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An equivalent-time-lines model for municipal solid waste based on its compression characteristics

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ABSTRACT

Municipal solid waste (MSW) demonstrates a noticeable time-dependent stress–strain behavior, which contributes greatly to the settlement of landfills and therefore influences both the storage capacity of landfills and the integrity of internal structures. The long-term compression tests for MSW under different biodegradation conditions were analyzed. It showed that the primary compression can affect the secondary compression due to the biodegradation and mechanical creep. Based on the time-lines model for clays and the compression characteristics of MSW, relationships between MSW's viscous strain rate and equivalent time were established, and then the viscous strain functions of MSW under different biodegradation conditions were deduced, and an equivalent-time-lines model for MSW settlement for two biodegradation conditions was developed, including the Type I model for the enhanced biodegradation condition and the Type II model for the normal biodegradation condition. The simulated compression results of laboratory and field compression tests under different biodegradation conditions were consistent with the measured data, which showed the reliability of both types of the equivalent-time-lines model for MSW. In addition, investigations of the long-term settlement of landfills from the literature indicated that the Type I model is suitable for predicting settlement in MSW landfills with a distinct biodegradation progress of MSW, a high content of organics in MSW, a short fill age or under an enhanced biodegradation environment; while the Type II model is good at predicting settlement in MSW landfills with a distinct progress of mechanical creep compression, a low content of organics in MSW, a long fill age or under a normal biodegradation condition. Furthermore, relationships between model parameters and the fill age of landfills were summarized. Finally, the similarities and differences between the equivalent-time-lines model for MSW and the stress-biodegradation model for MSW were discussed.

1. Introduction

Similar to soft clay, organic soil, and frozen soil, municipal solid waste (MSW) also generates a time-dependent strain under the overburden effective stress; that is, MSW demonstrates a noticeable time-dependent stress–strain behavior. The time-dependent strain of MSW, which may exceed the instant and time-independent strains due to the mechanical stress, makes a great contribution to the settlement of landfills and therefore enlarges the storage capacity of landfill (Gao et al., 2015). In addition, the differential settlement will have an adverse impact on the integrity of the cover system and the service performances of the leachate drainage system and the landfill gas collection system (Qian and Guo, 1995a, 1995b). The time-dependent strain of MSW is a focus of attention.

A lot of researchers have studied the soils' time-dependent stress-strain behavior, which is called delayed or secondary consolidation or creep compression (Berre and Iversen, 1972; Bjerrum, 1967; Graham et al., 1983; Borja and Kavazanjian, 1985; Leroueil et al. 1985; Yin, 1999; Yin and Graham, 1989; 1994). It is usually calculated by the secondary consolidation coefficient C_α, which is the slope of vertical strain ε_z versus $\log(t)$.

In accordance with research on soils' consolidation, Sowers (1975) first divided the compression of MSW into primary and secondary compressions based on Terzaghi's one-dimentional (1D) consolidation theory, and calculated the secondary compression with a parameter C_α. Based on the development process of the secondary compression and the contributions of various compression mechanisms of MSW, Bjarngard and Edgers (1990) proposed the bilinear model, which divided the time-dependent compression into two segments, while Hossain and Gabr (2005) put forward

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the trilinear model, which divided the long-term compression into three parts. Some researchers proposed a number of practical empirical compression models for MSW based on the settlements in landfills (Yen and Scanlon, 1975; Edil and Ranguette, 1990; Ling et al., 1998; EI-Fadel and Khoury, 2000; Edil et al., 1990), but these models cannot reflect the compression mechanisms of MSW. According to the rheological analysis, Gibson and Lo (1961) assumed the calculation unit was composed of a spring and a dashpot and proposed the rheological model for MSW. Park and Lee (2002) developed a MSW model, in which the mechanical creep was calculated by the mechanical creep coefficient, and the secondary compression due to the biodegradation was described by the first-order kinetic hydrolysis equation of organics. Marques et al. (2003), Sivakumar Babu et al. (2010) and Gourc et al. (2010) adopted Park and Lee's model and developed their MSW models. Chen et al. (2010) proposed a stress-biodegradation model for MSW based on laboratory compression tests. The model is capable of demonstrating two important compression characteristics of MSW, namely the stress-dependent compression caused by the biodegradation of organics and the decrease in compressibility due to the biodegradation of organics. Bareither and Kwak (2015) thoroughly evaluated the performance and applicability of MSW compression models by comparing the field monitoring settlement in the Yolo Country Pilot Project and the Deer Track Bioreactor Experiment (DTBE) with the simulated results of twelve models.

From the perspective of time-lines model for clays, also called elastic viscoplastic (EVP) model for clays (Bjerrum, 1967; Yin and Graham, 1989; Yin and Graham, 1990; Yin, 1990; Yin and Clark, 1994), an equivalent-time-lines model for MSW was developed based on the analysis of long-term compression tests for MSW under different biodegradation conditions. It provides a different way to analyze the time-dependent strain–stress relationship of MSW. The detailed derivation process, the physical meanings of model parameters and the ways to determine the parameters were described. After that, compression data of laboratory and field compression tests from the literature were simulated using the equivalent-time-lines model. The simulated compression results were consistent with the measured data. In addition, the application of two types of the equivalent-time-lines model were investigated through predicting the long-term settlement of nine landfill sites from the literature, and the relationships between model parameters and the fill age of landfills were summarized. In the end, the similarities and differences between the equivalent-time-lines model for MSW and the stress-biodegradation model for MSW were discussed.

2. Background

2.1. Time-lines model for clays

At the seventh Rankine Lecture, Bjerrum (1967) suggested a conceptual time-lines model for marine clays, where the time line represents a unique relationship between void ratio, overburden stress and time. That is to say, to any given value of the overburden stress and void ratio, there corresponds an equivalent time of sustained loading and a certain rate of secondary consolidation, independent of the way in which the clay has reached these values. Yin and Graham (1989) argued that the equivalent time was not the duration of load and the instant line was an elastic compression line instead of a normal consolidation line, as in Bjerrum's model. They developed the equivalent-time lines, as well as the relationship between the equivalent time and the duration of load. Therefore, they proposed a 1D elastic viscoplastic (EVP) model for clays. A logarithmic function was used to describe the creep compression strain. Long-term oedometer tests indicated that the logarithmic function may overestimate the strain due to creep. Accordingly, Yin (1999) revised the EVP model and utilized a new function to simulate the non-linear creep of soils.

2.2. Compression mechanisms of MSW and its compression progress

The main compression mechanisms of MSW include (Sowers, 1975; Edil and Ranguette, 1990; Edgers et al., 1992; Hudson et al., 2004): (1) rearrangement of the solid matrix by sliding, reorientation or distortion of waste particles; (2) compression of the pore fluid; (3) compression or crushing of waste particles; (4) breakage of particles, and softening of particle contacts; (5) degradation; (6) conventional mechanical creep; and (7) ravelling.

Bareither et al. (2013) proposed a conceptual model of MSW settlement as shown in Fig. 1, which divided the compression progress of MSW into four phases, namely the immediate compression, the mechanical creep, the biocompression and the final mechanical creep. In this paper, the compression progress of MSW consists of two parts, including the stress-dependent primary compression and the time-dependent secondary compression. There are a few points in Fig. 1 that need to be explained: (1) when the load is applied, the compression and extrusion of gas and liquid in the void of MSW and the compression of compressible particles are generated under the instantaneous stress. This progress is defined as the immediate compression. Since it happens quickly, it is included in the primary compression in this paper; (2) the stress-dependent primary compression is called the immediate compression in Bareither et al.'s (2013) conceptual model. The primary compression is caused by the rearrangement of the solid matrix by sliding, reorientation or distortion of waste particles, as well as the compression of the pore fluid and compression or crushing of waste particles. The end time of the primary compression (EOP) is denoted as t_p; and (3) the mechanical creep, the biocompression and the final mechanical creep in Bareither et al.'s (2013) model all belong to the time-dependent secondary compression in this paper. In Fig. 1, t_B and t_F represent the temporal transitions from the mechanical creep to the biocompression and from the biocompression to the final mechanical creep, respectively (Bareither et al., 2013). It is quite subjective to determine t_B and t_F and difficult to distinguish the contributions of the mechanical creep and the biocompression to the long-term

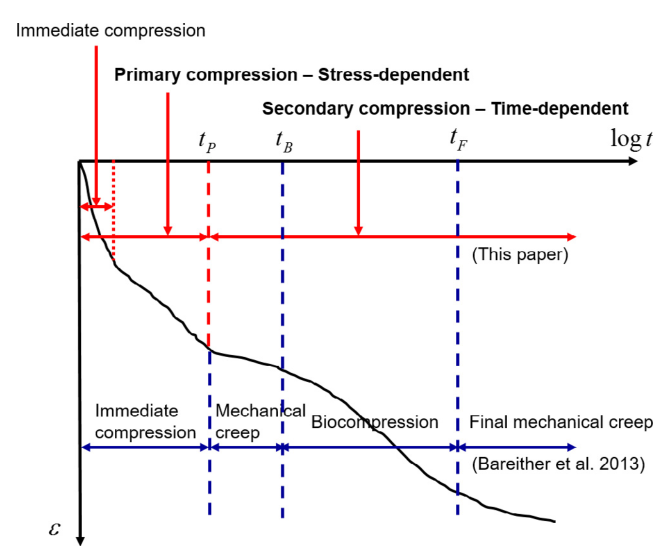

Fig. 1. Compression progress of MSW (after Bareither et al., 2013).

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