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RESEARCH ARTICLE

Effect of geomembrane liner on landfill stability under long-term loading: interfacial shear test and numerical simulation

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Abstract

Clay liners have been widely used in landfill engineering. However, large-scale clay excavation causes secondary environmental damage. This study investigates the feasibility of replacing clay liners with high-density polyethylene (HDPE) geomembranes with different specifications and parameters. Laboratory interface shear tests between municipal solid waste (MSW) samples of different ages and geomembranes were conducted to study the influence of landfill age on interface shear strength. Finite element method was adopted to compare the long-term stability of landfills with HDPE geomembrane versus clay as intermediate liner. The interfacial shear test results show that the cohesion of MSW increases in a short term and then decreases with landfill age. The internal friction angle exhibits an increasing trend with advancing age, however, the rate of its increment declines with age. The rough accuracy of the film surface can increase the interfacial shear strength between MSW. The simulation results show that, unlike clay-lined landfills, the sliding surface of geomembrane-lined landfills is discontinuous at the lining interface, which can delay the penetration of slip surfaces and block the formation of slip zone in the landfill. In addition, the maximum displacement of landfills with geomembrane is 10% lower than that with clay, and the absolute displacement of slope toe decreases with the increase of roughness at the interface of geomembrane. Compared with clay-lined landfills, the overall stability safety factor increased by 18.5–30%. This study provides references for landfill design and on-site stability evaluation, contributing to enhanced long-term stability.

Keywords Landfills · Stability · Age · HDPE geomembrane · Soil-geomembrane interface shear

Introduction

Municipal solid waste (MSW) landfills slip due to the time variability of MSW, the decrease of shear strength, and the increase in landfill height. The reduction in shear strength is the main reason for the slippage of the layered landfill (Koerner and Soong 2000; Blight 2008; Huang and Fan 2016). Due to the complex composition of MSW in the landfill, a large amount of organic matter and fibrous material are degraded over time. The strength characteristics will change accordingly; part of the landfill body will slip along the internal potential slip plane (Fan et al. 2016; Chavan et al. 2019; Hossain and Haque 2009). The instability of the landfill will cause a large amount of landfill waste and leachate to slide out of the site, which may cause severe environmental pollution and even cause casualties and property damage (Li et al. 2021; Eker and Bascetin 2022a, 2022b). The alarming finding that inorganic salt solutions, organic matter, and heavy metals in landfill leachate can increase the hydraulic conductivity of clay liners and geosynthetic clay liners, enabling dangerous leachate passage into groundwater (Özçoban et al. 2022), underscores the need for more protective and fail-safe landfill designs.

The shear strength of the soil-geomembrane interface in MSW landfill is an important factor affecting slope stability and has been extensively explored over the past decade (Stark et al. 2009; Chang and Feng 2020; Brachman and Sabir 2013). Hossain et al. (2009, 2009) conducted shear

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tests to study the effect of the physical properties of solid waste on the stability of solid waste slopes. Abreu and Vilar (2017) conducted large-scale direct shear tests to study biodegradation's effect on MSW's shear strength. Their findings revealed that the cohesion gradually decreased to 0, and the internal friction angle gradually increased over time. Reddy et al. (2011) compared the shear strength parameters of fresh and synthetic MSW through direct shear tests and came to similar conclusions. Since the landfill is constructed from bottom to top, the construction time is long, and the physical parameters of the landfill change due to the degradation of MSW; studying the interfacial shear properties of HDPE geomembranes and MSW at different ages is necessary.

Clay was one of the earliest materials used for landfill covers due to its non-toxic and ubiquitous properties. Well-compacted clay provides good impermeability and shear strength which increase with layer thickness. However, using 20–25 cm clay cover for every 2–4 m of landfill significantly reduces effective landfill volume (Chetri and Reddy 2021). Prolonged rainwater exposure raises the moisture content of clay over time, thus decreasing its compressive strength (Khan et al. 2014). Desiccation under sunlight also induces cracking that compromises its impermeability. Clay does not represent an ideal cover material. Therefore, alternative materials such as geomembranes have been explored to overcome these deficiencies while ensuring the stability of landfills and providing good impermeability for landfill covers. High-density polyethylene (HDPE) geomembrane is a geosynthetic liner formed as a result of the extrusion of high-density polyethylene and shaped homogeneously (ASTM D4439-23 2023), which has good durability, chemical stability, and flexibility (Develioglu and Pulat 2023; Chen et al. 2010). HDPE geomembrane demonstrates the best chemical stability among all geomembrane materials. Moreover, the engineering performance of geomembrane is not affected by aging in the early and middle stages (Rowe and Shoaib 2017). HDPE geomembrane is usually used as the material of choice to prevent harmful substances from invading the soil and protecting the environment, unlike clay where permeability can vary significantly depending on moisture content and preparation. Overall, HDPE geomembranes present advantages over clay including better durability, thinner and more predictable application, and increased landfill volume. In addition to the characteristics of the material itself, the shear strength and compatibility of the landfill interface largely determine the composite behavior and engineering performance of the multi-layer barrier system. Punetha et al. (2017) carried out direct shear tests on sand-geosynthetic interface using the modified large direct shear box. Test results showed that as the gravel's diameter increases, the geomembrane surface's scour decreases. Bacas et al. (2015) conducted 90 geosynthetic interface experiments using a large direct shear instrument. The results showed that the closer the roughness of the material to the geomembrane interface, the better the shear effect. Ling et al. (2020) studied the interfacial shear properties of dense clay liners and HDPE geomembrane under freeze-thaw cycles. Their findings revealed that the shear strength decreases with the increase of freeze-thaw cycles. Therefore, it is necessary to further study and compare the stability of HDPE geomembrane and clay liner in simulated landfill environment to determine whether it is suitable for long-term landfill capping and liner applications.

Nearly 50 years, as the limitations of the limit equilibrium method (LEM) have become more and more obvious, scholars are more inclined to use the finite element method (FEM) to analyze the stability of slopes. The finite element method considers the soil's stress-strain behavior and quantifies the slope's physical parameters, so its calculation results are more accurate (Zienkiewicz et al. 1975; Ugai and Leshchinsky 1995; Tano et al. 2016; Karthik et al. 2022; Bascetin et al. 2019). Many domestic scholars use the finite element method to analyze the stability of slopes and apply the safety factor to the evaluation, which greatly promotes the development of the finite element method in China (Ma et al. 2021; Liu et al. 2020; Bao et al. 2022).

At present, clay is widely used in landfill liners, but over time, it no longer meets the stability requirements of landfills. Therefore, we investigate the feasibility of HDPE geomembranes to replace clay as a landfill liner. Scholars have studied the influence of temperature, particle shape, load, and other physical properties on the shear strength of the soil-geomembrane interface in the past (Bilgin and Shah 2021; Liu et al. 2021; Ying et al. 2022). The main factor affecting interfacial shear capacity is its surface roughness (Xu et al. 2023; Abdelaal and Solanki 2022; Araújo et al. 2022; Zhou et al. 2020). In this paper, we carry out the interface shear test between MSW at different landfill ages and three kinds of HDPE geomembranes with different surface roughness and explore the influence of landfill age on the interface shear strength of the geomembrane. The results can provide a reference for numerical modeling. Then, the finite element method is used to compare the stability of the landfill when HDPE geomembrane and clay are used as the intermediate liner of the landfill. This study can provide a reference for selecting and installing liners to make landfills safer.

Materials and methods

Materials for interfacial shear test

The direct shear tested materials were taken from a plain-type landfill in Jiangsu, and the total construction landfill capacity is 476.5×10^4 m^3. Different landfill ages MSW

Table 1 Physical and mechanical properties of refuse soil sample

Sample	Age (a)	Water content (%)	Void ratio	Cohesion (kPa)	Internal friction angle (°)
Z1	1.5~2	75.5	2.33	23.3	9.8
Z2	4.5~5	71.4	1.65	23.8	17.5
Z3	8~9	66.9	1.96	16.1	26.0
Z4	10~11	62.7	1.88	6.51	25.5

Table 2 Tensile strength and tensile stiffness of HDPE geomembrane under yield strain

Type	Thickness (mm)	Tensile strength (kN/m)	Yield strain (%)	Tensile stiffness (kN/m)
Salient point	1.5	17.80	16	111.25
Smooth	1.5	20.51	14	146.50
Textured	1.5	17.51	14	125.07

were collected from the reconstruction and expansion project (10~11 a), second-phase project (8~9 a), continuation project (4.5~5 a), and second-phase project (1.5~2 a). Repackage the obtained soil samples by removing metal and glass wastes from the samples. The physical and mechanical indices of MSW sample are shown in Table 1.

The HDPE geomembrane with a different surface roughness of 1.5 mm thickness was selected for the interfacial shear test, their density is all greater than 0.94 g·cm^{-3}, and the black carbon content is in the range of 2~3% (Hsieh and Hsieh 2003), as shown in Figure 1. The tensile strength and tensile stiffness at yield strain are shown in Table 2. The tensile stiffness of HDPE geomembrane refers to the ability of the elastomer to resist tensile deformation. This paper uses the ratio of tensile strength to yield strain to express the tensile stiffness, as shown by Eq. 1:

$$E = \frac{T}{\varepsilon_y} \tag{1}$$

where E (kN/m) is the tensile stiffness; T(kN/m) is the tensile strength; ε_y is the yield strain.

Equipment and methods of interface shear test

This experiment adopted the THE-1000 large-scale direct shearing apparatus developed by Tianshui Hongshan Company in China, as shown in Fig. 2. The size of the shear box is 500 mm × 500 mm × 410 mm. The vertical stress of the shear box can be loaded up to 1000 kN, and the maximum horizontal displacement can achieve for 100 mm. After sampling in a borehole at the landfill, MSW samples were classified by age. Glass and stones were removed from the samples, and the samples were packed in plastic bags and sent to the laboratory, as shown in Fig. 3. Samples from a given age are compressed with calibrated loads (50, 100, 200, and 400 kPa) in four vertical directions following ASTM D5321/5321M-21 (2021). Each group

Fig. 2 Large-scale direct shear test apparatus

(a) Salient point HDPE geomembrane (b) Smooth HDPE geomembrane (c) Textured HDPE geomembrane

Fig. 1 Three types of HDPE geomembranes with a thickness of 1.5 mm

Fig. 3 Field sample

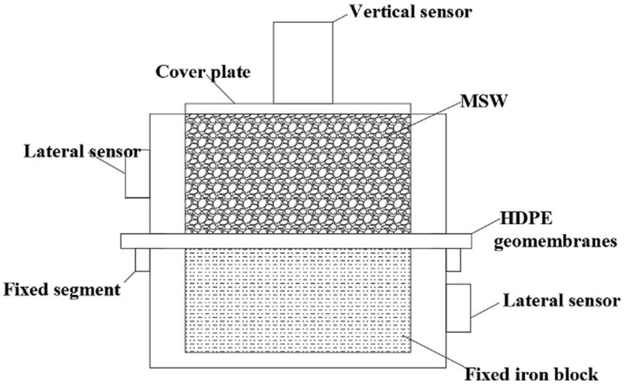


Fig. 4 Schematic diagram of shear test for HDPE geomembrane and MSW specimens

of samples should be compressed for at least 4 h, the maximum horizontal displacement is 100 mm, and the shear displacement rate is 2 mm/min (ASTM D5321/5321M-21 2021; Chen et al. 2022). To fix the geomembrane so it cannot slide during the experiment, as shown in Fig. 4. After the completion of the experiment, observe the condition of damage to the geosynthetic membrane during the testing process and promptly record the test data. Based on the shear stress under each level of vertical load, the shear strength under various normal pressures can be calculated using formula (2):

$$\tau\frac{F}{A} \tag{2}$$

where τ (kPa) is the shear strength; F(kN) is the shear stress; A(m^2) is the sample area.

The relationship between the shear strength parameters of MSW specimens and HDPE geomembranes at different ages were obtained based on the Mohr-Coulomb criterion, as shown by formula 3:

$$\tau_f = c + \sigma \tan \varphi \tag{3}$$

where τ_f (kPa) is the shear strength; c(kPa) is the cohesion; φ(°) is the internal friction angle.

Establishment of geometric model

In this study, Plaxis 2D software was used to conduct numerical modeling. It is a software for geotechnical engineering, especially for geotechnical analysis (Abdullah 2022). The four-layer MSW landfill in Jiashan, Changzhou, was taken as a reference. This model comprised a trapezoidal slope with a bottom length of 110 m, an upper length of 50 m, a height of 20 m, and a slope gradient of 1:3, 10 times slope height as the horizontal boundary and 2 times as vertical boundary (Christensen et al. 2020). According to PLAXIS 2D Reference manual (Brinkgreve et al. 2011), the vertical direction was free to move while the horizontal direction was constrained. The grid was divided into 74,206 nodes and 8747 units, consisting of 15-nodded triangular elements with an average size of 9.08 m. The model is shown in Fig. 5.

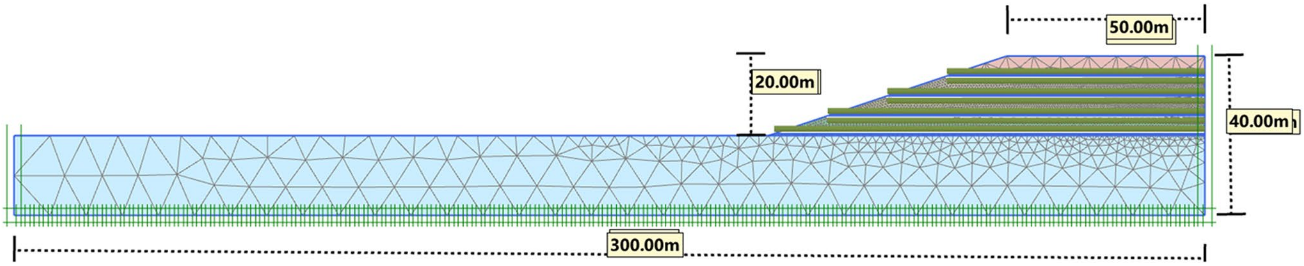


Fig. 5 PLAXIS landfill finite element model

Calculation parameters of the model

Landfill liner materials can experience performance degradation over time due to environmental factors such as temperature, oxygen, sunlight exposure, moisture levels, and leachate corrosion. For example, key mechanical properties like flexural strength, tensile strength, and elongation rate tend to diminish gradually as the liners age (Cazzuffi and Gioffrè 2020). Considering the complexity of replicating long-term aging processes, the experimental program reasonably concentrates efforts on quantifying reductions in shear resistance along the critical waste-liner interface. The measured declining trend in interface shear strength thus serves as an effective proxy for performance degradation over time (Zhao and Tian 2023) Based on Mohr-Coulomb's theory, the shear strength reduction technique was used to calculate soil-membrane interface interaction. In the PLAXIS finite element software, the shear behavior along the soil-geomembrane interface is modeled using the interfacial strength reduction factor $\mathrm{R}_{\mathrm{inter}}$, which is input as interfaces above and below the HDPE geomembrane layer in the software model. The interfacial strength reduction factor $\mathrm{R}_{\mathrm{inter}}$ is calculated based on the soil-geomembrane interface shear strength parameters obtained experimentally, as shown in Eq. (4) while also satisfying the requirement in Eq. (5):

$$c_i = R_{inter} c_{soil} \tag{4}$$

$$\tan \varphi_i = R_{inter} \tan \varphi_{soil} \le \tan \varphi_{soil} \tag{5}$$

where c_i (kPa) is the cohesion of MSW-liner interface; φ_i (°) is the internal friction angle of MSW-liner interface; c_{soil} (kPa) is the cohesion of MSW; φ_{soil} (°) is the internal friction angle of MSW; $R_{inter}$is the strength reduction factor of soil-membrane interface.

This elastic-perfectly plastic model requires 5 basic input parameters: Young's modulus, Poisson's ratio, cohesion, friction angle, and dilatancy angle. In most cases, MSW has no dilatancy, and the dilatancy angle is equal to 0. When the dilatancy angle is set to 0, it is considered that dilatancy is ignored (Bolton 1987). Taking the landfill time of the lowest layer as the initial time. The Mohr-Coulomb model parameters were obtained based on the outcomes of standard laboratory and field tests listed above. The parameters of MSW in Table 1 were assigned to each layer according to age. In Figure 5, the geomembrane was set at the interface of the different landfill layers. The parameters of the HDPE geomembrane in Table 2 were endowed to each intermediate cover. The landfill without HDPE geomembrane used a clay seal layer with a thickness of 300 mm to meet the specification (Christensen et al. 2020). The values of the physical parameters of the foundation soil, landfill layer, and clay seal layer of the site are taken in Table 3.

Results and discussion

The shear strength of MSW is generally described using the Mohr-Coulomb criterion in geotechnical engineering, as shown in Eq. (3). The cohesive strength and internal friction angle are indicators of the interface shear strength. The cohesive strength characterizes the intergranular cementation between the MSW and geomembrane. Larger cohesive strength indicates stronger adsorption and coagulation effects between the two, which is beneficial for maintaining the structural stability of the interface. Figure 6 shows the age-interface shear strength graph of MSW and HDPE geomembrane. According to Fig. 6a, the cohesion of the soil-geomembrane interface decreases obviously when the MSW is older than 5 years, while the decrease is ambiguous or even increases slightly when the MSW is younger than 5 years. There is no doubt that the interfacial cohesion of the three geomembranes has a similar change trend; the cohesion of MSW older than 5 years is worse than that of MSW younger than 5 years. The reason for this situation is closely related to age. It could be that the landfill age is short, the degradation of organic matter and fibers in the waste is insufficient, and so they can sustain cohesion. When the organic matter and fibers are sufficiently degraded, the particulate matter in the waste increases, resulting in a decrease in cohesion. Abreu and Vilar (2017) proved this view, and they conducted large-scale direct shear tests on MSW of different ages and found that the tested wastes older than 5 years have reached decomposition stages. Therefore, according to the construction sequence, the cohesion of MSW in the upper layer of the landfill is higher than that in the lower layer. The result agrees with Bascetin et al. (2022), which coincides with the present study.

Table 3 Table of material parameters of soil layers

Soil horizon	Young's modulus (MPa)	Poisson's ratio	Volumetric weight ($\mathrm{kN{\cdot}m^{-3}}$)	Cohesion (kPa)	Friction angle (°)
Foundation Soil layer	30	0.25	19.5	35	28.5
Clay	23	0.25	21	12	25
MSW	2	0.4	10.5	Reference Table 1	

The internal friction angle characterizes the ability of adjacent soil layers to resist sliding against each other. The larger the internal friction angle, the less likely the soil layers are to slide and fail, meaning the more stable the structure is and the higher the shear resistance. Figure 6b shows the relationship between friction angle and age. The interfacial friction angle of the three geomembranes also has the same change trend. Contrary to cohesion, the friction angle increases with age. As shown in Fig. 6b, from 0 to 8 age, the friction angle rises rapidly and then increases slowly or even decreases after age 8. Some reasons can be attributed to the increase in friction angle after age 8. Similar to cohesion, the organic matter and fibers in the waste degraded insufficiently in a short time, resulting in a small friction angle. After a period of full degradation, the organic matter and fibers in the garbage disappear, leaving only small waste particles. Abreu and Vilar (2017) found that small particles were essentially reinforcing components that can increase the interface friction angle. Therefore, the internal friction angle will not continue to increase or even decrease when the MSW is older than 8 years. It can be seen that the MSW shear strength parameters filled in the numerical simulation are basically consistent with the actual situation.

It can be seen from the test results that the surface of the geomembrane is rougher, and the cohesion and friction angle between the geomembrane and MSW will be greater. The three HDPE geomembranes are ranked according to their performance: salient point > textured > smooth. Develioglu and Pulat (2023) found that roughness on the geomembrane surface increases the friction force, and therefore, the interface friction angle also increases. But they ignored that age also affects the shear strength of MSW, which was discussed above. Abreu and Vilar (2017) proved that as MSW degraded, the waste material evolved from an initially highly cohesive material to one that lost cohesion yet gained in shear strength angle over time. However, they only studied the properties of MSW without considering the interfacial shear strength. This paper investigates the change law of shear strength at the interface between MSW and HDPE geomembrane at different ages. But the deterioration effect of geomembrane with age is ignored. Although HDPE geomembrane is less affected by age than MSW, its hydraulic properties decrease and produce additional tensile strains(Sun et al. 2019). This effect cannot be ignored, so this experiment's results are conservative; age's effect on HDPE geomembrane material remains to be studied.

When investigating the stability of MSW landfills, the shear strength parameters of the waste in each layer may vary. Therefore, a stratified approach can be adopted whereby each layer of the landfill is modeled separately with distinct shear strength properties assigned. Finite element models can then be established for each stratified layer to simulate and analyze the potential instability mechanisms (Hossain and Haque 2009). This study conducts sliding analyses on landfills with different liners to identify potential weak interfaces of the landfills through the observed sliding surfaces. For instance, if the sliding surface is found to penetrate through the clay liner, it indicates that the clay liner has relatively low shearing strength. Figure 7a shows the sliding surface of the clay liner landfill in the 11th year. It is found that the critical sliding surface penetrates the clay liner consecutively. The sliding surface of the landfill develops from the top to the toe of the slope and runs through the whole slope, forming sliding arcs. This form of destruction looks natural. According to Bascetin et al. (2021), the physical properties of clay and MSW are close, so the failure

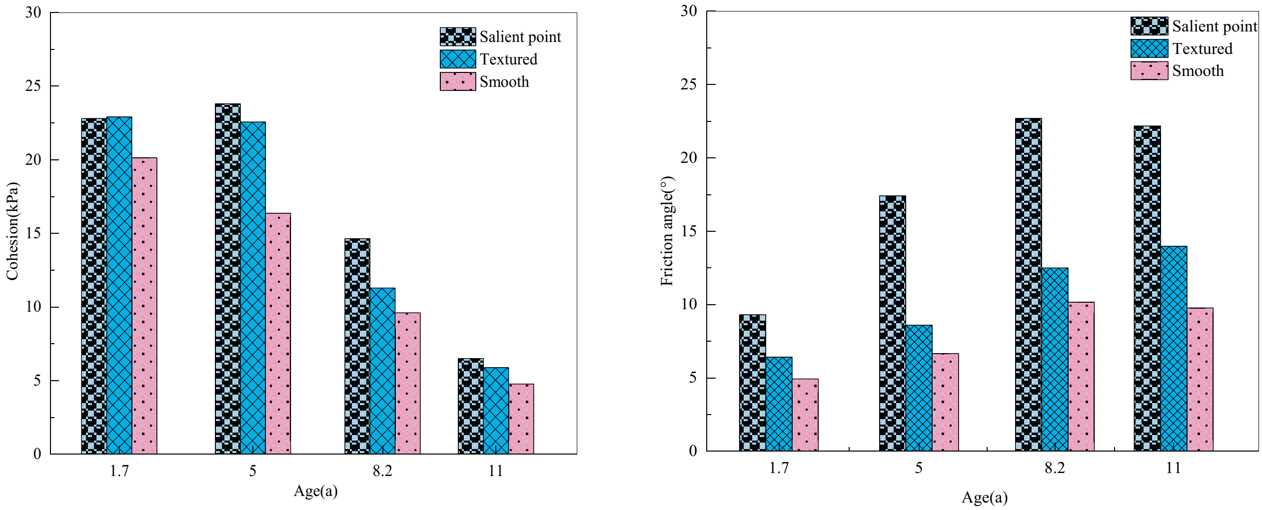
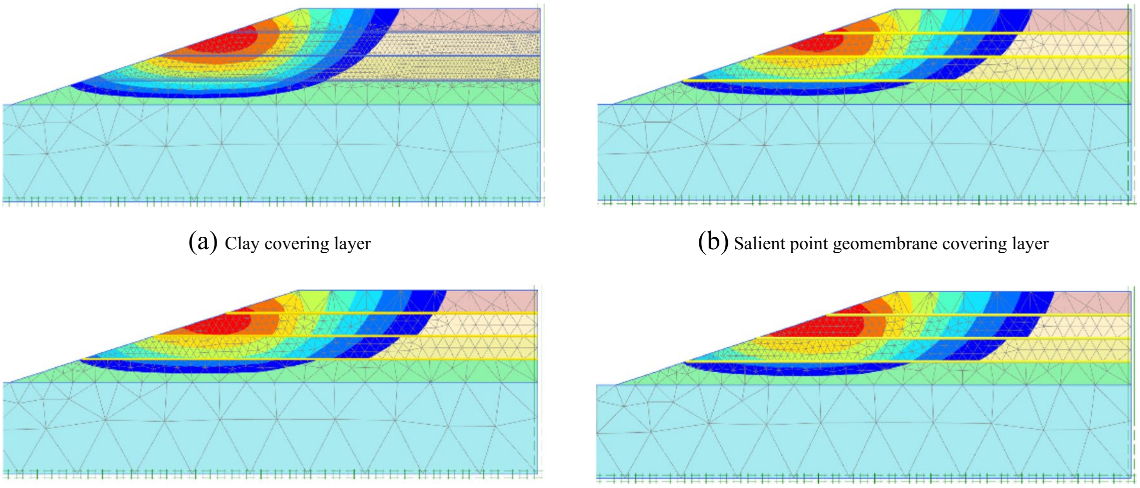


Fig. 6 Interface shear strength of MSW and HDPE geomembranes at different ages


(a) Clay covering layer

(b) Salient point geomembrane covering layer

(c) Textured geomembrane covering layer

(d) Smooth geomembrane covering layer

Fig. 7 Distribution of typical sliding failure zone affected by intermediate cover layers

mode of clay overburden is similar to that of MSW. This can only explain part of the phenomenon. At first, the middle block of the slope pushes to the toe of the slope under the action of gravity (Deng et al. 2020). Therefore, tensile cracks appear at the contact between the top of the slope and the middle block, and the strain is concentrated in the middle of the slope. At the same time, the toe of the slope is squeezed and begins to slip. The sliding surface is initially formed and gradually develops to the inside. Due to the poor continuity of the clay liner, it is easily torn by sliding surfaces.

Following is the finite element model image analysis of the geomembrane liner landfill. Figure 7b, c, and d show the sliding surface of landfills with different types of HDPE geomembrane liners in the 11th year. Unlike clay liner landfills, the sliding surface of the geomembrane liner landfill is discontinuous at the liner interface. They are all offset towards the inside of the slope along the liner interface, and the sliding distance increases with the slope toe. Fan et al. (2016) studied the stability of age-based stratified landfills by introducing a velocity field. It is considered that different blocks in the slope rotate around a certain point to form a sliding failure surface. On the one hand, the plasticity of the clay liner is poor, and slip arcs are easily formed inside the slope, while the HDPE geomembrane liner has strong flexibility, and the critical slip surface formed by this rotation is easily broken by it. The discontinuity of the sliding surface can instead relieve the strain concentration in the landfill and make the landfill more stable. On the other hand, elevated gas pressures were also a significant contributor to this phenomenon (Benson et al. 2012). When MSW degrades, a large amount of gas is produced. The geomembrane liner is denser than the clay liner, and the gas inside the slope is isolated by the geomembrane and cannot be discharged in time, which leads to the decrease of the normal stress required for the interface displacement, and then slip on the liner interface. The increase in the gas pressure will decrease the normal stress of the interface, and the offset of the liner interface will be larger. Last but not least, we learned above that interfacial shear strength decreases with age. The age of the bottom layer in the landfill is old, the interface shear strength resistance is weak, and the cohesion is close to 0. In summary, these reasons can explain why the bottom of the landfill has the greatest sliding distance. Due to the offset of the sliding surface of each liner interface, the slip of the upper and lower landfill layers of each liner interface is discontinuous. This discontinuity can relieve concentrated stress in the landfill and prevent the formation of strain concentration areas. In theory, it could make landfills safer. Whether the landfill is more stable still needs the following analysis.

The overall and local stability changes occurring in landfills as the waste age increases can be evaluated by analyzing the numerical value variations of the maximum displacement and bottom relative displacement in the simulation results of the landfill systems. Figure 8 shows the landfill's maximum and absolute displacement in 11 to 20 years. It can be seen from Fig. 8 that both the maximum and absolute displacements decrease with age. The top line graph represents the absolute displacement change and the bottom bar graph represents the maximum displacement change. The displacement of landfill with smooth HDPE geomembrane liner decreased by 21%, from 0.34 to 0.27 m; textured geomembrane decreased by 26%, from 0.33 to 0.24 m; and salient point geomembrane decreased by 26%, from 0.32 to 0.23 m. The maximum displacement of the landfill with HDPE geomembrane liner was greater than that of the clay

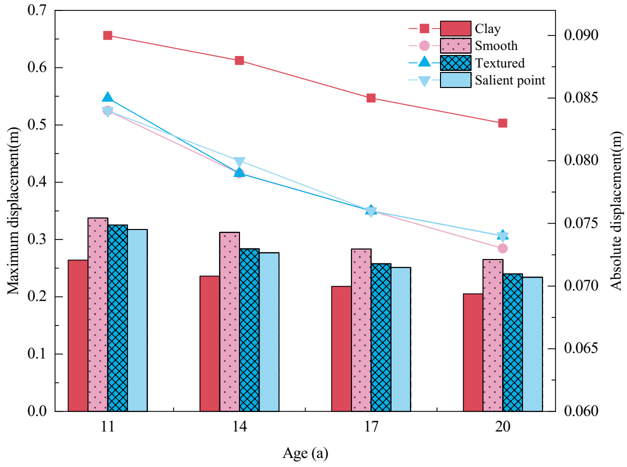


Fig. 8 Displacement of landfill

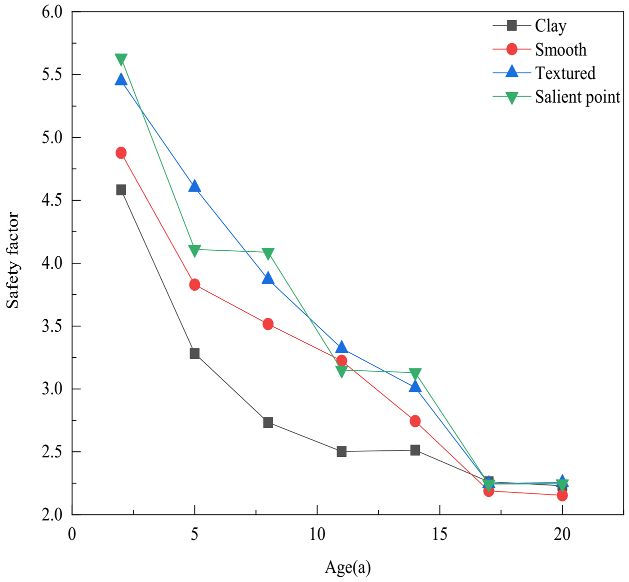


Fig. 9 Curve of safety factor with age

liner landfill. The reason is that a film of water exists at the clay–geomembrane interface, the MSW tends to slide at the interface, and its behavior is akin to the sliding of two essentially impervious rigid surfaces having a film of water in between (Sharma et al. 2007). The critical sliding surface slips along the geomembrane, causing more concentrated displacement at the shallow landfill. But we can find that the absolute displacement of the geomembrane liner landfill decreased from 0.084 to 0.073 m, which was 10% lower than that of the clay liner. This is because the geomembrane acts as a barrier and relieves the strain concentration in the middle of the landfill (Bascetin et al. 2022; Tuylu 2022). There was a significant hook-and-loop interaction, and as the roughness increased at the geomembrane interface, and reduced the absolute displacement of the slope toe (Develioglu and Pulat 2023). Three types of HDPE geomembrane can inhibit the development of bottom displacement of landfills effectively from 11 to 20 years. The comprehensive effect is salient point > textured > smooth.

According to the numerical simulation results, the relationship between safety factors and age is obtained. Figure 9 shows the variation of landfill safety factors over 20 years. Referring to the relevant provisions of *Landfilling of waste: barriers* (Christensen et al. 2020), the safety factor values of landfills should be higher than 1.25. It can be seen from Fig. 9 that the safety factors of both clay liner and geomembrane liner landfills decrease with age. In the initial stage of landfill operation, the main factor affecting its safety factor is the height of the landfill. As the height of the landfill increases, the safety factor of the landfill will decrease (Wu et al. 2018). When the landfill is closed, MSW begins to degrade. At this time, the physical and chemical properties of MSW affect the safety factor of landfill. The discussion section found that cohesion values decreased towards the bottom layers because the MSW there degrades first. The reduction in shear strength is the main reason for the slippage of the layered landfill (Koerner and Soong 2000; Blight 2008; Huang and Fan 2016). These reasons can explain why the safety factor of landfills decreases with age. Within 20 years, the safety factor of landfills with salient point geomembrane liner decreased from 5.632 to 2.246; the decrease of textured type was similar to that of salient point type, from 5.456 to 2.256; the safety factor of smooth decreased from 4.877 to 2.154. Even so, HDPE geomembrane liner landfills also have a higher factor of safety than clay liner landfills by 28% (salient point), 30% (textured), and 18.5% (smooth). This result could prove that geomembrane liners can make landfills more stable. After 17 years, the stability safety factor of landfills with geomembrane liner is equivalent to that of clay liner, which may be owing to geomembrane deterioration and loss of physical properties. The results show that HDPE geomembrane can replace clay as the intermediate liner for layered landfills, which plays a good role in safety and stability.

Conclusion

Clay is widely used as a liner in landfill construction. This paper investigates the feasibility of replacing clay with an HDPE geomembrane as a liner. On this basis, this paper considers the influence of age and proposes a way to arrange liners in all layers of the landfill. The influence of age and geomembrane liner on landfill stability was verified by direct shear test and finite element analysis. The results of this study are summarized in the following:

1. The cohesion of MSW decreases with age, and the friction angle increases with age. The shear strength of MSW will become poor at an advanced age.
2. The roughness of the geomembrane surface can increase the interfacial shear strength between MSW, and this is because as the roughness of the geomembrane interface increases, a hook-and-loop interaction will occur between the interfaces.
3. HDPE geomembrane liners can reduce the absolute value of bottom landfill displacement and improve the safety factor of landfills because it prevents the sliding surface from running through the liner, thereby alleviating the formation of strain concentration areas in the landfill.
4. The salient point geomembrane as a liner has the greatest improvement in the stability of the landfill, which can be improved by 30% compared with the clay liner. The construction methods and types of geomembranes in this paper can provide a reference for engineers to carry out difficult landfill construction.

Author contributions The authors confirm contribution to the paper as follows: study conception and design: Ziqing Pan and Xiong Xia; data collection: Xiankun Xie and Hongyong Qiu; analysis and interpretation of results: Ziqing Pan and Kai Guo; draft manuscript preparation: Ziqing Pan and Xiong Xia. All authors reviewed the results and approved the final version of the manuscript.

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Declarations

Ethical approval This study does not involve human participants and animals subjects. All authors strive to ensure that all research activities follow ethical principles and regulations to ensure the integrity and reliability of research.

Consent to participate All authors are willing to participate in the study. They understand the nature and purpose of the study, and their rights as participants.

Consent to publication All authors have read and approved this version of the article, and due care has been taken to ensure the integrity of the work.

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