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Research Paper

Instability phenomenon at municipal solid waste landfills in Vietnam: Case study at Cam Ly landfill, Da Lat City, Lam Dong Province

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ABSTRACT

In Vietnam, poor management of municipal solid waste (MSW), combined with changes in its physical and mechanical properties over time, increases the risk of instability in landfills. The instability poses significant environmental pollution risks and adversely affects infrastructure, production activities, and livelihoods of people living near these landfills. This study focuses on the Cam Ly MSW landfill in Da Lat City, Lam Dong Province, Vietnam, where the geotechnical properties of MSW and soil layers were determined through both in situ and laboratory tests. The findings showed that MSW typically has low resistivity values (< 30 Ωm), suggesting that geophysical survey is a useful tool for determining the thickness and distribution of MSW, providing valuable data for assessing landfill stability and post-closure planning. The instability type and causes at Cam Ly were analyzed using the Limit Equilibrium Method (LEM) through Geoslope/W software and the Finite Element Method (FEM) through Plaxis 2D software. The type of landfill instability identified is of the slip surface within the waste pile. The main causes of instability at the landfill were steep terrain, inadequate compaction of the MSW, and saturation due to prolonged heavy rain. Research on MSW landfill instability is essential for improving landfill management, reducing environmental impact, and safeguarding nearby communities.

1 Introduction

Currently, Vietnam has approximately 1,207 municipal solid waste (MSW) landfills handling around 60,000 tons of MSW each day [1]. Most of these landfills receive unsorted MSW from the source, with complex compositions, high organic content, large land usage, and generating substantial amounts of leachate. Poor management of MSW, along with changes in the physical and mechanical properties of MSW over time, increases the risk of instability at these landfills. Instability at MSW landfills can occur both during and after their operational phases, including during waste deposal and after landfill closure. This issue results in environmental pollution and has negative impacts on infrastructure, production activities, and the lives of nearby residents. There have been numerous cases of slope failures at MSW landfills in Vietnam

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and globally, such as at the Payatas landfill in the Philippines in July 2000 (Fig. 1a), at the Dona [2] Juana landfill in Colombia in April 2020 (Fig. 1b), at the Kiteezi landfill in Uganda in August 2024, at the Cam Ly landfill in Vietnam in August 2019, July 2020 (Fig. 3b), and October 2021, and at the Nam Son landfill in Vietnam in May 2024. Research into landfill instability is essential to improve landfill management and operations and to reduce negative impacts on the environment, infrastructure, and surrounding communities. This case study examines the Cam Ly MSW landfill in Da Lat City, Lam Dong Province, Vietnam. The geotechnical properties of MSW were determined through in situ and laboratory tests and the type and causes of slope instability at the landfill were analyzed and identified.

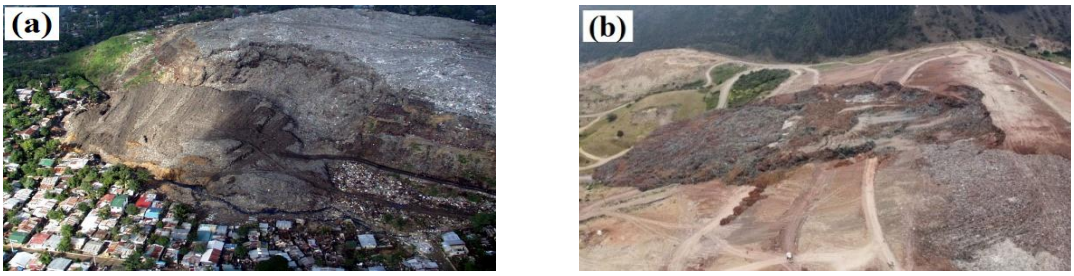


Fig. 1 – Slope failure at the MSW landfills: (a) Payatas MSW landfill in Quezon City, Philippines on July 10, 2000 [3]; (b) Dona Juana MSW landfill in Bogota City, Colombia on April 28, 2020 [4].

To evaluate the stability of MSW landfills, researchers have investigated the geotechnical properties of MSW through in situ tests (geophysical survey, piezocone test, standard penetration test, dynamic cone penetration test, drilling, direct shear test, permeability test, density test), laboratory tests (composition test, water content test, void ratio test, permeability test, shear strength test, compaction test, consolidation test), back-analysis of unstable slopes, and the effects of leachate accumulation on stability. Notable studies include those by Eid et al. (2000) [5], Blight (2008) [6], Jianguo et al. (2010) [7], Hyun II et al. (2011) [8], Feng et al. (2017) [9], and Sarmah et al. (2021) [10] (Fig. 2a). Zhang et al. (2020) [11] reviewed global cases of slope instability at MSW landfills over the past 40 years, analyzing 62 cases from 22 countries to identify the main factors contributing to landfill instability. They categorized three types of slope instability based on the location of the slip surface, as shown in Fig. 2b, accounting for 69.4%, 19.32%, and 11.28% of slope instability cases, respectively. The researchers also identified five primary causes of instability: High landfill leachate levels, responsible for 40.32% of cases; Inadequate compaction of MSW, accounting for 22.58% of cases; Insufficient bearing capacity of the foundation, contributing to 19.35% of cases; Low shear strength at the liner-MSW interface; and Rapid release or Subsequent deflagration of landfill gas. Additionally, various secondary factors, such as prolonged rainfall, differential settlement from waste decomposition, overloading of MSW, and extreme weather events like typhoons, can influence landfill stability. In most cases, landfill slope failures result from a combination of several adverse factors rather than a single cause.

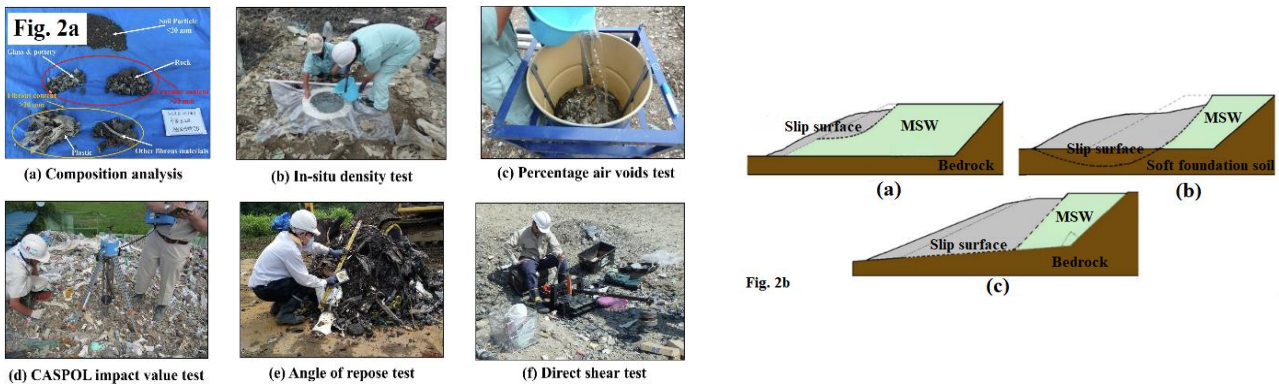


Fig. 2 – (a) In situ tests conducted at MSW landfills [10]; (b) Types of landfill slope instability [11]

Zekkos et al. (2014) [12] analyzed the slope failure of the Xerolakka MSW landfill using both the limit equilibrium method (LEM) and the finite element method (FEM). Their research highlights that each method has its advantages and limitations. In FEM analysis, predefined failure surfaces are not required; instead, the failure surface with the lowest factor of safety is automatically determined using the phi-c reduction method (Plaxis 2004). One of the main benefits of FEM is

its ability to compute displacements over a given calculation period, as well as to model evolving failures. In contrast, LEM calculates the safety factor for multiple potential failure surfaces, with the one yielding the lowest safety factor considered critical. However, LEM does not account for strain-softening materials as it does not consider deformations or displacements. Mehdizadeh et al. (2021) [13] applied the finite difference method (FDM) in conjunction with the Monte Carlo method to assess the reliability of MSW landfill slopes. In their reliability analysis, the random variables included soil unit weight, cohesion, and internal friction angle, assuming a normal statistical distribution for the safety factor, which was calculated through 2000 simulations. Their results indicated that this number of simulations was sufficient to determine the reliability of MSW slopes. Additionally, they found that higher coefficients of variation in the random variables led to lower reliability of the slopes.

2 Instability phenomenon at the Cam Ly MSW landfill

The Cam Ly MSW landfill is located atop a hill about 60 meters high in Ward 5 of Da Lat City, Lam Dong Province, Vietnam (Fig. 3a). Serving as the city's waste disposal site for many years, the landfill was established in 1976 and covers an area of approximately 90 hectares. It stretches around 1000 meters in length and over 900 meters in width (Fig. 3b). Each day, the landfill was tasked with handling 200 tons of unsorted MSW, which was poorly compacted and then covered with a layer of cohesive soil. The landfill has experienced instability multiple times. One notable incident occurred on August 10, 2019, following days of continuous heavy rainfall. A massive slope failure caused a large amount of MSW to collapse down the hillside, burying greenhouses, vegetable gardens, flower beds, farming equipment, and agricultural land. On July 6, 2020, the landfill experienced similar slope failures after another prolonged period of heavy rain. Hundreds of tons of MSW slid into a nearby valley, endangering gardens and greenhouses belonging to households farming below [14]. At the site of these failures, numerous streams of foul-smelling, black leachate were observed, significantly polluting the environment (Fig. 3b). Given the recurring instability, a thorough investigation is essential to guide the future management and operation of the Cam Ly MSW landfill.

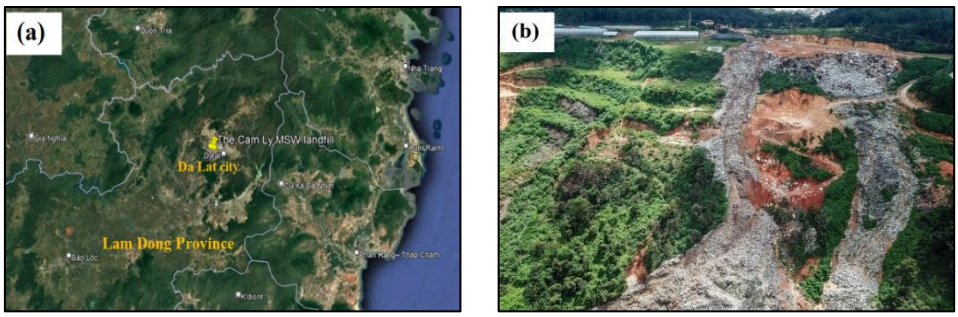


Fig. 3 – (a) Location of the Cam Ly MSW landfill (Source: Google Earth Pro); (b) The slope failure occurred on July 6, 2020, at the landfill [14]

3 Geotechnical properties of MSW at the Cam Ly MSW landfill

To assess landfill stability, it is essential to determine the geotechnical properties of MSW, including its stratigraphy, shear strength, composition, and bulk density. These properties can be evaluated through in situ and laboratory tests.

Since the composition of MSW in countries such as Vietnam, China, Thailand, and India is relatively similar (Fig. 4) [15], research methods and geotechnical properties findings from these countries can be referenced to guide studies on MSW in Vietnam.

3.1 Landfill stratigraphy

The stratigraphy of the landfill was determined through geophysical survey (Fig. 5) and drilling (Fig. 6). A total of 63 boreholes and 408 geophysical measurements of MSW and soil resistivity, down to a depth of 70 meters using the Wenner four-electrode method, were collected from previous studies [16-18]. Additionally, in 2024, the authors conducted 49 new geophysical measurements at the landfill following ASTM G57-06(2012) by ES-2 equipment. The results of the geophysical survey were found to be relatively consistent with the drilling data (Fig. 5 and Fig. 6). The resistivity of MSW

at the site ranged from 1.14 Ωm to 99.70 Ωm, with an average resistivity of approximately 30 Ωm. Areas with resistivity below 15 Ωm are considered to represent fully saturated zones.

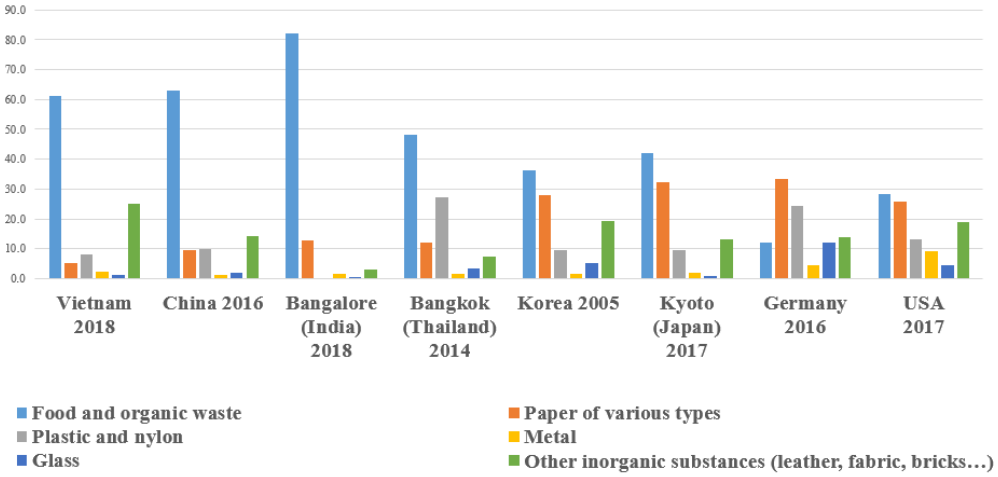


Fig. 4 – Composition of fresh MSW in some countries -calculated as % wet weight [15]

The landfill stratigraphy consists of four distinct layers:

- Layer F - Filling soil, with a thickness ranging from 0.2 to 0.5 meters;
- Layer 1 - MSW material, with a thickness ranging from 4.0 to 15.8 meters;
- Layer 2 - Weathered granite;
- Layer 3 - Fresh granite.

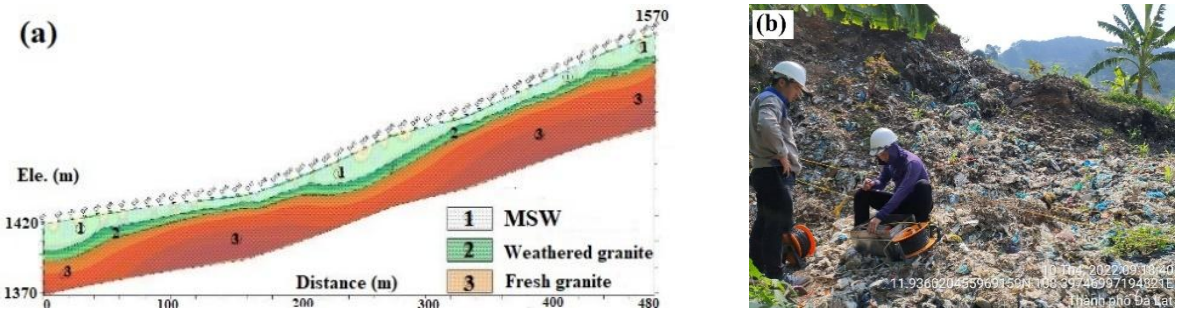


Fig. 5 – (a) Landfill stratigraphy (2D view) was determined through results of geophysical survey; (b) On-site geophysical survey was conducted by the authors in 2024

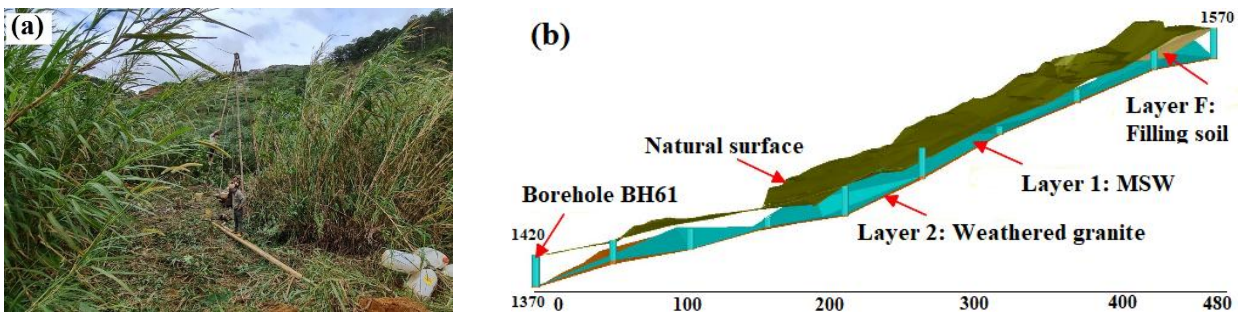


Fig. 6 – (a) Drilling [17]; (b) Landfill stratigraphy (3D view) was established by the author in 2024 using drilling data

3.2 In situ tests

3.2.1 Bulk density and composition of MSW at the landfill

To determine the bulk density and composition of MSW at the landfill, ten excavation pits measuring 0.5 x 0.5 x 0.5 meters were excavated at different elevations. The findings showed that the composition of fresh MSW consisted of soil (61.02% to 72.36%), textile and fiber materials (9.15% to 12.97%), wood and plastic materials (5.94% to 8.00%), glass, broken bricks, iron, and steel (the remaining percentage). For long-term MSW, the composition had shifted to silty sand (SM) and silt (ML, MH) with an organic content of about 15.5%. This change shows the decomposition of organic matter, which decreased from about 40% to 15.5%. As a result, the long-term MSW resembles soil and can be tested and classified according to standard soil testing procedures. The natural bulk density of MSW at the landfill was determined to be approximately 0.403 g/cm³. This data provides detailed information on the physical characteristics of the waste, which is critical for stability analysis.

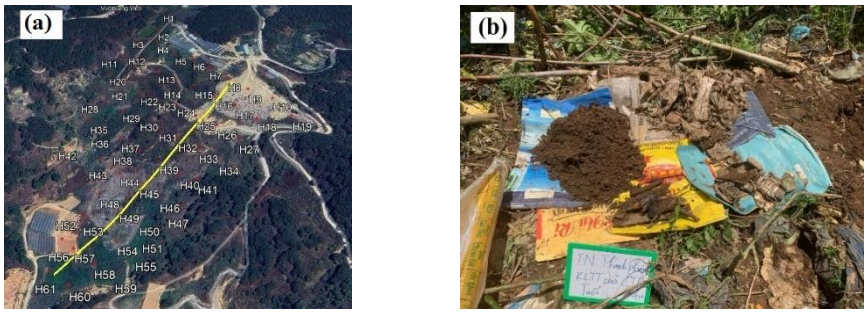


Fig. 7 – (a) Excavation pit locations (Google Earth Pro); (b) Composition of the MSW at the landfill

3.2.2 Internal friction angle of MSW at the Landfill

Dynamic cone penetration (DCP) tests were conducted at the excavation site (Fig. 8) following the procedures outlined in ASTM D6951M-18. Using correlation theory, probability theory, and mathematical statistics, the relationship between the internal friction angle (φ) of MSW and the dynamic cone penetration index (DCPI) was established as $\varphi = 48.93*DCPI^{-0.40}$ (Fig. 9). Based on the results of the DCP tests, the internal friction angle of MSW at the site was determined to range from 10° to 25°. This range provides valuable information for understanding the shear strength and stability of landfill material, which is important for assessing slope stability.



Fig. 8 – (a) Location of DCP tests;(b) Conducting DCP test

3.3 Laboratory tests

Laboratory tests on the geotechnical properties of long-term landfill MSW were conducted at University of Transport and Communications, the Institute of Transport Science and Technology (ITST), and the Geotechnical Design Joint Stock Company (HEC 14) in 2023 and 2024. These tests provided a comprehensive analysis of the material behavior and properties, which is essential to understanding landfill stability.

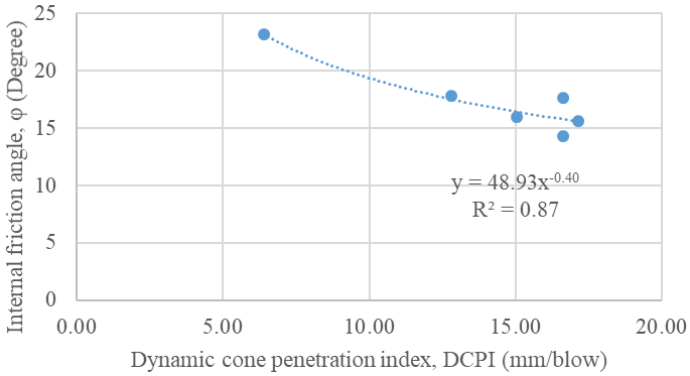


Fig. 9 – Relationship chart between internal friction angle and DCPI

Table 1 – Number of MSW samples and applicable standards

Test	Property	Quantity	Standard
Particle size analysis	Particle size distribution	01	TCVN 4198:2014
Compaction test	Optimum water content and Maximum dry unit weight	01	ASTMD698-12(2021)
Organic material test	Organic material percentage	01	ASTM D2974-20e1
Direct shear test on small sample	Shear strength	06	ASTMD3080-04
Direct shear test on large sample	Shear strength	06	ASTMD3080-04

Geotechnical tests conducted on long-term landfill municipal solid waste (MSW) have yielded the following results:

3.3.1 Particle size analysis and organic material tests

The composition of long-term landfill MSW is identified as silty sand (SM) and silt (ML, MH), with an organic content of approximately 15.5% (Fig. 10).

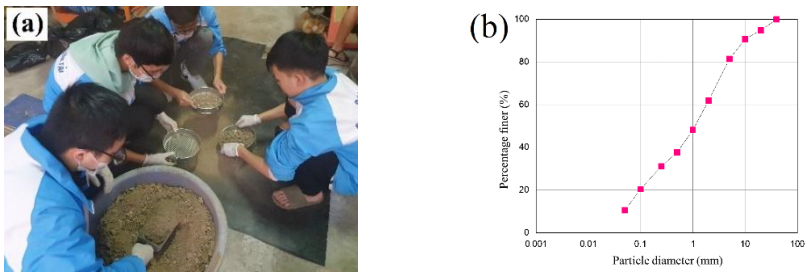


Fig. 10 – (a) Particle size analysis; (b) Particle size distribution chart

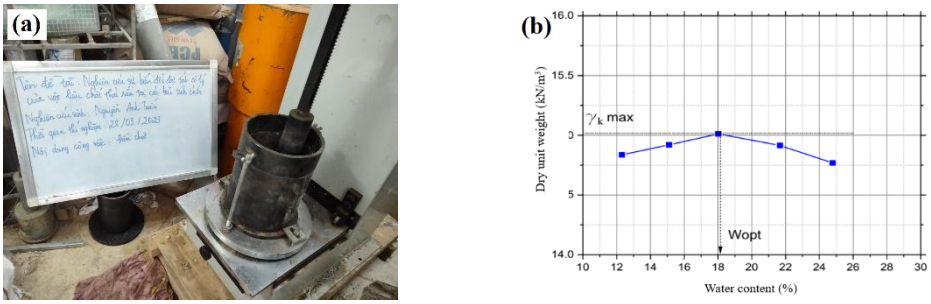


Fig. 11 – (a) Compaction test; (b) Relationship chart between γ_{dmax} and W_{opt}

3.3.2 Compaction tests

Maximum dry unit weight (γ_{dmax}) is 15.0 kN/m³; Optimum water content (W_{opt}) is 18.1% (Fig. 11).

3.3.3 Direct shear tests on small samples with a diameter of 62 mm

- At 90% compaction (R90): Average internal friction angle is 34°26'; Average cohesion is 45.34 kPa.
- At 95% compaction (R95): Average internal friction angle is 37°59'; Average cohesion is 48.97 kPa.

Table 2 – Direct shear test results on small samples with a diameter of 62 mm under optimum water content conditions

Sample	At R90 compaction		At R95 compaction	
	φ (Degree)	Cohesion, c (kPa)	φ (Degree)	Cohesion, c (kPa)
M1	34°11'	45.27	37°54'	48.58
M2	34°11'	40.85	37°22'	58.74
M3	32°11'	38.42	36°45'	41.73
M4	38°43'	47.14	39°44'	57.52
M5	34°30'	44.16	37°54'	37.54
M6	32°51'	56.21	37°36'	49.68
Average value	34°26'	45.34	37°59'	48.97
Average square deviation	2°24'	6.18	1°39'	8.39
Variation coefficient	0.07	0.14	0.03	0.17

with φ : Internal friction angle

3.3.4 Direct shear tests on large samples with dimensions of 100 x 100 x 100 mm

- Under saturated conditions at 90% compaction: Average internal friction angle is 22°34'; Average cohesion is 29.59 kPa.
- Under saturated conditions at 95% compaction: Average internal friction angle is 38°11'; Average cohesion is 26.43 kPa.

Table 3 – Direct shear test results on large samples with dimensions of 100 x 100 x 100 mm

Sample	Under optimum water content conditions				Under saturated conditions			
	At R90 compaction		At R95 compaction		At R90 compaction		At R95 compaction	
	φ (Degree)	Cohesion c (kPa)	φ (Degree)	Cohesion c (kPa)	φ (Degree)	Cohesion c (kPa)	φ (Degree)	Cohesion c (kPa)
M1	20°22'	60.45	40°33'	50.20	20°55'	34.55	35°09'	34.50
M2	24°38'	43.05	40°55'	38.50	25°25'	24.22	37°05'	23.50
M3	24°03'	40.35	41°32'	31.40	21°23'	30.00	41°00'	21.30
Average value	23°28'	47.95	41°13'	40.03	22°34'	29.59	38°11'	26.43
Average square deviation	2°31'	10.91	0°52'	9.49	2°54'	5.18	3°01'	7.07
Variation coefficient	0.10	0.23	0.01	0.24	0.11	0.17	0.08	0.27

with φ : Internal friction angle

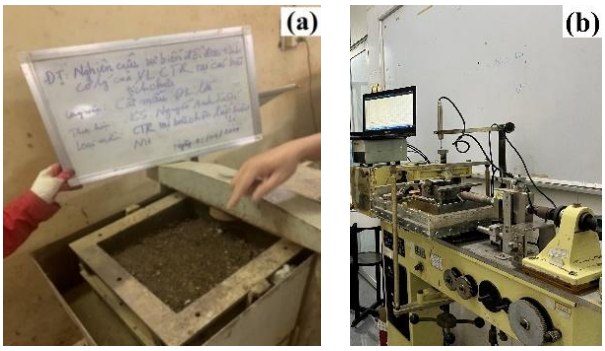


Fig. 12 – (a) Preparing sample for direct shear test; (b) Direct shear test on large MSW sample

These results provide important insights into the geotechnical properties of long-term landfill MSW, which are essential for stability assessment.

4 Stability analysis of the Cam Ly Landfill

4.1 Methods

The stability analysis of the Cam Ly MSW landfill was conducted using two separate methods: Limit Equilibrium Method (LEM) and Finite Element Method (FEM).

- LEM is a traditional method for stability analysis that calculates the safety factor of landfill. This method is based on established principles of equilibrium to evaluate the conditions under which failure may occur. The study was conducted using Geoslope software, which is widely used for slope stability assessment.

- FEM provides more complex analysis by considering the stress-strain relationship of the landfill material. This method allows modeling of the formation of failure zones based on the limiting properties of the MSW. FEM is generally considered more accurate and reliable because it can take into account complex interactions in the landfill structure and variations in material properties.

By employing both methods, the analysis aimed to provide a comprehensive understanding of the landfill stability, enabling effective management and mitigation strategies to address potential instability issues. The integration of LEM and FEM results provides valuable insights into the safety and performance of the Cam Ly MSW landfill under different loading conditions.

4.2 Materials

Due to the poor compaction of MSW at the Cam Ly landfill, geotechnical properties corresponding to 90% compaction for Layer 1 (MSW material) were used in the stability analysis. The geotechnical properties of the layers at the Cam Ly MSW landfill used for stability analysis are shown in Table 4 below.

Table 4 – The geotechnical properties of the layers at the Cam Ly MSW landfill

Geotechnical property	Layer F	Layer 1		Layer 2	Layer 3
		Case 1	Case 2		
Natural unit weight, γ (kN/m^3)	18.00	4.03	4.03	18.50	-
Cohesion, c (kPa)	17.70	47.95	29.59	19.40	-
Internal friction angle, φ (Degree)	$13^0$30’	$23^0$28’	$22^0$34’	$13^0$57’	$35^0$00’
Young modulus, E (kPa)	8,914	3,714	3,450	5,591	14,000
Poisson’s ratio, υ	0.30	0.35	0.35	0.32	0.30

4.3 Analysis results

The stability analysis of the Cam Ly MSW landfill was conducted using both LEM via Geoslope/W software and FEM using Plaxis 2D software. The analysis was conducted for two separate cases: (1) Dry season (c and φ of Layer 1 corresponding to 90% compaction and under optimum water content conditions were used); (2) Rainy season (c and φ of Layer 1 corresponding to 90% compaction and under saturated conditions were used).

The results are summarized in Table 5 and illustrated in Fig. 13 and 14.

Table 5 – The stability analysis results of the Cam Ly MSW Landfill

Analysis case		Material model	LEM via Geoslope/W	FEM via Plaxis 2D
Factor of safety (FS)	Case 1: Dry season	Mohr - Coulomb, Undrained A	0.842	0.700
	Case 2: Rainy season		0.423	0.400

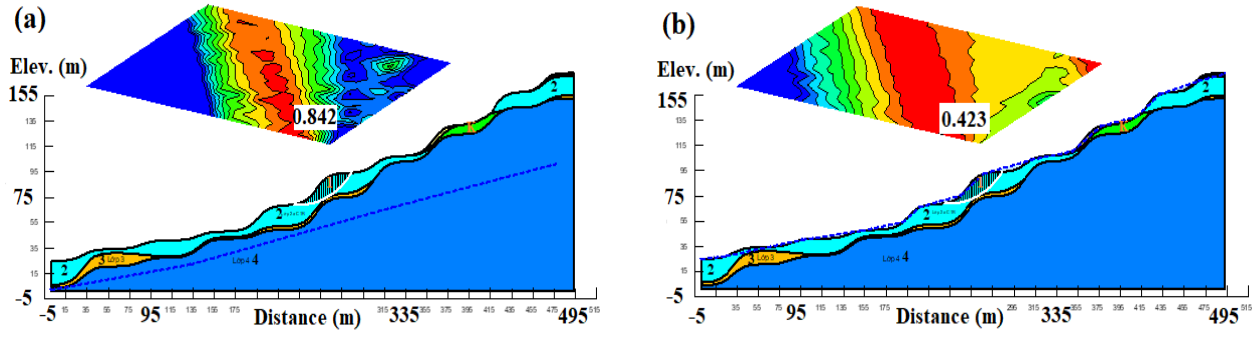


Fig. 13 – Failure surface at the Cam Ly MSW landfill was determined using Geoslope/W software for Case 1 (Fig. 13a) and Case 2 (Fig. 13b)

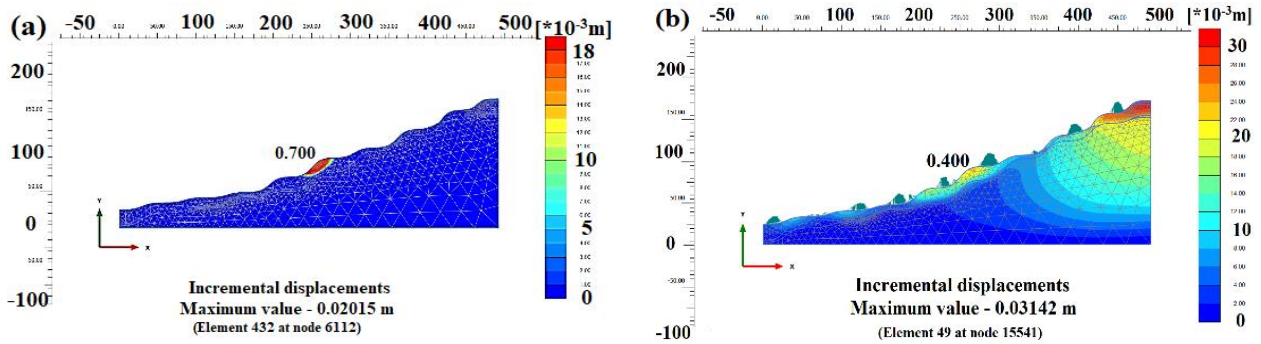


Fig. 14 – Failure surface at the Cam Ly MSW landfill was determined using Plaxis 2D software for Case 1 (Fig. 14a) and Case 2 (Fig. 14b)

4.4 Discussions

The results of the study showed the following:

The stability analysis results from both methods (Geoslope/W and Plaxis 2D) are quite similar, with a deviation range of deviations from 6% to 20%.

The factor of safety decreases significantly when the landfill is saturated. Under saturated conditions, the factor of safety decreases from 43% to 50%.

Comparison of stability analysis results with actual field observations shows that the predicted failure surface is close to the actual failure surface. The failure initiated at a steep section of the landfill and then spread to lower terrain. The slope failure first occurred in 2019 and further expanded in 2020 (Fig. 15).

The slope instability type at the Cam Ly MSW landfill corresponds to Type 1 (slip surface inside the waste pile) based on Zhang's classification.

The main causes of instability at the Cam Ly MSW landfill were the steep terrain, poor compaction of the MSW, and saturation due to prolonged heavy rain.



Fig. 15 – Failure surface at the Cam Ly MSW landfill was captured in August 2019 (Fig. 15a) and in July 2020 (Fig. 15b) (Resource: Google Earth Pro)

5 Conclusions

This study investigates the Cam Ly MSW landfill in Da Lat City, Lam Dong Province, Vietnam, where the geotechnical properties of MSW and soil layers were analyzed through both in situ and laboratory tests. The types and causes of slope instability at the landfill were examined. Fresh MSW primarily consists of soil (61.02–72.36%), textile and fiber materials (9.15–12.97%), wood and plastic materials (5.94–8.00%), and glass, broken bricks, iron, and steel (remaining proportion). The long-term landfilled MSW is predominantly composed of silty sand (SM) and silt (ML, MH) with an organic content of around 15.5%. This soil-like MSW can be tested and classified according to soil testing procedures. Geophysical survey results revealed that MSW generally exhibits low resistivity values (< 30 Ωm), indicating that geophysical surveys are effective tools for determining the thickness and distribution of MSW, which is useful for evaluating landfill stability and post-closure planning. A comparison of stability analysis results using the Geoslope/W and Plaxis 2D methods with field observations showed a high degree of consistency in predicting failure surfaces. The Finite Element Method (FEM) is considered more precise and reliable for such analyses. The instability at the Cam Ly MSW landfill is classified as type 1 (slip surface within the waste pile) according to Zhang's classification. The primary factors contributing to instability include the steep terrain, inadequate compaction of the MSW, and saturation from prolonged heavy rainfall. These findings enhance the understanding and management of landfills and offer insights for improving landfill stability in similar environments.

Acknowledgments

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