Geotextiles and Geomembranes 43 (2015) 24–34

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

In situ test and analysis method of air bulging under geomembranes in a shallow-lined reservoir

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A R T I C L E I N F O

Article history:
Received 21 October 2013
Received in revised form
24 October 2014
Accepted 18 November 2014
Available online

Keywords:
Geosynthetics
Geomembranes
Air bulging
In situ test
Analysis method

A B S T R A C T

Air bulging under a geomembrane is a problem in reservoirs that are lined with geomembranes. Three essential conditions influence the air bulging under geomembranes: earthworks construction, rapid decrease in reservoir water level, and rising of the underground water table for a geomembrane liner without defects. The theory of unsaturated soil mechanics is proposed to analyze the mechanism of air bulging under geomembranes by using a one-dimensional method. In the absence of a liner, no air bulging is produced because any air could be squeezed out easily. However, air pressure could increase in the presence of a liner because the pore air is isolated from the atmosphere. Whether water infiltration is caused by the rising of groundwater table or soil is compressed, pore air volume is reduced in the unsaturated soil, and the pore air pressure increases. Air bulging could be produced if the pore air pressure is greater than the load over the geomembrane. Then, the pore air pressure is computed with the two-dimensional consolidation method of unsaturated soil. A small-scale in situ test of the Datun reservoir was performed to analyze the air bulging phenomenon under the geomembrane in Shangdong Province, China. The earthworks construction and the rapid decrease in reservoir water level have insignificant effects on air bulging under the geomembrane because the pore air pressure under the geomembrane depends on the compression strain of the pore. The increment of the pore air pressure is always low because of less compression strain. The rise in groundwater tables has a significant effect on air bulging under the geomembrane because a linear relationship exists between the pore air pressure under the geomembrane and the increased amplitude of the underground water level.

1. Introduction

Many lined reservoirs are located in alluvial plain areas, such as those in the United States (Dougherty et al., 2007), Austria (Wu et al., 2008), New Zealand (Szabo, 1977), France (Poulain et al., 2011), and China (Gong and Song, 1999; Li et al., 2013; Shi and Li, 2005; Yi and Chen, 1999; Yu, 2003; Yuan et al., 2014). In China, the common regional geological features of alluvial plain areas are deep, strong permeable ground soil of silt loam, sandy loam, or fractured clay and thin or less impermeable soil of a layer of clay or loam. A seepage control scheme of many reservoirs in China that are completely lined by geomembranes is proposed to improve the efficiency of the plain reservoir. Geomembranes are continuous flexible sheets manufactured from one or more synthetic materials. They are impermeable and are used as liners for fluid or gas (Bathurst, 2007). Geotextile–geomembrane composites are manufactured from geomembranes and geotextiles. The geotextiles can be laminated on one or both sides of a geomembrane. The geotextiles provide increased resistance to puncture, tear propagation, and friction related to sliding as well as provide tensile strength in and of themselves.

Although the total geomembrane liner scheme of the reservoir completely solves the potential leakage problems of plain reservoirs with no strong impermeable soils in theory, a new problem that emerges is air bulging under the geomembrane and leakage. The geotextile–geomembrane composite liner, as a fully anti-seepage material, is laid in the main reservoir storage of the Golden Temple Reservoir in Kunming, China (Gong and Song, 1999). The current goal of anti-seepage effect is achieved in terms of the operation time. However, air bulging and leakage still occur in part of the liner. In the

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http://dx.doi.org/10.1016/j.geotexmem.2014.11.005
0266-1144/

Shengli reservoir (Shi and Li, 2005) in Xinjiang Uygur Autonomous Region and the Jiashanzi reservoir in Gansu Province (Yi and Chen, 1999), a phenomenon that was observed is that the rate of reservoir leakage increases when bubbles appear in the first filling of the reservoir. Air bulging led to geomembrane rupture and serious leakage in approximately 1,000,000 m^2 of geotextile–geomembrane composites installed in the Xincheng reservoir in Shandong Province. The geotextile–geomembrane composites were installed in the slope of the Beidianzi embankment of the Yuqing Lake reservoir in Shangdong Province. Serious air bulging and leakage occurred in front of the embankment within 10 m (Yu, 2003).

2. Review

The permeability of the geomembrane is low, specifically, 10^{-15} m/s to 10^{-13} m/s (Jiang et al., 2010; Gu, 2000). This permeability is usually a negligible source of leakage. Geomembrane liners have been used in reservoirs for decades (Hebeler et al., 2005). It is an objective fact that air bulging and leakage occur under the geomembrane of the geomembrane liner. The air bulging could be caused by leakage water that results from geomembrane defects (Li et al., 2013) because holes and wrinkles in geomembranes are common, and leakage occurs through holes and spreads in wrinkles (Abuel-Naga and Bouazza, 2014; Jiang et al., 2010; Messerklinger, 2014; Poulain et al., 2011; Rowe, 2007; Rowe, 2012; Rowe and Abdelatty, 2012, 2013). However, air bulging still exists under the geomembrane of the geomembrane liner without defects (Yuan et al., 2014). The two methods are performed to analyze the mechanism of air bulging under the geomembrane for a liner without defects.

The air bulging under the geomembrane is caused by the entrapped pore air of the unsaturated soil. The ground water level is deep and the unsaturated soil is thick in the reservoir construction period or during a long drought. Unsaturated soil is a multiphase system that comprises three types of matter: solid (soil particles), liquid (pore water), and gas. The degree of saturation expresses the volume of pore water content in the void ratio. A lower degree of saturation corresponds to a greater volume of pore gas content. The air phase of an unsaturated soil can be found in two forms, namely, continuous air phase and occluded air bubbles (Fredlund and Rahardjo, 1993). The air phase generally becomes continuous as the degree of saturation reduces to approximately 85% or lower (Corey, 1957). Under naturally occurring conditions, the flow of air through soil may be caused by certain factors (Jalali-Farahani et al., 1993; Latifi et al., 1994). Soil air pressure increases because the soil is compressed or water infiltration results in compression of the air in the soil pores. As water infiltrates the vadose zone, soil air is displaced and may become compressed ahead of the wetting front. Thus, air pressure increases. When air pressure is sufficiently high, air escapes from the soil surface, thereby causing a sharp decrease in air pressure and a significant increase in the rate of water infiltration (Grismer et al., 1994; Touma et al., 1984) Air compression below the wetting front generally leads to residual air entrapment in the transmission zone (Touma et al., 1984). The air-confining infiltration flow is unstable (Wang and Jan, 1998, 2000). Therefore, the entrapped air pressure under the geomembrane may increase more than the load over the geomembrane in the reservoir.

Wrinkles are one of the causes of air bulging and leakage under the geomembrane. Wrinkles can develop during the geomembrane liner installation. Rowe (2005) indicated that a significant length of wrinkle(s) with a hole is needed to explain most observed leakages in the primary liner of double-liner systems. Several other experimental studies have been carried out to investigate the factors that affect the leakage rate through a damaged GM, including the effect of defect geometric characteristics and the flow transport properties of the underlying liner material (Walton et al., 1997; Cartaud et al., 2005; Rowe et al., 2012; Rowe and Abdelatty, 2012). Wrinkles do not disappear when the lining system is covered and loaded (Brachman and Gudina, 2008; Take et al., 2012; Chappel et al., 2012). This study focuses on air bulging under the geomembrane without any wrinkles and holes. However, a discussion about the effects of wrinkles on air bulging is inevitable in this study.

To study the mechanism of air bulging under geomembranes without defect, a one-dimensional method of unsaturated soil was proposed to analyze three essential conditions: earthworks construction, rapid decrease in reservoir water level, and rising in the underground water table for the geomembrane liner without defects. The formulas were established based on different conditions and factors to determine the probability of air bulging under geomembranes. Then, the two-dimensional consolidation method of unsaturated soil was used to compute the pore air pressure to further analyze the air bulging phenomenon under the geomembrane. Finally, a small-scale in situ test of the Datun reservoir was performed in an area that measures 100 m × 50 m in Shangdong Province, China to prove the mechanism of air bulging under the geomembrane. The results of the one-dimensional and two-dimensional methods were also confirmed by the in situ test.

3. One-dimensional analysis of air bulging under the geomembrane

Excavating, remolding, and compacting soil result in an unsaturated material. The compacted soil has an initial degree of saturation of about 80% (Fredlund and Rahardjo, 1993). A low groundwater table is required during the embankment construction and installation of the geomembrane in the plain reservoir. Therefore, the dry season is generally chosen as the time for reservoir construction of embankments and installation of the geomembrane.

Three conditions are required to produce air bulging under geomembranes without defects: loading in the earthworks construction, compression–rebounding in the rapid decrease in reservoir water level, and water infiltration in the rising underground water table. For the first two conditions, the pore volume is reduced because unsaturated soil is compressed after loading. Both solid and liquid phases are incompressible in the unsaturated soil. Therefore, the mechanism of air bulging under geomembranes without defects is due to the fact that the pore air volume is reduced by compression, which results in increased pore air pressure in the isolated space. For the final condition, groundwater tables in the normal operating condition may rise with seasonal changes. As a result, water infiltrates the pore volume of the unsaturated soil and squeezes the pore air, thereby increasing the pore air pressure.

On the vertical distribution of space, a closed space in the area of the plain reservoir is formed after installing the geomembranes because of the impermeable geomembrane on the surface and low permeability of saturated soils and groundwater below. On the horizontal distribution of space, an approximated closed space is present because the ratio of the length or width of the reservoir area to the thickness of the unsaturated soil is more than 25 to 1000 times. This ratio leads to an extremely long path of horizontal drainage. Therefore, the issue of air bulging under the geomembrane can be simplified into a one-dimensional problem, as shown in Fig. 1.

3.1. No liner case

The pore air of unsaturated soil is connected to the atmosphere in the no liner case, as shown in Fig. 1(a) and (g). The constant of