Landfill Failure Mobility Analysis: A Probabilistic Approach

Ali Jahanfar, Brajesh Dubey, Bahram Gharabaghi, Saber Bayat Movahed

Abstract**—**Ever increasing population growth of major urban centers and environmental challenges in siting new landfills have resulted in a growing trend in design of mega-landfills some with extraordinary heights and dangerously steep slopes. Landfill failure mobility risk analysis is one of the most uncertain types of dynamic rheology models due to very large inherent variabilities in the heterogeneous solid waste material shear strength properties. The waste flow of three historic dumpsite and two landfill failures were back-analyzed using run-out modeling with DAN-W model. The travel distances of the waste flow during landfill failures were calculated approach by taking into account variability in material shear strength properties. The probability distribution function for shear strength properties of the waste material were grouped into four major classed based on waste material compaction (landfills versus dumpsites) and composition (high versus low quantity) of high shear strength waste materials such as wood, metal, plastic, paper and cardboard in the waste. This paper presents a probabilistic method for estimation of the spatial extent of waste avalanches, after a potential landfill failure, to create maps of vulnerability scores to inform property owners and residents of the level of the risk.

Keywords—Landfill failure, waste flow, Voellmy rheology, friction coefficient, waste compaction and type.

I. Introduction

IN 1977, a landfill in Sarajevo (Yugoslavia) failed leading to a movement of 200,000 m^3 of waste to a distance of up to one kilometer. Despite huge asset and environmental damages, no deaths were reported in this failure. Since then, in addition to environmental devastation, landfill failures causing fatalities have occurred in various parts of the world. A catastrophic Payatas landslide in July 2000 covered a valley by 30,000 m^3 of waste and killed hundreds of people. The Bogota landfill in Columbia failed in 1997 and the waste travelled 500 m, leading to creation of a waste dam on a river, polluting soil and water. One of the most recent landfill failures occurred in February 2005 in Bandung (Indonesia), where the waste flow due to failure encompassed an area of 200-250 m in width and 900 m in length. Around three million cubic meters of waste buried 147 people and destroyed rice fields [1]. A summary of slope failure cases are tabulated in Table I.

The hazard associated with landfill slope failure may cause significant risk if there is a consequence arising from the failure. It is possible to experience a high probability of hazard and a low probability of risk due to the low vulnerability (a vulnerable element, e.g., human, property, soil, water sources etc. could be located far away from landslide arising from slope failure). Thus, quantitative assessment of post-failure motion is a vital component in characterizing the extent of the endangered area, and eventually, the risk of landfill failure [2].

A landslide is defined as the movement of a mass of rocks, earth or debris down a slope which can be either natural or a result of human activity [3]. Landfills can be classified as man-made structures and their failures can be denoted based on human activity. Based on Rotaru [3], three major factors that control the potential of landfill failure are:

I. Slope gradient: Sarajevo, Istanbul, Payatas and Bandung dumpsite failures, with an approximately 45 degree slope prior to slope failure, suggesting that steeper slopes increase the likelihood of failure.
II. Waste Compaction: Most dumpsites have no systematic compaction [1]. In principle, the absence of waste compaction reduces the rainfall surface flow and increases the rate of water percolation into the waste. Infiltrated water may create excessive pore water pressures and reduce the waste shear strength. Further, Blight [4] determined that low waste compaction may lead to less cohesive waste material.
III. Water Pressure: Excessive pore water pressure reduces the waste shear strength. Hence, ten days of heavy rainfall in Payatas landfill and leachate injection in Bogota bioreactor landfill are examples where pore water pressure affected landfill slope failures [5].

Rotaru [3] listed different movement types of landslide including: fall, topple, slide, spread, flow and complex. Considering the waste material type, trigger mechanisms of failure and reported landfill failure characteristics, "flow-type" may potentially describe landfill post-failure movements. Differential shear strain along the slip surface is indicated in flow-type, as experienced in landfill failures. The Kettleman US landfill failure (1988) occurred along the base layer due to low strength of the liner system [6]. In another study, Koerner and Snoog [7] concluded that "wet clay beneath the geo-membrane" and "excessively wet foundation soil" is two liquid-related trigger mechanisms of landfill slope failures. Depending on the water content and failure movement velocity, waste flow can resemble "debris-flow" which is a flow-type movement (there are different flow-type movements such as rock-flow, earth-flow, debris-flow and mud-flow). Rapid movement of the saturated materials during the failure is the main characteristic of this flow-type. Considering the

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listed landfill failures (Table I), excessive water pressure due to the heavy rainfall and leachate build up saturates the waste materials. In addition, fatalities resulting from landfill failures may arise due to rapid movement of a waste flow preventing people from evacuating.

Since the early works of Hungr [8], landslide researchers have tried to better understand landslide mechanisms and to predict flow rheology. The rheology of the flow is denoted as "the resistance forces [that] interact inside the flow and at the interface between the flow and the bed path" [2]. Generally, rheology models are divided into cohesive and frictional types. Debris-flows as a mixture of solids and fluids are categorised as frictional types rather than cohesive types of mud-flows. The simplified frictional model and Voellmy's model are the two frictional types of rheology. Voellmy's model considers the effects of flow turbulence in addition to basic frictional features. Pirulli and Marco [9] reported overestimation with frictional rheology while the Voellmy model provides a much better estimation. Recently, the Voellmy model is found to be in agreement with observed global flow behaviour of landslides [2]. Researchers [2], [8]–[12] extensively used this common type of rheology in dynamic models and came up with reasonable results. In this study the waste flow is assumed to follow the Voellmy rheology.

TABLE I
HISTORICAL DUMP SITE FAILURES AND LANDFILL FAILURES

Reported by	Region	Year	Waste Volume	Failure Mode	Life Loss	Reason
[7]	USA	1984	110,000	Rotational	-	It was marginally stable before heavy rainfall occurred over 3 days period. Rapid rise in water table within the waste mass from elevation +0.0 m to +3.2 m.
[7]	USA, Kettleman	1988	490,000	Translation	-	Rainfall during construction and waste placement, as well as the consolidation water expelled from the CCL was reported to have caused an excessively wetted geo-membrane to CCL interface.
[7]	USA, Maine	1989	500,000	Rotation	-	After approximately 120 mm of rain fell for ten days prior to the incident.
[7]	Turkey, Istanbul	1994	12,000	Translation	39	Excessive leachate level buildup (estimated to be 5 m) within the old, decomposed waste caused by water infiltrating from adjacent surface water ponds
[7]	Europe	1994	60,000	Translation	-	Excessive wetness of the clay component of the HDPE geo-membrane to CCL interfaces. It was reported that the geo-membrane was placed during a very wet period when the CCL was already at high water content.
[7]	USA, Mahoning	1996	100,000	Translation	-	The triggering mechanism of the failure was a progressively increasing wet bentonite layer of the unreinforced geo-membrane GCL.
[7]	USA, Rumpke	1996	1.2 million	Translation	-	The additional buildup of leachate head in the landfill due to ice formation at the exposed waste face near the toe of the slope
[7]	Africa	1997	300,000	Translation	-	The failure occurred after 48-hours of rainfall. The triggering mechanism was determined to be excessive liquid waste placement into the already-saturated wood bark between the old and the recent sections of the landfill.
[7]	South, America	1997	1.2 million	Translation	-	The increase in leachate head within the waste mass due to the aggressive leachate injection operations.
[4]	Colombia, Bogota	1997	800,000	Translation	-	Pore pressure caused by recirculation of leachate
[4]	South Africa, Durban	1997	160,000	Rotation	-	Pore pressure caused by co-disposal of liquid wastes
[4]	Yugoslavia, Sarajevo	1977	200,000	Translation	-	N/A
[4]	Philippines, Payatas	2000	1.2 million	Rotational	330	10 days Heavy rain, Low waste density, Water percolation instead of drainage, reducing waste shear strength
[4]	Indonesia, Leuwigajah	2005	2.7 million	Translation	147	The extraordinarily large proportion of light waste (plastics) combined with disturbed water balances due to leachate circulation.

Voellmy [8] defined the resistance force (SF) as:

$$\mathrm{SF} = \mathrm{f} + \frac{\mathrm{u}^2}{\xi \mathrm{h}} \quad (1)$$

where, f is the friction coefficient, u is the flow velocity (m/s), ξ is the turbulence coefficient (m/s2) and h is the flow depth (m).

$$\mathrm{f} = \tan(\varphi_\mathrm{b}) = (1 - \mathrm{r_u}) \times \tan(\varphi), \quad (2)$$

where, φ_b is the bulk basal friction angle, r_u is the pore water pressure ratio and φ is the dynamic basal friction angle.

Unlike the moderate landslide models based on Coulomb's Law (Kinematics of sliding), the physical behaviour of excessive travel distances for the observed catastrophic landslides are hard to predict. This fact may depend on different reduction mechanisms of basal friction. Quan [2] explained friction reduction mechanisms within flow path and flow material intersection as:

I. Cushions of trapped air due to the water vapor by the friction heat can lubricate the flow. Specifically, gas generation in landfills by biochemical and chemical reactions may increase trapped gas volumes;
II. Originally smooth bed materials such as limestone, gypsum or glaciers as well as the regular bed materials which are made smooth by frictional melting may lubricate the flow; and,
III. The saturation of the flow materials increases the liquid content of the flow, and may reduce the interface friction between bed materials and flow materials.

However, in addition to the above reduction mechanisms of basal friction, the dynamic basal friction (φ) is normally less than static basal friction. Considering the effect of pore water pressure ratio (r_u), the bulk basal friction angle (φ_b), would range between 3° to 11°.

Recently, several numerical models such as MADFLOW, TOCHNOG, RAMMS, DAN3D, DAN-W, have been developed to simulate the run-out of landslides. These numerical models are able to compute different run-out aspects including travel distance (run-out distance), thickness, and velocity. The computed outputs can be associated with vulnerability for a quantitative risk assessment [2].

Sudden landfill slope failures continue to claim lives and destroy properties as well as pollute the environment. Waste travel distance after the landfill failure is critically important to calculate the extent of endangered areas, which can be developed by numerical models.

Dynamic run-out models are commonly used for back-analysis of past events. These models are sensitive to friction coefficient parameters, which leads to a lack of reliable calibration. This is the basic limitation of run-out models [2]. However, recent investigations contain a number of back-analyses to calibrate input parameters for run-out models in terms of rock, debris and soil materials failures [9], [10], [13], [14]. But as per the extensive literature review conducted as part of this research, no literature was identified to calibrate run-out models for waste material failures.

To summarize, some of the works on run-out model calibrations: Hungr and Evans [15] back-analysed 23 well-recorded rock avalanches with DAN-W software. Simple Frictional, Voellmy and Bingham rheologies have been alternatively used for all events. Both simple frictional and Bingham rheologies overestimated the landslide velocities, while the Voellmy rheology obtained a good fit. The best estimation of travel distance and thickness is also obtained by the Voellmy rheology [15]. Revellino et al. [10] presented successful calibration results which were obtained after 19 back-analyses of similar debris avalanches. A single set of the Voellmy rheology input parameters was employed in the Revellino et al. [10] calibration. Using a statistical approach, McKinnon [13] examined frictional and Voellmy rheologies using DAN-W software to investigate run-out model of 40 rapid flow-like landslides. Normalized mean values and associated standard deviations for run-out parameters were provided in the McKinnon [13] study, and were recommended as a reliable range for predictive modeling of future events.

Although the technical literature mostly contains resistance parameters (e.g. friction and turbulence coefficients for Voellmy rheology) and calibration to predict future run-out events, McKinnon [13] emphasized that the calibrated resistance parameters should not be deterministic. This is because of a failure may happen via various pathway situations of run-out, and the characteristics of flow materials are potentially different, spatially and temporally. Thus, it is not logical to claim constant values as resistance parameters, and so a "realistic range of parameters" may provide a probable condition for landslide run-out prediction [13]. Given this, the objective of this study is to provide an analysis tool (methodology) for modelling of waste flow in the event of landfill failure, approached by calibrated probabilistic distributions of resistance parameters. Resistance parameters are obtained by performing the back-analyses of previous landfill failures.

II. Methodology and Material

The dynamic software model, DAN-W, developed by Hungr [8], has been used herein to back-analyse the extent of waste movement from the landfill failures. Similar to most common debris-flow models in the reviewed literature [8], [9], [15], [16], Voellmy rheology has been chosen as the rheology kernel to simulate waste flow. In terms of the calibration, this rheology contains two major factors including friction and turbulence factors. The friction factors (Friction Coefficient and initial friction angle) mostly effect the travel distance of the flow, while the turbulence factor frequently influences the velocity of the flow [13]. High ranges of the turbulence coefficient potentially reduce the effect of velocity on the resistance force (SF).

Although DAN-W software can incorporate variable characteristics, including point dispalcements, thicknesses, velocities, etc., the focus of this study is on the travel distance of waste flow, following landfill slope failure. Because the maximum run-out distance is an apparent feature of the flow which can be measured with a high accuracy at any time after the failure, a temporal characteristic such as velocity is required for on-time monitoring or for indirect calculations which are not applicable and reliable for landfill failure case studies.

In comparison to deterministic stability analyses, a probabilistic approach with Monte Carlo simulations, can provide reasonable and practical mobility analysis considering natural heterogeneity in MSW geotechnical material properties. Three dumpsite failures (Sarajevo, Istanbul, Bandung,) and two landfill failures (Durban and Ohio) have been investigated in this study. Considering the fact that these slopes failures have already occurred, the travel distances of the waste flow after the landfill failures have been used to back-analyse the run-out models and improve estimates of input parameters. To approach this goal, "simplified probabilistic back-analysis" is employed (after [17]). Zhang et al. [17] described the mathematical equations to back-calculate the normally distributed parameters such that the travel distance of the run-out model equals (within ±0.05) the observed travel distance.

Voellmy rheology contains fixed and variable factors. Here, we assumed the friction coefficient and initial friction angle as variable factors. Babu et al. [18] reported that the normal distribution of friction angle of waste materials is 32.27° for the mean value and 7.89° for the standard deviation. So in this study, the range of the friction coefficient factor has been calibrated as a probabilistic distribution.

Due to the lack of information about waste flow velocity after the landfill failures, as per the McKinnon [13] recommendation, the turbulence coefficient is assumed equal to 1500 m/s^2 in all of the landfill failure models. However, the model's velocities have been calculated to exceed the human running speed (5 m/s), because all of the landfill failure case studies have been described as catastrophic or fatal events. Table II illustrates fixed characteristics of the waste materials in Voellmy rheology and default DAN-W parameter values which have been used in the back-analyses.

To estimate the friction coefficient, this study reviewed relevant studies on landslides and introduced statistical distributions for this parameter. McKinnon and Hungr [16] estimated typical friction coefficient ranges of 0.07 and 0.2 for debris-flow and 0.03 to 0.24 for rock avalanche models with DAN-W software. In another study, Mckinnon [13] estimated 0.1 for the friction coefficient in flow-type movement. However, Quan [2] indicated 0.162 and 0.136 for the mean and standard deviation respectively of the best-fit normal distribution to the friction coefficient histogram of 168 studied landslides. In this study, the primary probabilistic distribution of friction coefficient was assumed to be a normal distribution with mean= 0.15 and 0.1 for standard deviation. This primary distribution has been used as an input in the back-analyses.

TABLE II
DAN/W MODEL PARAMETER VALUES USED IN BACK-ANALYSES

Control Parameters	Default values	Material Parameters	Default values
Number of elements	50	Unit weight	11.13 kN/m^3 [18]
Time intervals	0.02-0.1 s	Turbulence Coefficient	1500 m/s^2
Smoothing coefficient	0.02	Erosion Depth	0.0
Tip ratio	0.5	Internal Friction Angle	32.27°mean and 7.89° standard deviation [18]
Stiffness coefficient	0.05		
Stiffness ratio	5		
Centrifugal force	On		
Boundary block geometry	Vertical		
Pressure term	modified		

Zhang et al. [19] stated the simplified probabilistic back-analysis equation for normally distributed parameters. Assuming μ_θ as a mean and C_θ as a covariance matrix of θ primary distribution, the objective of probabilistic back-analysis is then to improve the probabilistic distribution of θ to $\mu_{(\theta|d)}$ and $C_{(\theta|d)}$:

$$\mu_{(\theta|d)} = \mu_\theta + C_\theta H^T (H C_\theta H^T + \sigma_\varepsilon^2)^{-1} [1 - g(\mu_\theta) - \mu_\varepsilon] \quad (3)$$

$$C_{(\theta|d)} = \left(\frac{H^T H}{\sigma_\varepsilon^2} + C_\theta^{-1}\right)^{-1} \quad (4)$$

$$H = \left.\frac{\partial g(\theta)}{\partial \theta}\right|_{\theta=\mu_\theta} \quad (5)$$

Defining $g(\mu_\theta)$ as a ratio of travel distance in the run-out model over observed travel distance in reality; when this factor is equal to unity, the back-analysis loop is completed. "H" is the measured slope representing the sensitivity of $g(\theta)$ with respect to θ at point μ_θ. Quantifying the effect of model imperfection, μ_ε and σ_ε are considered as the mean and standard deviation of this factor. Regarding uncertainties of the simulation $\mu_\varepsilon = 0.01$ and $\sigma_\varepsilon = 0.01$ are suggested. The limitation of this method is that it is applicable only when $g(\theta)$ is largely linear around the point μ_θ.

Fig. 1 illustrates the flowchart of the methodology. Using literature data to characterize the friction prior to distribution, two landfill failures and three dumpsite failures were back-analysed to estimate the friction posterior distributions. Finally, the optimized probabilistic distributions for the friction coefficient have been provided. These results can be used for project-specific design when data are not available. Having the friction coefficient distribution, the range of travel distance can be obtained with the Taylor's series method.

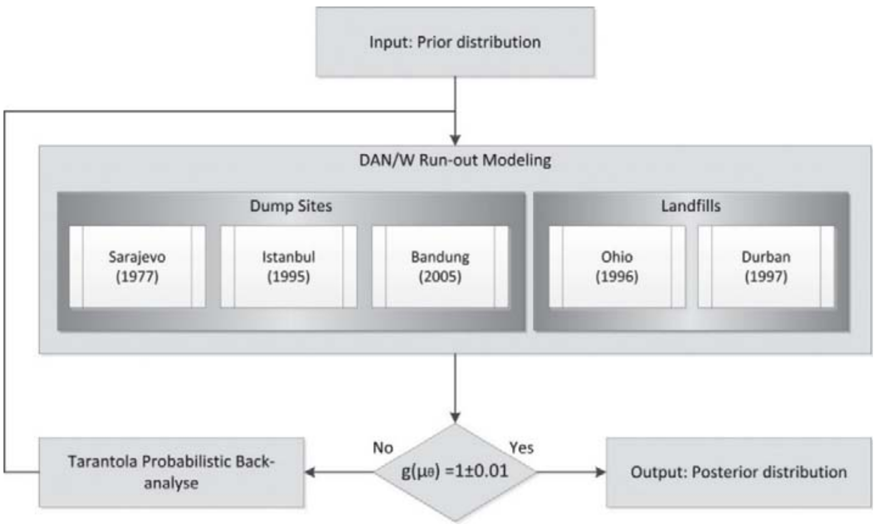

Fig. 1 The flowchart of methodology

Assuming friction coefficient and initial friction angle distributions as inputs (IP1, IP2) and travel distance distribution as an output (OP) of the model, the Taylor's series method can be used to calculate the mean value and standard deviation of the output distribution. The mean value of travel distance distribution can be obtained considering the mean value for friction angle and friction coefficient parameters. The standard deviation of travel distance distribution is equal to:

$$SD = \sqrt{\left(\frac{\Delta OP_1}{2}\right)^2 + \left(\frac{\Delta OP_2}{2}\right)^2}, \quad (6)$$

where, ΔOP_1 and ΔOP_2 can be provided by increased and decreased $IP_1$and IP_2 mean values by one standard deviation [20].

As a result, travel distance distribution can be obtained using the friction angle and friction coefficient distributions. This may be beneficial for finding the range of waste flow when the landfill failed.

III. Results

A. Sarajevo Dumpsite Failure (1977)

The MSW flow slide is reported in technical literature for Sarajevo dumpsite, 6 km away from city borders. In December 1977, 200,000 m^3 of waste slid down and traveled 900 m. No compaction was reported during the operation of this dumpsite. Although there were no injuries or deaths, two bridges and five houses were destroyed and extensive contamination of the environment was reported as two stream beds got filled with waste materials.

Fig. 2 illustrates the Sarajevo dumpsite simulation after the failure with DAN-W. The best-fit travel distance obtained when friction coefficient is equal to 0.14. The thickness of the waste deposit after 850 m of run-out from site location gained 2.5 m which is equal to Blight’s [4] estimation for the same distance (1.5-2.5 m).

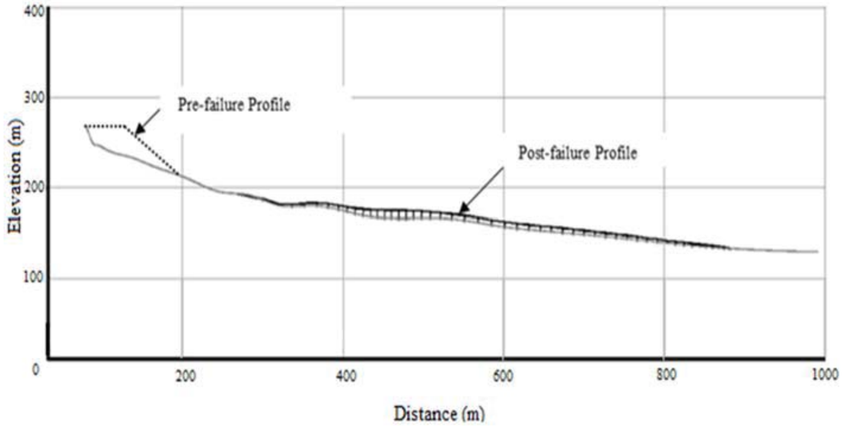

Fig. 2 Pre and Post failure profile of the Sarajevo dumpsite

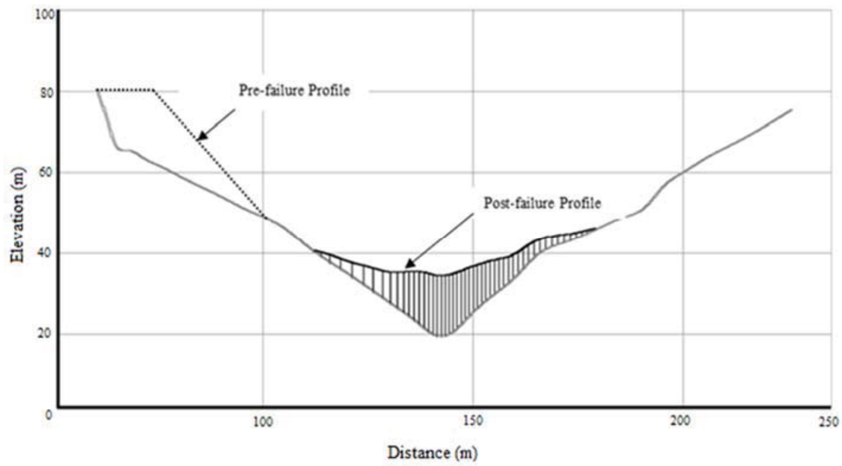

Fig. 3 Pre and Post failure cross-sectional profiles of the Istanbul Dumpsite

B. Istanbul Dumpsite Failure (1993)

This dumpsite, about 30 km away from Istanbul, is located on the upper side of a hill. The failure caused 39 deaths due to the waste material run in during the failure, in addition to 11 demolished informal brick-built houses. Due to a sewer fracture and dammed waste in front of sewage, serious environmental damage occurred. The waste materials were placed without any leakage protection (e.g. compacted clay or geo-synthetic) and there was no compaction and daily cover of the waste on the dumpsite.

The maximum travel distance of waste flow obtained was 170 m while the mean value of friction coefficient distribution was equal to 0.111 in Voellmy rheology (see Fig. 3). The waste depth on the bottom of valley reached 17.5 m, which is similar to the 16 m depth [4].

C. Bandung Dumpsite Failure (2005)

One of the most recent dumpsite failures occurred in February 2005 in Bandung (Indonesia) which covered 200-250 m width and 900 m in length. Two and a half million cubic meters of waste buried more than 147 people. These people were informal recyclers that lived in shack homes around the dumpsite. The top side of the landfill collapsed on the residential area. The left side of the landfill, which was surrounded by rice fields, was then covered by the waste. This man-made disaster resulted in huge impacts to the environment and to human life.

Fig. 4 demonstrates the run-out modeling of Bandung failure in DAN-W. The maximum waste flow (1 km) simulated in a condition with 0.109 for the friction parameter of Voellmy rheology. Although, Blight [4] claimed that waste thickness was equal to 3-4 m in most of the flow path, this depth happened in the last 200 m of the run-out simulation.

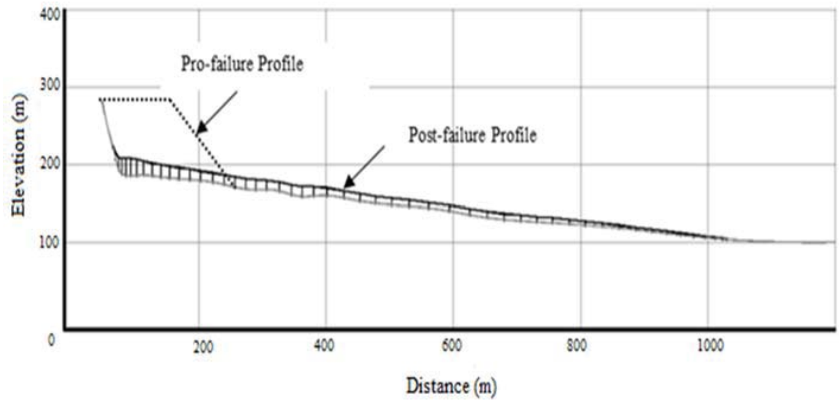

Fig. 4 Pre and Post failure profile of the Bandung dumpsite

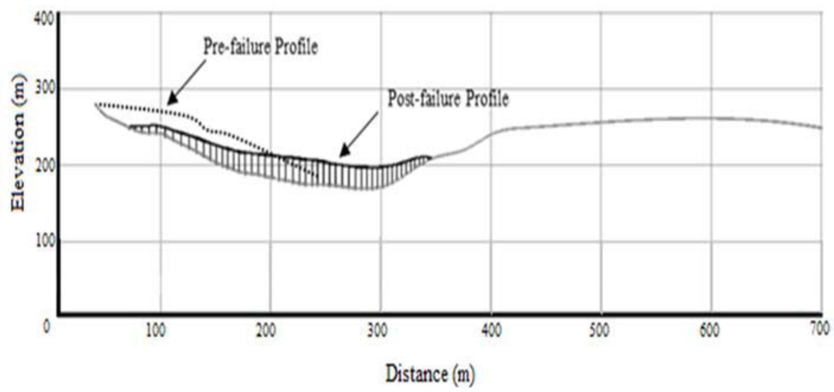

Fig. 4 Pre and Post failure profile of the Durban landfill

D. Durban Landfill Failure (1997)

The Bulbul landfill in Durban, South Africa, is a co-disposal landfill which was designed to fill with a specific “co-disposal ratio” of liquid and dry waste. To increase the slope stability, surrounding berms were provided across the toe of the landfill for each phase of disposal. Phase A had a compacted clay liner while Phase B contained the combination of clay and geo-membrane liner.

In September 1997, the landfill suddenly failed and 150-180 thousand cubic meters of the waste flowed onto the prepared area for a future phase of the landfill. Because the failure happened in the waste disposal area, no deaths or injuries occurred and the environmental destruction was limited.

Based on Fig. 5, the waste flow started from 346 m on the horizontal axis and continued for about 80 m. The maximum travel distance is obtained when the Voellmy frictional parameter had a mean value equal to 0.16. The depth of flow on the toe location after failure gained 15 m in DAN-W simulation while the Blight et al. investigative team [21] estimated 12.5 m for waste thickness at that location.

E. Ohio Landfill Failure (1996)

On March 1996, the largest slope failure in the US happened a few days after a 45 m excavation in front of the landfill toe. In addition, the site was overfilled by 13 to 15 m at the time of failure. Translational failure is more probable because of initial deep cracks at the top of the slope, and because of a block form slide [22]. Hence, the failure surface potentially crossed saturated brown native soil. Fig. 6 illustrates the failure surface before failure.

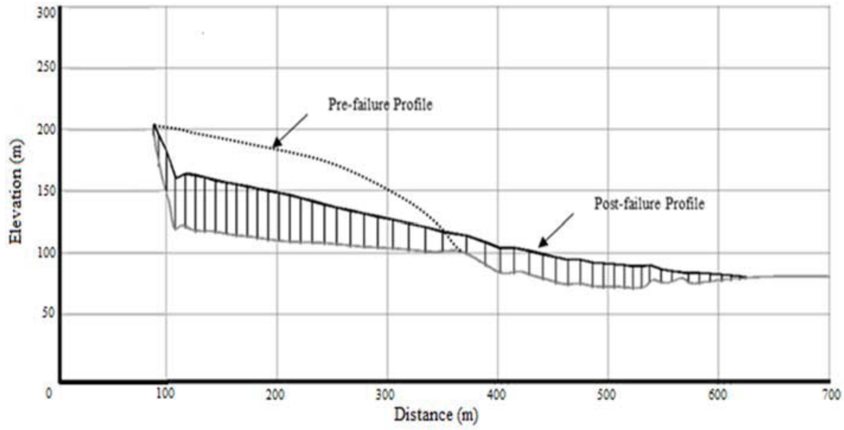

Fig. 5 Pre and Post failure profile of the Ohio landfill

DAN-W simulation for Ohio landfill is illustrated in Fig. 6. The back-analysis mean value for the friction coefficient in the Ohio landfill simulation is 0.143 when the travel distance of the simulation is equal to the real failure run-out. Stark and Eid [23] investigation on this landfill failure specified the waste thickness in four boreholes as 270m, 330m, 350m, and 500m on the horizontal axis. The waste depths in boreholes are obtained as 40m, 25m, 22m, 18m respectively, while the simulated run-out calculated 30m, 22m, 18m and 19m respectively, indicating a good compatibility.

IV. Discussion

Sarajevo, Istanbul and Bandung dumpsite failures, as well as Ohio and Durban landfill slides have been back-analysed in terms of waste mobility. Prior distributions of the friction characteristics of waste materials improved this process. Fig. 7 compares the posterior distributions of the friction coefficient for different sites. This parameter is equal to the tangent of the basal friction angle [8]. In terms of landfill failures, the angle is highly dependent on shear strength beneath the waste materials and on the failure pathway.

Waste density and waste types are two of the most important parameters influencing the waste shear strength [23], [24]. Hence, it would be reasonable to compare them with friction coefficient in Voellmy rheology. As seen in Fig. 7, higher friction coefficient distributions are associated with the failed landfills as opposed to dumpsites. Waste compaction may increase the frictional texture in the Durban or Ohio landfills, and the berm structures on the toe of the Durban landfill possibly prevented a failure large movement and increased the friction parameter -in this case- to the highest probabilistic distribution. Furthermore, in the absence of high strength waste materials such as wood, metal, plastic, paper and cardboard, the friction can be destructively affected. Blight [4] reported a waste distribution of 37% paper and cardboard, plastic, metal and glasses in combination with 31% food waste in the Durban landfill, while the Bandung dumpsite contained 15% high strength waste and 82% food waste [4]. The scavenging of the waste materials in Bandung dumpsite substantially changed the waste composition and reduced the shear strength, and eventually, the friction characteristics. This fact can potentially confirm the lowest friction coefficient distribution for the Bandung site.

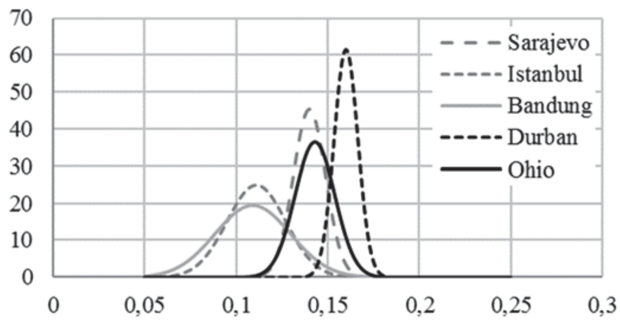

Fig. 6 Posterior distributions of the friction coefficient for different sites

Istanbul waste composition contained 21% frictional waste materials and more than 72% food waste as a result of the scavenging [4]. These findings indicate a low mean value for friction coefficient distribution of Istanbul dumpsite, similar to the Bandung case study.

Although the Sarajevo dumpsite contained a high range of frictional waste materials [4], the loose waste material justifies the lower mean value for friction coefficient distribution for this dumpsite in comparison with Durban landfills. However, the friction coefficient distribution of Ohio landfill shows the similar pattern to Sarajevo dumpsite and there is no significant difference between the normal distributions of friction coefficient of these two sites. Despite of waste compaction, the presence of low strength waste material in Ohio landfill can justify this trend.

Based on the waste compaction and waste type effects, Table III lists the classification of the friction coefficient for different situations. The global distribution for friction coefficient in each class is based on the back-analysis results.

TABLE III
POSTERIOR NORMAL PROBABILITY DISTRIBUTION PARAMETERS OF VOELLMY RHEOLOGY FRICTION COEFFICIENT BASED ON WASTE COMPACTION AND COMPOSITION TYPE

Class No.	Waste Compaction	Waste Type	Distribution Parameters	
			Mean	Standard Deviation
Class I	No	Low Strength	0.11	0.02
Class II	No	High Strength	0.14	0.01
Class III	Yes	Low Strength	0.14	0.01
Class IV	Yes	High Strength	0.16	0.01

Lower mean values for non-compacted and low frictional materials, as well as higher mean values for compacted and high frictional materials are classified in Table III. As can be seen, the dumpsites, which are contained and non-compacted disposal sites, with low frictional materials (e.g., paper, glass, metal, etc.) belong in class I (e.g., Bandung and Istanbul dumpsites). Class II contains dumpsites with a higher range of frictional materials (e.g., Sarajevo dumpsite). The Class III and Class IV of global distribution for frictional coefficients are appropriate for use with landfills that are developed with proper compaction for waste layers, with low strength (e.g., Ohio landfill) and high strength (e.g., Durban landfill) waste components, respectively. Class II and III have the similar distributions, meaning that the friction coefficient of dumpsite with high strength waste materials possess resemblance with friction coefficient of landfill with low strength waste materials.

V. CONCLUSIONS

Probabilistic analysis of the spatial extent of the complex waste avalanches covering land surrounding major landfills and dumpsites after a potential major slope failure is needed for assessment of the risks to properties and local residents. Landfill failure mobility analysis is one of the most uncertain types of dynamic rheology models due to very large inherent variabilities in the highly heterogeneous solid waste material properties.

Three well-documented historic dumpsites and two landfill failure case studies are back-analysed using the run-out modeling with DAN-W model with associated Voellmy rheology friction coefficient probability distribution functions for the solid waste material strength properties to match the simulated versus observed spatial extent of coverage after the failures. To approach this goal, "simplified probabilistic back-analysis" is employed to calibrate model parameters such that the travel distance of the run-out model equals (within ±5%) the observed travel distance.

Waste compaction and waste composition was used to classify the shear strength of solid waste material into four classes. Waste compaction in landfills significantly increases shear strength in comparison with the same material strength properties when loosely dumped in dumpsites. In addition, the lower the contribution of high strength waste materials such as wood, metal, plastic, paper and cardboard in the waste, the lower the shear strength of the composition.

The probability distribution functions for shear strength properties of waste material were proposed for each of the four classes (based on waste composition and compaction) to assist with probabilistic slope stability failure risk analysis of existing (or future) landfills and dumpsites. The probabilistic methods presented in this study can be used to assess the risk associated with the range of travel distance of the waste avalanches.

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