oil drilling processes, leakage from pipes and storage tanks, and oil release from oil production platforms [1]. The contamination of soils by petroleum hydrocarbons is of great concern due to the severe risks for human health and the environment. Therefore, petroleum-contaminated soils should be handled with great care. As stated by Streche et al. [2], with regards to financial and organizational issues, the remediation of soils contaminated with petroleum products is accepted as one of the most complex problems in Europe.

Soil remediation techniques briefly include the transportation of contaminated soils to another place for treatment or disposal and in-situ confinement of the contaminated soils [3,4]. The choice of the remediation method depends on the concentration, toxicity, mobility, and persistence of the contaminants in soil, and the potentially hazardous effects of the contaminated soil on the human health and the environment [5].

Containment of contaminated sites includes caps and subsurface barriers. When remediation methods are not cost-effective, and the utilization of the contaminated soil in engineering applications is not possible, capping the contaminated soil may be an effective alternative for the remediation of most contaminated sites [6].

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Capping involves covering of contaminated soil with clean soils or geosynthetic materials. The aim of capping application is not to remove contaminants, but to isolate the contaminated soil from the environment, and limit downward migration of contaminants to the groundwater while limiting the upward migration of contamination vapors [7,8]. Capping also provides a land surface that can be used for various purposes such as recreation areas, parks, and parking lots [8]. To ensure that the contaminated soil is isolated from the environment, caps are generally composed of various components. The most important soil properties that must be considered in a cap design are the shear strength and the hydraulic conductivity of the soil.

Compacted clay is a widely used material for capping applications. However, due to some favorable geotechnical properties such as its relatively high shear strength, low hydraulic conductivity [9–11], and contaminant removal abilities reported by various researchers [12–15], in this study, alum sludge is examined to be used as alternative capping material for contaminated soil capping. Alum sludge is a waste material generated at drinking water treatment plants when aluminum salts are used as the coagulant [16–20]. Up to now, the beneficial reuse of alum sludge has been investigated by various researchers. The results of these studies showed that alum sludge can be used in various geotechnical applications such as road constructions, landfill covers, and soil improvement applications [11,21–23].

The aims of this study were to: (a) perform a parametric study investigating the geotechnical behavior of a crude oil contaminated soil under different capping systems, crude oil contamination depths, crude oil contents, and surface loadings, (b) offer a beneficial reuse for alum sludges that are generated in significant amounts worldwide, (c) evaluate the engineering behavior of alum sludge vs. the traditional clay capping material, and (d) propose an economical and environmentally friendly alternative to capping for the protection of the soil and water environment from the spread of contamination using alum sludge instead of compacted clay, which has economic value and difficult to obtain in some places. Therefore, in this study, two-dimensional finite element analyses of a typical crude oil-contaminated site are carried out by PLAXIS to investigate the engineering behavior of alum sludge vs. the traditional capping material, clay. The finite element analysis results are discussed in terms of stability and settlement values.

2. Materials and methods

2.1. Statement of the problem

In this paper, two-dimensional finite element analyses of a typical crude oil-contaminated site were modeled to examine the use of compacted clay and alum sludge as contaminated site capping materials. Typical crude oil-contaminated site cross-sections and contaminated soil properties were studied in the analyses. Due to the symmetric cross-section of the investigated problem, half of the crude oil-contaminated site was modeled in the finite element analyses. The half-length of the modeled system was chosen as 50 m in length, which proved to be sufficient in minimizing the boundary effects.

In the analyses, the effects of two different capping materials (compacted clay and alum sludge), five different crude oil contents (0%, 4%, 8%, 12%, and 16%), and five different contaminated soil depths (0, 1, 3, 5, and 10 m) were investigated. The selection of the crude oil contents [6,24,25] and the contaminated soil depths [26–29] was consistent with the previously published work on crude oil-contaminated soils by various researchers. Besides, after capping the contaminated soil, this site was assumed to be used as a parking lot. Therefore, the stability of this area for two different uniformly distributed loads (2.0 and 5.0 kPa) was also evaluated.

The engineering properties of the soil layers and the geosynthetic materials used in the analyses are presented in Table 1. The side slopes of the contaminated soil were taken as 3*H*:1*V* (*H* is the horizontal distance, *V* is the vertical distance). The groundwater level was set-to the bottom of the uncontaminated soil layer for neglecting the effect of groundwater.

For the studied contaminated site geometries, two different capping materials were proposed as compacted clay and alum sludge. Due to its low hydraulic conductivity, compacted clay is the traditional material used for capping applications. On the other hand, the low hydraulic conductivity values of alum sludge ($1 \times 10^{-7} - 1 \times 10^{-9}$ cm/s) show that it can be a competitive alternative for compacted clay in landfill applications [9–22].

The capping system modeled in the finite element analyses is composed of 0.6 m vegetative cover soil layer, a geotextile layer, 0.3 m gravel drainage layer, a geomembrane layer, 0.6 m compacted clay or alum sludge, 0.15 m sand protection layer and a geotextile layer from top to bottom, respectively. The selection of the capping system was consistent with Rowe [30]. The studied problems are given in Fig. 1, and the details of the capping system are given in Fig. 2.

Staged construction was used in the finite element analyses, and the capping layers and the uniformly distributed surface loads were placed in consecutive stages. The in-situ geostatic stresses were generated in the first step. The lateral earth pressure coefficient was taken as $K_0 = 1-\sin\phi$, where ϕ is the internal friction angle of the soil. Once the in-situ stresses were in equilibrium, the construction of the capping system was simulated and the application of the different parking lot loads was defined.

The stability of the contaminated soil and the proposed capping system against slope failure is an important geotechnical concern in capping design [31]. The commonly accepted factor of safety (FS) value for slope stability is 1.50 [32]. In the PLAXIS finite element program, the FS against slope failure is computed by the ϕ–c reduction method, where the soil's tan ϕ and c are reduced to reach failure at the structure. The FS is obtained as the ratio of the available strength to the strength at failure.

2.2. Numerical modeling

2.2.1. Finite element mesh design

Finite element analyses have been performed to investigate the effects of different crude oil contents (0%, 4%, 8%, 12%, and 16%),contaminated soil depths (0, 1, 3, 5, and 10 m),capping materials (compacted clay and alum sludge), and uniformly distributed surface loads (2.0 and 5.0 kPa) on the vertical displacement (U_y), lateral displacement (U_x), and FS values of the contaminated site and the capping systems. The finite element program PLAXIS Version 2019 [33] was used for the finite element analyses. 15-node soil elements and 5-node geogrid elements were used for the generation of the finite element mesh. Due to the symmetric cross-section of the investigated problem, half of the system was modeled (Fig. 3), and approximately 1,631 elements were used for meshing the soil layers. The finite element mesh was refined

Table 1
Material parameters used in the finite element analyses

	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	E (kN/m^2)	ν (–)	c' (kN/m^2)	ϕ' (°)	ψ (°)	EA (kN/m)	References
Compacted clay liner	16	18	20,000	0.4	24	29	0	–	[34]
Alum sludge	3.6	11	5,400	0.4	0	39	9	–	[10]
Cover soil	19	21	40,000	0.3	17	22	0	–	[35]
Drainage gravel	18	21	100,000	0.35	0	40	10	–	[36]
Sand protection layer	18	21	50,000	0.3	0	34	4	–	[36]
Uncontaminated soil	21.56	21.60	4,982	0.33	27.2	33	3	–	[1,37]
4% Oil contaminated soil	20.46	21.42	4,464	0.33	19.5	32.9	2.9	–	[1,37]
8% Oil contaminated soil	19.98	21.24	4,815	0.33	22.7	32	2	–	[1,37]
12% Oil contaminated soil	19.42	21.24	3,981	0.33	21	26.2	0	–	[1,37]
16% Oil contaminated soil	18.60	21.12	2,113	0.33	33.6	26	0	–	[1,37]
Geotextile	–	–	–	–	–	–	–	500	[38]
Geomembrane	–	–	–	–	–	–	–	480	[39]

γ_{unsat}: unsaturated unit weight, γ_{sat}: saturated unit weight, E: Young's modulus, ν: Poisson's ratio, c': effective cohesion, ϕ': effective internal friction angle, ψ: dilation angle of the soil layers, EA: axial stiffness of the geosynthetic materials.

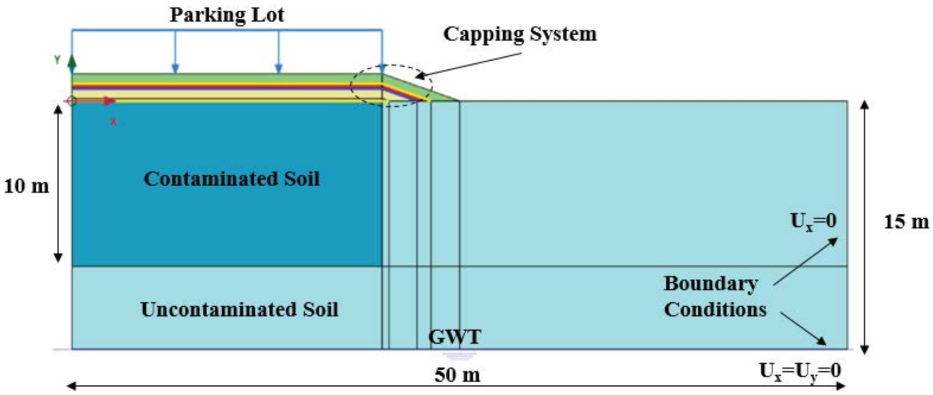

Fig. 1. The problem being analyzed for a contaminated soil depth of 10 m.

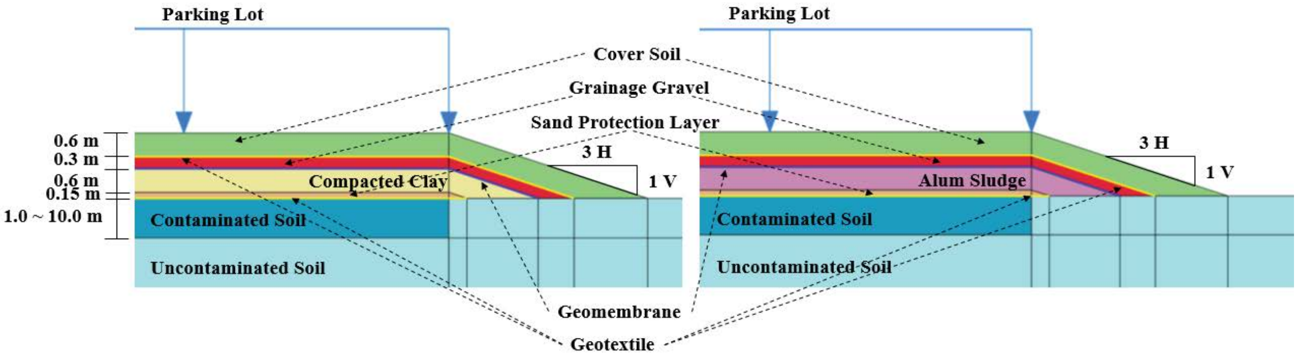

Fig. 2. The details of the capping systems modeled in the finite element analyses.

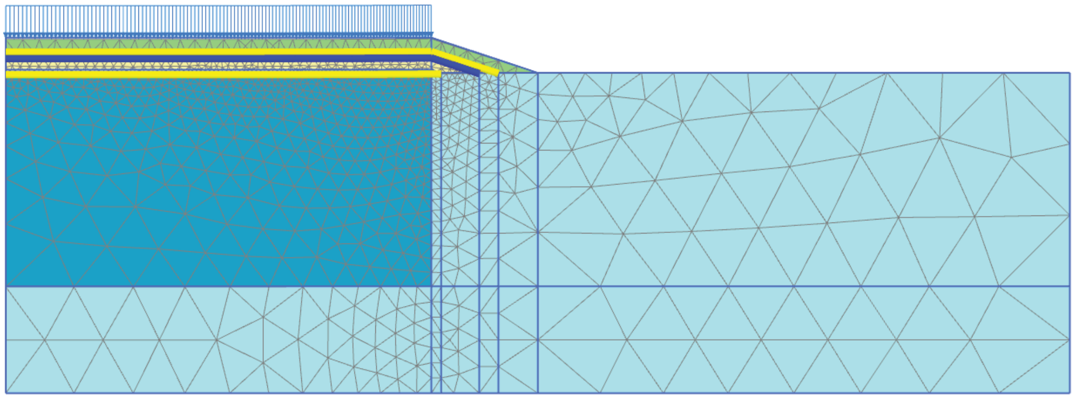

Fig. 3. Typical finite element mesh used to model the contaminated soil capping application for a contaminated soil depth of 10 m.

around the contaminated soil since stresses and strains were expected to vary in the vicinity of this region.

The effect of different mesh densities on the results was assessed by sensitivity analyses. For this purpose, different mesh densities were performed for a control case in the finite element analyses. The sensitivity analyses showed that the highest difference between the results obtained from different mesh refinement applications was 1.56%, which showed that the different mesh densities did not seem to lead to significant differences in the analysis results. Therefore, mesh with the lowest computational cost and competent accuracy was used in the analyses.

2.2.2. Materials used in the finite element analyses

In the finite element analyses, the plane strain model was used as a result of the assumption of the uniform cross-section and material properties of the contaminated site along the z-direction. The Mohr-Coulomb and linear elastic material models were used for modeling the soil layers and the geosynthetic materials, respectively.

FS values for the intermediate and long-term conditions under different capping materials and surface loading conditions were determined using the effective shear strength parameters of the soils. The material properties of the soil layers and the geosynthetic materials used in the finite element analyses are given in Table 1.

In the finite element analyses, the geotechnical properties of silty sand contaminated with various proportions of crude oil were used. The material parameters of the studied crude oil contaminated soils were obtained from previously published works by Hafshejani et al. [1] and Khamehchiyan et al. [37].

2.2.3. Boundary conditions

Half of the investigated problem was modeled due to symmetric geometry. Sensitivity analyses were performed to prove that the lateral and vertical dimensions of the model were sufficient to eliminate the boundary effects. The displacement boundary conditions used in the finite element analyses are given in Fig. 1. These boundary conditions indicate that the symmetry plane (x = 0 m) and the x = 50 m plane are prevented from movements in the lateral (x) direction by applying $U_x = 0$ boundary condition, and the bottom boundary is prevented from movement both in the lateral (x) and the vertical (y) directions by applying $U_x = U_y = 0$ boundary conditions.

3. Results and discussion

To determine the effects of the crude oil contaminated soil depth, crude oil content, capping material type, and surface loading due to the construction of a parking lot on the stability and settlement values of the investigated contaminated soil, various configurations of these variables were studied. Petroleum contamination affects the physical and chemical properties of soils. When oil spills on the ground, hydrocarbon materials are physically or chemically attached to the soil particles or entrapped in the pores and voids of the contaminated soil [40,41]. This leads to changes in the geotechnical properties of the soil, and affect the bearing capacity of foundations, settlement of structures, and stability of slopes [42,43]. Up to now, various researchers investigated the effects of petroleum contamination on the geotechnical behavior of soils. The results of these studies revealed that petroleum contamination decreased the internal friction angle, permeability, maximum dry density, optimum water content, Atterberg limits, and bearing capacity, but increased the volumetric strains of the investigated soils [37,40,44,45].

In this study, the results of the finite element analyses were evaluated in terms of vertical displacement (U_y), lateral displacement (U_x), and FS values, and compared to those of the uncontaminated soil corresponding to the same conditions. Figs. 4 and 5 present typical U_y and U_x contours of the crude oil contaminated soil under the capping and uniformly distributed load, respectively.

3.1. Effects of contaminated soil depth

To investigate the effects of the crude oil contaminated soil depth, the crude oil content was kept constant, and the material properties of the 12% crude oil contaminated soil were used in the analyses. The depths of the contaminated soil were assumed to be 0, 1, 3, 5 and 10 m, respectively. The 0 m contaminated soil depth corresponds to the uncontaminated soil condition.

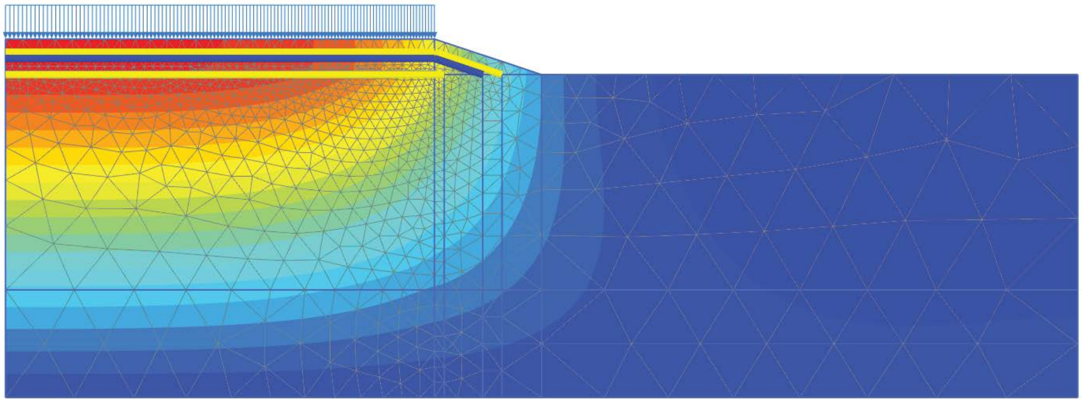

Fig. 4. Typical U_y contours under the capping and the uniformly distributed loads (contaminated soil depth = 10 m, parking lot design load = 5.0 kPa, oil content = 12%).

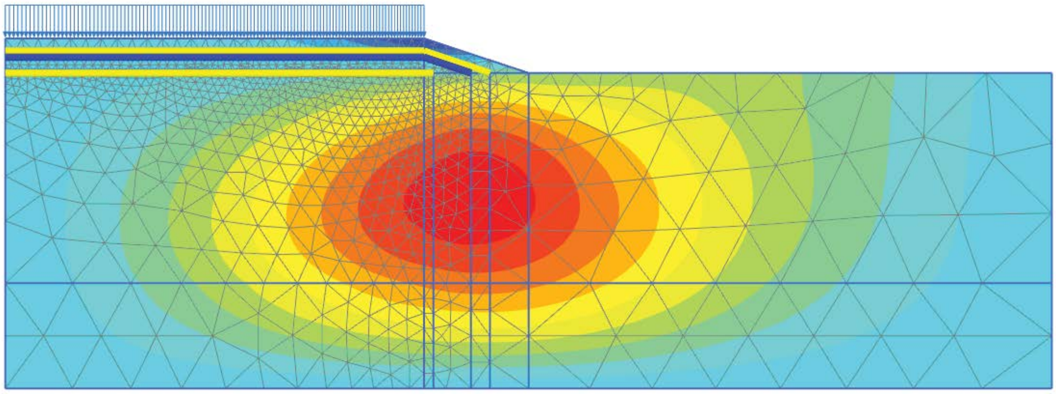

Fig. 5. Typical U_x contours under the capping and the uniformly distributed loads (contaminated soil depth = 10 m, parking lot design load = 5.0 kPa, oil content = 12%).

For the capping of the contaminated soil, the widely used compacted clay was chosen as the control case, and the alternative capping material was chosen as the alum sludge. Besides, since generally the remediated contaminated sites are used as recreation areas, parks, and parking lots [8], the suitability of the investigated contaminated site and the capping systems as a parking lot was also evaluated. For the modeling of the parking lot, two different uniformly distributed loads were selected as 2.0 and 5.0 kPa. These load values were consistent with ASCE7-05 [46] and TS498 [47], respectively. In ASCE7-05 [46], it is stated that parking garages for passenger vehicles should be designed for a minimum load of 1.92 kPa. However, according to the Turkish Standards for design loads for buildings (TS498) [47], a more conservative design load of 5.0 kPa is suggested as the uniformly distributed load for parking lots. Therefore, in the finite element analyses, these two design loads were considered, and the effects of these loads on the U_y U_x and FS values were evaluated.

Fig. 6 shows the effects of various contaminated soil depths, capping materials and parking lot design loads on the vertical displacements of 12% crude oil contaminated site modeled in this study. As can be seen from the figure, keeping all the variables constant, an increase in the contaminated soil depth leads to an increase in the settlement values. These results were in agreement with the results of Nasr [24] and Shin et al. [48], who reported increasing settlement values with increasing crude oil-contaminated soil depths. The increasing settlement is reported to be the result of the decreased angle of internal friction values due to crude oil contamination which leads to a decrease in the shear strength [6], and an increase in the compressibility [6,49] of the soil. As expected, for each capping material and contaminated soil depth, the 5.0 kPa surface loading resulted in higher settlement values than those of the 2.0 kPa surface loading. Besides, for each parking lot design load, the compacted clay (CC) capping caused higher settlement values compared to those of the alum sludge (AS) capping corresponding to the same loading conditions. This is a consequence of the higher unit weight of the compacted clay compared to that of the alum sludge, which consequently resulted in the development of higher effective stresses.

Fig. 7 presents the effects of various contaminated soil depths, capping materials and parking lot design loads on the U_x values of the 12% crude oil-contaminated site. Similar to the U_y values, although quite low, the U_x values also increased with increasing contaminated soil depth and increasing surface loading. Likewise, the compacted clay cap resulted in higher U_x values compared to the alum sludge cap corresponding to the same conditions as a result of its higher unit weight.

The FS variations for different contaminated soil depths, capping materials, and distributed loads for 12% crude oil contaminated soil are presented in Fig. 8. FS = 1.50 against slope stability is the commonly accepted value [32]. In all the investigated cases, FS values greater than 1.5 were obtained, indicating that the capping systems were stable under the investigated loading conditions. However, as can be seen from the figure, the FS values decrease with increasing contaminated soil depth and surface loading. On the other hand, higher FS values were obtained for the alum sludge capping cases compared to the compacted clay capping corresponding to the same contaminated soil depths and surface loading conditions.

3.2. Effects of crude oil content

To investigate the effects of the crude oil content on the displacements and FS values, the contaminated soil depth (10 m) and surface loading condition (5.0 kPa) that caused the highest displacement and lowest FS values were studied for different crude oil contents and capping materials.

The U_y variations under 0%, 4%, 8%, 12%, and 16% crude oil contents, and compacted clay and alum sludge capping materials for 5.0 kPa surface loading and 10 m contaminated soil depth are shown in Fig. 9. In the figure, 0% crude oil content corresponds to the uncontaminated soil conditions. This figure shows that keeping all the variables constant, due to its higher unit weight, the compacted clay capping resulted in higher settlement values compared to those of the alum sludge capping. As can be seen from the figure, settlement increased under the capping systems and parking lot design loads with increasing crude oil content. The increased settlement values with increasing crude oil contents obtained in this study were consistent with the results published by Nasr [24] and Shin et al. [48], who reported increasing settlement values with increasing crude oil contents. The increased settlement can be attributed to the increased compressibility and decreased shear strength of the soil due to crude oil contamination [6,49].

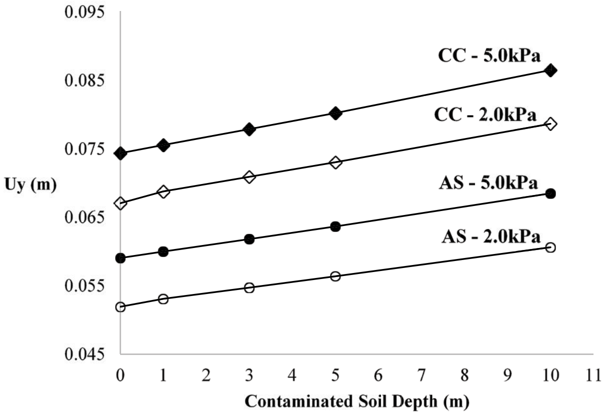

Fig. 6. U_y variations under different contaminated soil depths, capping materials and surface loading conditions for 12% crude oil-contaminated soil.

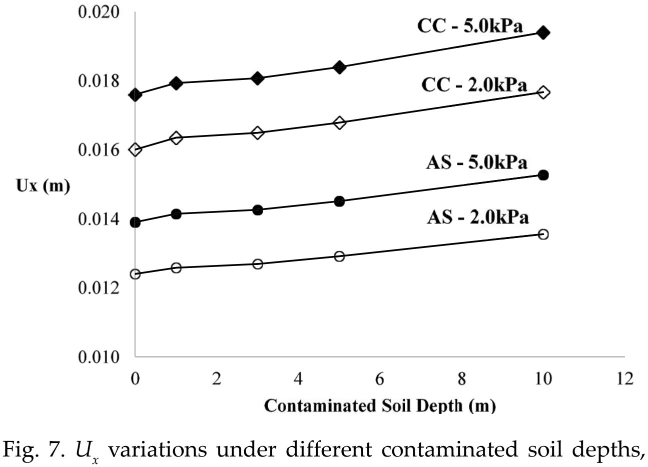

Fig. 7. U_x variations under different contaminated soil depths, capping materials and surface loading conditions for 12% crude oil-contaminated soil.

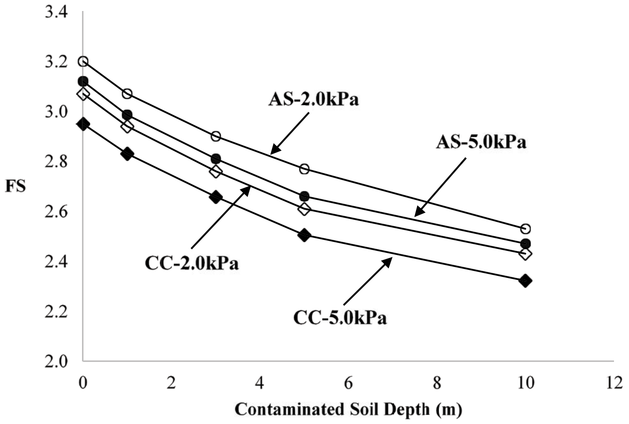

Fig. 8. FS variations under different contaminated soil depths, capping materials and surface loading conditions for 12% crude oil-contaminated soil.

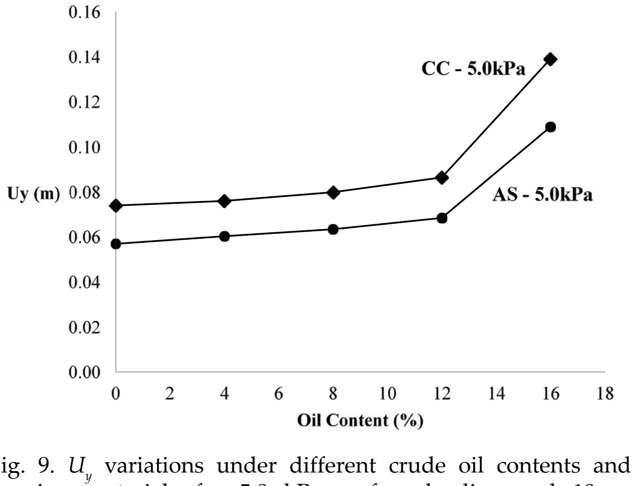

Fig. 9. U_y variations under different crude oil contents and capping materials for 5.0 kPa surface loading and 10 m contaminated soil depth.

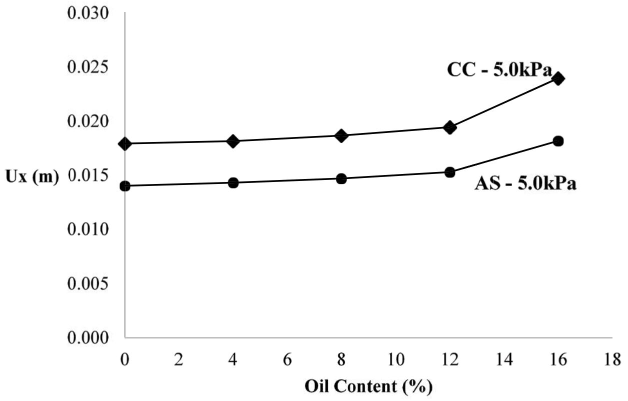

Fig. 10. U_x variations under different crude oil contents and capping materials for 5.0 kPa surface loading and 10 m contaminated soil depth.

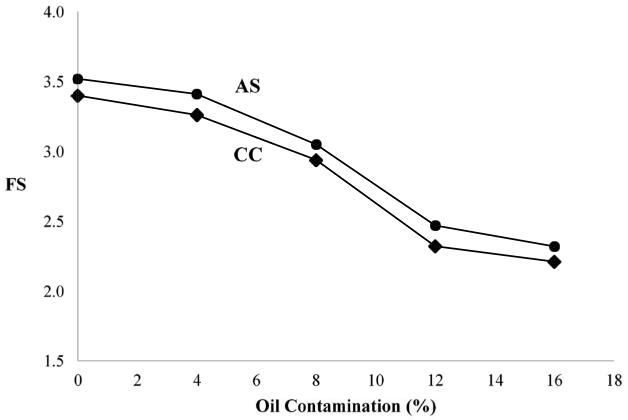

Fig. 11. FS variations under different crude oil contents and capping materials for 5.0 kPa surface loading and 10 m contaminated soil depth.

The effect of increasing crude oil contamination on the lateral displacement is evaluated in Fig. 10. Similar to the settlement values, the lateral displacement values also increased with increasing crude oil content, and the application of compacted clay as the capping material.

Fig. 11 shows the FS variation under different crude oil contents and capping materials. It can be easily seen from this figure that FS decreases with increasing crude oil content. On the other hand, although being on the same order of magnitude, slightly higher FS values were obtained when alum sludge was used as the capping material. Besides, for all the crude oil contents studied, FS values greater than 1.5 were obtained, indicating that both of the capping systems were stable under the investigated loading and site conditions.

4. Conclusions

The results of the two-dimensional finite element analyses indicated that higher U_y and U_x values were obtained when compacted clay was used as the capping material. The displacement values increased with increasing surface load, as expected. In the finite element analyses, the depth of the contaminated soil increased from 0 to 10 m, and the crude oil content increased from 0% to 16%. The results of the finite element analyses showed that the settlement values increased with increasing contaminated soil depth and crude oil content. Besides, for all the contaminated soil depths, crude oil contents, capping materials, and distributed load applications, FS values greater than 1.5 were obtained indicating that the chosen capping systems were stable under the investigated site conditions. Both of the uniformly distributed loads used for the simulation of the parking lot on the capped contaminated soil were obtained to be within acceptable limits in terms of slope stability. Therefore, based on the results of this study, it can be stated that the alum sludge examined in this study has mechanical properties that are suitable for a capping material for use in a crude oil contaminated soil capping application.

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