Slope Stability of Solid Waste Layers inside and outside of Japan

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EXECUTIVE SUMMARY

The present research aims to develop methods for assessment of slope stability of deposits of industrial solid waste that have been formed as a result of illegal dumping or similar acts in Japan. For this purpose the authors studied the patterns of slope failures by surveying 23 sites with reported threat of slope failure in Japan and studied cases of actual failures inside and outside of Japan with a focus on differences in the conditions under which the large-scale slope collapse occurred.

Strength tests including on-site loading test, in-site direct shear test, tensile test and a newly-developed repose angle test were performed at 8 sites in Japan, 1 site each in China, Indonesia and Turkey. A slope (height=9m, slope angle=63°, load weight=8.6kN/m^2) was formed so that the safety factor for possible failure predicted by the conventional soil ground slope stability analysis would be 0.56. However no collapse or even any displacement occurred.

The present research has revealed that solid waste layers that contain fibrous materials possess tensile resistance, which must be taken into account in addition to the angle of internal friction (φ) and cohesion (c) that are used in conventional circular slip analysis. Therefore, we propose a simplified equation of the infinite slope method that takes into consideration the tensile resistance.
The results of the direct shear tests showed that all the sites investigated had significantly large friction resistances comparable to normal soil; the data of sites in Japan containing fibrous materials were φ=46 - 51° and c =3 - 4 kN/m^2. The repose angle tests every case resulted in the repose angle after avalanching being nearly equal to the φ value obtained by the direct shear test.
The results of the infinite slope method and the circular slip surface analysis correlated well. In addition, the results of these calculations correlated well with the situations of the sites.

These tests and analyses enabled to quantitatively assess the slope stability of illegal dumping sites, reflecting the real situation better than by conventional assessment methodologies. The study explains the slope stability sufficiently well insofar as the dumping is on flat ground and is of typical composition with fibrous materials without containing excess water. With respect to dump sites sitting on inclined ground, however, large-scale failure is possible regardless of the front slope angle or of the composition of the solid waste. Furthermore, large-scale collapse can occur at a relatively mild angle inside nearly-saturated waste layers that are typically found in landfills in Southeast Asia and elsewhere.

1. INTRODUCTION

Deposited solid waste layers are often formed to have steep slopes and the threat of slope failure is discussed almost without exception. In reality, however, there is no confirmation regarding slope failures of significant scale among the large number of illegal dumping sites (Mainly debris and no kitchen waste) in Japan, with only one exception; as a result of heavy rain, there was a complete failure, along the slip surface, of the entire solid-waste layer positioned on an inclined surface. The authors investigated the strength test methods and analysis methods for more quantitative assessment of slope stability of deposited solid waste layers inside and outside of Japan.

2. MATERIALS AND METHOD

2.1 Site categorization for slope stability assessment and slope failure

The surveyed illegal dumping sites were categorized according to physical properties resulting from the different types of prior treatments (direct dumping (= no prior treatment), with intermediate treatment, and sorting residues) and from strength properties linked to the presence of fibrous materials (See Table 1). While no slope failures occurred at sites located on flat land except for one incident of surface collapse of an upright solid waste wall (Photograph 1), surface collapse or the like occurred in more than half of the dumping sites located on inclined ground. No slope failures caused by earthquakes have been reported at solid waste deposit sites containing fibrous materials in or out of Japan.

Table 1. Categories of illegal dumping sites and incidence of slope failure in Japan

Shape and type of waste (No kitchen waste)	**Sites of threatened slope failure by ground layer type** Note1) [ ]: were actual failure incidents Note 2)		
	Flat land	Inclined	Total
1. Mainly big debris, square timbers, and other bulky waste	2 [0]	2 [1]	4 [1]
2. Fibrous materials much contained (generally 10 cm or more in length)	9 [1] photo.1	3 [1]	12 [2]
3. Mostly fine grains (including plastics and fibers)	4 [0]	0 [0]	4 [0]
4. Mainly earth and sand and ash (little plastics and the like)	1 [0]	2 [2]	3 [2]
Total	16 [1]	7 [4]	23 [5]

Note 1) Number of sites known to the authors through government cleanup projects and their own research in the present study
Note 2) Number of sites that sufface collapse or slope failure

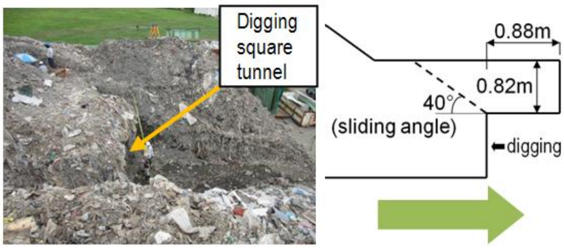
Photograph 1. Upright solid waste wall (Kanto-1 site, after surface collapse)

2.2 On-Site Loading/Collapsing Test

With a view to understanding the slope stability of solid waste deposits, a loading/collapsing test was conducted in the premises of a solid waste final treatment facility in Shanghai, China. A section of the Chinese site that had similar waste composition to those in Japan was chosen for the test (plastics content = 16 wt%, moisture content = 42%). A slope (Photograph 2, height = 9 m, slope angle = 63°, load weight = 8.6 kN/m^2) was formed so that the factor of safety for possible failure predicted by the conventional soil ground slope stability assessment method (circular slip analysis) would be 0.56 (see Figure 7(Right)) using strength parameters “*c*” (cohesion) and “φ” (angle of internal friction). In addition, cut-outs were made to both sides and in the back and external force was exerted from behind by injecting 10 cubic meters of water and by pushing with a backhoe bucket. No collapse or even any displacement occurred. The test confirmed that the conventional circular slip analysis for soil grounds is not suited to assess the slope stability of resilient solid waste deposits.

Then, with a view toward investigating the collapse phenomenon inside solid waste deposits, a square tunnel-like cavity was dug out slowly by a backhoe at a point approximately 0.8 meter below the top of an illegal dumping site in Japan (see Photographs 3-4). When the excavation depth reached approximately 0.9 m, abrupt dislocation and collapse occurred. The tensile stress that acted on the collapsing part of the solid waste layer was 34 kN/m^2. This tensile stress is approximately equal to the shear strength that is considered to have acted on an estimated slip surface of the loading test in Shanghai. The collapse occurred like a flow-down at an angle of 40°, unlike the vertical drop observed with ordinary soil. This is believed to be due to the tensile resistance of the fibrous materials contained in the deposit. It was suggested that a collapse of a solid waste layer containing fibrous materials is likely to occur at a relatively mild angle with a slip surface direction close to horizontal (the dominant direction of the fibers).

Photograph 2. Loading test
(Shanghai Site)
(Slope stable even though safety factor was 0.56 by conventional assessment)



Photograph 3. Collapsing test site
(Chubu-1 Site)

Photograph 4. After collapse
(Failed at 40°)

2.3 Strength Tests

Strength tests were conducted at 11 sites in and out of Japan. The angle of internal friction (φ), cohesion (*c*), and angle of tensile resistance (ζ) are the strength parameters that are needed to know the shear resistance (see Figure 1). Suitable tests to measure these parameters are direct shear tests (Figure 2) and tensile tests (Figure 3), given the slope surface and the direction of deposited fibrous materials shown in Figure 1. For the purpose of the present study, an apparatus was manufactured for direct shear tests at solid waste dumping sites. A mass having dimensions of 30 cm × 30 cm × 15 cm is cut out from the surface of the solid waste deposit carefully so as to avoid disruption of the solid waste layer. After shaping, the test sample is put into a shear box of the same dimensions for measurement of shear resistance. The tensile test was conducted with an apparatus originally developed by Koelsch [2] and redesigned and manufactured for the purpose of this study to a smaller size with necessary modifications to better suit the laboratory of local Japanese conditions. An apparatus consisting of two connected boxes, each measuring 50 cm × 50 cm × 50 cm, was used. For investigating stable slope angles of waste layers, repose angle tests were performed by using earthmoving machinery at sites. Solid waste was scraped and spread out using a backhoe to form heaps (see Photograph 5). The slope angle of each heap was measured by a slant rule.

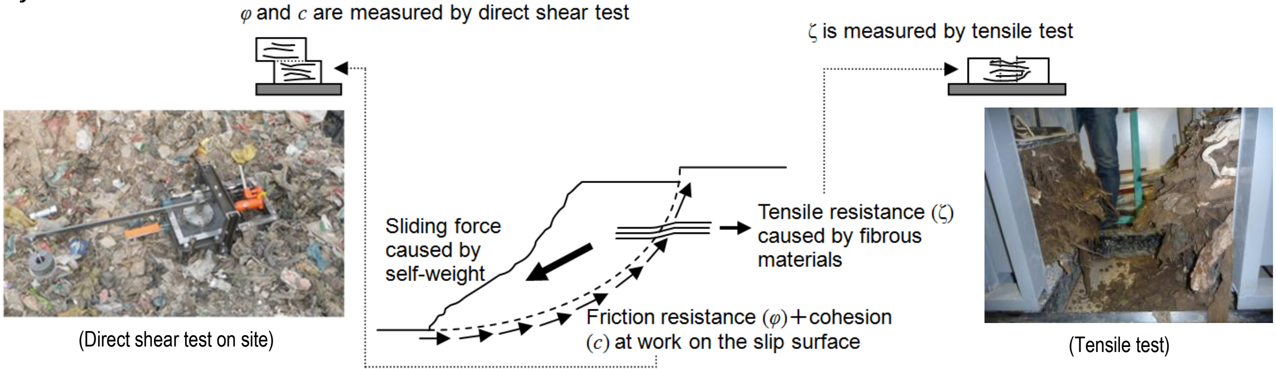


Figure 1. Model of the slope of a fibrous materials-containing deposit

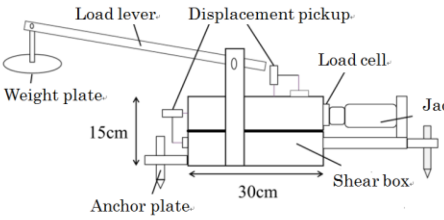


Figure 2. Direct shear test equipment

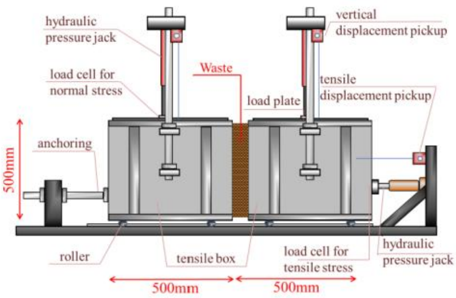


Figure 3. Tensile test equipment

Photograph 5. Repose angle test

3. RESULS AND DISCUSSION

3.1 Strength Tests

Results of strength tests in and out Japan are summarized in Table 2. The results of the direct shear tests showed that all of the sites investigated had significantly large friction resistances comparable to normal soil. The data for sites in Japan containing fibrous materials were φ = 46-51° and c = 3 - 4 kN/m^2; Tohoku site that consisted of crushed and sorted residues had φ = 47° and c = 11 kN/m^2, while Kyushu site that had mostly earth and sand showed φ = 45° and c = 3 kN/m^2. In every one of the cases tested, φ was greater and c was smaller than those of normal soil. The likely cause of such large friction resistances of deposited solid waste at illegal dumping sites and the like in Japan is the biting effect caused by the broad diversity of solid waste in size and weight as is evidenced by the considerably larger particle size distribution of such deposits than that of common soil. The overseas sites tested showed rather small φ values. This is likely due to the high moisture content caused by the dominant presence of kitchen waste and other household waste and the relatively low content of debris and other heavy solid waste, which made the friction resistance low. A direct shear test of Kanto-1 site sample in the laboratory (figure 4) confirmed anisotropy of shear resistence and its decrease by excessive water.

The tensile test was carried out using a sample from Kanto-1 site. A value of ζ = 18° was obtained from this test. This value is lower than the 25 - 35° that Keolsch [2] obtained for untreated municipal waste. The likely reason is that illegal dumping sites in Japan do not contain as much plastics or other fibrous materials as municipal waste.

The repose angle tests in every case resulted in the repose angle after avalanching being more or less equal to the φ value obtained by the direct shear test. The repose angle after avalanching is the angle of the slope that becomes stable after heavy materials slide down the slope of a heap formed by solid waste loading and spill-over (see Figure 5). It is considered that, when the heavy materials are sliding down the slope of the heap formed by the repose angle test, plastics and other fibrous materials in the solid waste cannot resist the fall energy of the heavy materials and the solid waste builds up without the effect of tensile resistance, and that the cohesion of the solid waste layer is so small that the repose angle after avalanching is determined only by the working of frictional resistance, resulting in the observed closeness to the φ value. In addition, the repose angles after avalanching were nearly equal to the angles of the stable slopes at the sites, and slope failures and cracks were observed in the slopes that were at larger angles than the repose angle after avalanching. These facts all point to the usefulness and effectiveness of the repose angle test as a convenient assessment method.

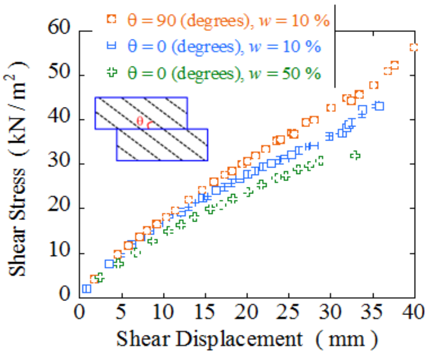


Figure 4. Result of Direct shear test of Kanto-1 site sample, varying shear direction and water contents

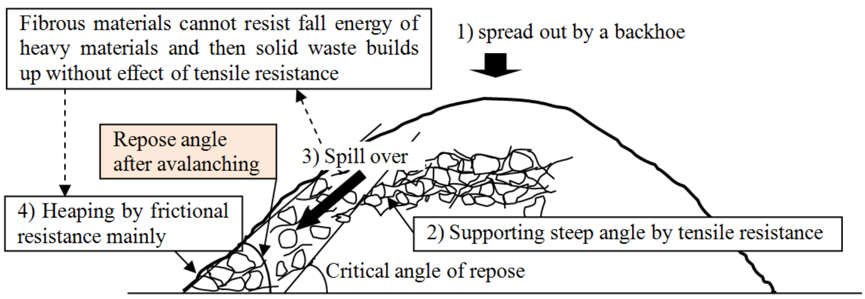


Figure 5. Repose angle after avalanching

3.2 Slope stability analysis

Koelsch [1] provides the tensile resistance resulting from fibrous materials through Equation (1) (2).

$$\tau(z) = G / b \tan\zeta \cdot \sin(1.5\theta) \quad (1)$$

$$T = \frac{G \cdot \tan\varphi + c \cdot b + G \cdot \tan\zeta \cdot \sin(1.5\theta)}{\mu \cdot \sin\theta \cdot \tan\theta + \cos\theta} \quad (2)$$

Where $\tau(z)$: tensile resistance exerted on the slip surface (kN/m^2)
T: Total shear resistance exerted on the failure surface (kN/m)
G/b: weight of solid waste on the slip surface for a given width (kN/m^2)
c: cohesion (kN/m^2) φ: angle of internal friction by Coulomb's formula (°)
ζ: angle of tensile resistance (°) θ: slope angle of the slip surface (°)
μ: reciprocal of the factor of safety

For the slope stability assessment of sites in Japan containing fibrous materials, we propose a simplified Equation (3) because the cohesion is small, as shown in Table 2. Equation (3) is the standard stability analysis equation used in the infinite slope method (Figure 6), but it includes the tensile resistance factor from Equation (1) and ignores the cohesion factor.

$$Fs = T / Tg$$

$$T \fallingdotseq N \cdot \tan\varphi + \tau(z) \cdot l \qquad Tg = G \cdot \sin\theta$$

Hence, $$Fs = \frac{\tan\varphi}{\tan\theta} + \frac{\tan\zeta \cdot \sin(1.5\theta)}{\sin\theta \cdot \cos\theta} \qquad (3)$$

Where Fs: factor of safety
Tg: force to cause slipping (kN/m)
Others: the same as in Equations (1) and (2)

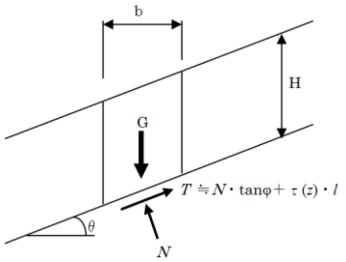


Figure 6. Infinite slope method

Table 2 and Figure 7 show the calculation results according to Equations (2) and (3). The results of Equations (2) and (3) correlated with each other well. Slope stabilities of upright wall (Figure 7 Left) and loading test result (Figure 7 Right) are explained by the calculation including tensile resistance (ζ).

Table 2. Results of Strength test and Slope stability analysis

Site	**Solid waste type** ( ): plastics content by weight (%) w: moisture content (%), γ: wet density (g/cm^3)	**Mean slope angle** ***θ*** **(°)** [ground]	**Slope height (m)**	**Repose angle after avala-nching (°)**	**Direct shear test** φ (°)	*c* **(kN/m^2)**	ζ(°)	***Fs*** **: Equa-tion (2)**	***Fs*** **: Equa-tion (3)**	**Condi-tions of site**
1.-1 Chubu-1	Mostly debris & earth (----) w: not measured	47 [Flat]	9	36	(36 *1)	(3 *2)	(7*2)	1.08	0.91	stable
2.-1 Kanto-1	Fibrous materials (16), w = 31, γ=1.2	90 [Flat]	11.5	50	46	3	18	1.08	-----	surface collapse
2.-2 Chubu-2	Fibrous materials (6), w = 13, γ = 0.9 (60° slope)	60 [Flat]	11	45–52	51	4	(10 *2)	1.23	1.12	cracks
2.-3 Chubu-3	Fibrous materials (50 by volume) w = 17, γ = 0.7	25 [Inc.-Flat]	30	45	(45 *1)	(3 *2)	(15 *2)	3.45	2.62	stable
3.-1 Tohoku	Sorting residues (0.4, wood 6) w = 40, γ = 1.1	40 [Flat]	3	40	47	11	0	3.45	1.28	mostly fine
4.-1 Kanto-2	Mostly earth & sand (2) w: not measured. γ = 1.4	30 [Flat]	40	-----	-----	>70	0	>1.14	-----	Conso-lidated
4.-2 Kyushu	Mostly earth & sand (Nearly 0) w = 23, γ = 1.4	30 [Inc. 20°]	40	44	45 [0]	3 [60]	0 [0]	1.92 [1.20]	1.88 [-----]	surface collapse
4.-3 Kansai	Mostly earth & sand (Nearly 0) w = 14, γ = 1.1	40 [Inclined]	20	36	(36 *1)	(3 *1)	0	0.93	0.87	surface collapse
Shanghai (test site)	Fibrous materials (16) w = 42, γ = 1.1	63 [Flat]	9	-----	38	5	0 (15 *2)	0.56 0.93	0.40 1.06	stable
Turkey (landfill)	Fibrous materials w=45, γ=1.0	25 [ca. Flat]	40	36-46	(36 *2)	(3 *2)	(15 *2)	1.72	1.98	rather wet
Jakarta (landfill)	Wet Fibrous materials Water content by volume = 72%, γ: not measured.	40 [Flat]	6.5	36–40	(36 *1)	(3 *2)	(15 *2)	1.56	1.34	wet

*1 : Repose angle after avalanching *2 : Assumed value (standard value based on test results and others)

Note: Circular slip calculation (Equation (2)) by "GGU-STABILITY VERSION 9" [4]

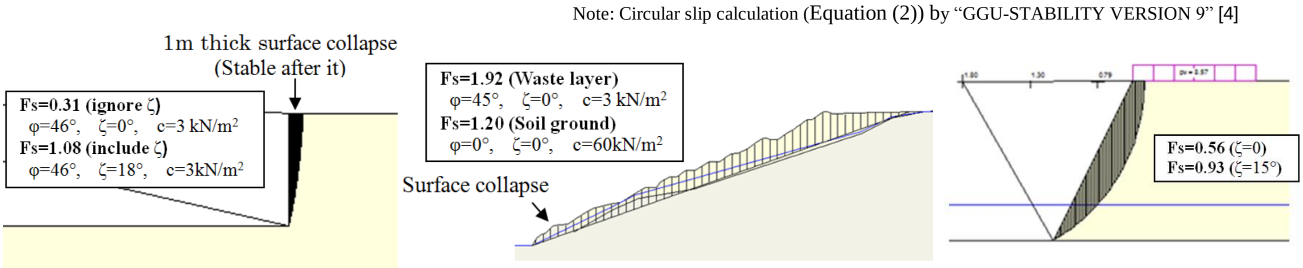


Figure 7. Results of circular slip analysis (Left: Kanto-1, Center: Kyushu, Right: Shanghai)

Note: Circular slip calculation by "GGU-STABILITY VERSION 9" [4]

3.2 Slope Failure Patterns Requiring Attention at Solid Waste Dumping Sites

Actual records of slope failures (Table 1) and slope stability analysis results (Table 2) show that sites situated on flat ground and containing fibrous materials are hardly prone to failure, because the deposit has a high shear strength including tensile resistance. The actual incidence of failure on flat ground is limited to a surface failure that occurred at a slope with an angle sharper than the repose angle after avalanching. The embankment surface failed in an action to remain stable at the repose angle after avalanching (see Figure 8 Left). Another cause of slope failures scarcely occurring at illegal dumping sites (Mainly debris and no kitchen waste) in Japan is the large volume of void (generally 20-40% in Japan) of the solid waste layer and the resulting quick drainage of rain, which hardly gives rise to pore water pressure.

Large-scale slope failures on inclined ground have occurred in Japan. A collapse of deposits on an inclined ground is a slip failure in which the entire solid-waste layer slides down along the valley (Figure 8 Right). There is in this case no tensile resistance acting on the interface between the solid waste layer and the ground. The slope stability analysis results in Figure 7 (Center) show that the factor of safety of the ground of the Kyushu site, which is a dump site sitting on an inclined ground, is 1.20, or smaller than the 1.92 factor of safety of the solid waste layer. We have confirmed in the present study that the shear strength decreases if the solid waste contains excess moisture (see Figure 4), as was found with the collapse incidents of kitchen waste deposits overseas. At a site like this or when some horizontal force or other excessive force is exerted, slope failure can occur inside the solid waste layer at a relatively moderate angle close to the dominant direction of the fibers (see Figure 9).

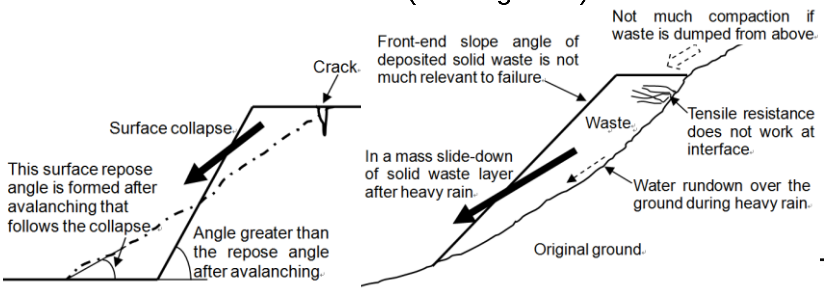


Figure 8. Typical slope failure patterns at solid waste sites in Japan (Left: Surface collapse, Right: Large scale failure)

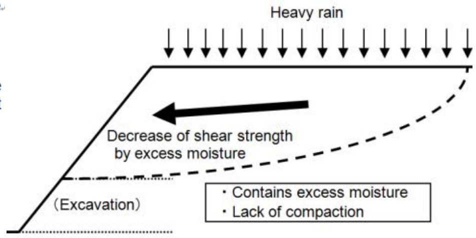


Figure 9. Mild slope failure (Mainly outside of Japan; kitchen waste etc.)

CONCLUSION

These tests and analyses enabled to quantitatively assess the slope stability of solid waste layers, reflecting the real situation better than by conventional assessment methodologies. The study explains the slope stability sufficiently well insofar as the dumping is on flat ground and is of typical composition with fibrous materials without containing excess water. With respect to dump sites sitting on inclined ground, however, large-scale failure is possible regardless of the front slope angle or of the composition of the solid waste. Furthermore, large-scale collapse can occur at a relatively mild angle inside nearly-saturated waste layers that are typically found in landfills in Southeast Asia and elsewhere.

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