Use of loess as final cover materials for MSW landfills in northwest China

Liang-tong Zhan(1), Wei-guo Jiao(2), Tao Wu(3) and Ping Chen(4)

(1) Professor, MOE Key of Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Hangzhou 310058, China. zhanlt@zju.edu.cn
(2) PhD student, MOE Key of Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Hangzhou 310058, China.
(3) PhD student, MOE Key of Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Hangzhou 310058, China.
(4) Associate professor, Department of Civil Engineering, Zhejiang Sci-Tech University, Hangzhou 310013, China.

ABSTRACT

In the northwest of China, loess is widely distributed, and the climate is mainly arid and semi-arid. The use of loess as soil cover material for landfills is promising. In this paper, water balance analyses were carried out to evaluate the technical feasibility with a consideration of the climate characteristics and the hydraulic properties of the loesses. The analyses demonstrate that the loess, having a considerable water storage capacity and relatively low conductivity for water and gas flow, is a good cover material for the arid and semi-arid regions. The required thickness of monolithic soil cover, depending on the climate condition and the type of loess, ranges from 0.5 to 2.0 m. For a given region, the designed thickness for the silty loess is the least, and that for the sandy loess is the largest. It is deserved to do more research and engineering practice on this topic.

Keywords: loess, final cover, landfill, water storage capacity, conductivity

1 INTRODUCTION

Soil is one of the most durable materials in the nature. Engineering practice of final covers in landfill demonstrates that compacted clay covers are more likely to be cracked as a result of wetting and drying cycles. Composite covers including geomembrane are costly, and severe the stability problem of sliding along the surface of geomembrane. The alternative earthen final covers are being studied and used in some European and American countries since 1990s. Currently there are two types: monolithic and capillary barrier. Monolithic cover is composed of fine soils such as silty soils. Its working principle is similar to that of sponge: the fine soil layer stores the infiltrated rainwater by its water storage capacity when raining, and in turn empties the water and resumes its water storage capacity by evaporation and evapotranspiration when there is no rain. The water balance as well as the control of percolation can be achieved by a proper design of the earthen final covers. When the soil materials are available locally, the earthen final covers have advantage over composite covers with respect to economic and technical aspects (William and Albright 2002; Zhan et al., 2014).

Since 1990s, European and American researches have been doing theoretical and experimental studies on the feasibility of soil covers. Most of the study demonstrated that the earthen final covers are generally effective in arid and semi-arid regions. Chen (1999) proposed a simplified water balance method for determining the required thickness of monolithic soil covers (Chen 1999). This method has been testified by the field monitoring data at several landfill sites. By using this method, Chen (1999) provided a contour map showing required thickness for the monolithic soil covers in arid and semi-arid regions of USA.

Climate in Northwest China is relatively arid. The region has a wide distribution of loess, which is well known for its great thickness and special engineering characteristics. With the Loess Plateau as the center, it covers the area of 630,000km². Previous study shows that although the grain size distribution of loess varies in different areas of Northwest China, most of them are silty soils having a good water storage capacity (Liu et al, 1985; Zhu and Tian 1993). The use of loess as soil
cover material for landfills located in Northwest China is promising. Currently there are some cases of using loess for landfill covers in some cities in Northwest China. However, the technical feasibility has not been enough investigated. This paper aims to evaluate the technical feasibility with a consideration of the climate characteristics and the hydraulic properties of the loesses by using the simplified water balance method proposed by Chen (Chen 1999).

2 CLIMATE CONDITION IN NORTHWEST CHINA

The average annual precipitation in northwest China ranges from 700mm to 200mm, showing a decreasing trend from southeast to northwest. As the landfills are usually located in urban areas, three representative cities in northwest China are selected to present the climate condition. They are: Yinchuan of Ningxia Province (arid climate), Lanzhou of Gansu Province (semi-arid climate) and Xi’an of Shaanxi Province (semi-humid climate).

Yinchuan, being to the north of the Loess Plateau, is a city of representative continental arid climate. The statistics of precipitation from 1950 to 2000 shows an average value of annual precipitation (P) of about 200 mm, potential evapotranspiration (PET) of about 1100 mm, and humid index (P/PET) of about 0.2~0.5. Lanzhou, being in the middle of the Loess Plateau, is a city of representative continental semi-arid climate. For the city of Lanzhou, the annual precipitation (P) is about 350 mm, potential evapotranspiration (PET) about 600~800mm and humid index (P/PET) about 0.5~0.8. Xi’an, being in the southeast of the Loess Plateau, is a city of representative semi-humid climate, with annual precipitation (P) of about 500mm, potential evapotranspiration (PET) of about 600~700mm and humid index (P/PET) of about 0.5~1.0. Figure 1 shows a distribution of annual precipitation in Xi’an from 1950 to 2000. The data statistics indicates that the average value of annual precipitation during the latest 50 years is 550mm with the maximum value of annual precipitation at 903.2mm in 1983. The average number of annual precipitation days is 90. Figure 2 shows the distribution of daily precipitation in 2008 in Xi’an. The data indicates that the total annual rainfall is 525.5 mm and it is not uniformly distributed in the year. There is more rainfall in the summer from May to September while little in December, January and February. It should be noted that the rainy season in this region coincides with the plant growing period.

Table 1. Extreme precipitation parameters for the three representative cities during the latest 50 years (unit: mm).

| Precipitation parameters | Arid area (Yinchuan) | Semi-arid area (Lanzhou) | Semi-humid area (Xi’an) |
|--------------------------|----------------------|--------------------------|-------------------------|
| Humid index P/PET        | 0.2~0.5              | 0.5~0.8                  | 0.5~1.0                 |
| Annual rainfall max P_{aw} | 354.5               | 546.7                    | 903.2                   |
| Annual snowfall max P_{as}* | 72.3*               | 69.8*                    | 232.9*                  |
| Non-growing period rainfall max P_{aw} | 48.2               | 46.5                     | 155.3                   |
| Non-growing period snowfall max P_{as}** | 48.2               | 46.5                     | 155.3                   |

Remark: * P_{as} is assumed to be equal to 1.5 times P_{aw} according to the local snowfall period; ** P_{as} is assumed to be equal to P_{aw}.

The climate condition during the non-growing period of plants is required for using the water balance method proposed by Chen (1999). Previous study shows that the months between April and October are the main growing period of vegetation in the Loess Plateau, and most of the plants stop growing from November to March. The statistics of precipitation during the latest 50 years shows that the precipitation during the non-growing period of plants ranges from 15 to 30mm in the city of Yinchuan with the maximum value of 48.2mm in 1989. In the city of Lanzhou, the value
ranges from 20 to 40 mm with the maximum value of 46.5 mm in 1977. The value in the city of Xi’an ranges from 50 to 80 mm with the maximum of 155.3 mm in 1958. The extreme precipitation parameters (\(P_{tw}, P_{ts}, P_{ow}, P_{om}\)) for the three representative cities are summarized in Table1.

3 LOESS DISTRIBUTION AND HYDRAULIC PROPERTIES

3.1 Distribution of loess in northwest China

The loess in Northwest China can be divided into three categories, i.e., sandy, silty and clayey loesses. The particle size of loess shows an increasing trend from southeast to northwest (Xu et al, 2007). In a given area, one type of loess is dominant yet the other two types also exist. For instance, in Yinchuan of Ningxia Province and Yulin of North Shaanxi, the sandy loess dominates but silty and clayey loesses also exist. The silty loess is mainly distributed in the Middle Loess Plateau such as Lanzhou of Gansu Province and Taiyuan of Shanxi province. Clayey loess is mainly distributed in the Southeast Loess Plateau such as Xi’an of Shanxi province and Qinyang of Henan Province.

Figure 3 shows particle size distribution curves for the three types of loess, i.e., sandy, silty and clayey loesses. It can be seen that the dominant particles are silty particles (0.075~0.005 mm) with a percentage greater than 50%. The percentage is less than 40% for both sand particles (2 mm~0.075 mm) and clay particles (smaller than 0.005 mm).

3.2 Hydraulic properties of loess

Figure 4 shows soil-water characteristic curves for the three types of loesses, sandy, silty and clayey loesses (Wang and Lu 2008; Zhao and Zhang 2010). The values of water retention parameters for the three types of loesses are shown in Table 2. It can be seen that the saturated water content \(\theta_s\) for the sandy and silty loesses are close to each other at 40%~55%, and that of clayey loess is higher at 50%~60%. The field capacity \(\theta_f\) corresponding to a suction of 33 kPa is 25% for the sandy loess, 33%~38% for the silty loess and 30%~35% for the clayey loess. The water content corresponding to withering point \(\theta_m\) is about 8% for the sandy loess, 10~13% for the silty loess and 10~15% for the clayey loess. The available water storage capacity \(\theta_a\) is 20% for the sandy and clayey loesses, and 25% for the silty loess. The data indicates that the three types of loesses have a good water storage capacity, and they can be used as the water buffer material for landfill covers in Northwest China.

![Fig. 3. Particle size distribution curves of 3 types of loesses.](image1)

![Fig. 4. SWCCs of 3 types of loesses.](image2)

| Parameters                      | Sandy loess | Silty loess | Clayey loess |
|---------------------------------|-------------|-------------|--------------|
| Saturated water content \(\theta_s\) | 40%~55%     | 40%~55%     | 50%~60%      |
| Field capacity \(\theta_f\)     | 25%         | 33%~38%     | 30%~35%      |
| Water content corresponding to withering point \(\theta_m\) | 8%          | 10~13%      | 10%~15%      |

Fig. 5 shows the change of hydraulic conductivity with compaction dry density for the clayey loess of Xi’an. The hydraulic conductivity of the clayey loess, ranging from \(10^{-9}\) m/s to \(10^{-6}\) m/s, decreased exponentially as the compaction dry density increased. Fig. 6 shows the change of gas permeability with compaction dry density for the clayey loess, which was measured on the specimens compacted at the same water content of 13.0% (Zhan et al, 2014). The gas permeability of the loess, being in the order of \(10^{-14}\)-\(10^{-12}\) m², decreased exponentially as the compaction dry density increased. The observed effect of the compaction dry density on the gas permeability is believed to be associated with the soil-air content. For a given compaction water content, a higher dry density of the soil leads to fewer gas pores, which reduces the gas pore connectivity. As a
result, the gas transport in the soil becomes more difficult, i.e., the gas permeability is lower.

Fig. 5. Relationship between the hydraulic conductivity and the compaction dry density for the clayey loess.

Fig. 6. Relationship between the gas permeability and the compaction dry density for the clayey loess.

4 SIMPLIFIED WATER BALANCE METHOD FOR DETERMINING REQUIRED THICKNESS OF MONOLITHIC SOIL COVER

This section is to introduce the simplified water balance method proposed by Chen (1999). The method takes into account the water storage capacity of the cover soil and the most critical meteorological years for use in design. In the method, the maximum water storage capacity of the soil cover, $S_c$, is assumed to be corresponding to the field capacity $\theta_c$ of the soil at the matrix suction of 33 kPa, and that is $S_c=\theta_cL$ ($L$ is the cover thickness). The lowest water storage capacity of the soil cover is corresponding to the water content $\theta_m$ at the withering point (matrix suction $\varphi=1500$ kPa). The available water storage capacity in the soil cover, $S_a$, is corresponding to the space between field capacity ($\theta_f$) and withering point ($\theta_m$), and that is $S_a=(\theta_f-\theta_m)L$.

The meteorological data for latest 50 years are required to determine the covers’ thickness. The method consists of two steps: 1) collect the meteorological data of latest 50 years in the research region, find out the wettest year on record and the snowiest year on record. The total precipitation of rainfall and total precipitation of snowfall recorded for these two years are $P_{tw}$ and $P_{ts}$, respectively. The total precipitation of rainfall and total precipitation of snowfall during the non-growing period of plants recorded for these two years are $P_{ow}$ and $P_{os}$, respectively 2) calculate the required thickness for the monolithic soil covers using the two water retention parameters ($S_c$ and $S_a$) and the four extreme precipitation parameters ($P_{tw}$, $P_{ts}$, $P_{ow}$, $P_{os}$):

$$L_{ptw} = F_f \frac{P_{tw}}{2S_c / L}$$  \hspace{1cm} (1)

$$L_{pts} = F_f \frac{P_{ts}}{2S_c / L}$$  \hspace{1cm} (2)

$$L_{ctw} = F_c \frac{P_{tw}}{2S_a / L}$$  \hspace{1cm} (3)

$$L_{ctw} = F_c \frac{P_{ts}}{2S_a / L}$$  \hspace{1cm} (4)

$$L_{ctw} = F_c \frac{P_{ow}}{2S_a / L}$$  \hspace{1cm} (5)

$$L_{ctw} = F_c \frac{P_{os}}{2S_a / L}$$  \hspace{1cm} (6)

Where $F_f$ and $F_c$ are functions related to the target percolation rate ($P$) and were defined empirically by Chen (1999).

Functions $F_f$ and $F_c$ are

$$F_f = \frac{\alpha_f - \log P}{k_f}$$  \hspace{1cm} (7)

$$F_c = \frac{\alpha_c - \log P}{k_c}$$  \hspace{1cm} (8)

The parameters $\alpha_f$, $\alpha_c$, $k_f$, and $k_c$ are empirical parameters based on an analysis of results from unsaturated flow simulations. Details of these parameters can be found in Chen (1999).

Six estimates of the required thickness of the cover are then made by using the above six formulas. The maximum value of the six estimates is preliminary design thickness for the soil cover, $L_p$.

$$L_p = \max[L_{ptw}, L_{pts}, L_{ctw}, L_{ctw}, L_{ctw}, L_{ctw}]$$  \hspace{1cm} (9)

To apply this method for determining the thickness of loess soil covers, the climate conditions in Northwest China and the water retention capacity of loess should be investigated firstly.
5 DETERMINATION OF REQUIRED THICKNESS FOR MONOLITHIC LOESS COVER IN NORTHWEST CHINA

On the basis of the climate data and water retention characteristic of loess, attempt was made to determine the required thickness of monolithic loess cover for three representative cities in Northwest China (i.e., Yinchuan, Lanzhou and Xi’an) by using the method proposed by Chen (1999).

Table 3. Calculated thickness of monolithic loess cover in Xi’an (unit: m).

| Calculation formula | (1) | (2) | (3) | (4) | (5) | (6) |
|---------------------|-----|-----|-----|-----|-----|-----|
| L_{f tw}            | 1.45|     |     |     |     |     |
| L_{fts}             | <1.45|     |     |     |     |     |
| L_{ctw}             | 0.38|     |     |     |     |     |
| L_{cow}             | 0.21|     |     |     |     |     |
| L_{cts}             | <0.38|     |     |     |     |     |
| L_{cos}             | <0.21|     |     |     |     |     |

Table 3 shows the calculation for the city of Xi’an, in which the dominant category of loess, i.e., clayey loess, is considered as the material for the monolithic soil cover. It can be seen from Table 3 that the maximum value of thickness among the six calculation results is the one calculated from the formula (1), i.e., 1.45 m. This means that the maximum value of annual precipitation during the latest 50 years is the controlling parameter for the soil cover in this area.

As mentioned previously, sandy and silty loesses also exist in Xi’an. When these two types of loesses are considered as the cover materials, similar calculation was conducted. Similar calculation was also conducted for the other two representative cities (Yinchuan and Lanzhou). The required thickness of monolithic loess covers with sandy, silty and clay loess as cover materials is listed in Table 4.

Table 4. The required thickness of monolithic loess cover in the three representative cities (unit: m).

| City     | Sandy loess used | Lanzhou | Xi’an |
|----------|-----------------|---------|-------|
| Yinchuan | 0.78            | 1.23    | 1.92  |
| Lanzhou  | 0.53            | 0.86    | 1.33  |
| Xi’an    | 0.54            | 0.93    | 1.45  |

As shown in Table 4, the required thickness of monolithic loess covers in Northwest China ranges from 0.54 m to 1.92 m, depending on the climate condition. In the city of Yinchuan with an arid climate, the required thickness of cover is 0.78 m when the dominant category of loess (i.e., sandy loess) is used, and it is 0.53 m when the silty or clayey loesses are used. In the city of Lanzhou with a semi-arid climate, the required thickness of cover is 0.86 m when the dominant category of loess (i.e., silty loess) is used, and it is 1.23 m when the sandy loess is used. In the city of Xi’an with a semi-humid climate, the required thickness of cover is 1.45 m when the dominant category of loess (i.e., clayey loess) is used, and it is 1.92 m and 1.33 m when the sandy and silty loesses are used.

6 CONCLUSIONS

In Northwest China, the widely-distributed loesses can be divided into three categories, i.e., sandy, silty and clayey loesses. All the three types of loesses contain more than 50% silt particles (0.075–0.005 mm), and their water capacity is greater than 20%. The magnitude of conductivity for water and gas flow are 10^{-9}–10^{-6} m/s and 10^{-14}–10^{-12} m^2, respectively. The climate condition in northwest China changes from arid, semi-arid to semi-humid from northwest to southeast. The rainy season in this region coincides with the plant growing period. When the loess is used as soil cover material, the required thickness of monolithic soil cover ranges from 0.54 to 1.92 m, being dependent on the climate conditions and the types of loess. In the same region, the required thickness for silty loess covers is the least while that of sandy loess covers is the largest.

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