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Evaluation of the use of alum sludge as hydraulic barrier layer and daily cover material in landfills: a finite element analysis study

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ABSTRACT

In this study, the uses of alum sludge (AS) as hydraulic barrier (HB) layer and daily cover (DC) material were investigated using two-dimensional finite element analysis. In the analyses, typical landfill geometries were carried out for two different side-slope steepness (*2H*:1*V* and *3H*:1*V*), two different HB materials (compacted clay (CC) and AS) and four different DC scenarios (no DC, sand (S), compost, and AS), two landfill heights (20 m and 30 m) and two different municipal solid waste decomposition conditions (freshly disposed waste and old waste), and the effects of these variables on the displacements, and factor of safety (FS) values were investigated. For all the cases studied, FS values higher than 1.5 were obtained which indicated that the landfills were stable against sliding, and the displacement values were within the limits reported in the literature. The results of the finite element analysis also showed that AS used as HB and DC material yielded compatible results with the ones for the CC and S, which are widely used materials as HB and DC in landfills, respectively. Therefore, it can be said that, considering its low hydraulic conductivity, high shear strength, high contaminant removal abilities, and easy availability at no cost, AS can be used as an efficient alternative HB and DC material for landfills.

Keywords: Landfill; Alum sludge; Hydraulic barrier; Daily cover; Finite element analysis

1. Introduction

The disposal of municipal solid waste (MSW) in an environmentally safe manner is an important global problem due to the increase in the world's population, and the consequent increase in the amount of wastes produced each year. Although some volume reduction processes such as incineration or composting may be regarded as alternatives to landfilling, they basically produce wastes in the form of ashes or slags, which needs to be disposed of as well. Therefore, landfills can be regarded as one of the most economic and feasible means of disposing MSW [1–4].

Landfills are generally composed of several main components including bottom and lateral liners, waste cells, final covers, leachate and gas collection and removal systems, and storm water management system. A typical landfill cover design includes a hydraulic barrier (HB) layer in order to control drainage into the underlying waste [5]. Usually, geosynthetic clay liners or carefully compacted fine-grained

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soils (compacted clay (CC) liners) having hydraulic conductivities of less than 1×10^{-7}cm/s are used as HB layer in landfills [6–10].

In MSW landfills, the compacted waste and its daily cover (DC) form a structure called cell. DC is a layer of 15–30 cm of compressed soil which is laid on the top of the working face of the waste at the end of each operating period. Traditionally, any soil material that is workable and has stability (gravel, sand (S), clay, etc.) can be used as DC. However, some recyclable materials, such as compost (CO), construction and demolition wastes, shredded tires, coal or incinerator ash, glass aggregate, spray-on slurries, paper mill sludge, and water treatment sludge (WTS), have been reported to be used as alternative DC materials [4,6,11–15].

WTS is a solid waste generated during the treatment of potable water. WTSs contain materials removed from raw water (S, 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. Alum sludge (AS) is the solid waste generated during the treatment of potable water at the water treatment plant when aluminum salt is used as the coagulant [16–20].

Storing in sludge lagoons, landfilling in dedicated monofills or municipal landfills after dewatering by mechanical or thermal means, and incineration are the principal disposal options for WTSs [20–22]. However, the increasing demand for clean drinking water due to the increase in the world's population, and the consequent increase in the amount of WTSs raised concerns about their disposal. Therefore, their recycle for several beneficial uses has now become a challenge for scientists in order to decrease the necessary area and costs for landfill disposal, and prevent environmental concerns [19,22–25].

The aims of this study were to carry out two-dimensional finite element (FE) analysis (2D FEA) in order to: (a) investigate the effects of side-slope steepness (SSS), HB and DC materials, landfill height, and decomposition of MSW on the vertical (U_y) and horizontal (U_x) displacements, and factor of safety (FS) values of MSW landfills, (b) discuss whether AS can be used as HB layer, a function which is normally performed with CC, and (c) DC material, a function which is normally performed with soil materials such as S, and (d) propose an alternative beneficial use for the waste AS produced in large quantities worldwide.

2. Statement of the problem

In this paper, 2D FEA of typical landfill geometries was carried out to investigate the use of AS as HB layer and DC material. Typical landfill cross-sections were chosen for this purpose. In the analyses, half of the landfill was modeled because of the symmetry of the system. The half system was assumed to be 130 m in length. This length was sufficient to minimize the boundary effects.

The different stages of decomposition of the MSW were simulated using two different MSW properties as top and bottom waste, engineering properties are given in Table 1. The SSS of the landfills was assumed to be $2H{:}1V$ and $3H{:}1V$ with H being the horizontal distance, and V being the vertical distance. For each SSS, two different HB layers were used as CC, the widely used material for providing impermeability in landfills; and AS, which is a byproduct of water treatment facilities produced in huge amounts worldwide, and has low hydraulic conductivity values on the order of 1×10^{-7}cm/s [20,21]. Apart from the SSS and the type of the HB material, the availability of a DC layer and the type of DC material were also evaluated for each case. For the landfills with DC, three different materials were chosen as S, CO, and AS. The effects of landfill height on the U_y, U_x, and FS values were also evaluated for comparison. The details of the analyses performed in this study are shown in Fig. 1 as a schematic diagram.

As stated by Rowe [26], unweathered clayey soils have been considered to represent a relatively ideal environment for the location of waste disposal sites. Therefore, in the FEA, the natural soil at the landfill site was chosen as silty clay. The water table was assumed to be at the bottom of the silty clay layer, and the effect of groundwater was neglected.

The final cover of the landfill consisted of a vegetative cover soil (CS) layer underlain by geotextile (GT), gravel drainage layer (DG), geomembrane (GM), CC or AS, and sand protection layer (SPL). Similarly, the bottom liner consisted of a SPL underlain by GT, DG, GM, SPL, GM, and CC or AS. The selection of the final cover and bottom liner systems were consistent with Rowe [27]. Typical cell height, width, and DC thickness of 3.0, 20.0, and 0.03 m were selected, respectively. These values were consistent with the ones reported in the literature [6,13].

The problem being analyzed is illustrated in Fig. 2. For the sake of clarity, the widths of the landfills were assumed to be constant for the landfill geometries simulating two different SSS and heights.

In the design of the landfills, staged construction was used. The in 'situ geostatic stresses were modeled in the first step. The coefficient for lateral earth pressure (K_0) was taken to be $K_0 = 1 - \sin \Phi$ (for angle of internal friction of the soil, Φ). After equilibrium of in' situ stresses was reached, the analysis proceeded to

Table 1
Material parameters used in the FEA

	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	E (kN/m^2)	ν (–)	c' (kN/m^2)	Φ' (°)	ψ (°)	EA (kN/m)	Ref.
Compacted clay	16	18	20,000	0.4	24	29	0	–	[32]
Compost	6.8	16.4	5,000	0.25	0	15	0	–	[2]
Cover soil	19	21	40,000	0.3	17	22	0	–	[33]
Drainage gravel	18	21	100,000	0.35	0	40	10	–	[34]
Sand protection layer	18	21	50,000	0.3	0	34	4	–	[34]
Silty clay	19	21	150,000	0.35	48	35	0	–	[35]
Top waste	9.4	10.8	1,000	0.25	10	30	0	–	[36,37]
Bottom waste	11	15.4	2,500	0.35	30	20	0	–	[36,37]
Alum sludge	3.6	11	5,400	0.4	0	39	9	–	[31]
Geotextile	–	–	–	–	–	–	–	5,000	[38]
Geomembrane	–	–	–	–	–	–	–	5,000	[38]

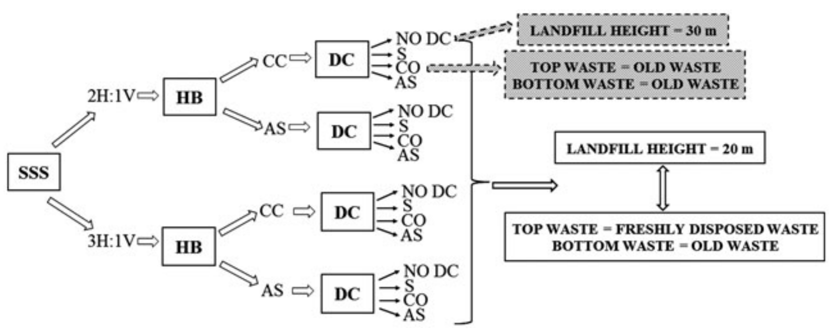

Fig. 1. Schematic diagram of the FEA performed in this study.

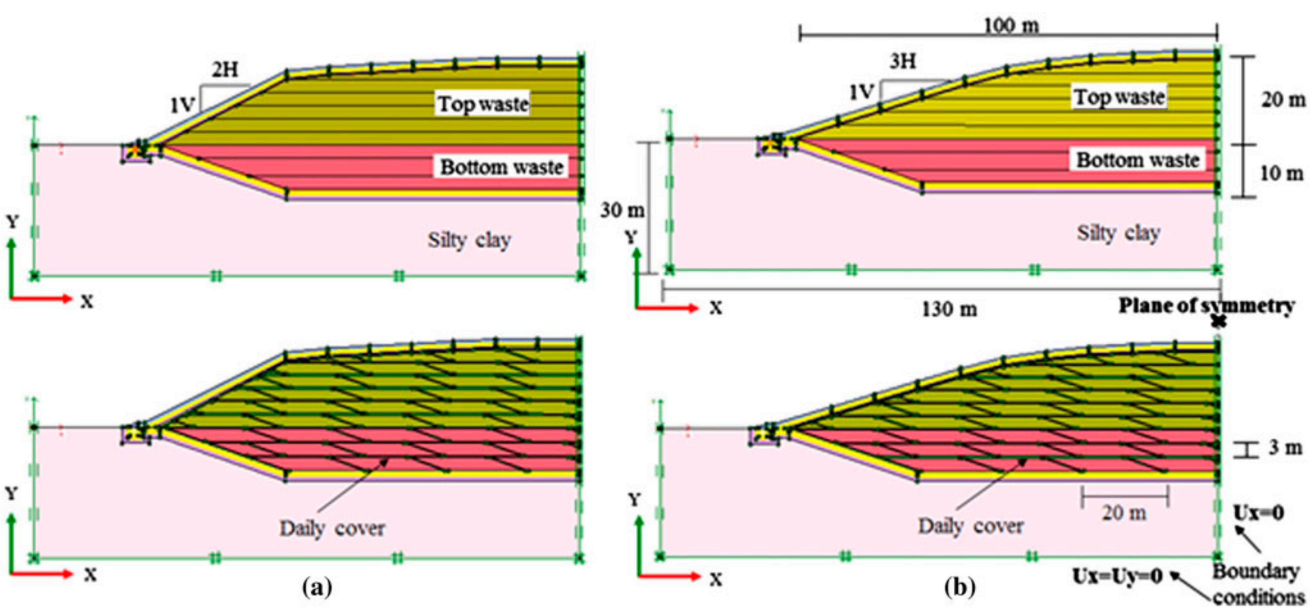

Fig. 2. The problem being analyzed: (a) SSS = $2H$:$1V$, without and with DC, (b) SSS = $3H$:$1V$, without and with DC.

the next steps where the excavation of the natural soil, laying of the bottom and lateral liners, filling of the waste material, laying the DC, and final cover systems were simulated.

Stability of landfills against slope failures is one of the major geotechnical concerns in landfill design [28]. The FS for slope stability is commonly accepted as 1.5 [29]. In this study, the FS was computed by Φ-c reduction method of PLAXIS FE program [30]. In the safety analyses, tan Φ and cohesion (c) of the soil are successively reduced until failure of the structure occurs, and the FS is obtained using the following equation:

$$\left(\mathrm{FS} = \frac{\text{Available strength}}{\text{Strength at failure}}\right) \tag{1}$$

3. Numerical modeling

3.1. Mesh design

For the generation of the FE mesh, 15-node soil elements and 5-node geogrid elements were used. A total of approximately 14,914 elements were employed throughout the mesh to model the soil layers. A finer FE mesh was used around the landfill, where rapidly varying stresses and strains were expected.

Sensitivity analyses were performed to evaluate the effect of different mesh densities on the FEA results. The maximum difference between the results obtained from different mesh densities was 1.98%. This shows that the different mesh densities do not seem to have a significant effect on the displacement and FS values of the landfills investigated in this study. To obtain the computational efficiencies needed for study of this complex 2D problem, mesh with lowest computational cost is used subsequently, since this maintains sufficient accuracy (Fig. 3).

3.2. Materials

An elastic material modeling was used for the simulation of the geosynthetic materials, while an elasto-plastic material modeling was adopted for the soil layers using the Mohr–Coulomb model, which is often used for representing the behavior of geomaterials. Effective shear strength parameters were used in the analyses in order to determine the FS values against instability of the landfill slopes for the intermediate and long-term conditions under different landfill designs studied in this paper. An average Young's modulus of the AS was interpreted from the deviator stress vs. axial strain graphs by O'Kelly [31]. The material properties used for the soil layers and the geosynthetic materials were consistent with the values reported in the literature, and are given in Table 1 along with their reference numbers.

In the table, γ_{unsat} is the unsaturated unit weight, γ_{sat} is the saturated unit weight, E is the Young's modulus, ν is the Poisson's ratio, c' is the effective cohesion, Φ' is the effective internal friction angle, Ψ is the dilation angle of the soil layers, and EA is the axial stiffness of the geosynthetic materials used in the bottom liner and final cover systems.

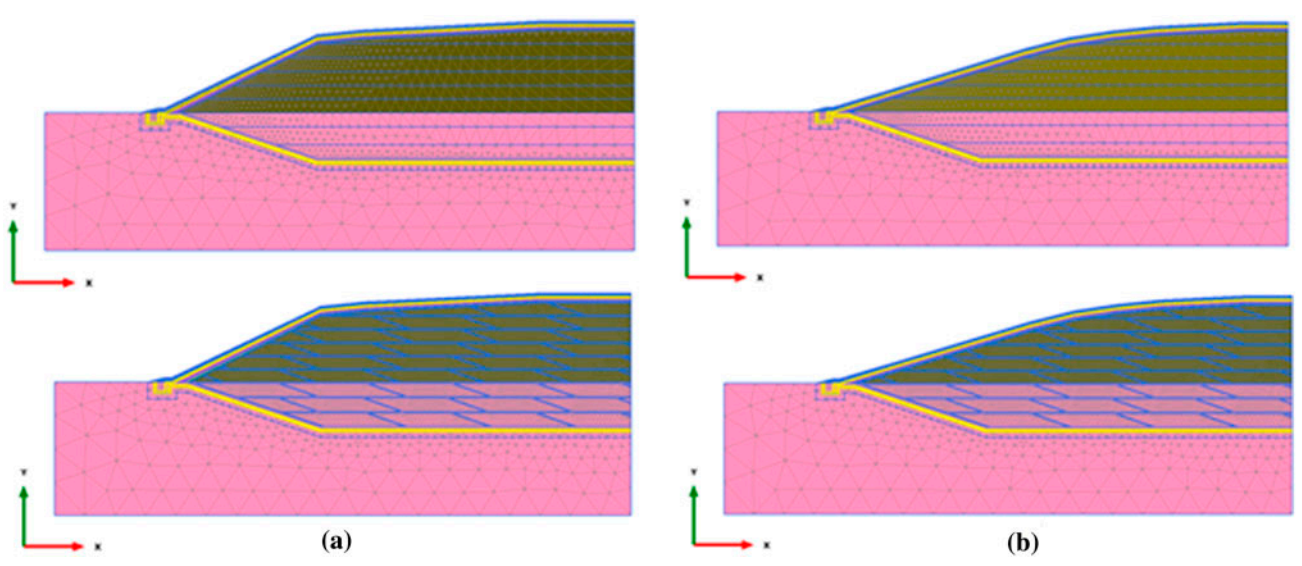

Fig. 3. Typical FE meshes used to model the landfills: (a) SSS = $2H$:$1V$, (b) SSS = $3H$:$1V$.

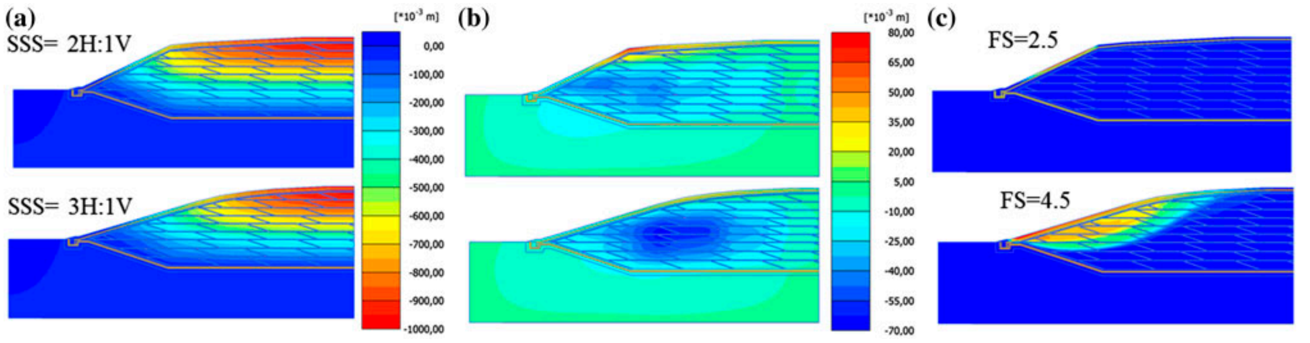

Fig. 4. Typical (a) U_y, (b) U_x, and (c) FS diagrams for SSS = $2H{:}1V$ and $3H{:}1V$ for HB = CC, DC = AS.

3.3. Boundary conditions

Sensitivity analyses were undertaken to demonstrate that the proximity of the boundaries had a negligible effect on the results (results changed by less than 1.0% as boundary was moved further from the region of interest). Two classes of displacement boundary conditions were considered in the analyses (Fig. 2):

- The $x = 0$ plane and the plane of symmetry featured movements prevented normal to these planes by applying $U_x = 0$ boundary condition.
- The bottom of the soil layer is restrained against movement in the x and y directions by applying $U_x = U_y = 0$ boundary conditions.

Table 2
The results of the FEA with respect to SSS, HB and DC material

		2H:1V			3H:1V		
HB	DC	U_y	U_x	FS	U_y	U_x	FS
CC	No DC	2.5	0.14	2.2	2.5	0.13	3.8
	S	2.4	0.13	2.2	2.4	0.14	3.9
	CO	2.3	0.15	1.6	2.3	0.14	3.1
	AS	2.1	0.12	2.5	2.1	0.12	4.5
AS	No DC	2.4	0.17	2.2	2.4	0.13	3.8
	S	2.3	0.12	2.2	2.3	0.14	3.7
	CO	2.2	0.13	1.7	2.2	0.14	2.9
	AS	2.0	0.13	2.3	2.0	0.12	4.2

4. Results and discussion

4.1 The effects of side SSS

In order to determine the effects of the SSS on the U_y, U_x, and FS values, two different landfill geometries with $2H{:}1V$ and $3H{:}1V$ slopes were considered in the analyses as given in Fig. 2. In the analyses, two different HB materials (CC and AS), and four different cases for DC material (No DC, S, CO and AS) were used for each SSS. For the sake of clarity, only the results for HB = CC and DC = AS are shown in Fig. 4.

The results of all the analyses are summarized in Table 2. Fig. 5 presents the results obtained in terms of U_y vs. DC material graphs. The FEA results showed that, as expected, the maximum U_y occurred at the center of the landfills for each case since this was the part of the landfill experiencing the highest overburden pressure (Fig. 4(a)). By keeping all the variables constant (HB, DC), increase in the SSS did not change the maximum U_y values of the landfill geometries studied in this paper (Table 2, and Fig. 5). This was expected since the heights of the landfills, and so the maximum overburden pressures were the same for the two SSS investigated.

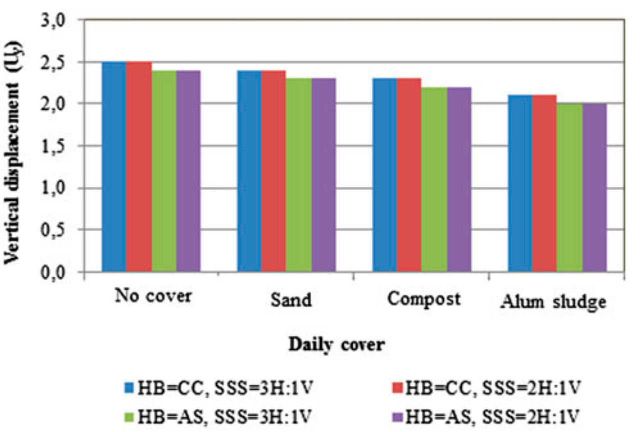

Fig. 5. Variation of the U_y values for different landfill designs.

The results of the analyses are summarized in Fig. 6 in terms of U_x vs. DC material graphs. As can

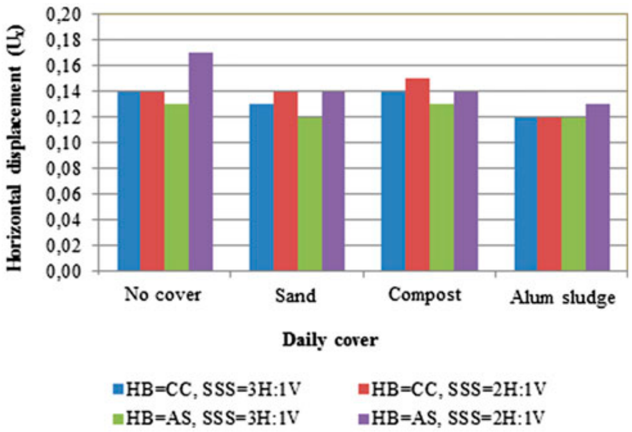

Fig. 6. Variation of the U_x values for different landfill designs.

be seen from the figure and Table 2, although on the same order of magnitude, slightly higher U_x values were obtained for the SSS of 2H:1V (U_x = 0.12–0.17 m) than those for the SSS of 3H:1V (U_x = 0.12–0.14 m). These results were in agreement with the results of a study by Singh [39] in which decreasing U_x values were reported with decreasing landfill slopes. However, keeping all the variables constant (HB, DC), the maximum U_x difference between the two different slopes was found to be 0.04 m. This indicates that the maximum U_x values were not significantly affected by the increasing SSS, since the heights of the slopes were constant. Typical U_x figures are presented in Fig. 4(b) for different SSS.

On the contrary to the displacement values, the FS values were significantly affected by the SSS (Fig. 7). The FEA results showed that, as the SSS increased from 3H:1V to 2H:1V, the FS values decreased for each

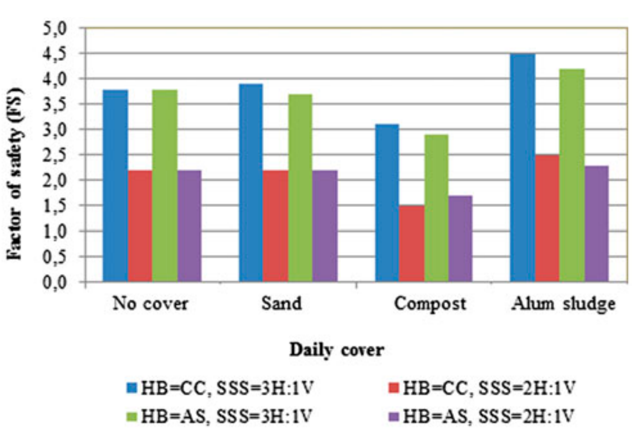

Fig. 7. Variation of the FS values for different landfill designs.

case, which indicated that the SSS of 3H:1V was safer than the SSS of 2H:1V. This was expected because a steeper slope has a higher driving force than a flatter slope and this driving force reduces the FS value. Besides, lowering the SSS also tends to force the failure surface deeper into the ground, and consequently increases the resisting forces because then the shear strength is distributed over a wider area. This increases the stability of the landfill, since the shearing resistance is proportional to the length of the failure surface [2,40]. The deeper circular failure plane leading to higher FS of the flatter slope can be easily seen from Fig. 4(c).

4.2 The effects of HB material

An impervious material with a hydraulic conductivity of less than 1×10^{-7} cm/s is required for landfill liners and capping systems. For this purpose, usually a clay liner is constructed in a layer of 0.6–1.0 m thickness. Clay has low hydraulic conductivity value which is a very important property for reducing or eliminating seepage of leachate from landfills. It also has the ability to adsorb and retain certain chemical constituents found in leachate. However, it may not be an economic and easily accessible material for use in HB in every landfill site [5,6,41–46]. On the other hand, AS is a waste material that is usually landfilled. Instead, it can be used as a HB material because several researchers have reported hydraulic conductivity values on the order of 10^{-7}–10^{-9} cm/s for AS, which corresponds to the drainage characteristics ranging from practically impervious to poor. The effective shear strength properties of the AS were reported to be in the ranges of c' = 0 kPa, and Φ' = 39–44, respectively [21,31,47,48]. These indicate that the AS does not only have the hydraulic properties desirable of HB, but also has significant strength that will resist shear failure of typical landfill slopes. AS is also lighter in weight compared with the traditional HB materials, has no commercial value, and can be easily obtained from water treatment facilities which make it an economic alternative to the traditional HB materials. Besides, AS is known to be effective in the removal of several contaminants such as phosphorus [23,49], copper, zinc, and lead [50] from wastewater. AS has also been investigated for use in geotechnical applications such as road pavements and subgrades, landfill covers, and soil improvement methods [21,51].

In the analyses, the effects of the HB material on the U_y, U_x, and FS values were investigated using two different HB materials. Fig. 8 shows the details of the typical bottom liner and final cover systems used in the FEA. The left-hand side of the figure shows the

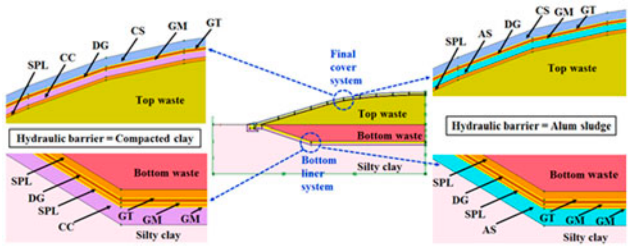

Fig. 8. Details of the bottom liner and final cover systems used in the FEA.

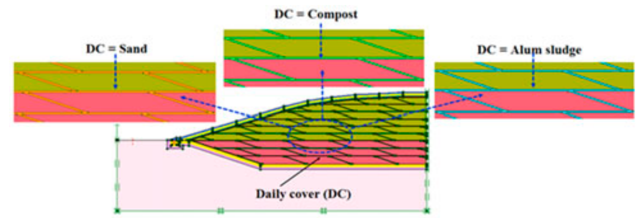

Fig. 10. Details of the DC systems used in the FEA.

design for HB layer composed of CC, and the one on the right-hand side shows the details of HB layer composed of AS.

The FEA results showed that, for the same SSS, similar values were obtained in terms of U_y, U_x, and FS when the results for HB = AS were compared with those of the traditional HB = CC (Figs. 5–7) case. Keeping all the variables constant, the maximum U_y, U_x, and FS differences corresponding to the same cases with different HB materials were obtained to be 0.1, 0.03, and 0.3 m, respectively. These findings indicate that the AS can be a good alternative to the CC for use as HB in landfills. Typical displacement and FS diagrams are presented in Fig. 9. For the sake of clarity, only the results for SSS = 3*H*:1*V* and DC = AS are given in this figure.

4.3 The effects of DC material

DCs are important elements of MSW landfills in terms of their efficacy in erosion litter, odor, vector, fire, and moisture control, and for enabling vehicle access to the active face of the MSW. However, several researchers have reported that the placement of soil DC can lead to 25% space loss of the total capacity of a MSW landfill [52,53]. Therefore, the beneficial use of waste materials in landfills as DC is encouraged, since using soils that can be used for other purposes may lead to ineffective use and consumption of the valuable landfill space [52,54–57]. On the other hand, the use of alternative DC materials may be an economic and practical solution at places where sufficient quantities of suitable soils are not readily available. Therefore, AS is thought to be a promising alternative to the traditional DC materials with its unique geotechnical properties, high contaminant removal capacities, and easy availability at no cost.

The effects of the DC material on the U_y, U_x, and FS values were investigated using three different DC materials. *S* is the typical material used for DC. However, since it has economic value, and may not be easily found in every site, low cost and easily available alternatives to S; CO and AS were also studied. Fig. 10 shows the details of the DC systems used in the FEA.

For the sake of clarity, only the results for HB = CC and SSS = 3H:1V are given in Fig. 11. The results of the FEA showed that, if all the other variables are held constant (SSS, HB), the presence and the type of the DC material slightly affected the U_y values. While the highest U_y value was obtained for the case without a DC (U_y = 2.5 m), the lowest U_y was obtained for the case with AS as the DC material (U_y = 2.0 m). However, the maximum U_x values did not show significant

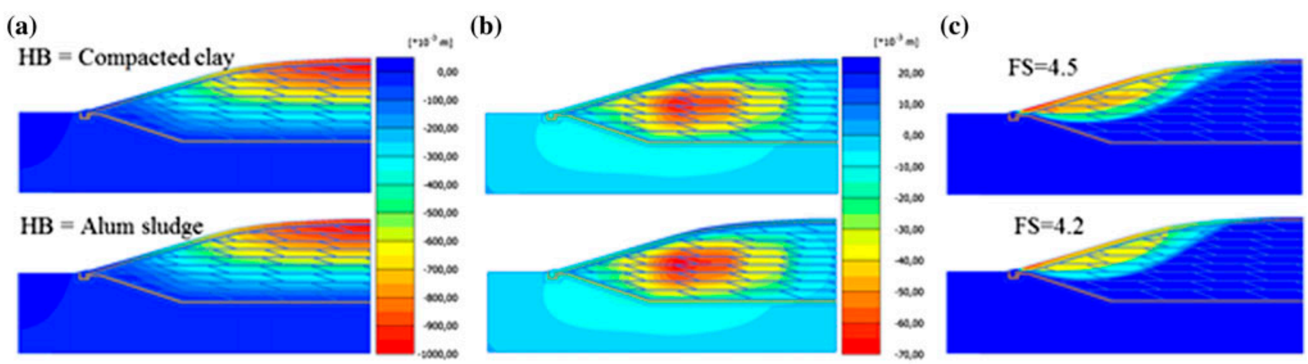

Fig. 9. Typical (a) U_y, (b) U_x, and (c) FS diagrams for HB = CC and AS (SSS = 3*H*:1*V*, DC = AS).

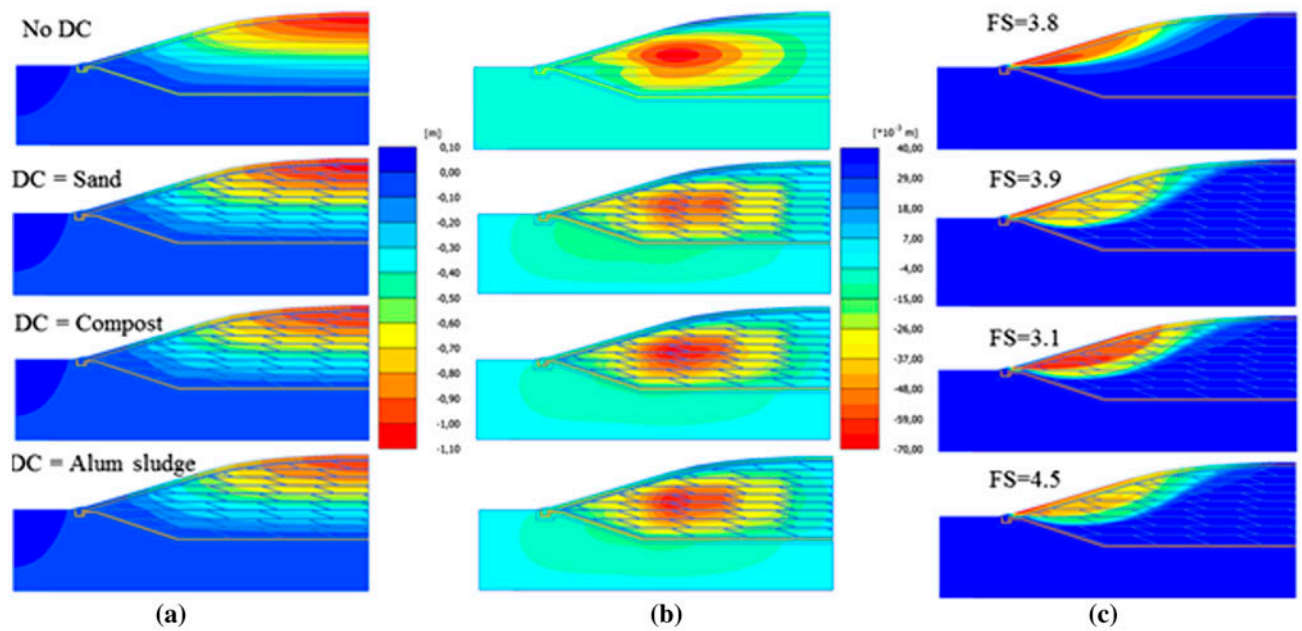

Fig. 11. Typical (a) U_y, (b) U_x, and (c) FS diagrams for different DC materials (HB = CC, SSS = 3H:1V).

differences between different DC materials. The maximum U_x difference was 0.04 m for different DC cases with the highest U_x corresponding to the case simulating no DC and the lowest one simulating a DC composed of AS (Table 2, and Figs. 5–7). The reason for obtaining high displacement values for no DC case is that, when soil materials were not used between MSW layers, the landfill did not benefit from the shear strength of the DC material layers. The AS yielded the lowest displacement values since it has high shear strength properties, but is lighter in weight compared to the other DC materials used in the analyses.

The settlement of landfills occurs as a result of immediate compaction of void space and particles due to a superimposed load (initial compression), consolidation due to the dissipation of pore water and gas from the void spaces (primary compression), and creep of the waste skeleton and biological decay (secondary compression) [58–62]. Several researchers have reported that landfill settlement continues over an extended period of time, and the final settlement can be as large as 5–50% of the original thickness of the landfill [63–69]. The maximum U_y value of 2.5 m obtained for the no DC case corresponds to 12.5% of the landfill height, which is within the ranges reported in the literature.

The FS values were affected by the presence and the type of the DC material. Keeping all the variables constant, the highest FS values were obtained when the AS was used as the DC material. The higher FS values obtained for AS could be attributed to its high shear strength properties (Table 1). The lowest FS values were obtained for the cases with CO as the DC. The reason for this trend is thought to be the lowest shear strength properties of the CO. However, even for the cases simulating a DC composed of CO, FS values higher than 1.5 were obtained which indicated that the landfills were stable under static conditions [29]. When the results were compared for DC = AS and DC = S, the traditional DC material, it was seen that significant differences were not obtained. This supports the hypothesis that AS can be used as DC in landfills.

Singh [39] stated that, based on the previous studies on MSW, the shear strength of waste has generally been found to be adequate, which confirms that carefully engineered and monitored landfills are unlikely to experience catastrophic failure during their service life unless the operating conditions change significantly. This statement supports the findings of this FEA study, in which FS values of higher than 1.5 were obtained for all the cases investigated in this paper.

4.4 The effect of landfill height

In order to determine the effects of landfill height on the displacement and FS values, the landfill design leading to the highest U_y value (SSS = 2H:1V, HB = CC, and No DC) was chosen. In the analyses, the landfill height of 20 m was increased to 30 m (Fig. 12).

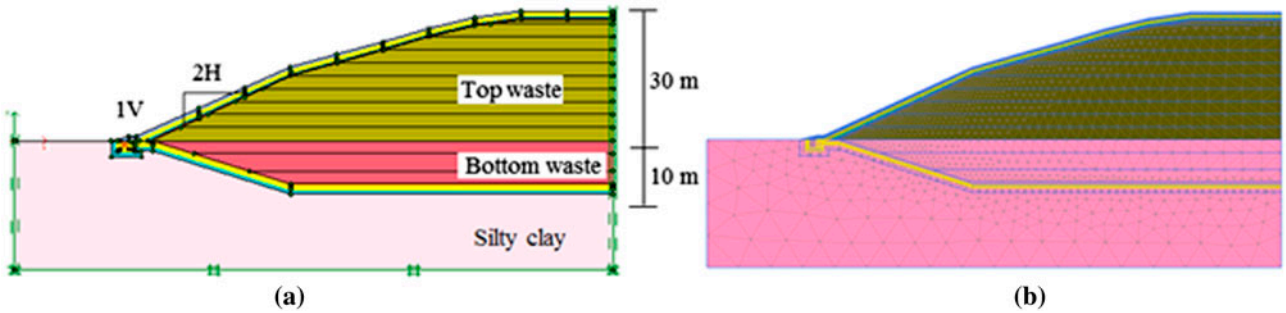

Fig. 12. A typical (a) landfill cross-section, (b) FE mesh for 30 m high landfill (SSS = 2*H*:1*V*, HB = CC, and No DC).

The results showed a sharp increase in the maximum U_y ($U_y = 4.7$ m) and U_x ($U_x = 0.32$ m) values compared to the results of the landfill having a height of 20 m ($U_y = 2.5$ m and $U_x = 0.17$ m). This was a consequence of the increasing overburden pressure of the MSW. The findings of these analyses were supported by the results of a study by Singh [39] which stated that increasing landfill height increased the U_x values due to the reduction in the stiffness with the increasing deviator stress. The results of the FEA yielded a FS value of 2.3, which indicated that the landfill was stable under static conditions. A comparison of the typical U_y, U_x, and FS diagrams for landfills of 30 and 20 m height are presented in Fig. 13.

4.5 The effects of MSW decomposition

MSW undergoes chemical and biological degradations with time, therefore its characteristics change with time, degree of degradation, and the type of waste disposed [70]. As stated by Gabr et al. [71], the time difference between placement of MSW at the bottom and top of a landfill may vary between 15 and 35 years. Therefore, the degree of decomposition of MSW between these two parts of the landfill is expected to be different. As the waste degrades with time and the increasing effective stress due to the increasing fill height, larger particles are broken down into smaller particles and fill the voids within the waste mass, and consequently increase the unit weight of the MSW. Therefore, older waste has a higher unit weight than freshly disposed waste [36,72–75]. Similarly, the shear strength of MSW also changes with time which may affect the long-term stability of a closed landfill [36,72,76]. The increasing fines content with time and degradation leads to a decrease in the friction angle and an increase in the cohesion value. Matasovic and Kavazanjian [74] reported that the values of Poisson's ratio at deeper portions of the landfill (waste with advanced stage of decomposition) were greater than those located closer to the surface (freshly deposited waste). Typical geotechnical properties of MSWs can be found in the literature [39,70,77,78].

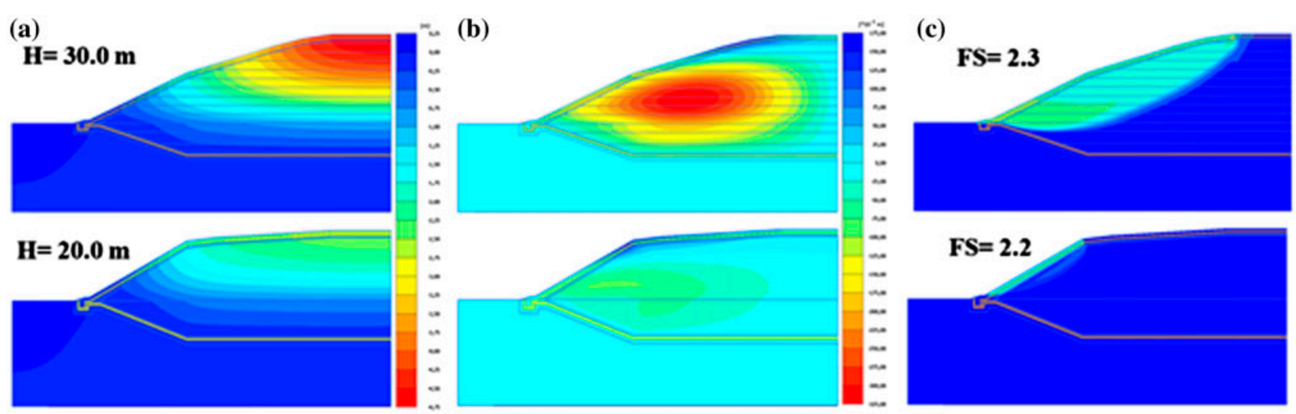

Fig. 13. Comparison of the typical: (a) U_y, (b) U_x, and (c) FS diagrams for landfills of 30 m and 20 m height (SSS = 2*H*:1*V*, HB = CC, and No DC).

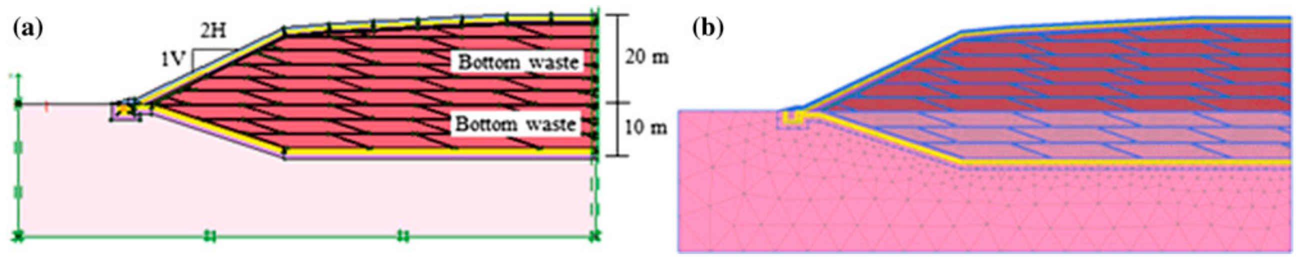

Fig. 14. A typical (a) landfill cross-section, (b) FE mesh for an old landfill site (SSS = 2H:1V, HB = CC, and DC = CO).

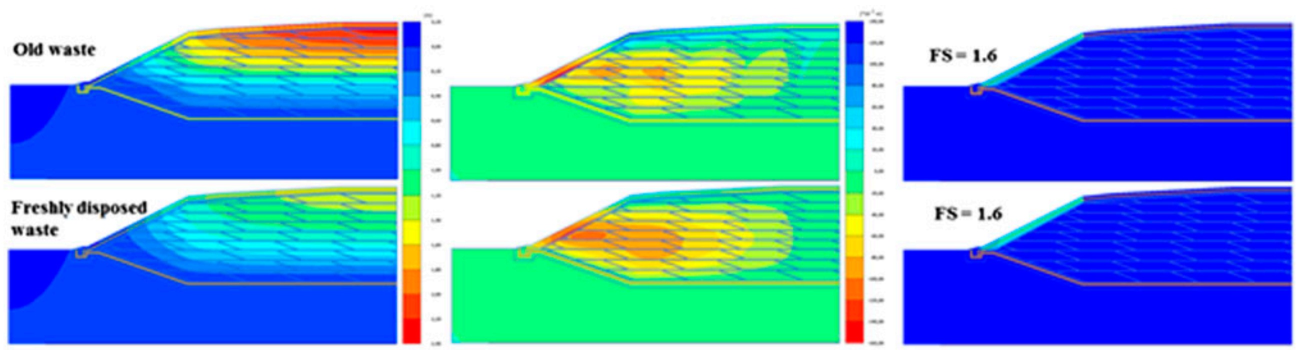

Fig. 15. Comparison of the typical: (a) U_y, (b) U_x, and (c) FS diagrams for an old waste landfill and a freshly disposed landfill (SSS = 2H:1V, HB = CC, and DC = CO).

In the previous analyses, landfills with active filling period were simulated using two different MSW properties. The bottom waste corresponded to the older waste while the top waste represented the freshly disposed waste. In order to determine the effects of MSW decomposition on the displacement and FS values, a landfill design simulating an old landfill site was also investigated (Fig. 14). For this purpose, the case yielding the lowest FS was chosen (SSS = 2H:1V, HB = CC, and DC = CO).

The results of the FEA indicated that the older waste resulted in less U_y (U_y = 1.3 m) and U_x (U_x = 0.11 m) compared with the freshly disposed waste. This trend was expected because, based on the material properties of the MSW studied, the older MSW had a higher Young's modulus compared with the freshly disposed waste, which is an indication of its stiffer structure. Older wastes are known to have higher unit weights [36,72–75]. As stated by Singh [39], an increase in the unit weight results in an increase in the overburden stress. The increase in the overburden stress leads to an increase in the effective confinement, which consequently results in higher stiffness.

A FS value of 1.6 was obtained for the slope indicating it was stable under static conditions. A comparison of the typical U_y, U_x, and FS diagrams for an old waste landfill and freshly disposed waste landfill are presented in Fig. 15.

5. Conclusions

This study aimed to investigate whether AS, a material that is normally disposed of in landfills as a waste, could be used as HB layer and DC material in MSW landfills. For this purpose, 2D FEA of typical landfill geometries was carried out using PLAXIS FE program, and the results of the analyses were evaluated in terms of U_y, U_x, and FS values.

The results showed that keeping all the variables constant: (a) FS values were almost the same for HB layers composed of CC and AS, increased with the use of AS as the DC material, were not significantly affected by the increased landfill height and decomposition of the solid waste; (b) U_y values were not significantly affected by the type of the HB material, and similar vales were obtained for HB layers composed of CC and AS; however, decreased for the old landfill case and with the use of AS as the DC material, increased with increasing landfill height, but were not affected by the increased SSS for landfills with the same height; (c) U_x values were not significantly affected by the HB and DC materials, and the decomposition of solid waste, but slightly increased for steeper slopes and sharply increased for the increasing landfill height.

Within the limitations of this study, it can be concluded that the AS examined in this paper has hydraulic conductivity, shear strength, and contaminant removal characteristics that are desirable for a HB and DC material for use in a typical MSW landfill. The significance of this investigation can be considered in three aspects: (a) it suggests a beneficial use for the huge amounts of AS that should otherwise be disposed of in landfills as a waste material, and consume landfill space, (b) highlights the benefits that can be gained in terms of the high contaminant removal ability of AS by possibly eliminating certain heavy metals from landfill leachate, and (c) propose an economic solution to landfill cover and liner systems.

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