Waste Management xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Large scale centrifuge test of a geomembrane-lined landfill subject to waste settlement and seismic loading

Edward Kavazanjian Jr. [a], Angel Gutierrez [b,*]

[a] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287-3005, United States
[b] United States Bureau of Reclamation, Yuma, AZ 85364, United States

ARTICLE INFO

Article history:
Received 15 March 2016
Revised 3 October 2016
Accepted 20 January 2017
Available online xxxx

Keywords:
Centrifuge
Modeling
Liner
Waste
Landfill
Strain
Downdrag
Geomembrane
Seismic

ABSTRACT

A large scale centrifuge test of a geomembrane-lined landfill subject to waste settlement and seismic loading was conducted to help validate a numerical model for performance based design of geomembrane liner systems. The test was conducted using the 240 g-ton centrifuge at the University of California at Davis under the U.S. National Science Foundation Network for Earthquake Engineering Simulation Research (NEESR) program. A 0.05 mm thin film membrane was used to model the liner. The waste was modeled using a peat-sand mixture. The side slope membrane was underlain by lubricated low density polyethylene to maximize the difference between the interface shear strength on the top and bottom of the geomembrane and the induced tension in it. Instrumentation included thin film strain gages to monitor geomembrane strains and accelerometers to monitor seismic excitation. The model was subjected to an input design motion intended to simulate strong ground motion from the 1994 Hyogo-ken Nanbu earthquake. Results indicate that downdrag waste settlement and seismic loading together, and possibly each phenomenon individually, can induce potentially damaging tensile strains in geomembrane liners. The data collected from this test is publically available and can be used to validate numerical models for the performance of geomembrane liner systems.

1. Introduction

Large scale centrifuge testing of a model geomembrane-lined landfill was conducted to assist in validation of a numerical model for performance-based design of geomembrane liner systems subject to waste settlement and seismic loading. Current state-of-practice design procedures for geomembranes have proven to be inadequate for determining their performance when subject to waste settlement or seismic loads (Arab et al., 2011). The current state-of-practice for seismic design of geomembranes is based upon Newmark seismic displacement analyses. However, Newmark analyses only provide an index of seismic performance and do not actually evaluate the strains and forces induced in the liner due to seismic loading. Furthermore, analyses conducted in accordance with current seismic design criteria cannot explain the tears that occurred in the liner of the Chiquita Canyon Landfill as a result of the 1994 Northridge earthquake (Kavazanjian et al., 2013a).

Forces and strains imposed on side slope geomembranes due to waste settlement are often ignored in practice, though some engineers recognize their potential impact on liner system integrity and employ design details to minimize such loads (Thiel et al., 2014). Therefore, a numerical model for explicitly evaluating the forces and strains in geomembrane liners subject to waste settlement and to seismic loading was developed at Arizona State University (Arab, 2011; Kavazanjian et al., 2014). This model includes the ability to account for relative displacement (slip) between the liner and overlying materials during settlement or seismic loading, a particularly important and vexing issue. However, this numerical model lacks validation and there is no field data available to do so. Rather than install instrumentation in an actual landfill and wait for the waste to settle and an earthquake to occur, a centrifuge model was constructed and tested to provide a data set suitable for model validation. While there are substantial differences between how waste settlement was modeled in the centrifuge and how waste settles in the field in a landfill, the results of the centrifuge test also provided an indication of whether or not there was a potential for damaging strains to be induced in landfill liner systems in the field by settlement or seismic loading.

2. Centrifuge model setup

2.1. Centrifuge modeling principles

Centrifuge testing enables testing of scaled models of geotechnical systems by amplifying the body stresses within the centrifuge

* Corresponding author.
E-mail address: angel.gutierrez@asu.edu (A. Gutierrez).

http://dx.doi.org/10.1016/j.wasman.2017.01.029
0956-053X/Published by Elsevier Ltd.

model. As the model is accelerated using the centrifuge, body stresses (e.g., gravity loads) increase in direct proportion to the centrifuge acceleration. Based upon centrifuge scaling laws, prototype length also then scales proportionally to the centrifuge acceleration. However, the shear strength and unit weight of the materials in the model remain the same. Furthermore, the stress–strain behavior of materials in the centrifuge model do not need to be scaled (although particle size may be an issue). Therefore, as centrifugal acceleration increases so does the scale of the model and the body stresses and strains in the model are comparable to the stresses and strains in the field. Some geotechnical centrifuges can also apply earthquake-like horizontal motions to the model simultaneously with centrifugal acceleration. Scaling laws require that the frequency content and horizontal acceleration of the earthquake motion also scale with the centrifuge acceleration, but once again stresses and strains need not be scaled. Scaling laws for centrifuge modeling are summarized by Garnier et al. (2007).

2.2. Model configuration

Centrifuge testing of a model of a geomembrane-lined landfill was conducted using the 2-m × 1-m shaking table on the 9.1 m-radius, 240 g-tonne centrifuge at the University of California at Davis Center for Geotechnical Modeling under the U.S. National Science Foundation Network for Earthquake Engineering Simulation Research (NEESR) program. A 0.051 mm specialty thin film membrane was used to model the liner system. The landfill foundation was constructed of lightly cemented sand and the waste was modeled using a peat-sand mixture. For model validation purposes, the side slope membrane was underlain by a thin (0.1524 mm) low density polyethylene (LDPE) membrane lubricated on the top side to maximize the difference between the interface shear strength on the top and bottom of the specialty membrane and thus maximize the tension induced in the membrane.

Flexible Shear Beam Container number 1 (FSB1) at the University of California at Davis (UCD) centrifuge facility was used as the model container. The container was lined with a LDPE membrane to mitigate the potential for damage to the container due to the cemented sand base of the model. The foundation of the landfill was created using cemented sand to provide a firm foundation for the geomembrane liner system. Centrifuge scaling laws prevented use of a high density polyethylene (HDPE) liner (the typical material used for landfill geomembrane liners in practice) to model the landfill liner due to thickness issues. In the field, a HDPE geomembrane liner is typically between 1.5 mm and 2 mm thick. The minimum available thickness of HDPE geomembrane was on the order of 0.5 mm, which would result in a prototype liner thickness of 30 mm at a centrifuge acceleration of 60 g (the proposed maximum acceleration for the model). This prototype thickness was not representative of actual landfills and therefore was considered unacceptable. To account for the scaling up of the membrane thickness as the centrifuge acceleration increased, the landfill liner was modeled using a 0.051 mm Nafion™ perfluorosulfonic acid/polytetrafluoroethylene (PFSA) membrane resulting in a scaled prototype thickness of approximately 3 mm at the maximum centrifuge acceleration of 60 g (all prototype dimensions are referenced to the 60 g maximum centrifuge acceleration).

A cross section of the centrifuge model is presented in Fig. 1. The height of the landfill side slopes in the model was about 0.3 m on both sides, resulting in a scaled side-slope height of 18 m for the prototype. The waste material was created using a mix of Nevada sand and peat moss proportioned to yield a compressibility similar to that of municipal solid waste. The maximum thickness of the waste was about 0.52 m (prototype height = 31 m). The inclination of the side slope was 2H:1V (Horizontal:Vertical) on the left side of the landfill model and 1H:1V on the right side. Both side slopes in the model had a 76 mm-wide bench (4.6 m prototype dimension) two-thirds of the way up the slope (12 m above the base in the prototype). A 0.1524 mm-thick LDPE membrane was placed on the side slopes beneath the geomembrane and lubricated on the top side to lower the interface strength between the foundation and the bottom of the PFSA geomembrane liner and thereby maximize the tension induced in the liner due to downdrag from settlement of the waste and seismic loading for model validation purposes.

2.3. Cemented sand landfill foundation

The foundation for the landfill model (the portion of the model between the landfill liner and the centrifuge container walls) was constructed using a mixture of Nevada sand and 4% Portland cement (by weight). The Nevada sand and Portland cement were placed in a cement mixer and water was added to provide a water-to-cement ratio of 0.5. The sand, cement, and water were then thoroughly mixed. The initial lifts of the landfill foundation were then constructed by placing sand in the centrifuge container in 25–50 mm horizontal lifts and compacting each lift. Compaction was achieved by first tamping the sand-cement mixture and then placing a wood board on top of the tamped sand-cement mixture and loading the board with a 54 kg mass. The surface of the lift was then scarified prior to placement of the next lift to mitigate the potential for separation of the sand-cement mass between lifts. Two oversized cemented sand mounds were created on each side of the model container by compacting the soil in lifts but without placement of the 54 kg load on top of each lift (to avoid failure of the mounds). Upon completion of the mounds, the cemented sand base and mounds were allowed to set for about 2 h. Following this 2-h period, the cemented mounds were shaped into the 2H:1V and 1H:1V side slopes with benches. A LDPE cover was then placed over the container and the cemented sand foundation for the landfill was allowed to cure for 3 days. Fig. 2 shows the landfill foundation after shaping of the side slopes.

Data on the strength and compressibility of the cemented sand foundation material was collected simply to demonstrate that it would provide a firm, unyielding base for the landfill. The unit weight of the cemented sand foundation was calculated to be 16.6 kN/m^3 based upon model dimensions and the amount of material employed in model construction. Triaxial compression tests were then conducted on cemented sand samples compacted to the same density. The results of the triaxial compression tests are presented in Fig. 3. Based upon these test results, Fig. 4 was developed, which represents the shear strength of the cemented sand by a friction angle of 29 degrees and a cohesion of 18 kN/m^2.

One-dimensional compression tests were also conducted on the cemented sand model foundation material. Fig. 5 shows the results of two one-dimensional compression tests conducted on the cemented and material. The one-dimensional compression ratio, $C_{\varepsilon c}$, defined as the vertical strain per log cycle of stress, for the sand-cement was on the order of 0.01 (1 percent).

2.4. Liner system

The PFSA membrane used to model the landfill liner was the only membrane we found that came in a large enough sheet to cover the foundation of the model and was also thin enough to offset the centrifuge scaling effects. The measured thickness of the PFSA membrane was 0.051 mm, which scaled up to a prototype thickness of about 3.1 mm when the model was accelerated to 60 g. The scaled thickness of 3.1 mm was considered to be close

Please cite this article in press as: Kavazanjian Jr., E., Gutierrez, A. Large scale centrifuge test of a geomembrane-lined landfill subject to waste settlement and seismic loading. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.01.029