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Analysis of Case Studies on Landfill Failures – Lessons Learnt

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Abstract. The safety and serviceability of Municipal Solid Waste (MSW) landfills are directly linked to environmental and public health. They are usually achieved by proper design and meticulous monitoring. However, even after adequate design and diligent monitoring, certain circumstances could result in landfill failures. This paper presents and analyses major landfill failures relying on documented case studies for different landfill components like liner, side-slope, final cover, leachate collection system, etc. The various factors affecting their failure include elevated leachate level, erosion of soil cover, overbuilt waste slopes, poor installation of geotextiles, poor soil foundation, freeze/thaw condition, movement of heavy equipment during operation stages, etc. In most cases, these landfill failures are triggered by one of these variables or a combination of them affecting the natural environment, human health, and safety duly discussed in this article. The documented remedial works, including a survey of a landfill, method of installation of liner system, avoiding construction activities near the landfill, regular monitoring and maintenance of leachate and gas collection system in landfill are delineated in this article. This article will assist practicing engineers in better designing landfills and will prepare them to overcome or handle such catastrophic failures.

Keywords: Serviceability, Landfills, Soil Cover, Baseliner, Remedial work, Reconnaissance.

1 Introduction

Waste has been an integral part of human beings from the start of their civiliza- tion to the present day. The archaeological evidence states that the concept of the land-fill was adopted in the early 5000 B.C. when waste was deposited in pits that were subsequently covered up with Earth. As the people civilize and modernize, the number of waste generation rises. The factors influencing it are population growth, urbaniza-tion, and economic growth. Landfilling is the most common and economical waste dis-posal method, isolates waste, and protects the environment from contamination by toxic substances. The 'sanitary landfill' (known then as 'controlled tipping') was pioneered in England in the late 1920s. Later in 1935, the first sanitary landfill was developed in Fresno, California, USA. The sanitary landfill concept then got familiarized and got its reputation in the mid-50s to 70s, leading to many landfill constructions in the USA and European countries. However, as landfills increase, many failure cases have been re-ported worldwide in the last four decades.

Landfill failures led to significant slope mass failures, which caused property loss and human casualties. So, these types of failures could have been prevented by reconnais-sance of the landfill, method of installation of liner system, avoiding construction ac-tivities near the landfill, and regular monitoring and maintenance of leachate and gas collection system in a landfill. The reasons for landfill failures are discussed in the suc-cessive sections.

There are two types of landfills that are practiced worldwide based on the facilities provided; one is engineered landfills, and the other is non-engineered landfills. Engi-neered landfills are the ones with provisions of extra facilities for handling various functions to maintain and run them effectively (even though there are many chances that they fail which are shown in Fig. 1.). In contrast, non-engineered landfills are ones with waste dumping in areas with depressed topography. They may or may not be cov-ered completely to close the landfill, and no proper maintenance is adopted; thus, hav-ing higher chances of failure.

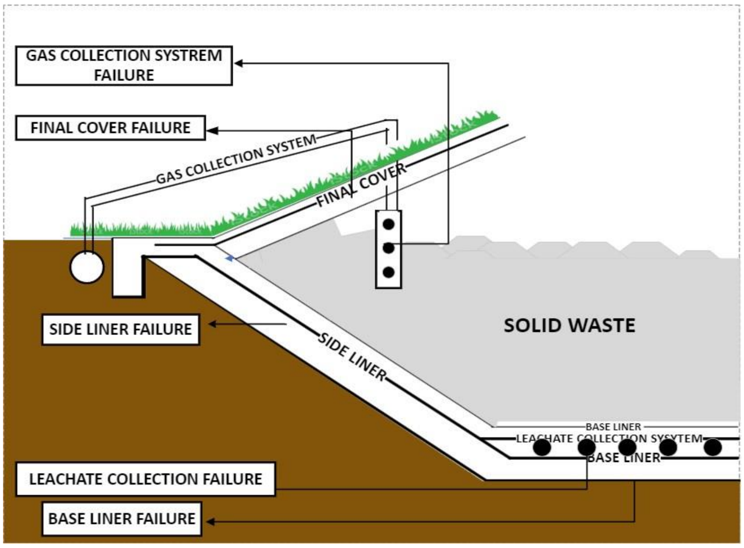

Fig.1. The landfill failures and their location in an Engineered landfill

The engineered landfills consist of a baseliner, side liner, final cover, leachate collection system, gas collection & monitoring system. The non-engineered landfills / open dump sites are hazardous and often lead to catastrophic failure and affect human and environmental welfare. However, more than 50% of the landfills being dumped now are non-engineered landfills. Engineered landfills are provided to manage the wastes and handle them so that they are isolated from the environment and do not affect human health and the environment. Unlike non-engineered landfills, they involve initial investment but ensure safety, as most of the failures of landfills are observed in non-engineered landfill.

2 Landfill Failures

A landfill fails when it is unable to accomplish its goal of isolating the waste and safeguarding the environment from waste contamination. The flowchart depicting various types of landfill failures is shown in Fig.2.

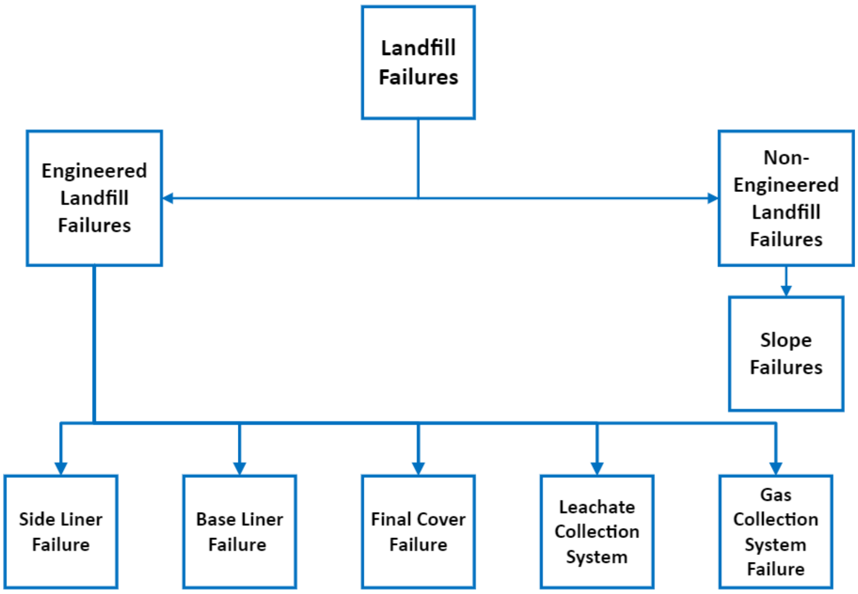

Fig. 2. The landfill failures and their types

3 Non-Engineered Landfill Failures

As mentioned in an earlier section, these landfills do not have any safeguards against groundwater contamination, air pollution, or environmental protection. This type of landfill often fails due to its height of waste accumulation, non-compaction of waste, inbuilt high leachate level, and spontaneous fire, which leads to instability of landfill slopes. Many catastrophic landfill collapses have been documented throughout history, resulting in economic and human losses. The major reasons (R) for the failure of these eight major non-engineered landfills are provided below.

- R01-Slope formed by landfill waste is very steep (more than 45˚)
- R02-Sudden accumulation of heavier waste loads like demolition waste, etc.
- R03-Blasting near the landfill
- R04-Toe-excavation near the landfill
- R05-Strain incompatibility between MSW and native soil
- R06-High leachate generation due to heavy rainfall
- R07-Lack of drainage facilities
- R08-Explosion due to sudden bio-gas release
- R09-Reduction in shear parameter due to biodegradation
- R10-No proper compaction of waste
- R11-Ignoring the potential failure cracks
- R12-Landfill fire due to Hot loads, equipment loads
- R13-Erosion near a landfill
- R14-Landfill gas from biodegradation increases the pore water pressure.
- R15-Greater height of landfill waste

All the case studies mentioned in Table 1 show us the major reason for catastrophic failures and how these failures can be prevented by following suitable precaution measures. Some of the main reasons that led to the collapse of this landfill are due to great height of landfills (R15), very high steepness of the landfill(R01), high leachate accumulation during heavy rainfalls (R06), Sudden accumulation of heavier waste loads like demolition waste(R02) and lack of proper drainage facilities(R07) (Fig.3)

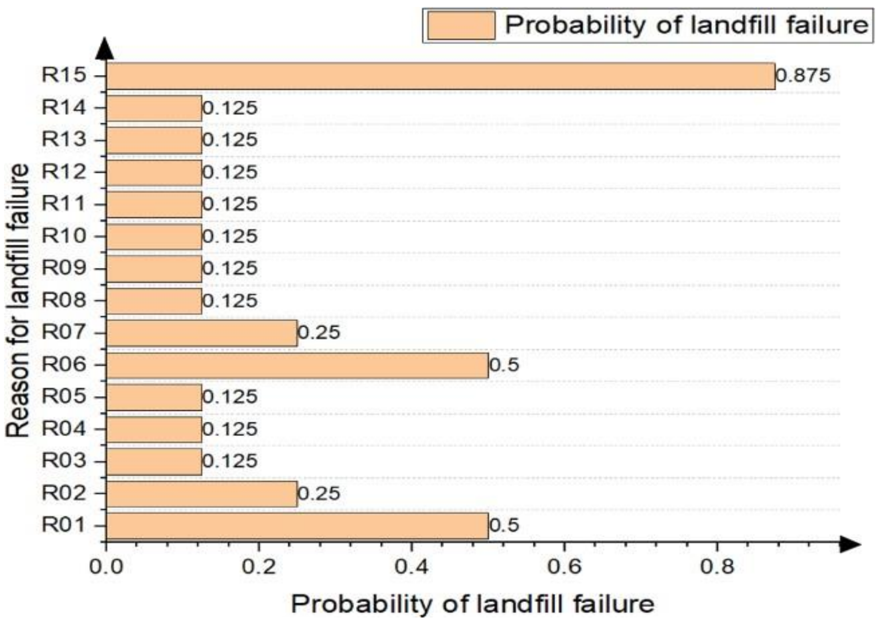

Fig. 3. Probability of reason that led to the failure of a non-engineered landfill in select cases

Table 1. Reasons, remedial measures, economic losses, and fatalities due to Non-Engineered Landfill failures

Site	Height and slope of a dumpsite	Reasons for failure	Remedial measures	Fatality and economic losses
Umraniye-Hekimbaşi dumpsite (1993) [1]	55-60m 1H:3V	R01, R02, R15	Reduce steepness and monitor Waste disposal	11 houses got buried & 39 causalities
Rumpke dumpsite (1996) [2]	13-15m 2.6H:1V - crest level 1.85H:1V -toe level	R01, R03, R04, R05	Check interface shear strength, including large FOS for shear displacement, and avoid over-stocking waste.	1.2 million m3 of waste slid. Largest slope failure based on volume
Hiriya dumpsite (1997) [3]	60m 1.3H:1V to 1.6H:1V	R01, R06, R07, R13, R15	Soil Cover should be provided to avoid infiltration of rainwater	There was no fatality loss, but the nearby river "Ayalon" was blocked for some days.
Payatas dumpsite (2000) [4]	30m 0.5H:1V to 2.5H:1V	R06, R14	Provide proper soil cover and maintain the leachate collection system properly	330 people died, and many homes destroyed
Leuwigajah dumpsite (2005) [5]	70m 1H:1V	R05, R06, R08, R12, R15	Landfills must be engineered with liners and proper gas and leachate collection system.	1-3.5 million m3 volume displaced. Buried 71 houses and 143 Causalities.
Meetho-tamulla dumpsite (2014) [6]	45-50m 1.2H:1V to 577H:1V	R01, R02, RO5, R06, R15	Do proper site selection and regulation of landfills	Causalities and 87 houses were damaged.
Koshe dumpsite (2017) [7]	40m 1H:1.2V	R09, R15	The height of the landfill needs to be maintained. Never open closed landfill to meet waste demand. Maintain a proper channel for leachate outflow.	113 Causalities and many injured.
Ghazipur dumpsite (2017) [8]	55-60m 2H:1V	R07, R10, R11, R12, R15	Stop disposing of waste at the top; establish interim on-site landfilling locations. Reduce the amount of waste to be disposed of at the landfill	2 Causalities and 5 People were injured.

3.1 Slope failure of landfill

There are many reasons why a landfill could fail, but a fundamental cause for them to fail include the steepness of the trash fill, poor waste delivery management, non-compaction of waste, and improper waste placement, which results in a weak and compressible waste mass that is readily unstable in locations with steep slopes. When disposing of waste, pushing waste up onto the upper side slopes typically creates steep, uncompacted side slopes with weak shear strengths, which played a part in the landfill's slope failure. So, stopping the accumulation of waste on top of waste lessens the instability of the waste slope.

The heavy rainfall led to one of the primary reasons for the failure of landfills, which increases the leachate generation, raises the pore water pressure and reduces the factor of safety against sliding. All flat-to-slope waste surfaces should be graded by at least 5 to 10 percent to aid positive surface runoff and reduce water infiltration during the rainy season. It is also advised to regularly monitor liquid levels within the waste pile areas where a build-up of liquids can cause slope instability. The landfill needs to be compacted so that it increases its shear strength and decreases its compressibility. The compaction of waste can be accomplished using a compactor designed for landfill applications or other heavy equipment. Compaction must be avoided near or on very steep side slopes where the movement of equipment compacting is challenging. Regularly checking for tension cracks, deformation, or rapid settlement in the landfill region is needed as these signs point to a higher risk of slope failure.

Choosing a new sanitary landfill site that addresses all issues, including slope instability, landfill fires, site capacity, and others, if the amount of waste building up in the landfill is above the designed capacity. To operate the landfill safely, and sustainably and to avoid any accidents that have occurred in the past, it is necessary to regularly examine and maintain it.

4 Engineered Landfill Failures

The engineered landfill failures can be further divided into side liner failures, baseliner failures, final cover failures, leachate collection system failures, and gas collection system failures. These types of failures are discussed in detail.

4.1 Side Liner Failures.

Side liner failure may not be a primary reason for failure as liner failure is the result of causes like improper working of internal components like leachate or gas collection system (as observed in most cases). Examples of side liner failures that happened in history are Kettleman hills (1988) [9], Mahoning landfill (1996), Geneva landfill (1997), Shenzhen landfill (2008) [10], etc.

- In general, the liner system fails due to lower shear strength between different layers of a multi-layer liner system. The reason for the reduction in shear strength is different in different cases. Interface friction between the layers is the variable measure to determine shear strength. Numerous factors, such as the presence of wet or dry surfaces, level of polishing, and even the layers' inclination concerning the direction of applying shear stress have an impact on frictional resistance.

- During construction there are high chances for some areas to get wet, because of which considerable pore-water pressures might remain at the compacted clay liner interface, and these pore pressures could be of magnitude almost as great as the overburden pressure of the overlaying materials.
- The above-discussed scenario can also be found in the case of usage of leachate recirculation wells, because of which there will be an increase in pore water pressure which adversely affects slope stability. Saturated conditions and piezometric pressures can occur if surface water is not properly managed, resulting in slope instability.
- The other reason for the side liner failure can be the result of an increase in leachate level (which is discussed in LCS failure in the later part of the paper) which in turn increases the weight of the MSW. Due to the significant waste body deformation caused by the drag load, a landslide occurs within the liner system.

The various measures that can be taken for these types of failure are:

- Water in the landfill waste is pumped and drained to lower the water level, and clogged drains are cleared to allow surface water to drain, using sandbags to apply back pressure to the bulging area at the bottom of the slope and covering the waste body with plastic film to prevent infiltration.
- Cracks in the ground surface should be checked regularly by the site staff as they indicate shear displacement and damage to the underlying composite liner system. Waste may need to be shifted to another region, or a slower trash movement process may be required to guarantee that the slope is not overbuilt, and hence the action of higher magnitudes of drag forces on the side liner can be avoided.
- Correct estimation of the degree of consolidation, post-compaction wetting, and overburden stress helps design the liner properties like cohesion and angle of internal friction. It is also essential to plan the filling sequences in such a way that adequate factors of safety at all heights and for all geometries of the landfill can be maintained. The strength of liner can also be increased using biopolymers [11].

4.2 Base Liner Failure.

The landfill liner system acts as a barrier between soil and waste by isolating landfill waste from the environment and draining the leachate into the collection system. It protects the surrounding soil and groundwater from contamination by leachate. The liner system is decided on the type of waste the landfill is accommodating. Some liner systems include single liner systems, composite liner systems, double liner systems, etc. No matter how much care is taken while designing the landfill components, sometimes failure occurs.

If the leachate produced in the landfill is not properly drained into the collection system, it gets accumulated over the liner causing overburden pressure on the liner. Sometimes to accelerate the rate of degradation of waste, leachate is recirculated into the waste. This method can reduce the FOS value if the leachate under pressure gets pumped into the interface (A.C. in Fig. 4). If the localized leachate (the area in the landfill body in which leachate gets trapped and does not infiltrate into the bottom) comes in contact with potential failure surfaces like liner interfaces (B.C. in Fig.4), it further decreases the FOS making the landfill unstable [12]. The base liner failure may occur when the leachate head exceeds a certain value (generally 300mm) or when there is low interface shear strength in composite liner systems. These failures come under translational failure. Translational failures are either linear along a single plane or consist of several linear segments. The failure is quite often across discrete boundaries formed by the linear system. Kettleman hills waste landfill failure is one such failure that comes under the liner failure [13]. Improper design of the interface between the liner is one of the reasons for Durban landfill failure.

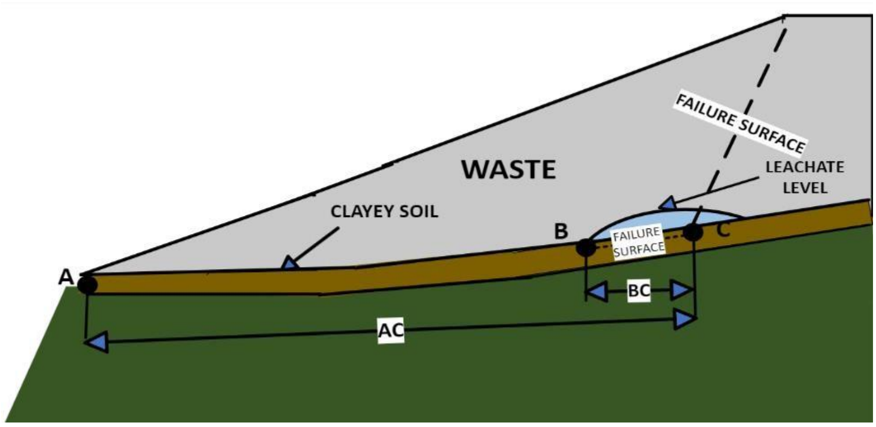

Fig.4. Localized leachate on the failure surface

Few precautions to be taken to avoid this type of failure include landfill filling planning, i.e., the sequence of fill stages should be developed in such a way that an adequate factor of safety can be maintained at all types for all fill heights and geometries; adequate testing programs that cover the full range of anticipated field conditions as minor changes in moisture contents can alter interface shear strength; providing good leachate collection system; selecting the Geosynthetics material for liner system.

4.3 Final Cover Failure.

Only a few cases of final cover failures are observed in history. However, the final cover of the landfill (Wisconsin, USA) [14] slipped a few days after the gas collection system, and the leachate collection system was stopped for repair work. Based on the observations, two failure mechanisms are summarized. They are:

- Reduction of shear strength due to elevated gas pressures at the GM-GCL interface.
- The action of water pressure on the lower side of GCL due to perched leachate.

The exact reason for the two cases can be determined from field observations and laboratory tests. For the first case, if gas is present, it will come from fine cracks and cavities in the subgrade earth. When a hand was placed near the fractures or voids in the subgrade soil, a whistling sound could be heard, and gas flow could be felt. To know if only excess gas pressures are the reason, then soil samples should be collected and tested. The results indicate that there were no signs of pore water pressures being enhanced, such as free water or saturation, or leaks (Despite the fact that water was seen in test holes created in the subgrade soil, free water and seeps should not be present at the subgrade soil's surface.). In case free water is found in a considerable amount, then further investigation should be done to know the primary reason for the failure.

Laboratory tests like conventional direct shear tests and stress reduction direct shear tests are to be done. However, an increase in landfill gas pressures results in a decrease in effective stress. As a result, slope instability occurs due to insufficient shearing resistance between the GM. and GCL [15]. This failure may have been prevented if the gas collecting system had been properly maintained or by implementing a mechanism to lower gas pressures in MSW landfills, especially those having high rates of gas production, which includes landfills that use leachate recirculation. It is really necessary for proper consideration of rates of recirculation and procedures adopted for filling to ensure that waste is kept transmissible for efficient collection of gases. The base of the final cover should have as little gas pressure as feasible, hence transmissive gas collecting layers should be taken into account.

4.4 Leachate Collection System Failure.

Leachate collection system (LCS) is one of the main reasons for the failure of landfills. When failure of the leachate collection system is undetected causes leachate to build up on top of the liner and leads to failure of the liner system. The Shenzhen landfill failure (2008), and Brasilia landfill failure (2019) are examples of LCS failure. The main reason for the failure of the leachate collection system (Fig.5) is system clogging. Other reasons include differential settling and detonation of the drainage pipe due to chemical attack or corrosion. If the landfill has a great accumulation of water due to a wet mass of waste in landfill disposals or due to heavy rainfall due to typhoons leads to a high leachate head which in turn blocks the landfill gas and reduces the efficiency of the gas collection system and reduces the shear strength of the whole landfill.

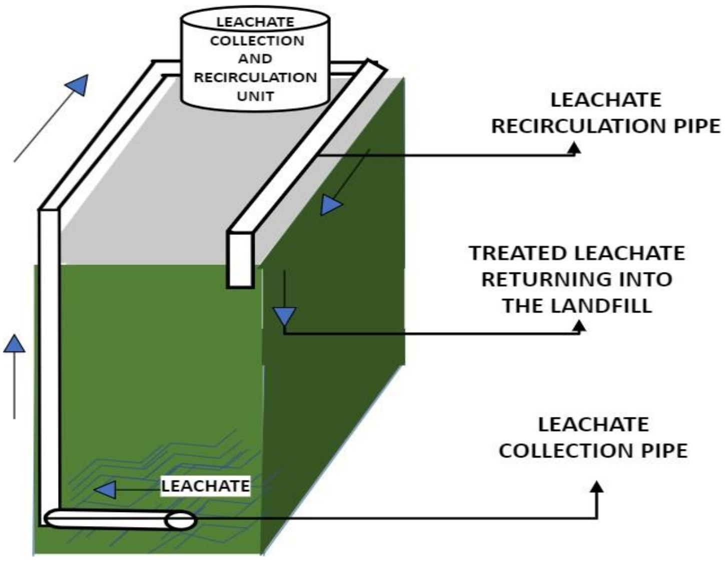

Fig. 5. Schematic drawing of a leachate collection system

The clogging of LCS is caused due to mechanism of growth of biomass, precipitation of minerals, and deposition of suspended solids. The clogging rate of landfills increased with decreasing grain size of drainage, increasing mass loading, and increasing landfill temperature. McIsaac & Rowe (2007) [16] reported that 38 mm gravel in the saturated zone for 12.6 years worked substantially better than the 19 mm gravel during 6 years under similar conditions. Clogging is greatest where there is most significant mass load- ing (near the inlet in this case, but likely near the collection pipes in a field situation). Armstrong (1998) [17] looked at the effect of temperature (10˚C, 21˚ C, and 27˚ C) on clogging rate and found that the higher the temperature, the faster the clogging rate. Therefore, it is always recommended to operate the LCS in unsaturated conditions.

Designing of LCS. The design includes pipe location, redundancy in design, maintenance features, and avoidance of specific clogging mechanisms. Pipe location is one of the essential aspects of design many times, pipes get crushed or displaced due to equipment loading or differential settlement. This can be prevented by carefully placing the pipe in a trench while considering its loading conditions and proper bedding. When flow through the pipe is constrained, one of the key approaches to provide redundancy in design is to construct collecting laterals so that drainage requirements can be supplied solely by the gravel layer. Avoidance of specific clogging mechanisms can be achieved by the selection of grain size of distribution in the filter material to exclude solids, providing minimum slope, and maintaining flow velocity; cell-specific selection of construction materials helps in avoiding chemical compatibility problems at waste facilities.

Construction of LCS. To ensure that the completed leachate collection system should meet or exceeds the design criteria, construction quality assurance (CQA) is required. This entails keeping track of and documenting the quality of the materials used and the conditions and method in which they were placed. Before wastes are received at the plant, CQA is used to detect deviations from the design due to contractor error or neglect and to arrange for appropriate corrective actions. Due to a lack of sufficient CQA, problems with leachate collection systems arise during construction.

Maintenance of LCS. Finally, the important one is an operation that includes regular inspection and maintenance of LCS. The build-up would have been avoided if the apparatus that produced the 100 ft "worm" had been flushed regularly. Some clogs, such as biochemical precipitation of iron, are relatively easy to clear when they are young. Still, they become difficult, if not impossible, to flush out as they grow (Ford 1980). Early detection is required for these types of deposits to eliminate the requirement for excavation and repair of the clogged drain.

4.5 Gas Collection System Failure.

The main reasons for landfill gas production are bacterial decomposition, volatilization, and chemical reactions, which are inevitable in a landfill. These gases will migrate fromone generated point to another by diffusion or permeability of waste or gas pressure. There are many issues with landfill gas like damage to the geomembrane, greenhouse effect, chances of an explosion which can lead to fatality, safety and health issues of nearby residents, etc. So, it must be collected using gas collection systems (whether active gas collection system or passive gas collection system).

Different gases that landfills possess are methane, carbon dioxide, carbon monoxide, and also traces of oxygen, hydrogen, nitrogen, ammonia, and non-methane organic compounds (NMOCs) such as benzene, vinyl chloride, and trichloroethylene.

Reasons for the failures of Passive Gas Collection Systems are improper working of vents or trenches. If they are placed at distances other than optimum to each other, then it becomes relatively tough to prevent gases to migrate, and passive methods fail to successfully remove landfill gas when the pressure in the dump is insufficient to force the gas to the venting device; whereas reasons for the failures of Active Gas Collection System is the failure of the mechanical blower which is attached to gas extraction wells.

Remedial Measures. Firstly, for Passive Gas Collection Systems, lateral gas migration can be controlled if well vents are placed closer to each other. To locate the best vent placement, preliminary sampling should be done to identify the gas gathering points. In the case of trench vents the depth of the trench can be dug down to the point where groundwater or an impermeable formation limits the depth of gas flow; also, to improve control effectiveness, the outside of the trench can be lined with impervious material.

Secondly for Active Gas Collection Systems to effectively collect landfill gas from every area of the landfill an effective collection system should be designed and configured in which the pumping system and collection well valves should be monitored by the landfill operator.

5 Conclusions

The following salient features are drawn from the extensive review of engineered and non-engineered landfill failures:

- The failure of non-engineered landfills is mainly due to their high steepness, great height, sudden disposal of heavy loads, high leachate accumulation during heavy rainfall, and lack of a proper drainage system. These can be controlled and stopped using compaction, grading, and regularly examining waste. The steepness of the landfill should be maintained within the limit of 1:3, and benches should be provided with at least a 5m width for every 10-15 m rise in the vertical distances down the slide slope.
- The side liner failure can be prevented by laying liners under dry conditions with a correct estimation of the degree of consolidation followed by post-compaction wetting, regular inspection of side slope, unclogging of drains, laying plastic film to prevent infiltration of water, monitoring of waste load disposals and ensuring that slopes are not overbuilt or over steepened.
- The base liner failure can be avoided by executing adequate testing procedures before base liner construction that spans the full range of predicted field circumstances, choosing proper geosynthetics for the liner system, and supplying an effective leachate collection system.
- The final cover failure can be restricted by maintaining an adequate gas pressure, particularly in high gas generating landfills such as leachate recirculation landfills, and by ensuring the leachate level in the landfill.

- The leachate collection system (LCS) failure can be forestalled by better design, construction, and maintenance of LCS. The design includes pipe location, redundancy in design, maintenance features, and avoidance of specific clogging mechanisms. The regular maintenance should include simple mechanical cleaning by flushing the pipe network and managing the pH level of waste inputs to reduce their biological activities.
- The gas collection system failure can be avoided by placing the outlet vents/trenches at an optimum distance and the best position can be obtained by preliminary sampling to identify the gas gathering points and for higher gas generating landfills, the pumping system, and collection well valves should be monitored regularly.

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