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ENGINEERING ASPECTS OF LANDFILLING MUNICIPAL SOLID WASTE*

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Abstract: Sanitary landfilling is the most important method of municipal solid waste disposal in China. Landfill sites are always set up in mountain valley, on plain or beside seashore. A complete landfill consists of base system, cover system, and leachate collection and gas extraction system. This paper reviews the state-of-the-art landfilling technology in China and collection discusses research projects for engineers.

Key words: municipal solid waste, sanitary landfill, final cover, base, leachate, landfill gas
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INTRODUCTION

In the last decades, Chinese urban population increased rapidly as a result of the accelerated economic development and urbanization. At the same time, the estimated of the amount of municipal solid waste (MSW) generated and collected per person per day has been growing year by year as shown in Table 1. The rising quantity of MSW presents serious problems such as pollution of environment, threat to human health or safety, and hindrance to the sustainable development of the urban economy, and urgently needs resolution.

Table 1 Production of MSW in Hangzhou

Year	MSW production($\times 10^4$ t)	Population($\times 10^4$)	kg/(person·day)
1990	43.89	133.89	0.90
1991	45.39	134.97	0.92
1992	47.44	136.30	0.95
1993	50.85	138.33	1.01
1994	56.66	141.27	1.10
1995	63.47	162.79	1.07
1996	65.72	166.72	1.08
1997	72.00	169.29	1.17
1998	77.00	171.89	1.23

Note: The population data is from The General Project of Hangzhou City.

Before the 1970's, the small quantity of MSW was always transported to suburbs of counties for natural composting and used in agriculture. But by the end of the 1970's, the suburbs could no longer accommodate the increasing quantity of MSW, so alternative methods had to be employed to resolve the troublesome MSW disposal problem and minimize the MSW occupation of cultivable lands. Concentrated filling was applied. But the landfills were often carelessly arranged due to the lack of policy and experience. Consequently foul odors, vectors, explosions, spills and accidents were serious MSW landfill problems at that time. In recent years, people's consciousness of environmental protection has been awakened, and some sanitary

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MSW landfills projects have been implemented. With the development of incineration technology, some cities, like Shenzhen, have started incinerating their garbage. In short, composting, landfilling and incineration are the three main methods for disposal of MSW in China today (Zhou et al., 1998).

At present, most Chinese MSW are not suitable for incineration due to their low average caloric value. However, reliable landfill sites are always available, and the policy is obviously prone to favor landfilling technology (Chen et al., 1997). Sanitary landfill is land disposal of MSW, employs engineering methods and has the advantages of accommodating large volume of MSW, accepting all types of municipal solid wastes, and low cost, so it fits in well with the current Chinese practice of collecting and transporting not sorted MSW. This paper reviews state-of-the-art review of landfilling in China and discusses the tasks for the engineers.

SITE SELECTION

Site selection is the first consideration in a landfill design project. According to Domestic Refuse Landfill Pollution Control Standard (GB16889 - 97, 1997), the distance from the landfill to the public property boundary or water supply intake of residents or livestock must be at least 500 meters. In choosing a location, other than the above requirement of minimal distance, the engineers should make allowances for public opposition, proximity of major roadways, load limits in roadways, haul distance, climate, and availability of cover material. They should also investigate the hydrological and geological conditions, and estimate the site capacity.

Three basic types of landfill are involved based on different local terrain in this country (Zhou et al., 1998), and are called Valley Landfill, Plain Landfill and Seashore Landfill, as illustrated in Fig.1. Valley Landfill is set up in natural valleys or basins that are always surrounded by mountain on three sides. This type of landfill is the most common case, especially in south China where rolling terrain and canyons are common and the engineering geology and hydrogeology conditions are always advantageous. To controll leachate percolation, it is recommended that Valley Landfill be set up in a site with self - governed hydrological conditions. Plain Landfill often takes advantage of local depressions or requires the presence or excavation of a trench; the solid waste is deposited on the depression surface or placed in the trench and compacted, and then covered with a layer of compacted soil at the end of each working day. The pretreated leachate may enter the urban sewage net. Seashore Landfill is a besieged land by the seashore and is mostly applied in coastal cities, where directing of treated leachate into the sea is feasible. However, as leachate is a potential pollutant of the sea environment, the effluent must be ensured to be pollution free.

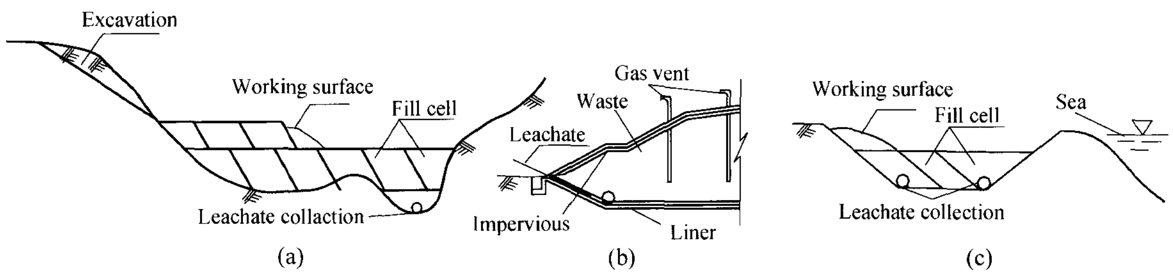

Fig.1 Landfill types in China (a) valley landfill; (b) plane landfill; (c) seashore landfill

THE COMPOSITIVE SYSTEMS OF SANITARY LANDFILL

The sanitary landfill of MSW can be conceptualized as a biochemical reactor whose main input items are solid waste and water, and main output items are leachate and gas. The negative effects of a landfill on the environment mainly result from the leakage of leachate and uncontrolled dissipation of gas, so the target of landfill construction is to intercept the pollutants before they reach the environment. The controlling methods are (1) to restrict the downward or lateral escape of waste and leachate and the upward movement of ground water into the landfill; (2) to prevent rainfall or surface water from infiltrating into or precipitating onto the solid waste; (3) to provide suitable collecting system of leachate and gas. For controlling pollution, a complete sanitary landfill should be composed of four parts: base system, final cover system, leachate collecting system and gas venting system.

1. Base System

To prevent escape of waste or entry of ground water, a continuous layer of synthetic materials or natural clay or earth materials are always placed below and at the sides of a landfill. Material selection is almost the most important for an effective base liner. According to Domestic Refuse Landfill Pollution Control Standard (GB16889-97, 1997), for natural control landfill, there must be at least 2 meters thick low permeability soil with a hydraulic conductivity of 1×10^{-7} cm/s or less, below the bottommost solid waste or from any side of the landfill. In fact, there is hardly any natural ground meeting the above specification. However, there are some case records of application of engineered landfill base liners referred to as HPDE GM Liner (Fu, 1997), using compacted clay, compacted bentonite and bitumen-concrete (Nie et al., 1998). The technique of applying vertical curtain grouting for resisting leachate leakage is in current use (Ma, 1998) and worthy of extension, and will be discussed in the next paragraphs.

The target of base preparation is to control the leakage of wastewater produced in the active life of a landfill. The assessment of the leakage quantity Q of leachate from the landfill bottom can be expressed as

$$Q = F \times K \times \frac{H_1 - H_2}{L} \quad (\mathrm{m}^3/\mathrm{d}) \qquad (1)$$

where F = area of percolation section (m^2); $H_1 - H_2$ = differential head over the percolation distance (m); L = distance of percolation path (m); K = coefficient of average percolation over L (m/d).

It may be noticed here that the leakage quantity Q depends not only on the value of K, but also on the differential water head, distance of percolation and percolation section area. Therefore, we can take advantage of the natural ground whose hydraulic conductivity is about $1 \times 10^{-4} - 1 \times 10^{-6}$ cm/s but with a fairly wide-spread area and a depth of hundreds of meters. At the same time, local curtain grouting should be installed in the possible path of leakage to decrease the coefficient of the average permeability of the total percolation sections. This is called vertical anti-seepage, and is commonly used for valley landfill with suitable site selection. The design contents should include (1) installing grouting holes with proper spacing and to an adequate depth, (2) applying proper grouting pressure and (3) selecting suitable ratio of water to cement in slurry. Moreover, it is important to control the water sorption ratio at $\omega \leqslant 3 - 1$L/min.m.MPa.

The empirical results from the Tianziling landfill, a valley landfill in south China, has proved the vertical anti-seepage method is acceptable. After the landfill had experienced 5 years of service, the observed water quality at monitoring holes on the lower reaches of the fill-dyke seemed free from infection (Ma, 1998).

However, the vertical anti-seepage method is not applicable for the site where the geological fault is inevitable and the hydrological condition is not self-governed. The engineers should carry out tests on more suitable liner materials such as HDPE GM Liner, PVC GM Liner and GCL for horizontal barriers, and optimal structures.

2. Final cover system

Final cover means a layer consisting of soil and, in some cases, other natural or synthetic materials that are placed on any surface of a landfill where no additional solid waste will be deposited and serves to restrict the infiltration of precipitation, to support vegetation, to control landfill gas, to restrict access by wildlife, and to promote surface drainage.

Based on the final cover, present landfills can be classified as sealed and semi-sealed (Zhang et al., 1998). In sealed landfill, mainly used for special waste landfill, impervious material is necessary for inclusion in the final cover as well as in the base liner and on the sides to restrict percolation of rainwater or other water into the landfill, as shown in Fig. 1 (b). The semi-sealed landfill only employs topsoil to directly cover the waste surface and is commonly used in MSW landfill. For leachate control, sealed landfill is recommended. Its use in the Yulongkeng landfill, Shenzhen, may be referred to.

Although no regulation has been published, the final cover compact soil should be at least 60 cm thick and have a hydraulic conductivity of 1×10^{-5} cm/s or less. Combined with specific site condition, compound soil can be employed in the cover system when high quality clay is not available or too expensive while the alternative materials are available. The percolation resistance of the compound soil is usually better than any aggregate included because the aggregates are different materials that complement some qualities such as swelling, absorption and geometry figure (Zhang et al., 1994). As an example, the optimum mixture ratio and the corresponding performance of Illite-Coal Fly-Ash compound soil are shown in Table 2. Tests for other compound soil products, including materials and mixture, are encouraged.

The topsoil layer depth is closely related to the type of vegetation proposed. The soil layer must provide the requisites for vegetation growth and protect the plants from harmful methane generated in the fill, and at the same time, the impervious layer on top of the landfill should not adversely affect the plant roots. Tests in the Hudao landfill yielded Table 3 and Table 4 data on the recommended thickness of the topsoil for the sealed and semi-sealed landfill.

The final cover system should be appropriately designed and constructed, to meet the needs of gas collection and recovery systems and the drainage control system. Moreover, the cover should be constructed with a slope of 33% or so taking into account the successive settlement of landfill, rainfall drainage control and the topsoil stability.

Table 2 Mixture ratio and performance of Illite-Coal Fly-ash compound soil

Sample Code	1	2	3	4	5	6
Compaction degree/($g \cdot cm^{-3}$)	1.6	1.5	1.5	1.5	1.2	1.1
Thickness/(cm)	4.2	4.3	4.2	4.1	4.5	4.7
Cement content/(%)	7	15	23*	31*	73	86
Percolation coefficient/($mg \cdot s^{-1}$)	1.8×10^{-7}	2.1×10^{-7}	5.4×10^{-8}	7.1×10^{-8}	1.8×10^{-7}	5.1×10^{-6}

Note: * is recommended for utility.

Table 3 Thickness of topsoil of semi-sealed landfill (cm)

Landfill age (annual)	Vegetational types					
	Lawn	Pasture	Farm crop	Shallow-root wood	Medium-root wood	Deep-root wood
0	10	20	25 – 50	25 – 50	50 – 70	50 – 90
1	10	10	25	25 – 50	50 – 70	50 – 80
2	< 5	5 – 10	20 – 25	20 – 35	40 – 60	40 – 70
4	< 5	5 – 10	15 – 20	20	30	30

Table 4 Thickness of topsoil of sealed landfill (m)

Vegetation project						
Farm	Pasture	Lawn	Tree nursery	Shrub forest	Shallow-root timber forest	Deep-root timber forest
1.0 – 2.0	2.0 – 3.0	1.0 – 1.5	2.0 – 3.0	1.5 – 2.0	2.0 – 3.0	3.0 – 3.5

3. Leachate Collection and Gas Extraction

Solid waste placed in a sanitary landfill may undergo a series of biological, chemical, and physical changes. Aerobic and anaerobic decomposition of the organic matters result in both gaseous and liquid end products. Some solids are dissolved in water percolating through the fill. The contaminating leachate will cause groundwater pollution and the concentration of the gas, which may include a large amount of methane, may lead to explosion. In such cases, leachate collection system must be provided to intercept the pollutants before they enter the underlying groundwater, and the gas venting system should be installed.

4. Leachate collection system

It is necessary for the leachate collection system designer to estimate the quantity of leachate generated. The design should be based on the maximum quantity and ensure the drainage be expedited at all times during a landfill's service period. It was found that the quantity of leachate is a direct function of the amount of external water entering the landfill. The maximum leachate can be expressed as a function of storm precipitation (Zhang et al., 1999):

$$Q_L = C \cdot I \cdot A \quad (2)$$

where Q_L = quantity of leachate generation ($m^3/24h$);

C = coefficient of storm water infiltration;

I = maximum intensity of storm precipitation ($m^3/24h \cdot km^2$), based on local decennial or bi⊖nnial storm statistics;

A = water collecting area of landfill site (km^2).

A leachate collecting system generally consists of horizontal or vertical collecting pipes, regulation tank, diving pump, and/or treatment facilities (Wang et al., 1998). In the Valley Landfill, the natural canal in bottomland is usually used as drainage so as to save on investment and optimize the design, as shown in Fig. 1a.

The design of the leachate collection system should be combined with other leachate control methods. For example, surface water diversion can prevent storm water runoff from contacting the wastes. The designed effluent capability of the collection system determines the dimension and layout of the sewage pipes, which must stand the weight of the MSW in order to avoid blockage resulted from pipe deformation, for which reason, they are always buried in channels with gravel fill for protection against bending stress.

The collected leachate may be treated by biological method and then discharged into river or urban sewage network. However, the more attractive method is recirculating collected leachate into landfill for natural evaporation. This method is still questionable due to leachate clogging in the landfill. Thorough knowledge of the impact and technical aspects of leachate recirculation is in the engineers' interests.

5. Gas Venting System

According to measurement, the landfill gas is mainly composed of methane and carbon dioxide in addition to other poisonous or harmful gases. The potential emission of the landfill gas is related to waste character, climate, and landfill management. From experiences, most of the gas emission arises in the first 1-2 years of the landfill service, and semi-aerobic method will facilitate the stabilization of the landfill. The assessment of the emission potential of CO_2 or CH_4 is described by the following expression (Chen et al., 1997):

$$V_{CH_4/CO_2} = 1.8667 \times R_{CH_4/CO_2} \times (1 - W) P \times C \quad (3)$$

where V_{CH_4/CO_2} = volume CH_4 or CO_2 gas generation by 1kg waste in standard condition, m^3;

C = content of organic carbon in waste, %;

P = content of organism in 1kg waste, %;

W = water content of waste deposit, %;

R_{CH_4}/R_{CO_2} = volume conversion ratio of organic carbon to CH_4/CO_2, %;

1.8667 = conversion ratio of 1kg organic carbon to ideal gas, m^3.

In order to prevent combustible gas' concentrations that exceed or are predicted to exceed the lower explosive limit in soils, the installation of gas venting systems is a prerequisite requirement, and two gas venting systems are adopted, i.e. active and passive gas venting as shown in Fig. 1 (b) and Fig. 2 respectively (Gao et al., 1996). In the passive gas venting system, only ducts are employed in the landfill to lead out the gases for direct venting into the air; and in the active gas venting system, gas pump and recovery and management system are needed as well as the ducts. In most cases, the sewage pipes for collecting leachate can also serve as venting ducts. Such a technology is called combined system. The vertical pipes for releasing gas should reach 1 meter over the final cover. Gas monitors should be located on site to measure the methane content. In the event that gas recovery and management systems are required, the gases should be pumped out through the pipe net to a concentrated management plant for combustion or other treatment, as applied in the Tianziling landfill, Hangzhou.

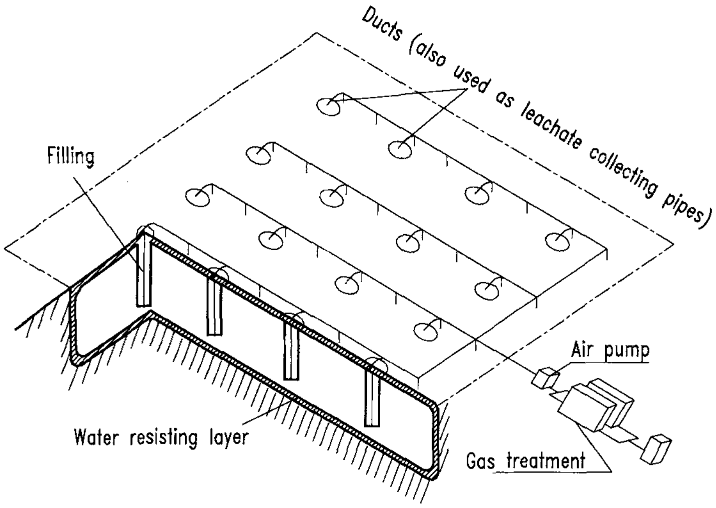

Fig.2 Gas venting system

Investigations showed that landfill conditions are always serious. The necessary anaerobic conditions for organism decomposition may be impaired, and on the other hand, the local concentration of methane in the landfill is a potential risk. For gas venting and recovery, it is important to ensure a reliable cover on top of the deposited MSW and install extraction wells in the landfill.

SETTLEMENT AND SLOPE STABILITY OF LANDFILL

More and more empirical data show that the settlement of a landfill is remarkable both during and after the filling process. It is a two-faced problem. On one hand, the settlement during the filling process can help to accommodate more volume waste than expected on a landfill site, and will increase the stability of the landfill. On the other hand, the differential settlement may tear the impervious liner on top of the landfill, deform the embedded leachate and gas pipes, and impede the reuse of the landfill site. So the proper assessment of landfill settlement is worthy of careful study, for which in situ observation and simulating tests are effective methods.

The slope stability deserves thorough research, as slope sliding will lead to environmental pollution, as was formerly the case with the Tianziling landfill. The influencing factors such as slope angle, MSW properties and leachate head in the slope, should be taken into consideration seriously.

Aside from careful consideration of the above problems, the engineers must be responsible for the sectional operation project, maintenance of completed landfill, and analysis of earthquake reaction of a landfill.

CONCLUSIONS

Sanitary landfill is composed of a base system, final cover system, and leachate collecting and gas venting system. The design contents also include settlement and slope stability analysis.

The engineering aspects of an optimally designed landfill project should be closely linked to environmental protection policy. The engineers should determine their tasks in landfill construction, and cooperate with technicians on major concerns such as leachate treatment and gas recovery. Appropriate technology and sufficient investment should ensure that a landfill project is safe and effective.

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