J Mater Cycles Waste Manag (2005) 7:■■–■■
DOI 10.1007/s10163-005-0133-6

ORIGINAL ARTICLE

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Past, present, and future of MSW landfills in Japan

Received: September 29, 2004 / Accepted: February 14, 2005

Abstract This article focuses on the historical development of landfill technology since the beginning of the nineteenth century in Japan. The regulations and guidelines that form a framework for the technology are reviewed, and the historical background and the current state of Japanese municipal solid waste (MSW) management are described. Through the analysis of data collected from facility leaflets, changes in the leachate treatment system are surveyed. Finally, the concept of the "sustainable bioreactor landfill with low organics" is proposed.

Key words Landfill · Municipal solid waste · Leachate treatment · Regulation · Sustainability

Introduction

In Japan, the incineration process has been considered the primary disposal system for solid waste for the past century, and landfill was only a secondary system, mainly used to receive residues. However, as a result of increasing concern about the environment and difficulties in constructing new landfills, which is caused by the not-in-my-backyard (NIMBY) reaction of residents, achieving a reduction in the quantity of waste to be landfilled became an urgent goal in waste management for both local and national government.

Since landfilling involves a much slower degradation process of solid waste than incineration or other options of solid waste management, environmental risks must be minimized in the long term as well as the short term. The construction and operation of a landfill should be considered over its whole lifetime. Control of input waste and the leachate treatment system is critically important for the reduction of risk, and is secured by regulations and guidelines. Stabilization of waste over a shorter period is required to reduce lifetime risk and cost of sustainability.

In this article, the historical development of landfill technology in Japan is reviewed. First, regulations and guidelines are reviewed because technologies have been developed to meet these regulations. Then the historical background and the current state of Japanese municipal solid waste (MSW) management are described, and changes in the leachate treatment system are surveyed. Finally, after state-of-the-art landfill technology is described, the concept of the "sustainable bioreactor landfill with low organics" is proposed.

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Historical development of regulations for landfill

Dumping

Like other countries, solid waste landfills were treated just as dump sites, without any control, even after World War II. One of the most famous landfills was "Yume-no-shima" (literally "a dream island"), which was an offshore landfill in Tokyo Bay. The landfill was operated from December 1957, and accepted 84% of the MSW collected in the Tokyo metropolitan area. It became well known after a notorious accident in 1965. In addition to spontaneous fires, open burning was often practiced there to reduce landfill volume. Because of the smoke and dust, burning was stopped, but there was still a problem with rats and flies. In 1965, the number of flies dramatically increased and they spread on the wind to residential areas. Spraying pesticide over the whole area to exterminate vermin did not prove to be effective, so heavy oil was spread on the refuse layer and set alight.

Sanitary landfill and technical regulation

After the event at Yume-no-shima, the practice of covering landfills with soil 30 cm thick was started, and this continued in most areas of Japan in the 1960s. With intermediate cover, it was called the sandwich-like landfill method, but there was no technical standard until 1971. Around the same time, research on landfills was initiated by Prof. Hanashima in both full-scale and lysimeter-scale. He proposed the structure of a "Semiaerobic landfill"[1,2] to aerate solid waste in landfills by natural convection.

With the increase of solid waste due to the growing economy, a problem of water and air pollution emerged in addition to the increase of waste. In 1971, the solid waste management law was enacted, and by this law "the standard of landfill disposal" was applied to landfills constructed after 1971. This law said that "pollution of surface waters and groundwater with leachate should be prevented if pollution was expected." However, this was a nominal standard without technical practice.

Technical standard of landfill

"The technical standard of operation and construction" was issued 5 years after the law of 1971, and defined the need and structure of leachate control and management. However, it was limited to landfills larger than $2000\,m^2$. In 1979, guidelines for the design, construction, and operation of landfills were published as "Guidelines for MSW landfill," which became the minimum requirement to obtain a subsidy from the national government, which covered a quarter of construction costs.

The guidelines contain the descriptions listed below.

1. Landfilling is a process by which waste is stabilized and assimilated to the ecosystem.
2. Its functions are to stabilize waste through a natural metabolic mechanism without any adverse effect on the environment;
3. and to contain waste and leachate, and to treat waste, leachate, and landfill gas.
4. To support these functions a liner system, leachate collection, and drainage system, and a leachate treatment plant are required (detailed design criteria were not included).
5. Daily cover (30 cm) should be applied after compaction of refuse. Intermediate soil cover (50 cm or more), and final cover must be applied.

Strengthened technical standards

The technical standards were revised in 1988 to strengthen the standard of the liner and the leachate treatment system. In a revised "Guidelines for MSW landfill," a vertical impervious wall structure was approved for the leachate containment system in any area with an impermeable subbase or natural liner. This is a dam of waste, and was used when waste was filled between ridges in a mountainside. When a plastic liner was used at the bottom of a landfill, a single liner was the standard at this time. Detailed instructions for the construction and operation of a leachate treatment plant were also included in the manual of the guidelines.

In the 1990s, solid waste management had become a critical social issue, and strong opposition by residents to landfill construction was common due to a NIMBY reaction. Concerns about landfills escalated after reports of a leak from an MSW landfill, and environmental pollution caused by uncontrolled landfills of industrial solid waste. Under such social pressures, in 1997, the "standard of landfill disposal" was extended to apply to every landfill, regardless of size. The enforced technical standard was set in 1998, in which a double liner was mandated for the bottom liner system instead of a single liner. The "standard for terminating aftercare" was established at the same time, although the criteria for the biological stability of waste are still being debated.

In 2000, the "guidelines for the performance of MSW landfills" became the criterion for the national subsidy instead of the "guidelines for MSW landfill." Thereafter, any landfill can be subsidized if it meets the criteria on liner, leachate collection, etc. Meanwhile the "guidelines for MSW landfill" somewhat limited the innovation of landfill structures. This shift opened new technology to the market, although the environmental standards, e.g., effluent standards, became stricter at the same time. As a result, the development of the new technology described in the final section of this paper was promoted.

Aerobic landfill with low organics

Recent trends in landfill strategy in developed countries are aeration and less organic content in waste. Historically, landfills have been operated in anaerobic conditions, but recently aerobic or hybrid bioreactors (aerobic and anaerobic systems) as well as anaerobic bioreactors have been studied in the USA.[3] In EU countries, some old landfills are aerated to promote biological stabilization.[4,5] On the other hand, by the landfill directive of 1999, EU member states need to limit the organic content of landfilled waste. Mechanical biological pretreatment (MBP) has been studied intensively, but incineration seems to be the only option to meet the criteria set by the directive. In Japan, on the other hand, natural aeration by the "semiaerobic landfill" has been the technological standard for a quarter of a century. Incineration of MSW has been the national strategy since the first modern law of solid waste in 1900, and incombustible contents are removed at source before incineration. Source separation of combustibles from incombustibles is commonly practiced in municipalities in Japan. To promote the stabilization of waste, Cossu et al.[6] proposed the pretreated aerobic flushing (PAF) model, but flushing has been a common practice in Japan since the lack of capping allows the infiltration of rainfall. As a result of such traditional ways, Japan is leading the world in sustainable landfill strategies which promote stabilization and after-use of the land.

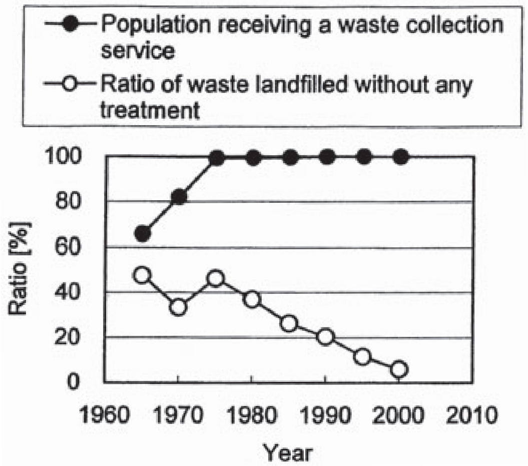

Fig. 1. Percent of population receiving a waste collection service, and the amount of waste landfilled without any treatment

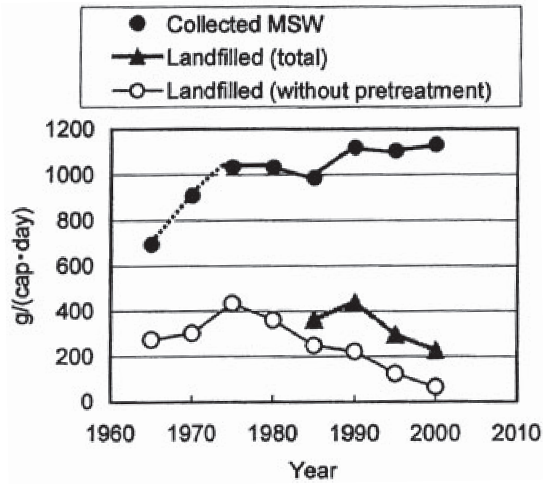

Fig. 2. Per capita amount of municipal solid waste (*MSW*) collected or landfilled

Historical development of MSW landfill in Japan

Background of MSW landfill

Figure 1 shows the percentage of the population receiving a waste collection service. In the economic boom of the 1960s, there was a strong need for waste management owing to the increase in the amount of waste. Previously refuse had been collected on an irregular basis, but in the late 1960s many municipalities started "collection at refuse stations" on a regular basis. A "station" is actually just a place on the curbside that is shared by several householders. There is no equipment, and the collection fee has been abolished. This reflects the idea that the waste collection "service" should be provided by the municipality. This idea has been a key principle of municipal solid waste management since 1900, when the first waste management law was enacted.

Another waste management strategy held for a century was "waste should be incinerated," which was also adopted for reasons of public health in 1900. The result is the high incineration rate of MSW: 45% in 1965, 60% in 1979, and 77% in 2000. This high rate was because almost 2000 MSW incinerators were owned by municipalities. Before the dioxin problem became a major concern in 1997, 100% incineration of combustible MSW was the national target. As a consequence of the increasing incineration rate, the amount of waste landfilled without any treatment decreased from 48% in 1965 to 6% in 2000.

Current situation of landfill

Figure 2 shows the per capita amount of MSW in Japan. Here, MSW is defined as household, commercial, and institutional waste, and recovered recycled material before collection is not included in the waste statistics. On average, every citizen contributes 0.6 kg per day to refuse collection, or 1.1 kg when commercial and business waste is included. While the amount of MSW is increasing, the amount landfilled without any pretreatment is decreasing.

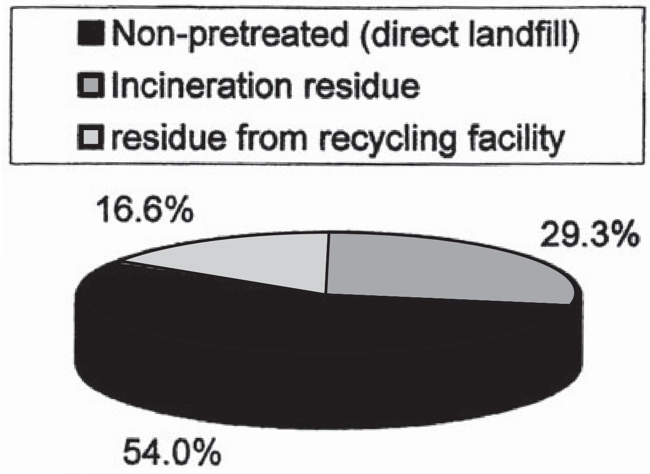

Fig. 3. Breakdown of landfilled waste in 2000 (on a weight basis)

A breakdown of landfilled waste in 2000 is shown in Fig. 3 (on a weight basis). Incineration residue account for 54% of the total, and 17% is residue from recycling or material recovery processes. Untreated waste accounts for only 29%. Owing to the common practice of pretreatment to reduce the amount of residual waste, the total waste landfilled decreased to 0.23 kg per person per day in 2000 (see Fig. 2). As well as the increase in the incineration ratio, active recycling of packaging waste (glass bottles, steel/aluminum cans, and plastics), which was promoted by the Containers and Packaging Recycling Law in 1997, is contributing to the decrease.

Figure 4 shows the number of landfill sites categorized by location. There are about 2000 MSW landfills, of which 70% are constructed on mountainsides by using the space

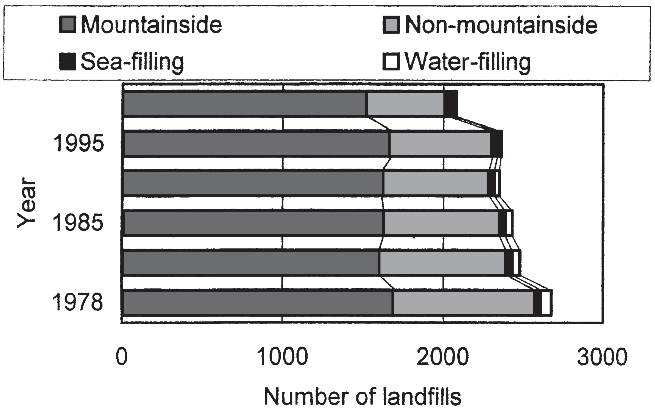

Fig. 4. Number of MSW landfills by location

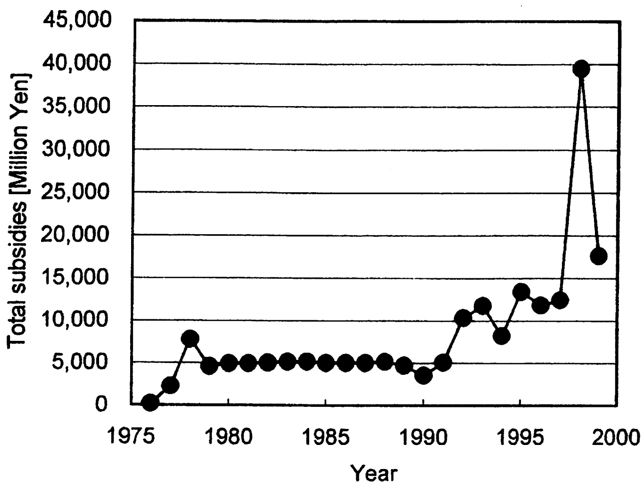

Fig. 5. National subsidies for landfill construction

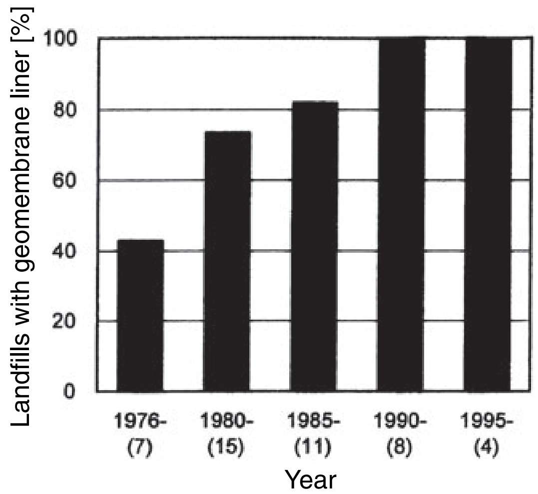

Fig. 6. Percentage of landfills with a geomembrane liner (the number of facilities are shown in parentheses)

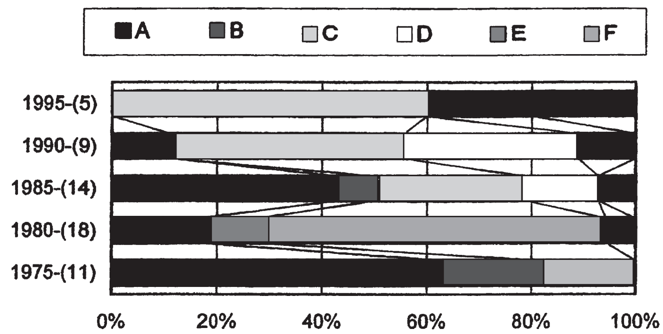

Fig. 7. Development of leachate treatment systems (the number of facilities are shown in parentheses)

between ridges. The reason for such siting is the strong NIMBY reaction of neighbors, and limited land space. Sea-filling or water-filling is unique to Japan. It accounts for only 2% of the total number of sites, but 28% of landfill volume because of their relatively large size.

MSW landfill construction has been subsidized by the government since 1976, i.e., 13 years later than MSW incinerators. As shown in Fig. 5, the expense increased in the 1990s. The peak high in 1998, 40000 million yen (which is eqivalent to 330 yen or 3US$ per capita), was due to the strengthened technical standards.

Development of the leachate treatment system

The development of the leachate treatment system in Japan was reviewed by collecting facility leaflets, which are commonly provided by municipalities to visitors, and contain information ranging from landfill design to construction costs. After collecting leaflets from many municipalities and studying related articles in journals, the data from 59 facilities were used for analysis. In order to understand the status quo of technology at the time, the facilities were grouped according to the year when their construction was planned, not by the year they started operation. The numbers of facilities surveyed are 12 for 1976–1979, 18 for 1980–1984, 14 for 1985–1989, 10 for 1990–1994, and 5 for 1995–2002.

The number of landfills with geomembrane liners is shown in Fig. 6. Leaflets without information on liners were excluded. Only 40% of landfills had a liner during 1976–1979, but this figure increased to 100% after 1990 as a result of the strengthened technical standards in 1990. After 1997, the double-liner system was mandatory for new landfills.

The development of the leachate treatment system in Japan is summarized in Fig. 7. A standard leachate treatment system, denoted by A in Fig. 7, consists of a leachate volume adjustment tank, biological treatment, a coagulation–sedimentation stage, and a disinfection stage. Systems B–E are advanced systems that add various processes to system A. System B is a process in which sand filtration is placed after coagulation–sedimentation, and the further addition of activated carbon adsorption to B is noted as C.

Systems D and E are more sophisticated systems based on C. Chelate resin adsorption was installed for heavy metal removal in D, and a calcium precipitation process is further conducted in E before the biological process. System F is the "other" category, and includes the simplest process, with a coagulation–sedimentation stage only, and also the most advanced combination of coagulation–sedimentation and biomembrane-filter processing. Although they are not shown in the figure, superadvanced water treatment processes, such as advanced oxidation treatment for dioxin removal, and reverse osmosis for chloride ion removal, have also been introduced.

From Fig. 7, the development of the leachate treatment system can be described as follows: system A was commonly used around 1975, then sand filtration (system B) and activated carbon adsorption (system C) became popular in 1980–1984. B and C are called advanced processes. After 1985, the chelate process (system D) was used. System A was not used after 1995, and superadvanced treatments such as the advanced oxidation process and reverse osmosis were introduced in some cases.

Figure 8 shows the use rate of unit processes: sand filtration, activated carbon adsorption, and chelate resin adsorption. The denitrification process is also shown.

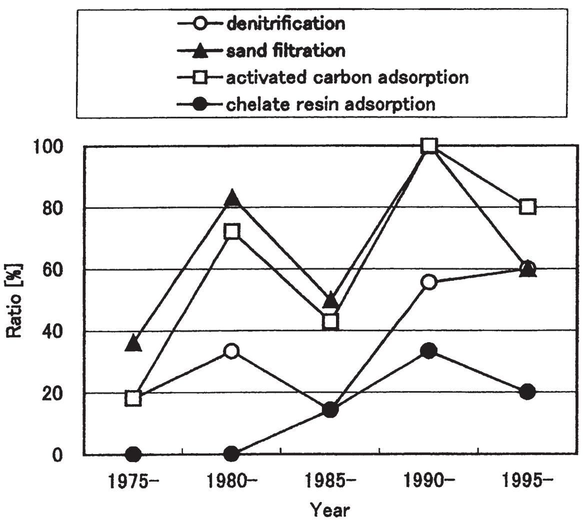

Fig. 8. Use rate of unit processes in leachate treatment systems

Whereas sand filtration and activated carbon adsorption are carried out in most landfills, chelate resin adsorption is used in only 20% of landfills. On the other hand, an increasing number of landfills have the denitrification process, from 20% to about 60%.

In Fig. 9, the design values for raw leachate and effluent in the leachate treatment plant are plotted for BOD, chemical oxygen demand by potassium permanganate under acid conditions (COD), and T–N. Some interesting characteristics are shown in these figures.

1. For BOD and COD, the design values of raw leachate are decreasing with time.
2. The design value for BOD in raw leachate was of the order of thousands of mg/l around 1975 when mixed refuse was disposed of, but now it has decreased to the order of hundreds of mg/l owing to the disposal of incineration residue and incombustible waste.
3. The design values for effluent are very low, i.e., less than 10 mg/l. To meet the target, a highly advanced treatment system is necessary.
4. Owing to the low C/N ratio of 0.8 in raw leachate when assuming that TOC = BOD·(12/32), denitrification has been very difficult to carry out in recent years.

In Japan, BOD in raw leachate is usually very low because:

1. a semiaerobic structure forms an aerobic zone around leachate collection pipes;
2. landfills are not deep (5–20 m, see Fig. 11);
3. the organic content of waste is low because of source separation and the incineration of organics.

On the other hand, there are also some problems.

1. The low C/N ratio in leachate leads to increase the operational costs because the denitrification process needs an additional carbon source, such as methanol.
2. In landfill of incineration residues, dioxins, chloride, and calcium ions are concentrated, and additional processes to remove them are needed in some cases.

Capacity and cost

For the landfills surveyed, the surface area is decreasing, as shown in Fig. 10. However, in 1999, 53% of 2068 MSW landfills (of which 400 were closed, and 49 were under

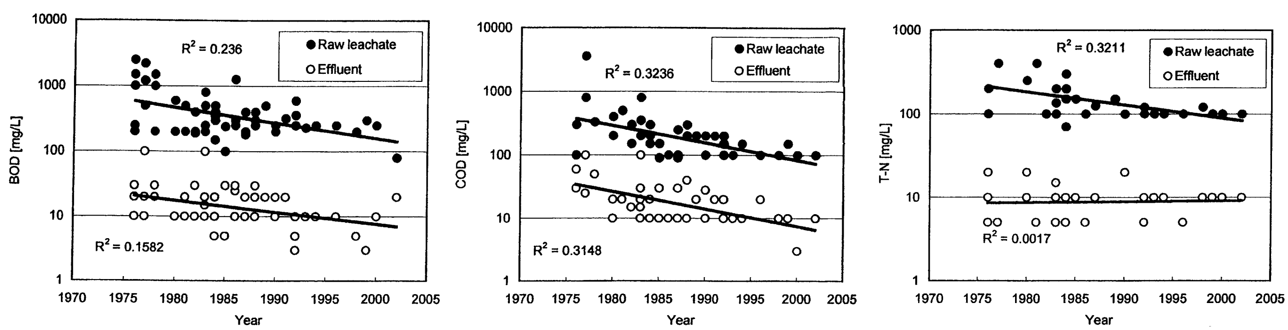

Fig. 9. The design values of raw leachate and effluent

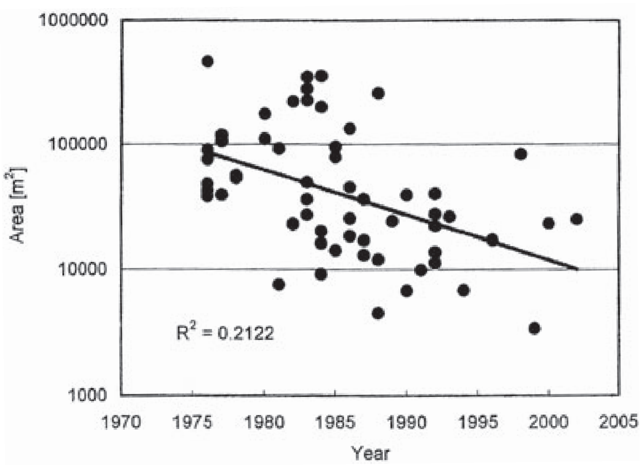

Fig. 10. The size of landfills

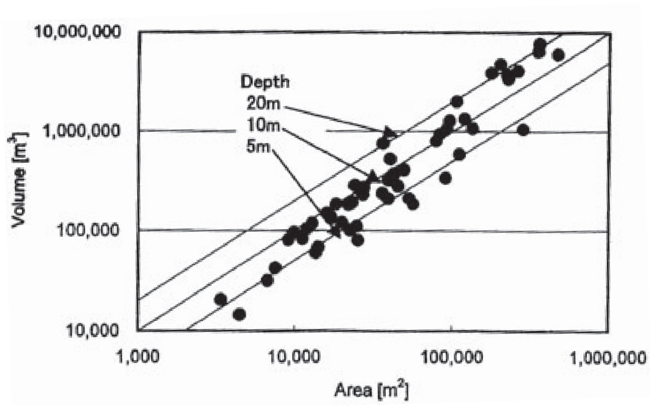

Fig. 11. The relation between landfill area and volume

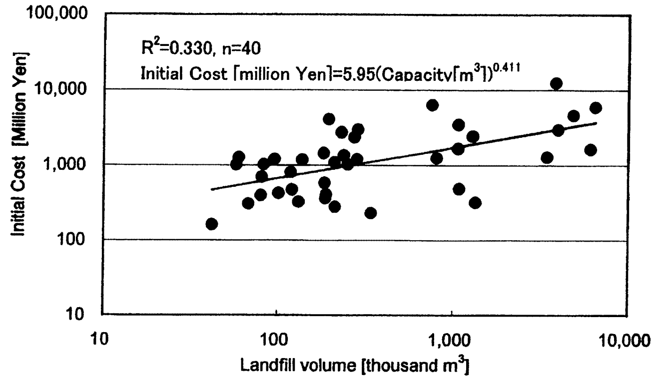

Fig. 12. The relation between landfill volume and initial cost

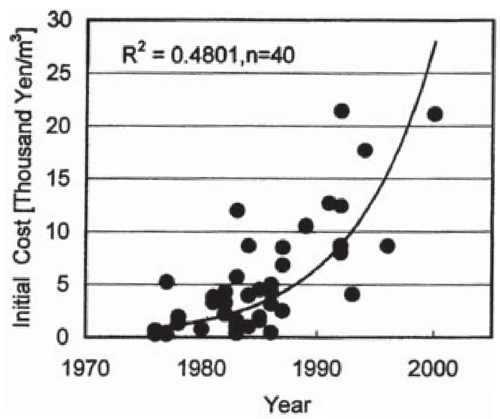

Fig. 13. Increase in initial costs

construction) were smaller than 10000 m^2, and 30% were 5000 m^2 or smaller. The average depth of landfills is calculated from Fig. 11, where surface area and landfill capacity are correlated. From this figure, it can be seen that the depth increases with landfill size, but the overall average is only 10 m.

Construction costs, including landfill and leachate treatment plants, are correlated with landfill volume in Fig. 12. The cost has been adjusted by the Japanese price index to the 2000 basis. There is an economy of scale for cost: cost per cubic meter decreases from 10000 to 5000 yen as a landfill becomes bigger. However, construction costs have soared recently, as shown in Fig. 13.

Future perspectives for sustainability

In the 1990s, constructing new landfills became increasingly difficult in Japan, mostly because of the NIMBY reaction of local residents. Landfills should be safe and acceptable to the public. Figure 14 shows the lifecycle of MSW landfills in Japan, from the planning stage to closure. An environmental impact assessment (limited to air, water pollution, odor, noise, and vibration) has been mandatory for all landfills, regardless of size, since 1997, when the solid waste management law was revised. For environmental control, "the standard of landfill structure and maintenance" was revised and became stricter. A lower level of effluent standards or a higher performance for an MSW landfill is required in order to receive a subsidy from the government. Outputs or emissions from a landfill, and the health of the environment, are monitored, as shown in Fig. 15.

As a consequence of source separation, incineration of waste, and the semiaerobic structure, the Japanese landfill strategy seems to be good for promoting the stabilization of waste. However, further advanced approaches are now being taken. One of these is the minimum landfill approach by recycling incineration residues as input material for cement production, or by melting incineration residue to form slag as a construction material. The other approach is the minimum risk approach through innovative landfill structures, such as the container-type landfill with a roof and walls in which moisture is controlled by a constant spray of water. Landfills lined with steel plates in which incineration residues are flushed to reduce the concentration of contaminants is another example of the latter approach. However, there is criticism that the energy and cost required for these approaches outweighs the environmental benefits, i.e., they are not sustainable landfill methods.

For sustainability of landfill, input waste should be controlled and the waste should be biologically assimilated to natural soil in one generation. To achieve that goal, the appropriate characteristics of waste are:

1. a minimum amount of recyclables (shredding and separation is needed);
2. a minimum amount of plastics;
3. several percent of organic matters to maintain biological degradation;
4. a minimum amount of hazardous chemicals, such as heavy metals.

The third requirement is based on the fact that incineration ash transforms soil texture when landfilled with compost.[7,8] If these conditions are satisfied, leachate and landfill gas will be stabilized within 20–30 years, and therefore such a landfill can be called a "sustainable semiaerobic bioreactor landfill with low organics."

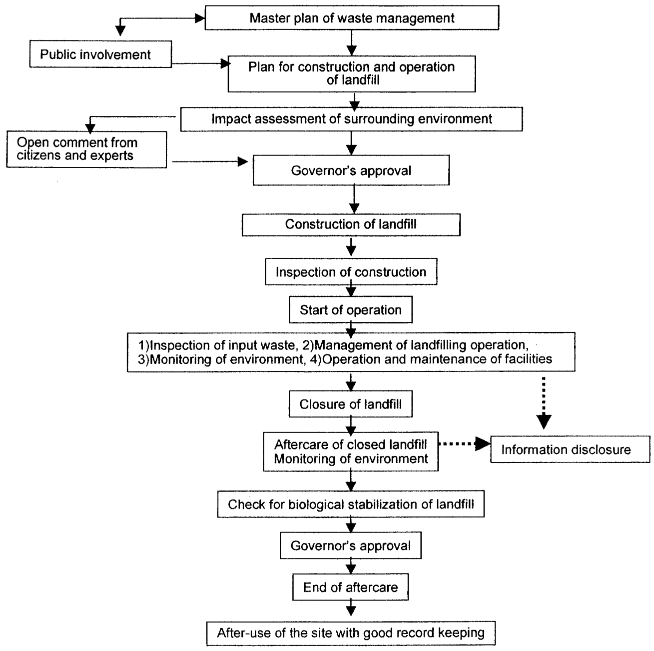

Fig. 14. Lifecycle control of MSW landfills in Japan

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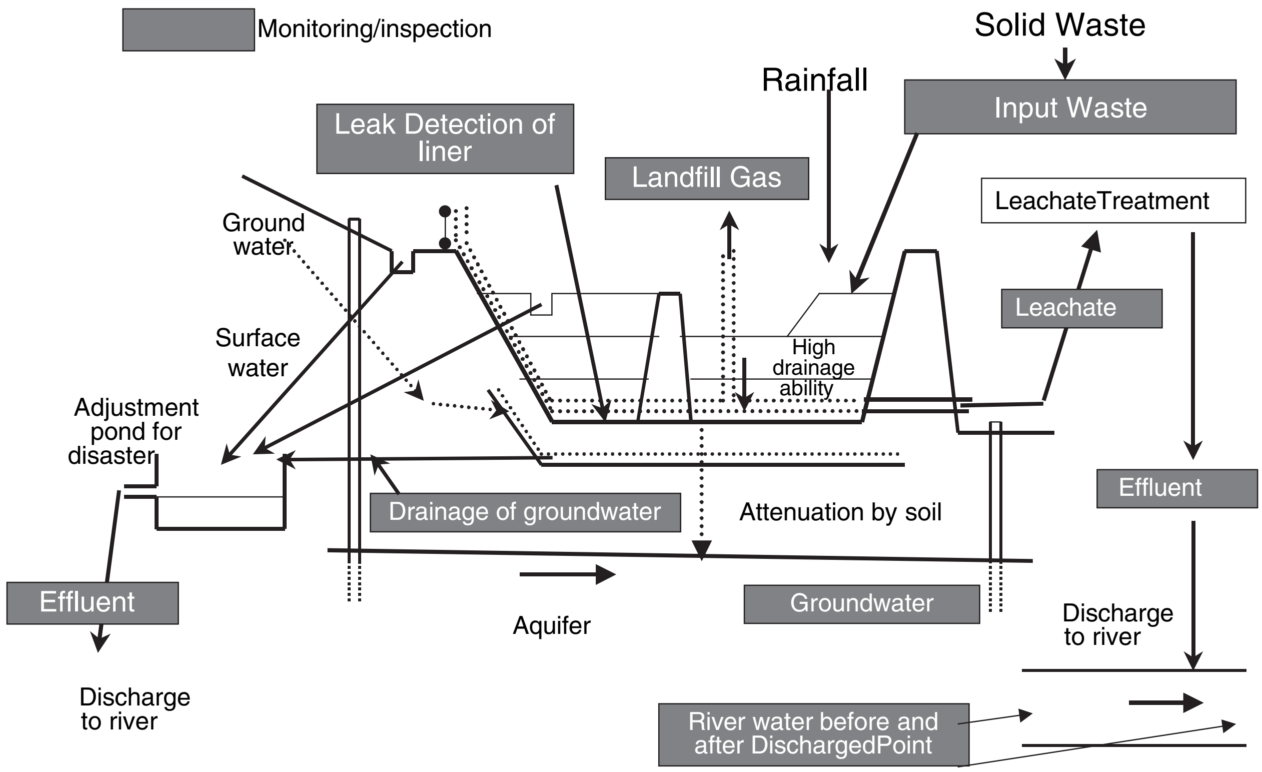

Fig. 15. Multibarriers for the safety of MSW landfills

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