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This paper is part of the Proceedings of the 8th International Conference on Waste Management and The Environment (WM 2016)
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Development of a sustainable MSW landfill as an intrinsic part of a low-priced, integrated waste management facility

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Abstract

Usually, a landfill is designed to function as an independent technological unit from the inception of the facility to the post closure stage of its development. However, sustainable technologies like in-situ aeration and landfill flushing dramatically shorten the duration of aftercare period. The aftercare phase comes to an end when the actual emissions appear to be so low that the site can be abandoned with essentially no risk to environmental quality and public health. Closed sections, if rapidly stabilised, offer an opportunity for real-time land reclamation for the establishment of waste recycling and recovery activities there while the landfill is still active as well as afterwards. Environmental, logistic and other infrastructure already present at the site are very much applicable for purposes of integrated waste management, too. In this way, a landfill site is slowly transformed into an integrated waste management complex diverting more and more waste away from burial in the landfill. This process may last a decade or two. After the post-closure care period ends the operator is still actively present on-site which simplifies liability concerns. Additionally, synergistic effects can result in significant economic benefits for the owner and the operator, which can be considered as the money held in escrow for purposes of covering post-closure costs. In the case of a small pilot-scale Slovenian landfill, these costs appear to be very low because its design was focused on issues like socio-economic sustainability and rapid waste stabilization. Since waste disposal of untreated MSW is still widespread in low-income countries today, the approach could be of current interest for smaller, self dependent urban areas in developing countries.
Keywords: flushing landfill, semiaerobic landfill, low-cost landfill, integrated waste-management, land reclamation, transition period.

1 Introduction

Landfilling is universally considered to be the least sustainable method of waste management. In the industrialized countries, complex integrated waste management systems have been gradually established diverting large portions of recyclable, biodegradable and combustible municipal solid waste (MSW) fractions away from landfill. The remaining active MSW landfills tend to be large, highly engineered facilities. In some countries, only thermally or mechanically-biologically pretreated MSW can be landfilled.

On the other hand, a large part of MSW generated in developing countries continues to be deposited in numerous small, poorly managed, not fully controlled sanitary landfills or even in open dumps, threatening the local environments there.

Municipalities in developing countries are often left on their own in order to solve their local environmental problems. Great difficulties have to be overcome trying to define useful MSW management strategies due to low technical experience and low financial resources that often cover only collection and transport costs, leaving little resources for safe disposal (e.g., Diaz *et al.* [1]).

All the same, municipalities in several European countries faced similar challenges just a decade or two ago. Many succeeded in establishing intermunicipal associations for the operation of new MSW management systems complying with the new technical standards and also succeeded in receiving funding from a wide range of national and/or international bodies. Basic environmental problems were ultimately solved, but costs and fees sky-rocketed, too. Such approach can be rarely duplicated in low-income developing countries today.

However, there were also cases when municipalities decided to choose a relatively uncommon, low-cost path due to uncertainties and peculiar economical circumstances they were facing at the time. Some succeeded to realize their objective to a satisfactory degree, largely on their own. Such experiences could be informative today for local waste management developers in low-income countries who find themselves in comparable situations.

2 Recognising environmental benefits of low waste compaction: a case study

Ajdovščina and Vipava municipalities (~25,000 inhabitants, Slovenia) inherited a non-compliant dumpsite intended to be closed down in 2001 which was however accidentally located on an environmentally and logistically adequate site and still had an available capacity for additional waste. The proposed alternative solution at the time appeared to be very costly and environmentally unreasonable. Consequently, it was decided that the particular site should remain active. It eventually began to operate and develop as a pilot research facility (Madon [2]).

The related general strategic direction in regard to the development of the site approved by the two local municipal councils some fifteen years ago appeared to be quite straightforward, as delineated below:

1) Low cost managerial and technical interventions could make substantial impacts compensating for the deficiency of funds. Therefore, our own municipal company was given the responsibility to develop the system and an educated person who understands the scientific concepts and facts that underlie environmental issues was employed in order to cope with the demands.
2) The existing semi-controlled dump had to be legalized, rehabilitated and enlarged in order to be functional for the next fifteen years by introducing sustainable waste disposal practices at the site. However, it had to be done in the most economically feasible way.
3) During the same period of time, some simple, but effective and flexible system of integrated waste management had to be established at the site as well, diverting most of the collected MSW and other waste from entering the landfill.

It was already known that the particular dump was not among the worst ones which were active in the country during that time: the elementary public health provisions were already implemented by the local operator carrying out regular cover operations and most importantly, the hydrogeological setting was found to be optimal (Madon [3]). The facility was lacking some basic infrastructure in order to be called a 'sanitary landfill': leachate and gas collection systems, reception platform and a weighbridge among other deficiencies.

By monitoring the emissions from the old sanitary landfill sites and dumps in developed countries (e.g., Kjeldsen and Christ [4], Komilis and Stegman [5]) it was recognised that MSW buried in these facilities generally tends to stabilize quickly. The very same encouraging conclusions were derived by performing environmental research at this particular local dump site and in the nearby surroundings in 2001/02. Leachate oozing out of the foothills of the dump appeared to be of comparably good quality, objectionable odours were almost completely absent and methane concentrations in the landfill gas samples taken below the sanitary cover were found to be low. Atmospheric gases were found to be present in small concentrations in deeper parts of the landfill, too, penetrating laterally from the slopes. Dissolved oxygen was almost always present in the saturated zone on the bottom of the landfill in small concentrations as well.

Many coincidental factors were believed to have contributed in creating favorable environmental conditions within the interior of the buried waste: 1) The dump was formed as an above-ground, self-draining waste pile (landraise), at the time not yet capped; 2) Compaction energy input was minimal, since daily waste shipments were not spread over the slightly inclined working face areas in order to be compacted in thin layers (slices), but by applying compaction over a subhorizontal, 2.5–3 m thick layer of waste forming a lift in one incremental step utilizing a bulldozer only; 3) Marly-clayey soil was mostly used for carrying out daily (sanitary) cover operations. It was arriving continually from the many local construction sites without any cost for the operator.

The resultant waste pile appeared to be a subhorizontally stratified structure featuring imperfect alternation of up to 3 m thick, lightly compacted layers of disposed of waste and up to 0.5 m thick, almost impermeable lenses of clayey soils. Saturated hydraulic conductivity through the layers of disposed of waste was later found to exhibit values around $k_{sat} \approx 5.10^{-5}$ m/s , whereas in the vertical direction the value appeared to be smaller for one decadic order of magnitude, which was related to the particular pattern of stratification (Madon [3]).

The passive structure demonstrated some unique, environmentally and economically important features, uncommon for the ordinary, anaerobic sanitary landfills, which was interpreted as written below:

1) High permeability of loosely compacted layers of waste allowed for aqueous and gasseous products of decomposition to be quickly removed from the very microlocations where they were formed, indirectly enabling fast rates of stabilisation and mineralization processes to occur unabated in continuation. Lightly compacted layers of waste transmit fluids efficiently by themselves. In modern landfills specifically engineered gravel layers and blankets were constructed in order to facilitate leachate drainage, landfill gas collection and distribution of recirculated waters within the waste body.
2) Semiaerobic environment within the dump provided for a) less generated methane, b) faster decomposition releasing simpler, non-odorous substances into the environment, c) lower amonium concentrations within the leachate (e.g., Jokela *et al.* [6]) and d) positive reduction potential (ORP) resulting in low precipitation of hydrous ferric and manganese oxides after leachate oozed out on the surface. Advantageous characteristics of landfill aeration have been confirmed by many researchers (e.g., Matsufuji [7]).
3) Marly clay used for sanitary covers worked as a pH buffer, resulting in consistently low heavy metals concentrations in the landfill leachate.
4) Considerable air space lost due to low in-place compaction appers to be recovered promptly during the active phases due to high settlement rates. The initial density of ~300 kg/m^3 increases to ~400 kg/m^3.

It was acknowledged that all these positive environmental indicator values would be lost altogether as soon as operating techniques on the working face would eventually change in order to achieve higher in-place waste densities. However, extending a landfill's life for the long-term was not the goal the operator was seeking. According to the requirements of European legislation in effect at the time and by observing trends in some neighboring, highly developed European countries during that time it was already anticipated that small municipal landfills will be closed down gradually between 2005 and 2015 and only a few, brand new, large regional landfills would remain active in the country.

3 Concept of a low-cost, sustainable, high-permeability landfill

Design of the modern, highly engineered sanitary landfills is focused on long term isolation of disposed of waste and on minimizing specific costs of disposal by maximizing the quantity of disposed of waste per square meter of the available footprint area. Investment, operational, closure and post-closure costs appear to be high, which applies to both, dry and wet (bioreactor) landfills. Even the best liner and leachate collection systems will fail eventually. Heavily compacted waste can be stabilised only with difficulty. Therefore, this approach can not be considered to be sustainable.

An alternate conceptual approach to sustainable sanitary landfilling and facility development was applied at the research-oriented site fifteen years ago. The focus was put on providing low-cost, rapid stabilization and decontamination of the landfill already during the time the liable operator is still actively present on site (Madon [3]). The approach implicates the operator is able to demonstrate the pollution potential would be abated down to a effectively safe, negligible level soon after the last active landfill cell would be closed.

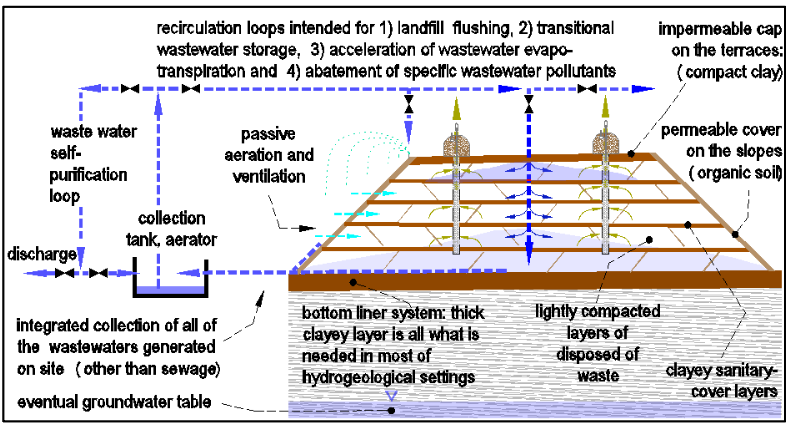

Figure 1: High-permeability landfill features.

Such-a distinct setting in turn allows for an opportunity to reclaim land of the completed landfill sections for purposes of establishing complementary waste management activities there in a real time and in a safe manner. The transformation process could pass almost unnoticed because the transition period can last for many years or even decades, depending upon the circumstances and situations encountered by the owner and/or the operator during the course of time.

Schematic of a low-cost, high-permeability landfill as was implemented on the Ajdovščina research site is depicted in Fig. 1. The most important systems are compiled below:

3.1 Multi-branched system for recirculation of wastewater

High hydraulic transmissivity and high dynamic water storage capacity are distinctive characteristics of a stratified, low-density landfill which allows for much more versatile and effective uses of recirculation technologies in comparison to conventional bioreactor landfills. Instead of focusing solely on leachate management, all of the wastewaters of comparable characteristics generated on site (polluted run-off included) are intercepted and treated together recirculating within the multi-loop system in relatively large quantities.

Recalcitrant pollutants are flushed out of the landfill by periodically flooding buried layers of waste alternately changing water injection locations. A particular horizon to be flooded is selected by sealing the choosen perforated borehole at a selected depth using an inflatable plug. In combination with an effective passive landfill aeration, in a matter of a decade, the waste body gradually transforms into a stabilized, decontaminated mass and the aftercare phase period of the actual landfill cell essentially comes to an end.

Information related to the environmental performance of the implemented recirculation systems at the pilot research site together with the related hydraulic and hydrologic data were presented elsewhere (Madon [3]).

3.2 Passive system for landfill aeration and management of landfill gases

3.2.1 Working face

Due to light waste compaction, landfill conditions are already semiaerobic during the early stages of filling a cell. Recirculation of leachate on the active working face is avoided.

3.2.2 Contour bunds

Cover on the slopes is constructed in a way to be permanently permeable for gases and waters during the operational phase, i.e., contour bunds are purposedly constructed from soils which do not contain too much clayey fractions and compaction is avoided. The related saturated hydraulic conductivity in the pilot site was found to fluctuate around the value of $k_{sat} \approx 5 \cdot 10^{-5}$ m/s, which is the same representative value as valid for lightly compacted layers of waste.

3.2.3 Final cover on the top of the landfill

Final cap on the terraces and benches is made from thick, compacted clayey soil in order to prevent any gas exchange between the interior and exterior of the landfill there. The clay layer itself is covered with organic soil or paved by gravel, respectively (depending on the final use) in order to prevent formation of dessication cracks.

3.2.4 Landfill shape

The shape of the landraise is intentionally designed in a way that the ratio between the parameters 'volume of the facility' and 'surface area of the slopes' is as low as possible ($r \leq 20 m^3/m^2$ in the pilot study case). It was found that the lateral distance from the inner parts of landfill to the the nearest slope surfaces should not exceede approximately 70 meters to prevent anaerobic zones to form in the lower central parts of the landfill, which can persist there for a few years. Therefore, the considered low-cost semiaerobic waste disposal facility appears to be suitable only for smaller capacities or for settings where prolonged, narrow-shaped landraises can be erected. Broader landfills of this type would be feasible, too, if additional measures are provided in order the air could reach the innermost parts of the facility. For example, large diameter pipes can be laid down at the bottom of the landfill conected with the vertical vents as Fukuoka method suggests (Matsufuji [7]).

3.2.5 Gas extraction wells

Vertical passive gas extraction wells of 1 m diameter were build in on ~50 m spacings to depths around 80% of the landraise height. Unsophisticated, fabricated on site coupled flare/ biofilter units were instaled over the outlets of the passive gas extraction wells on the top of the completed landfill sections (Fig. 2) in order to cope with low flows and/or low concentrations of methane. Gas oxidation unit works in a way that when the valve is manually closed, the gases are not conveyed to the burner any more but are forced to pass through a biofilter stack filled with compost instead. Similarily, on the active working faces, removable biofilter bundles were used to cover gas wells outlets to prevent direct venting (Fig. 2).

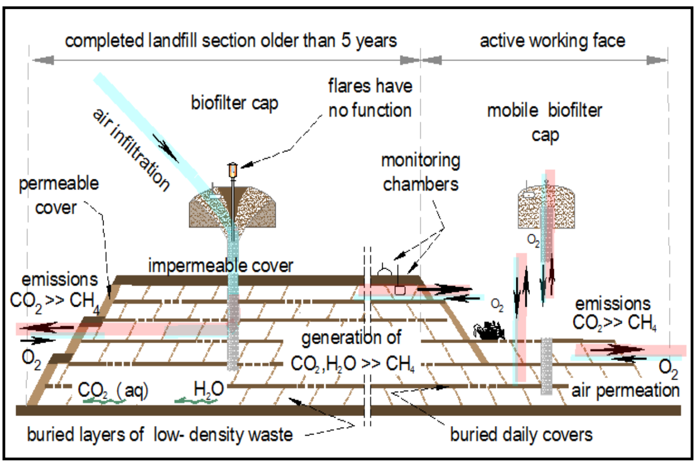

Figure 2: Passive aeration in high-permeability landfill.

3.2.6 Method description

Subhorizontal layering is a vital part of the concept of a passive, high permeability semiaerobic landfill. Landfill gases generated within the permeable waste layers are constrained to migrate horizontally through them in-between the impermeable clayey layers until reaching one of the passive gas wells or eventually reaching a permeable topsoil on the landfill slopes. Overpressure within this type of landfill is always low (generally tenths of milibars to few milibars at most) due to 1) high porosity of the landfilled waste (n > 50%), 2) fast removal of the generated gases, 3) limited methane production due to the existance of aerobic zones and 4) high solubility of CO_2.

In landfill sections and zones where the buried waste is young, landfill gases prefer to migrate upwards through the gas shafts. Consequently, air is induced into the landfill from the landfill slopes horizontally along the waste layers The driving force is a buoyancy effect (e.g., Kim [8]) caused by the moderately increased temperature within the waste body (up to 35°C). Oxygen tends to penetrate into the landfill interior also by means of diffusion, which can happen only through the permeable slope surfaces or through the biofilter stacks installed on the surface above the vertical gas wells. Permeable soil cover on the landfill slopes and biofilter stacs packed with compost are both permeated with air and function as biofilters (e.g., Stern *et al.* [9]).

Methane levels were too low to sustain continuous flaring even if the applied candle flares were equipped with wind shields. Six flare-and-biostack composite units were installed, but only one flare sustained the flame continuously for seven months and another one intermittently for three months. Landfill gases were therefore diverted to pass through the biofilter stacks.

Few years after completion of a particular landfill section the intensity of anaerobic as well as aerobic decomposition began to decrease which was manifested by the drop in landfill interior temperatures to some 20°C and in decrease of methane levels. Direction of ventilation have changed gradually, too: air was no longer entering into the waste body from the permeable slopes and landfill gases were escaping into the environment from the biofilter stacs on the top of the landfill, but the opposite became true (Fig. 2). This shift can be largely attributed to the change in density of the landfill gas mixture: CO_2 was now the gas which prevailed in the landfill atmosphere. Even during the early stages, significant quantities of CO_2 escaped into the environment from the landfill foothills, not from the vents.

3.2.7 Landfill performance monitoring gas emissions

In order to acquire gas emission rates from the biofilter stacks installed on the top of the passive gas wells as well as to assess fugitive emissions from the landfill surfaces, a static flux chamber method was applied in adition to conventional approaches. Portable flame ionization detector Photovac Microfid was the most important instrument used to fulfill the task.

It is worth noting that hydrogen sulphide was detected only once in the period of a decade and more. Year after year it was recognized that less than 10% of biodegradable carbon placed in the landfill ends up into the atmosphere as methane emissions, which is a very good result in comparison to most conventional landfills. Summary of monitoring results from 2013 considering greenhouse gasses is presented in Table 1.

3.3 Upgrading low-cost landfill site into a low-cost waste management site

Completed landfill sections pertinent to conventional, highly compacted landfills are typically of no productive use to landfill owners/operators, which is due to:

1) risks associated with possible methane gas releases, 2) the fact that space is already largely occupied for functioning and maintenance of gas collection and control systems, 3) excessive differential settlements, 4) very long aftercare period, 5) inability to manage the potential storm water pollution derived from these areas. Properly designed and operated sustainable, high-permeability landfills are practically non sensitive to these impediments.

Table 1: Emissions from the pilot site in 2013.

Emission source	Surface area [m^2]	Emiss. of CH_4 [t]	Emiss. of CO_2 [t]
Completed landfill sections			
'Methane emiss. windows' on the slopes	380	21.9	103
Other slope surfaces	26700	0	310
Terraces and benches	15800	0	15
Biofilter stacks (above gas wells)	6 × 6	0	3
Non-completed and active landfill sections			
Working face	2850	5.0	110
Uncovered working front slopes	2200	27.5	680
Gas well covered with portable biofilter	5	1	10
Other emission sources			
Area on the landfill for temporal storage of pretreated sewage sludge	2000	1	11
Composting platform and complementary areas	1600	13	260
Thinly applied pretreated sewage sludge over the completed landfill slopes	25500	0	300
Ponds, lagoons, artificial wetlands	1770	1	60
Total	5 ha	69.5	1860
Complementary data (rounded values)			
Landfilled MSW and similar waste 2007–2012 [t/year]	7.000	of this biodegr. carbon 1.100	
Received, treated and on-site utilized biodegradable waste 2007–2012 [t/year]	1.200	of this biodegr. carbon 300	
Received, stored and on site spread sewage sludge 2007–2012 [t/year]	2.000	of this biodegr. carbon 300	
Filled capacity of the completed landfill sections [t]	MSW 175.000	of this biodegr. carbon 24.000	
Already filled airspace of the active landfill section [t]	MSW 39.000	of this biodegr. carbon 4.400	

3.3.1 Pretreated sewage sludge storage, final treatment and usage

Completed landfill slopes and benches are suitable for thinly spreading the material over the surfaces at the beginning of the summer season (Madon [3]). The systems for drainage and collection of the polluted surface runoff are already designed to be an integral part of the multibranched recirculation system, therefore, from the environmental standpoint, the operations can initiate immediately after the closure of a cell. Sequential photochemical and microbial degradation of humic substances (e.g., Amador *et al.* [10]) reduces the quantity of the applied organic matter during the course of time, so the processes can be repeated for many years. Up to 200 tons per hectare (expressed in dry matter) is applied annually at the pilot facility (Fig. 4).

3.3.2 Outdoor plant for processing and sorting of waste

It is known that at sites where poor initial compaction was achieved and large amounts of precipitation were allowed to percolate into the waste, settlement was quicker and more extensive. The settlement potential has been largely consumed during the active operational phases. Additionally, at the pilot research site, after capping the landfill, a recirculation system was installed performing flushing of the landfill interior. Waste layers were intermittently flooded horizon by horizon, which has led to a fairly uniform settlement. In conventional landfills, however, significant subsidence can be observed on the capped surfaces, especially around the gas extraction wells and injection boreholes.

At the study case site, a 70-metre long plant for sorting and shredding of waste was installed in 2006/07 on the top terrace of the oldest part of the landfill just two years after final cover was applied (Figs 3 and 4). During the 2006/07 the settlements of the 20 m high landfill were on the order of 10 cm per year and diminished to 2.5 cm per year in 2013/14, while differential settlements ranged around 2 cm on 10-meter distances in 2006/07 and diminished to few millimeters over 10 meter distances in 2013/14. Geodetic levelling of bases of the uprights which support the steel frame construction was performed once per year and steel plates of proper thicknesses were laid under the base plates (Madon [2]). It can be concluded that seven years after capping of the cell differential settlements were small enough the procedure can be applied just once per three years instead of once per year.

Figure 3: Sorting plant installed on the landfill terrace.

3.3.3 Facility for storage of biodegradable municipal solid waste (BSW)

As the quantities of MSW diminish year after year, quantities of separately collected biodegradable waste fractions rise. Providing appropriate transient storage of BSW in an enclosed facility before applying further treatment is important for the environment. Terraces of high-permeability landfills are suitable locations for the instalation of such facilities. Seven years after closure of a particular landfill section the remaining potential for differential settlement appears to be easily manageable. Additionally, produced leachate can be drained directly into the waste body through a large-diameter drainage well (Fig. 4). Environment within the interior of the permeable, already stabilized landfill is very effective for treating leachate oozing out of the transiently stored BSW, mineralizing organic matter and removing nitrogen compounds (e.g. Jokela *et al.* [6]).

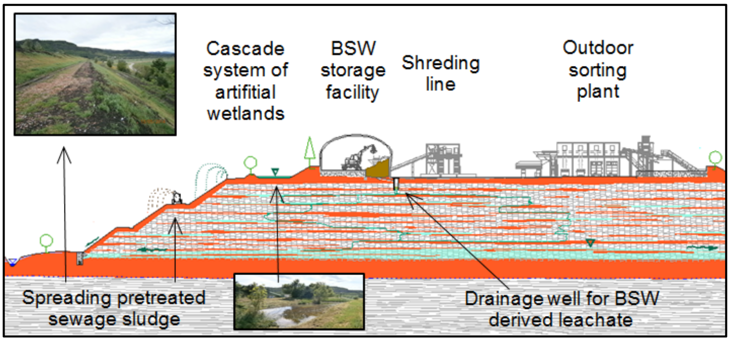

Figure 4: Real-time, low-priced uses of reclaimed land.

4 Conclusions

Sanitary landfilling has lost its relevance in developed countries. It is, however, still the most important waste management method used in many parts of the world. In low income countries, only low cost solutions seem to be viable either when coping with short term waste disposal problems or when making decisions about the long term development strategies. At the research-oriented waste management site in Ajdovščina, Slovenia, it has been demonstrated that high permeability landfill types can be developed in a way to be cost effective and environmentally friendly during the active phases and to be satisfactorily stabilized soon after closure. This approach allows for real time land reclamation of completed landfill sections for purposes of implementing complementary waste management activities there. With fairly low investment, the local waste disposal site can gradually transform into a low priced, but still sufficiently effective integrated waste management facility.

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