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Technical note

Numerical simulation of geomembrane wrinkle formation

Ping Yang [a, b, *], Shou-Bao Xue [a], Li Song [a], Xue-wen Zhu [a]

[a] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, 200092, China
[b] State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu, 610059, China

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ABSTRACT

Three outdoor experiments are reported where a wrinkle was allowed to develop and grow in a narrow strip of 2-mm-thick HDPE geomembrane when subjected to solar heating. The increase in length of the strip was used to obtain an effective coefficient of thermal expansion for the particular configuration tested. That effective coefficient of thermal expansion was then used as input into a finite element model, along with an assumed temperature dependent Young's modulus. The finite element model was able to replicate the formation of a geomembrane wrinkle when subject to solar heating.

1. Introduction

Geomembrane wrinkles form in HDPE geomembrane from solar heating when left exposed. These wrinkles create a gap between the geomembrane and the underlying material. If a wrinkle is buried and there is a hole in the wrinkle, there will be increased leakage compared to a hole in the geomembrane which is in direct contact with the clay liner (Rowe and Abdelatty, 2013; Abdelaal et al., 2014; Take et al., 2012). Rowe et al. (2012a,b) discussed effects of leakage of connected wrinkle. Previous studies have shown that large-area seepage is primarily caused by space between wrinkles and the bottom barrier layer as well as misplacements of seams (El-Zein and Rowe, 2008; Rowe and Abdelatty, 2013; Rowe et al., 2016, 2017; Brachman et al., 2017).

In solid waste landfills, geomembranes (GMBs) and geosynthetic clay liners (GCLs) form an impervious barrier system (Rentz et al., 2016). During the installation of barrier systems in solid waste landfills, GMBs are exposed to solar radiation and can achieve peak temperatures in the range 75 °C (Take et al., 2012). The increase in temperature forces the GMBs to expand in-plane thermal, cause localized buckling and result in vertical protrusions from the GMBs surface (Fig. 1). Scholars have conducted some research about GMB wrinkles. Rowe et al. (2012a,b) and Chappel et al. (2012a,b) took pictures of a GMB site using aerial photography and observed wrinkle development over time of one day, obtained parameters such as large-area wrinkle distribution and maximum wrinkle connected length. Take et al. (2012) performed a series of outdoor and laboratory experiments and found that cross-sectional geometry of GMB wrinkles after landfilling follow a Gaussian shape. The relationship between temperature and height of GMB wrinkles after backfilling was analyzed. Jafari et al. (2014) monitored liner temperature and discovered changes in liner temperature over time. Take et al. (2014, 2015) discovered that the temperature of wrinkles was higher than other location. Rentz et al. (2017) discovered that relative to the black geomembrane, significant wrinkles on the white geomembrane formed later in the morning and went away sooner in the evening. However, very little research attention has been focused on numerical simulation of geomembrane wrinkle formation.

The objective of the paper is to see if a numerical model can reproduce wrinkle formation.

2. Method

In this study, the HDPE GMBs (density = 0.95 g/cc, tensile strength ≥ 16 MPa and break elongation ≥ 700%) with 2 mm in thickness were used.

When HDPE GMBs undergo thermal expansion, HDPE GMBs wrinkles may form in the GMB rolling direction, crossed rolling direction, or other directions (Chappel et al., 2012a,b). However, the majority of the wrinkles formed in the rolling direction (Take et al.,

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* Corresponding author. Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, 200092, China.
E-mail address: pingyang@tongji.edu.cn (P. Yang).

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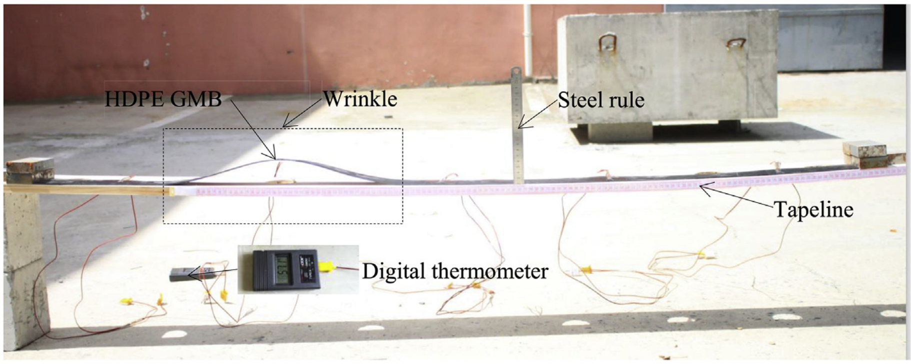

Fig. 1. Layout of the HDPE GMBs outdoor experiment.

2012). Therefore, in this study, the experiments primarily focused on wrinkles formed along the rolling direction. The HDPE GMBs with 0.05 m in width and 2 m, 1.5 m and 1 m in length was used to ensure great ratios of length to width and to eliminate the possibility of wrinkles forming along the crossed rolling direction.

The two ends of GMB liners used in landfills are restrained (Take et al., 2012). Therefore, the two ends of GMBs were securely restrained in outdoor experiments. Five thermocouples, placed 20 cm away from the two ends of the HDPE GMBs, were uniformly adhered to the upper and lower surfaces of the HDPE GMBs so that changes in the temperature of the HDPE GMBs exposed to natural solar radiation could be obtained. During the experiments, the Canon EOS-700D camera was used to take pictures of the HDPE GMBs every 30 min. A digital thermometer was used to record the temperature of the surrounding environment as well as that of the upper and lower surfaces of the HDPE GMBs. The photos were processed by the MATLAB to obtain HDPE GMBs wrinkle length, the arch height, and the arch width. Fig. 1 shows the layout of the HDPE GMBs outdoor experiment.

The experiments were performed on a cloudless day to eliminate the influences of cloud cover. The experiments began from 7:30 a.m. to 4:30 p.m.

Based on the results obtained from the HDPE GMBs outdoor experiments, the Abaqus finite element analysis software was employed to perform numerical simulation to investigate the formation of HDPE GMBs wrinkles when temperature changed.

The finite element model was built on the basis of the Abaqus shell S4R, which can create deformed three-dimensional shell elements. The contact surfaces and grid types adopted were C3D8R deformable solid elements and 4-node grids, respectively. The contact body under GMBs is compacted clay liner. HDPE GMBs Poisson's ratio and coefficient of friction was 0.4 and 0.2, respectively. The aim of this paper is to discuss thermal expansion effect of GMBs under different temperature. The area increment of GMBs depends on coefficients of thermal expansion and Young's modulus. Thus, both coefficients of thermal expansion and Young's modulus are important parameters. Outdoor experiments were conducted to study the relationship between coefficients of thermal expansion and temperature (shown as Equation (3)). And the Young's modulus was proposed by Fang et al. (2010), which was an empirical Equation (1).

$$E = 779 \times 0.978^{\mathrm{T}} \tag{1}$$

Where E is Young's modulus (MPa) and T is temperature (°C).

The two ends of the HDPE GMBs were securely restrained and the HDPE GMBs width was 0.05m.The height of the initial geometric imperfections is 0.01m. The finite element model is shown in Fig. 2.

In outdoor experiments, the wrinkles were generated randomly. In numerical simulation, a little initial geometric imperfections was formed randomly at the beginning, which developed into a wrinkle later.

3. Results

3.1. Relationship between temperature and HDPE GMBs coefficients of thermal expansion in outdoor experiments

To analyze the relationship between temperature and HDPE GMBs expansion characteristics, a series of HDPE GMBs specimens were exposed to solar radiation for varying periods, the initial temperature was 28 °C. HDPE GMBs coefficients of thermal expansion was calculated by Equation (2).

$$L1{=}L0(1{+}\alpha\Delta \mathrm{T}) \tag{2}$$

where α is the coefficients of thermal expansion, L_0 is the initial length of the HDPE GMBs, L_1 is the final length of the HDPE GMBs, ΔT is the temperature incremental in HDPE GMBs.

Fig. 3 shows the relationship between temperature and HDPE GMBs coefficients of thermal expansion. The experimental results indicated that the HDPE GMBs coefficients of thermal expansion changed with temperature and the coefficients of thermal expansion was not a constant. Xu and Yang (2007) and Maija et al. (2013) had got the similar results.

Fig. 3 shows a nonlinear relationship between temperature and coefficients of thermal expansion, which can be described by Equation (3):

$$\alpha = 4 \times 10^{-4} - 7 \times 10^{-6} \times T + 8 \times 10^{-8} \times T^2 \tag{3}$$

Where α is the coefficients of thermal expansion and T is the temperature (°C).

Equation (3) is obtained from particular experiments for HDPE GMBs of 2.0 mm in thickness. If the same polymer but of a different thickness (e.g., 1.5 or 2.5 mm) were used the results may not necessarily be the same.

3.2. Changes in height and width of HDPE GMBs wrinkle with temperature in outdoor experiments

Fig. 4 shows change in the upper and lower surface temperatures of the HDPE GMBs between the hours from 7:30 a.m. to 9:30 a.m. and from 3:30 p.m. to 4:00 p.m. However, from 9:30 a.m. to 3:00 p.m., the upper surface temperature was slightly higher than