Geotextiles and Geomembranes 46 (2018) 166–182

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

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

Development of a numerical model for performance-based design of geosynthetic liner systems

E. Kavazanjian Jr.[a,*], X. Wu[a], M. Arab[b], N. Matasovic[c]

[a] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ85282, USA
[b] Department of Civil and Environmental Engineering, University of Sharajah, Sharajeh, United Arab Emirates
[c] Principal & Director of Earthquake Engineering, Geo-Logic Associates, Costa Mesa, CA92626, USA

ARTICLE INFO

Keywords:
Geosynthetics
Geomembrane
Liner system
Performance based design
Settlement
Seismic loading

ABSTRACT

A numerical model for performance-based design of the geosynthetic elements of waste containment systems has been developed. The model offers a rational alternative to the current state of practice for design of geosynthetic containment system elements in which neither the strains nor the forces in liner system elements are explicitly calculated. To explicitly assess the ability of the geosynthetic elements of a containment system to maintain their integrity under both static and seismic loads, a large strain finite difference model of waste-liner system interaction was developed. Modular features within the model allow the user to select the appropriate features required for any particular problem. A beam element with zero moment of inertia and with interface elements on both sides is employed in the model to represent a geosynthetic element in the liner system. This enables explicit calculation of the axial forces and strains within the liner system element. Non-linear constitutive models were developed to represent the stress-strain behavior of geomembrane and geosynthetic clay liner beam elements and the load-displacement behavior of the beam interfaces. The use of the various features on the model is illustrated using available experimental data, including shaking table test data on rigid and compliant blocks sliding on geomembranes. Analysis of geomembranes subject to waste settlement and subject to seismic loading demonstrate applications of the model and provide insight into the behavior of geosynthetic liner system elements subject to tensile loads.

1. Introduction

1.1. Objective

A numerical model for performance-based analysis and design of the geosynthetic elements of waste containment systems has been developed using a commercial two-dimensional explicit finite difference code. The model enables a design engineer to explicitly model waste-liner system interaction in order to calculate the forces and strains in geosynthetic liner system elements subject to static and seismic loads. This model provides a rational alternative to current state-of-the-practice design methodologies based upon avoidance of tension or an index of seismic performance. Current geosynthetics design practice typically does not explicitly consider the development of tension in the containment system elements. The large settlement associated with municipal solid waste (MSW) and mine tailings can drag down and induce tensile strains on the geosynthetic elements of side slope liner system. Seismic loading can also induce tension in the geosynthetic materials used in liner systems.

Excessive tensile strains can cause irreparable damage to the geosynthetic elements of a landfill liner system. Furthermore, damage due to tensile strains induced by settlement or seismic loading may be hidden beneath the waste, with no visible expression to alert the engineer, operator, owner, or regulator that there is a problem.

1.2. Methodology

The finite difference model of waste-liner system interaction described in this paper is based upon the methodology of Fowmes et al. (2006) and Fowmes (2007) in which a beam element with zero moment of inertia and with interface elements on both sides is used to represent a geosynthetic element in a liner system. The advanced features incorporated into the Fowmes et al. (2006) and Fowmes (2007) model are modular, allowing the design engineer to select the appropriate features for a particular problem. A non-linear beam element for geomembranes and geosynthetic clay liners (GCLs) was developed based upon available information on the stress-strain behavior of high density polyethylene (HDPE) geomembranes and the internal shear behavior of

---

[*] Corresponding author.
E-mail address: Edward.Kavazanjian@asu.edu (E. Kavazanjian).

https://doi.org/10.1016/j.geotexmem.2017.11.005
Received 11 September 2016; Received in revised form 24 November 2017; Accepted 27 November 2017

GCLs. An elasto-plastic interface model was developed based upon available experimental data from shaking table tests of rigid and compliant blocks sliding on geomembranes. Both the interface model and the GCL model account for post-peak degradation of shear strength and hysteretic behavior based upon large scale cyclic direct shear testing. The finite difference model not only provides a basis for performance based design of the geosynthetic elements of waste containment systems but can also be used in a variety of other situations in which geosynthetic materials are subject to large external forces.

2. Background

2.1. Liner system design for tensile loads

Prediction of tensile strains (or forces) induced by construction and service loads is a primary concern with respect to the integrity of geosynthetic barrier systems in landfills and other waste containment systems, as geosynthetic liner system elements generally are not intended to carry sustained tensile loads. Even if they are designed to carry some tension, excessive tensile strain can eventually lead to tearing of a geosynthetic element of a liner system. Downdrag due to soil and waste placement against side slope liners and due to waste settlement and seismic loading are among the most common sources of tensile strains in liner system elements (Fowmes et al., 2005, Kavazanjian et al., 2011). Furthermore, strains from different sources of tension may be additive. Centrifuge tests conducted by Kavazanjian and Gutierrez (2017) demonstrate that tensile strains due to waste settlement must be superimposed upon tensile strains due to seismic loading to get the total tensile strain in a geomembrane liner. A non-uniform subgrade (Mitchell et al., 2016) can also be a source of tension in the geosynthetic elements of a liner system.

Fig. 1 shows two mechanisms of identified by Dixon and Jones (2005) for distress to side slope liner and cover systems due to the waste settlement. Yazdani et al. (1995) presented three years of in situ measurements from strain gauges installed on a 1.5 mm (60 mil) HDPE geomembrane liner placed on a 3H:1V (horizontal:vertical) side slope at the Yolo County municipal solid waste landfill in Northern California. The liner system consisted of 0.6 m of 1×10^{-9} m/s compacted clay overlain sequentially by a 60 mil (1.5 mm) HDPE geomembrane, a geonet, a non-woven geotextile, and a 0.3 m “operations layer” of soil. Strain gauges were installed on the geomembrane at the top middle and bottom of the slope at 7 stations along the perimeter of the waste cell. Fig. 2 presents the strains recorded at Station C over a 30-month period, showing the progressive development of tensile strains at the top of the slope due to waste placement and settlement. Note that some of the tensile strain induced in the liner, e.g., the tensile strain at mid-height, were attributed by Yazdani et al. (1995) to settlement of the base of the landfill as the waste was placed.

Fig. 3 shows tears observed in the liner system of the Chiquita Canyon Landfill following the 1994 Northridge, California earthquake (Matasovic et al., 1995). These tears were attributed to tension induced by seismic loading due to strong shaking during the earthquake and associated waste movement (EMCON, 1994). However, analyses conducted by Kavazanjian et al. (2011) suggested that the tears in the Chiquita Canyon system were not due solely to the tension induced in the geomembrane by waste placement and seismic loading. The Kavazanjian et al. (2011) analysis indicated that strain concentrations at seams perpendicular to the tensile load and at scratches adjacent to the seam due to placement of caps over areas where coupons were removed for construction quality assurance testing contributed to the tensile strain exceeding the yield strain of the geomembrane. Giroud (2005) provides theoretical equations for evaluating strain concentrations at seams and due to scratches.

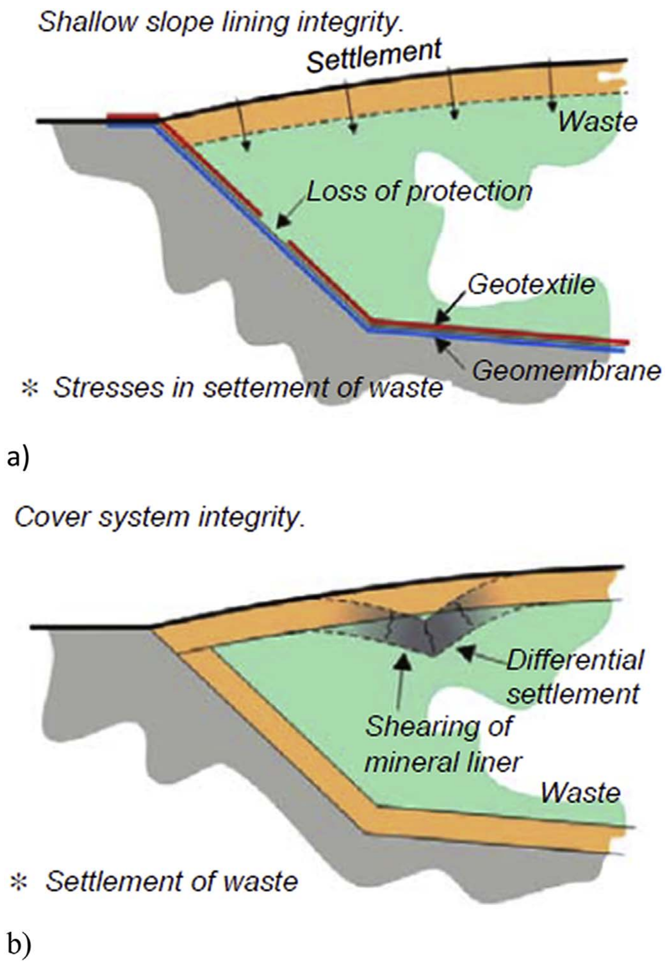

Fig. 1. Mechanisms of liner and cover system integrity failure: a) slope lining and b) cover system (Dixon and Jones, 2005).

2.2. State of practice

Current practice for design of landfill liner systems to withstand downdrag loads imposed by soil and waste placement settlement is based upon avoidance. With regard to soil and waste placement against side slope liners, the standard of practice is to provide a limit equilibrium factor of safety of at least 1.0 at all times without reliance upon the tensile strength of the liner system. However, limited tension is sometimes allowed as long as the tensile load is a transient load due to an interim configuration. Giroud and Beech (1989) provide a methodology for calculation of both the static factor of safety and the induced tension in a side slope liner due to placement of a soil or waste veneer against the slope. One manner in which downdrag induced by waste settlement is accommodated in current design practice is through use of a “slip layer” that allows relative movement between the waste and barrier layers in the side slope liner (Thiel et al., 2014). Fig. 4 illustrates the slip layer design concept.

The state of practice for seismic design of geosynthetics-lined waste containment facilities still generally follows the methodology reported on by Seed and Bonaparte (1992). The ability of the geosynthetic elements of a liner system to resist earthquake strong ground motions is based upon the displacement calculated in a decoupled Newmark-type analysis (Newmark, 1965). This methodology is referred to as a decoupled method because seismic response of the waste mass is calculated without consideration of the influence of the relative displacement (slip) at liner system interfaces on the response. This response is then used to calculate the relative displacement (slip) at the liner interface (hence the calculation of seismic response is decoupled from the