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Design Parameters and Possible Soil Deformation in Landfill Areas

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ABSTRACT : *Like all civil engineering projects, landfill construction projects have fundamental requirements related to strength, safety and economic concerns. There are precautions that must be taken in the planning period of a sanitary landfill project, at every step of the construction and after the completion of waste deposition at the site. The objective is to provide long term stability, environmental protection, ensure regulatory compliance and achieve cost effective utilization of manpower, equipment and space. This paper discusses the criteria for site selection, possible soil problems and their effects on safety and necessary precautions. Studies have shown that the major possible soil deformation modes are landfall, overturn, sliding, lateral deformation and outflow.*

Keywords: *landfill failure, sanitary landfill, soil stability, waste mechanics, deformation types.*

I. INTRODUCTION

From the design through the construction period of a sanitary landfill site, there are many important factors to consider relating to safety and environmental impact. Even if the site is designed and constructed only for domestic/municipal solid wastes, industrial wastes may also periodically come to the sanitary landfill site and also the domestic wastes may contain hazardous materials such as empty detergent or paint containers, insecticides, unused medicines or batteries. Wastes of varying size, stiffness and density will be deposited at a landfill site, including food waste, packaging waste, glass, plastic, metal, clothing, textile waste, garden waste, grass clippings, ash and even debris from the construction demolishment or excavation work. Landfill site managers have to face the environmental problems of leachate and gas produced and other associated factors [1]. Waste characteristics differ not only by district and by community, but may also differ even within one landfill site due to the ion concentration in the leachate [2, 3].

These differences can also be seasonal and also depend on the lifestyle and income level of the served population. Seasonal changes affect the overall temperature and moisture of the landfill embankment itself; however the calories of the leachate reflect the landfill biodegration and its chemicals. Leachate temperature, quality and quantity affect the landfill stabilization decision tools and decision closure [4]. Additionally, changing legislation, active recycling campaigns, technological improvements, municipal administration changes and even staffing changes may result in different waste characteristics and disposal techniques. The decreasing amount of ash and increasing amount of packaging waste collected are good examples of this phenomenon. Biodegradable plastics, lower organic contents in food wastes, widespread recycling activities, and increasing pretreatment techniques help to stabilize and homogenize waste characteristics. However, the design period of a sanitary landfill must take the cultural and geographic circumstances of the country and community into consideration. A good project for a certain area may not be successful in other areas.

With so many variables, successful design cannot be achieved every time. However, an engineer cannot refuse or postpone the design of a project based on these difficulties. For this reason, the optimum solution is to determine the common parameters as much as possible.

During the site selection for a sanitary landfill, all the possible landfill areas should first be evaluated in terms of geographical, topographical and geological conditions. After a first round of elimination of unacceptable sites, the remaining sites should be evaluated with respect to the waste parameters. If this order of operations is not followed, the success of the project may be compromised.

II. WASTE MECHANICS

Before discussing the soil analyses involved in determining soil suitability for a landfill project, firstly a general discussion will be presented about soil behavior to clarify the idea of “waste mechanics”. The behavior of the waste itself and its interaction with the soil should be examined, as this interaction is the key point in understanding the general behavior of the landfill. This interaction should be analyzed both by the behavior of the waste in contact with other wastes and by the behavior of waste in conjunction with the soil. Yamawaki, et. al., reported that waste grounds including plastics have high slope stabilities [5]. These interactions on a small scale combine to affect the general behavior of the whole landfill. The study of this behavior is called "waste mechanics". This is a new discipline that has been developed to explain the engineering characteristics and the different behaviors of landfill sites regarding stability. Normally, undisturbed soil specimens are obtained by bore sampling and analyzed in the laboratory to understand soil strength and stability in an area convenient for landfill construction. The results of soil analyses also provide information on the slope stability of the inclined areas. Erosion or soil flow usually occurs on steep slopes, such that landfill areas with steep slopes are similar [6]. As the solid wastes are deposited at the site in layers and compressed, an embankment is formed by backfilling. For this reason, this embankment should be treated as a soil embankment and examined according to the fundamentals of soil mechanics. The engineering goal is of assessing the optimal disposal rate to maximize the landfill volume with the lower operating costs [7]. It is also important to consider the mechanism of primary compression, time-dependent mechanical creep and biodegradation effects that occur in the landfill site [8]. In a landfill, during waste degradation processes leachate is formed that can potentially cause clogging of bottom drainage layers. To ensure stability of landfill construction, the physical properties of its components have to be controlled [9].

As in the soil exploration phase of traditional soil mechanics studies, undisturbed soil samples should be taken to keep the original specifications of the soil which lets you to investigate in the laboratory [10]. Likewise, in order to make stability investigation, boreholes should be used to sample at the landfill site and undisturbed waste specimens should be collected and analyzed. Shear strength parameters are the key factors in stability analysis for municipal solid waste landfill [11]. However, it is very difficult to obtain undisturbed waste specimens safely, in part due to bulky wastes such as furniture and debris (concrete and excavation soil), generate another difficulty in sampling. A very large sampling apparatus may be a solution, but these types of large tools are difficult to operate and also present safety problems. Additionally, there are many different waste types and thus a nearly unlimited number of different combinations of waste. In addition, waste compositions change frequently, and due to the high cost for very large sampling tools, this type of sampling is seldom practical or useful. Because of these problems, there are still no internationally accepted standards for the sampling and testing of waste stability.

This uncertainty in sampling combined with the limitless variation of waste combinations results in the difficulty of this type of study. The engineering properties, that affect directly the stability of the landfill, are complicated and subject to change. For this reason, landfills can easily become unstable under the influence of external factors; landfill stability is the most significant engineering issues in landfill operation [12]. If the waste parameters were limited, it would be possible to model the circumstances even without sampling. This would be possible by changing each parameter and predicting the effects of each component on the behavior of the landfill; conditions could be normalized and an empirical solution could be found that could be adapted to many different circumstances. However, due to the difficulty of obtaining an accurate sampling of the countless combinations of wastes, it is almost impossible to change each parameter one by one and monitor the variations.

Normally, waste is classified according to its origin, calorific value, and biodegradability, among other parameters [8]. This kind of classification is oriented primarily towards recycling. However, classification according to the mechanical properties of the waste would be more useful for understanding the engineering properties of the whole site and possible deformations that may arise in different parts of the site. In an ordinary landfill site, waste material exists in the solid, liquid and gas phases, where each has a different behavior. Solid waste has different behavior with and without entrained liquid. The liquid phase exhibits different behavior when moving (dynamic) than when stationary. Dynamic liquid movement is found in the leachate collection pipes, in the voids and in between particles (interparticle flow); capillary movement can also be classified as dynamic movement. Stable forms of liquid are observed in intraparticle behavior, i.e., liquid that is locked to the soil and absorbed moisture bound to hygroscopic particles. Each of these movement and interaction processes affects the whole body, so all of them should be considered in the analysis.

III. SELECTING THE SITE AND SOIL EXPLORATION

Important parameters during the site-selection phase include safety, economy and the ability to efficiently treat wastes of any type and quantity. The detailed site exploration focuses on factors including optimum distance to the residential area, climate, geography, topography, geology, hydrology and geotechnical features of the selected site. After the site is selected, the main items to be explored are soil conditions and groundwater level. The geological type of the soil might be less important than the geotechnical conditions. Strength parameters should be initially determined. While different soil types have different behaviors, sanitary landfill sites undergo a preparation stage where compressed clay and a geomembrane are applied to reduce the direct contact of the solid waste and liquid (leachate) with the base soil. In these conditions, any kind of chemical or biological reaction of the wastes with the soil is avoided, and the most important consideration becomes whether the soil can withstand this new load (pressure).

Soil analyses must be performed to answer this question as listed in Table 1 [13]. After the necessary tests, soil strength and possible behavior under load are estimated. These are the key points for safe and economic landfill design. Soil exploration is important for the following purposes:

1- selecting a stabilization method for the base soil
2- estimating liquefaction risk
3- estimating slope stability
4- estimating soil pressures
5- selecting a stable cell and lift design
6- determining the compression efficiency of the daily and intermediate cover

Clay permeability is minimized at the optimum water content and at moisture levels up to 4% higher from the optimum water content. Increasing water content makes the soil difficult to compress and thus the permeability also increases [13]. Permeability is not only related to the size of soil particles but also to the water content and density. It is very important to compact the clay layer beneath the geomembrane to decrease its permeability as much as possible. As a general rule, the coefficient of permeability should not be less than 1×10^{-7}m/s and 1×10^{-9} m/s is considered ideal. Although the permeability depends on this coefficient, the compaction degree is crucial here, because if the compaction is performed at a lower than optimal water content level, swelling will occur later. This swelling can cause deformation of the impermeable layer and even rupture of the geomembrane. Excessive dynamic load during compaction can also cause the same problems.

The deformation may not be limited to swelling and rupture of the geomembrane: cracking, settlement and movement may also occur within the soil. Clay has a sponge-like structure, so it can absorb a great deal of water; subsequent moisture loss causes a decrease in volume. The water content in the clay tends to decrease from the optimal level due to the fact that natural water content is always less than the optimum water content. For this reason, a clay barrier alone is insufficient to form an impermeable layer; the synthetic geomembrane is always needed to form a completely impermeable layer as the base foundation. Together, they form a barrier to the leachate, preventing mixture with groundwater. Cost restrictions can never be an acceptable reason to forget geosynthetics [14]. Limited precautions, such as a single layer of impermeable sheet, cannot be compensated for when a problem occurs. Problems tend to occur frequently because the impermeable layer (base foundation) construction remains at the bottom and is very difficult to monitor after new layers are laid down.
Water is accepted as an incompressible fluid in soil mechanics. A volume change occurs in the soil when water or air (void) exchange places among the soil particles. The migration of water and air can take place any time due to changing environmental conditions. Even changing weather conditions or moving objects around on a soil body can constitute changing environmental conditions. Air movement between soil particles tends to cause fewer problems than water movement because the water cannot be compressed as mentioned above.

For this reason, water movement always causes changes in pore water pressure, which in turn causes soil changes, i.e., either a volume change or movement by deformation [13]. Compressibility is not only related to the soil type and properties but is also related to confinement history. Sedimentary soil and alluvial ground tend to have higher compressibilities than other types of soils. In general, clay, silt, peat and high-organic-content soils have high compressibility capacities. Sand and large gravel (pebbles) have lower compressibilities.

Consequently, different types of soils show different compression speeds. Pebbles and sandy soils require quite short times to achieve their low compression maxima, while cohesive soils like clay and silt need long periods for compaction. Thus, compaction for landfill areas requires long-term compression that should be applied at certain intervals. [15] When a compacted layer is produced, the layer above should be compressed with a higher water content level than the plastic limit of that soil specimen. If the water content is adjusted to 1.2-1.3 times the plastic limit, the soil will become easier to handle with construction machinery; moreover, crack formation due to soil movement should be avoided. During this compression work, air voids should not comprise more than 5% of the soil volume. Undisturbed soil samples taken during construction will allow these parameters to be monitored. This will help make the overall layer structure more stable, durable and efficient in the sense of less settlement for a long period. As the layers above are formed by solid waste, this foundation layer will show plastic behavior and will absorb vertical stress to a certain degree [10]. Pressure increases with depth; however, if the water content also decreases with depth, the deformation (settlement) caused by vertical stress can be avoided.

IV. SOIL STRESSES

There are several loads acting on a given structure and they can be classified into different categories based on different viewpoints. Thus, stress analyses may differ depending on this classification; however, the stresses that affect a landfill site can be summarized as follows:

1) Weight of construction materials: All the materials used for sanitary landfill construction have their own weight. This load can be calculated according to their quantity and density. As these values will be different for each site, the load must be calculated according to the particular conditions of each site.

2) Stress due to compaction: In addition to the base foundation preparation, compaction is applied daily to the site when the solid waste arrives, not only to decrease the volume but also to impart the necessary stiffness to the waste embankment. This compaction work will affect the whole body in different positions with the changing parameters of compaction-load type, load period, soil type, environmental conditions, elevation and slope.

3) Pore water pressure: The water within the covering soil layer, the water arising from the decomposition of waste (leachate), precipitation and storm water that enters the site and the water within the base-foundation layer will all cause pore water pressure and serious stress over the whole site. The movement of the water within each layer will also cause additional stress at the site.

4) Seismic Loads: The additional loads caused by earthquakes or the loads caused by soil movement due to earthquakes.

V. DEFORMATION TYPES

The design and construction of landfill sites should be embraced as a multi-disciplinary study. Human interference with nature, careless excavation and backfilling, and natural soil movement may cause mass movement, erosion or many kinds of accidents that can do great harm [16]. ***Huang*** and ***Fan***'s study (as cited in [12]) found that; in recent years, many cases involving landfill instability have been reported. Landfill failures in uncontrolled landfills or open dumps occur mainly as flow slides in the MSW body. The types of landfill failures and the likely causes of instability are listed in Table 2 [12].

In order to prevent from unstable conditions of the landfill, the whole site should be under control from first waste dumping period throughout the whole operation period of the landfill site. Furthermore; continuous care should be given to the site, as the microbial activities will not finish even after the closure of the landfill site. Beside the stability precautions during compression, the soil conditions addressed below may provide ideal conditions for mass movements causing to accidents that should be monitored carefully.

1) Deficient material that tends to show plastic movement
2) Sensitive ground like soft soil layers
3) Cavity soil
4) Decomposed or eroded soil
5) Crushed or sheared zones
6) Cracked masses
7) Discontinuous soil (fault line, dislocation, rift valley, and so on)
8) Bulk properties, such as bedding stratification and segmented fractions.
9) Problems related to permeability and its effects on groundwater level
10) Differences in rigidity (e.g., a brittle layer on soft ground).

These kinds of soil and environmental conditions may cause different soil deformations. In fact, soil movement is possible even with stiff soil layers and zones. However, under these conditions, the danger is greater that soil movements may cause tremendous deformations and resulting environmental impact. Soil deformations known to occur in landfills are discussed below.

1) LANDFALL: This process begins with the separation of a soil body from a plane on which dislocation has not happened previously, with continuous mass movement such as free falling, rolling or tumbling, as shown in Figure 1. Gravity pulls part of the soil down with bigger force than the strength of the soil holding the soil in place. Rainfall, infiltration from runoff, sea waves or the properties of soil can be the reason for such kind of deformation. The presence of water reduces the effective stresses between soils particles reducing the strength, as well as increasing the weight of the embankment. The momentum in this fall is due to gravitational acceleration.

2) OVERTURN: The soil or rock mass affect the behavior of the embankment. The behavior is mainly controlled by its structural geological features [12]. External factors also act as powerful weathering agents. Earthquakes are important factors for instability. On the other hand, rainfall is the most common factor that induces failure of geological bodies. Rainfall infiltration increases the deformation between the layers of the structure by allowing to a mass movement. When the cohesive soil that exists in between the layers is washed out, soil body moves forward behind its center of gravity or turns over its axis, as shown in Figure 2.

3) SLIDING: An embankment or slope, no matter natural or artificial, is under the influence of dynamic engineering geological processes. A landfill body can be seen as an artificial geologic body that is under the effect of the same type of stresses. The strength and deformation behavior of a geological body with a layered structure are controlled by the behavior of the planes. Geological bodies with a layered structure deform easily and sliding occurs along the bedding. The bottom liners of the landfill, the partial soil foundation, and the interim cover soil can be looked upon as the macroscopic structural planes of the landfill body. Because of the different ages of the material within the landfill body, the influence of the degree of degradation, and the existence of intermediate covering soil layers, landfills show different top-down properties. The structural features of waste bodies include the body's structure planes, the water zone, and the sealed high-pressure gas zone within the waste body [12].

A soil body moves by sliding on a surface. Usually, this type of failure happens on circular slope surfaces as shown in Figure 3. This failure line is usually localized on a thin and dense shear zone through the hillside [17]. This sliding movement continues the slip plane caused by long term loading of the embankment. If the bulky wastes gathers at a certain zone or if the organic wastes starts to decompose with extraordinary speed due to different reasons such as high acidity or sealed gas zone. This slip plane triggers this type of deformation. This is a typical shear failure of the soil; the great majority of deformations are of this type.

4) PENETRATION: Expansive soils contain minerals such as smectite, bentonite, montmorillonite, illite and chrolite clays that are capable of absorbing water. When they absorb water they increase in volume. The more water they absorb the more their volume increases. Expansions of ten percent or more are not uncommon. This change in volume can exert enough force on an embankment or other structure to cause damage. Soil analysis to identify the types of soil present and determine their expansive properties are very important in predicting structural deformations.

Especially, if the clay content is too much, it has the potential of significant expansion in the presence of moisture. If the water content remains constant they will generally not cause a problem. The situation where greatest damage occurs is when there are significant or repeated moisture content changes.

Zones of cracking, ground fissures and extensional cracking, lateral displacements, settlements with vertical displacements, and compressive deformation in the form of soil and pavement warps and buckles are also accepted in this group of failure occurred by the localization of ground failure.

On the other hand, sometimes several layers lie over different soil types due to tectonic movements. If the cohesive soil layer lies on a soft ground layer, it is easy to move with a small external force. Cohesive soil usually penetrates the soft layer by cracking and lateral spreading as shown in Figure 4. This type of deformation does not form a shear zone. However, this type of ground cracks, if occurred on lateral surfaces, may damage buildings and streets on the surface and fracture water, sewer, electric and gas pipes underground.

5) OUTFLOW: This is a kind of three-dimensional, consistent deformation caused by a temporary weak shearing force (Figure 5). This type of deformation usually occurs when the shearing faces are very close to each other. The speed of the flow is the same as the movement of a viscous liquid. Ground cracks that resembled liquefaction-related lateral spreads and settlements are accepted in this group of failure. Tectonic movement associated with folding above the blind thrust may also cause such kind of displacements like flood.

The most widely distributed ground failures in this group appear to be associated with areas of filled land and soft soil zones without any significant vegetation. Some occurrences were clearly the result of liquefaction, while others lacked direct evidence for liquefaction. In nearly all cases, due to shallow ground water level and any recent natural deposits. Areas of filled land need to be identified and characterized to determine the likelihood of failure during future earthquakes.

All these effects may disrupt soil equilibrium and landfill construction should aim to prevent these types of deformations. All landfills must be constructed in a safe and cost effective manner. It has become easier to control mass movement or deformation due to the development of better technology and more durable materials. Many different parameters can be analyzed during the investigation of a disaster or after an accident, with the following as the main parameters:

1) hillside, slope or embankment geometry
2) surface and underground water hydrology
3) the distribution of the low-strength soil zones among the backfill hillside
4) any other problems necessitating stabilization

Despite these issues, disasters and accidents can be avoided by the formation of slope geometry with safe and controlled techniques, the avoidance of steep slopes, the control of water movement (both precipitation and leachate), structural precautions and the improvement of environmental conditions.

VI. MONITORING WELLS

At the site of the landfill, observation wells for underground water and gas leakage monitoring are other safety precautions that should be taken during the operation and during the post-closure care period. If pollution starts for underground water samples, it means that there is damage at the bottom of the landfill. Likewise, gas probes also give idea about the diffusion at the soil layer surrounding the landfill. Beyond the environmental precision, these wells may be indispensable indicator by alerting about any tearing or displacement for the impermeable layer due to lateral or vertical soil movement that should be seriously interfered.

VII. CONCLUSIONS

The usual problems occurring in landfill sites such as inadequate compaction and slope-stabilization problems depend completely on design and operational problems. Design mistakes usually done by unauthorized designer who are unaware about the behavior of the embankment. Even though the designer got used to the behavior of the soil embankment, the behavior may not be the same for the waste embankment. It is a fact that, the compaction procedure of the waste is different from the soil compaction. The procedure may be even different according to the composition and characteristics of the waste such as bulk density, moisture content, organic matter content of the waste and the place (soil type and topographical conditions) that is deposited. The problem about stiffness is not only related with the steep slopes, the deformation can occur even at a gentle slope, if the compaction procedure is not fulfilled. This is not only a problem of construction, but also a serious problem for the landfill operation and management. The storm water and leachate may cause serious damage to the stiffness of the landfill. The direct precipitation above the landfill and the storm water that reaches to the site from the vicinity may carry the cover soil and waste itself by causing cracks, landfalls, sliding phenomena and outflows. The leachate that occurs between the layers of the landfill may cause pore-pressure and confining stress, which is a huge pressure under the soil that may cause overturn and collapse.

To avoid the problems at the landfill site, soil types and characteristics should be analyzed carefully and possible mass movements should be predicted beforehand. According to the analysis and determination of these movements, necessary precautions should be taken to mitigate factors that may disturb the natural balance and equilibrium of the landfill. These precautions are necessary not only for initial landfill construction but also for the safety of the landfill site over its entire life.

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Table 1. Soil Exploration Analyses

Analysis	Testing Standard
Water Content Test	ASTM D 2216
Atterberg Limits Test	ASTM D 4318
Sieve Analysis and Hydrometer	ASTM D 422 & C 136 -01
Unit Weight Test	ASTM D 854
Natural Unit Weight Test	ASTM D 1556 & D 4914 & BS 1377
One-dimensional Compression Test	ASTM D 2435
Triaxial Tests (UU, CU)	ASTM D 2850 & D 4767
Swelling Index Test	ASTM D 4546
Shear Box Test	ASTM D 3080
Permeability Test	ASTM D 5084
Standard (or Modified) Proctor Test	ASTM D 698-00a & D 1557-00
Vane Test	ASTM D 2573

Table 2. Reprinted from ***Huang & Fan 2016***, Selected Case Histories of Landfill Failures Described in the Technical Literature [12]

	Case and references	**Time**	**The types and descriptions of landfill failures**	**Likely causes**
Engineering or sanitary landfills	Kettleman Hills America (Mitchell et al. 1990; Chang et al. 2005)	March 19, 1988	Sliding along interfaces within the clay liner system, lateral displacements of waste up to 10.5 m and vertical settlements up to 4.5 m	The failure of the liner system underlying the waste
	OII America (Matasovic et. al. 1995)	January 17, 1994	Failure of the cover soil, cracking in MSW body	Northridge earthquake
	Beirolas landfill (Rowe 1999)	June 25, 1995	Slide extend about 270 m along most of the area, almost with 4 m of vertical movement and several meters of horizontal movement	The shear strength of the soft clay overestimated
	Cincinnati America (Eid et al. 2000; Stark et al. 2000)	March 9, 1996	Failure is translational along a weak foundation layer, with lateral and vertical displacements of up to 275 and 61 m, respectively, the volume of waste involved in flow is 1,200,000 m^3	Slope overbuilt, toe excavation and rock blasting, brown native soil
	Bulbul South Africa (Blight and Fourie 2005; Blight 2004)	September 8, 1997	Mass movement of waste flow and the distance is 80 m, the volume of waste involved in flow is 160,000 m^3	Large liquid wastes deposited
	Dona Juana Columbia (Blight 2008)	September 27, 1997	Flow slide of the landfill with lateral and vertical displacements of up to 500 and 100 m, respectively	Leachate recirculation
	Shenzhen Xiaping China (Zhan et al. 2013)	February 15, 2009	Flow slide of the landfill sludge, the volume is 40,000 m^3	Large liquid sludge was deposited
	Xerolakka landfill Greece (Athanasopoulos et al. 2013)	December 29, 2010	A 30-m-high slope failed, the volume of the slide waste mass is estimated about 12,000 m^3	Inappropriate disposal, inadequate compaction, leachate and gas generation, and steepening of the landfill slopes increased
	Shiraz landfill Iran (Jahanfar 2014)	May, 2013	The failure mode is rotation, life loss is 11	The firework of waste materials in landfill caused exceeding pore water pressure and collapse
	Yugoslavia Sarajevo (Blight 2008)	December, 1977	Flow slide of landfill, the distance is 1,000 m, the volume is 200,000 m^3	Winter rain infiltration, steep hillside
	Skellingsted Denmark (Kjeldsen and Fischer 1995)	March 21, 1991	Landfill gas explosion, damage to landfill in a 20 X 120 m area	Excess gas pressure
	Istanbul Turkey (Kocasoy and Curi 1995)	April 28, 1993	Flow slide of the landfill, about 1,200,000 m^3 of MSW, are displaced, the distance is 60 m	Winter rain, gas explosion, superimposed load
	Payatas Philippines (Merry et al. 2005)	July 10, 2000	Flow slide of the landfill, the volume is 13,000–16,000 m^3, the distance is 40 m	Heavy rain, excess pore pressure due to the buildup of landfill gas
	Chongqing Geleshan China (Shi et al. 2010)	June 15, 2002	Mass movement of waste flow and the volume of waste involved in flow is 50,000 m^3	Heavy rain
	Bandung Indonesia (Koelsch et al. 2005)	February 21, 2005	Flow slide of the landfill, the volume is 2,700,000 m^3, the distance is 900 m	Heavy rain

Figure 1. Landfall

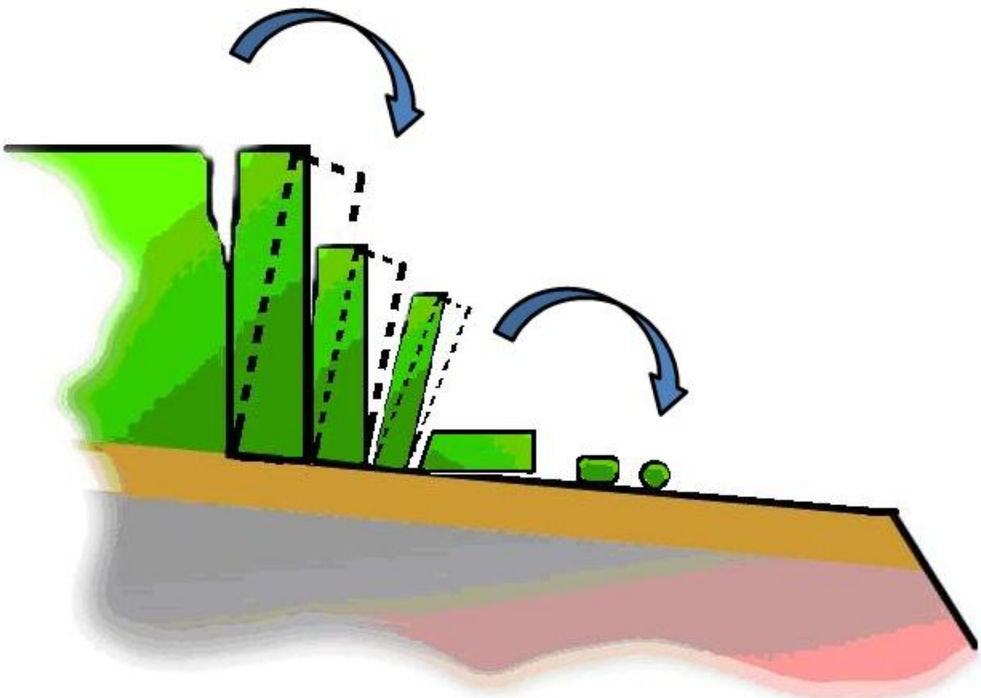

Figure 2. Overturn

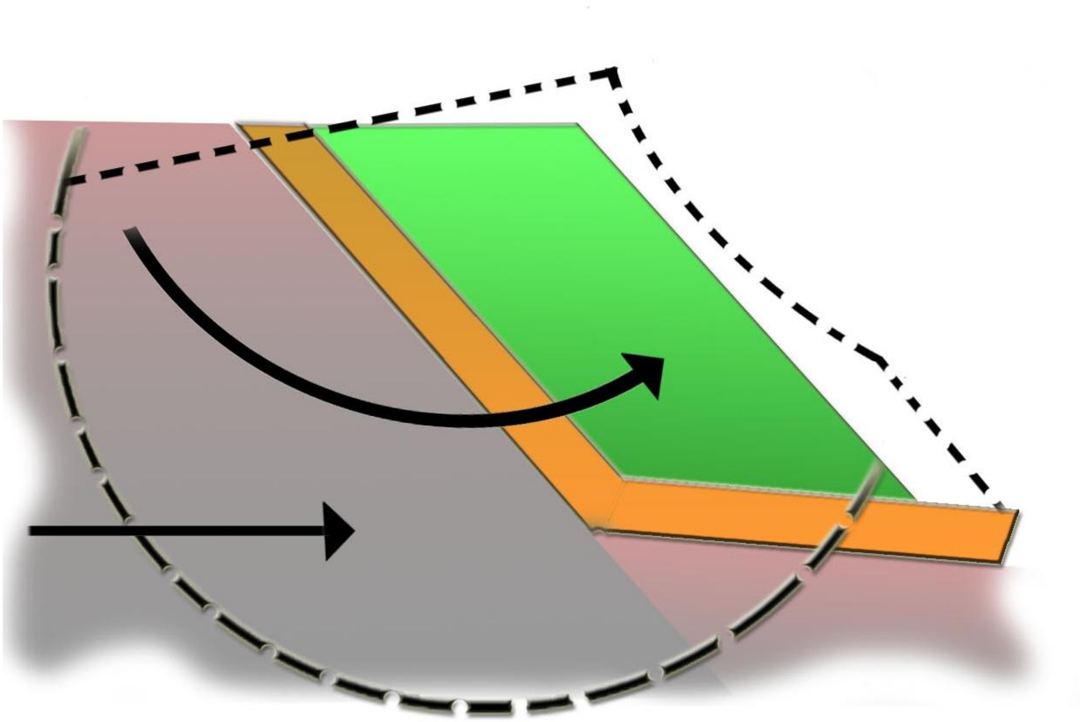

Figure 3. Sliding

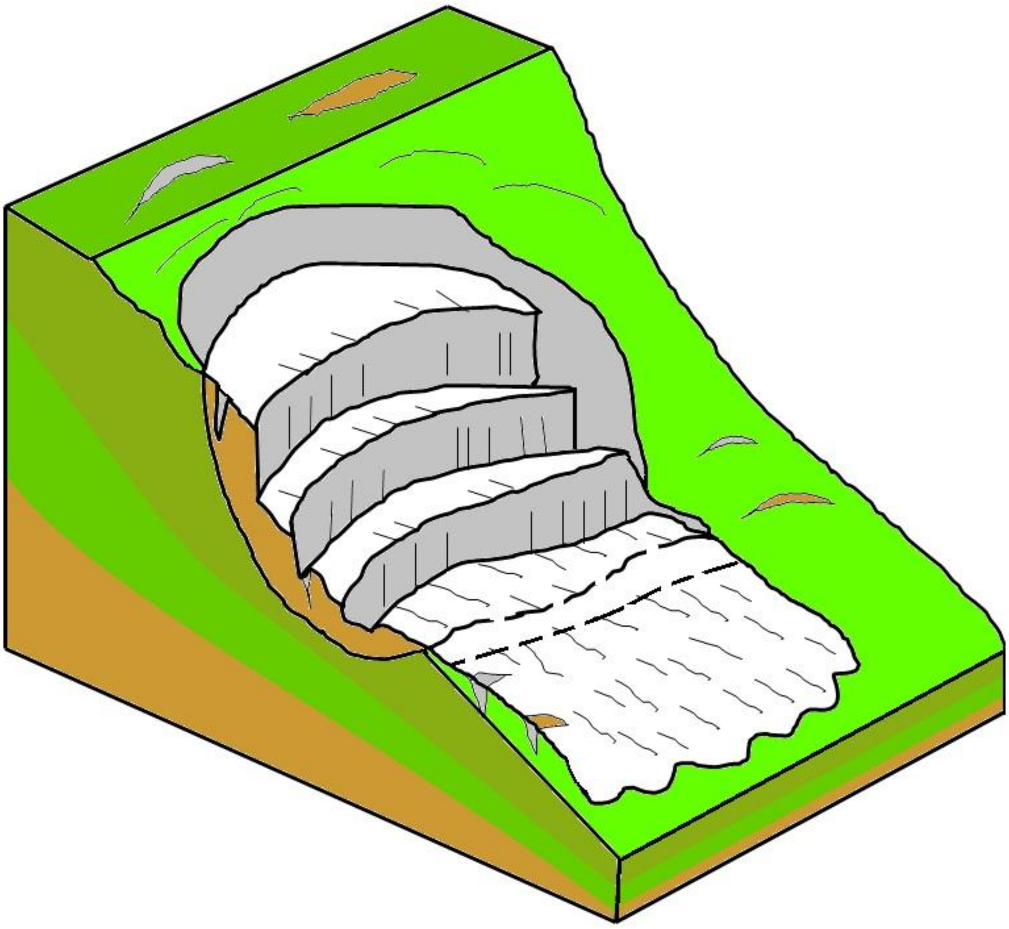

Figure 4. Penetration

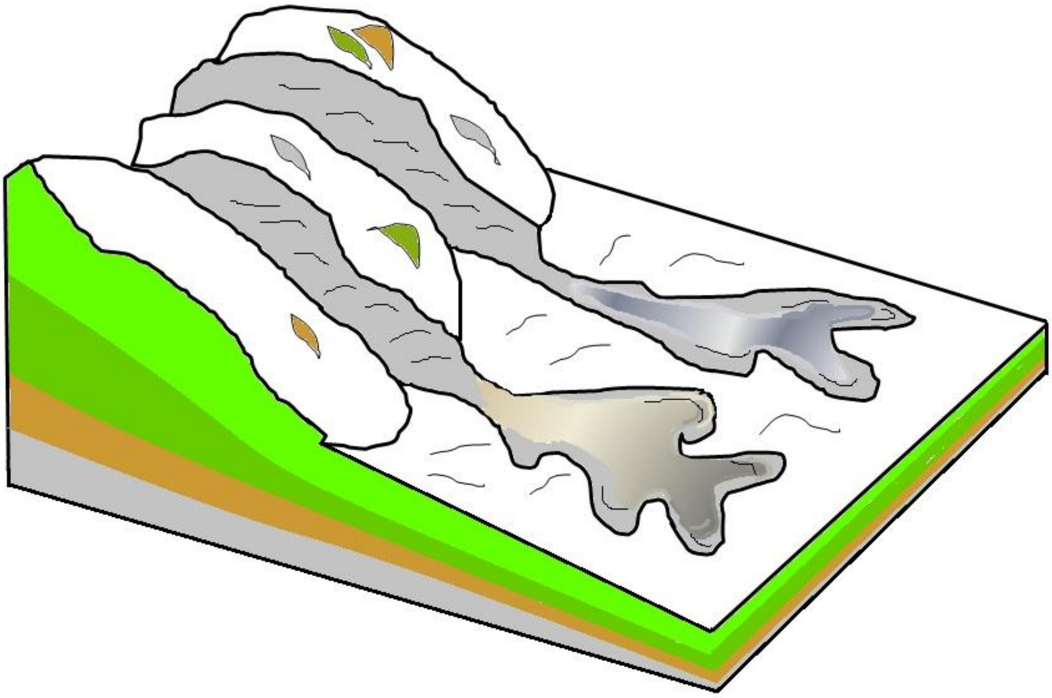

Figure 5. Outflow