

**Reliability assessment of bioreactor landfills using Monte Carlo simulation and coupled
hydro-bio-mechanical model**

Krishna R. Reddy

Professor, University of Illinois at Chicago, Department of Civil & Materials Engineering, 842
West Taylor Street, Chicago, IL 60607, e-mail: kreddy@uic.edu (Corresponding author)

Girish Kumar

Graduate Research Assistant, University of Illinois at Chicago, Department of Civil & Materials
Engineering, 842 West Taylor Street, Chicago, IL 60607, e-mail: gkumar6@uic.edu

Rajiv K. Giri

Graduate Research Assistant, University of Illinois at Chicago, Department of Civil & Materials
Engineering, 842 West Taylor Street, Chicago, IL 60607, e-mail: geoenlab@gmail.com

B. Munwar Basha

Assistant Professor, Department of Civil Engineering, Indian Institute of Technology,
Hyderabad, Telangana, India, Formerly Visiting Scholar, University of Illinois at Chicago,
Chicago, IL, e-mail: basha@iith.ac.in

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Abstract: The performance of a bioreactor landfill is highly influenced by the simultaneous interactions of several coupled processes that occur within the landfill. In addition, the high uncertainty and spatial variability in the geotechnical properties of municipal solid waste (MSW) poses significant challenge in accurately predicting the performance of bioreactor landfills. In this study, a 2D coupled hydro-bio-mechanical (CHBM) model was employed to predict the behavior of MSW in bioreactor landfills. The numerical model integrated a two-phase flow hydraulic model, a plane-strain formulation of Mohr-Coulomb constitutive model, and a first order decay biodegradation model. The statistical ranges (mean and standard deviation) of some of the major influential MSW properties were derived from the published studies. Random fields of spatially variable MSW properties were generated following the log-normal distribution. Reliability-based analysis was carried out by performing several realizations of Monte-Carlo simulations and the statistical response of the output results including the moisture distribution, pore fluid pressures, landfill settlement, and interface shear response of the composite liner system were quantified. The results clearly indicate the importance of considering spatial variability of the geotechnical MSW properties and its influence on the performance of bioreactor landfills during leachate injection operations. A comparison of the results with the deterministic analysis was performed to evaluate the relative benefits and to emphasize the need for reliability-based analysis for effective design of bioreactor landfills.

Keywords: Reliability-based design; Monte-Carlo simulation; coupled hydro-bio-mechanical processes; leachate recirculation; settlement; interface shear stress-displacement.

Introduction

The concept of a bioreactor landfill primarily involves the recirculation of leachate into the MSW through leachate recirculation systems (LRS) in order to increase the overall moisture levels and accelerate waste degradation (Barlaz et al. 1989; Reinhart et al. 2002; Sharma and Reddy 2004). This in turn results in numerous benefits such as enhanced methane production, high settlement rates and thereby leading to early waste stabilization. However during the course of leachate recirculation operations the landfilled MSW undergoes highly complex coupled hydraulic, mechanical, bio-chemical, and thermal processes that must be adequately accounted in order to design safe and effective bioreactor landfills (El-Fadel and Khoury 2000; McDougall 2007; Reddy et al. 2017a, b).

Several studies have reported the evaluation of the performance of bioreactor landfill in terms of moisture distribution, generation and distribution of pore fluid pressures, landfill settlement (compressibility), stability of landfill, and integrity of composite landfill liner and final cover systems (Reddy et al. 1996; White et al. 2004; Jones and Dixon 2005; McDougall 2007; Chen et al. 2012; Sia and Dixon 2012; White et al. 2013; Reddy et al. 2017b). Some of the above mentioned numerical modeling studies focused on one-dimensional individual and/or coupled hydro-bio-mechanical processes in bioreactor landfills. In addition, some of these studies considered the waste as homogeneous and isotropic, but most of them incorporated real field waste conditions (i.e., heterogeneous and anisotropic MSW). However, all of these previous studies employed a deterministic approach for assessing the landfill performance by considering a single set of the geotechnical properties for the MSW, and ignored the uncertainties and spatial variability in the MSW properties on leachate injection operations and landfill performance. The limitations of these reported numerical models are discussed in detail in Reddy et al. (2017a).

Some of the previous studies (Babu et al. 2012; Reddy et al. 2013), that did use a probabilistic approach in predicting the bioreactor landfill performance, focused only on hydraulic behavior of MSW and did not account for the simultaneous influence of mechanical settlement, waste degradation and subsequent changes in waste properties with time for a holistic performance assessment of bioreactor landfills.

Reliability-based analysis in geotechnical and geoenvironmental engineering has received substantial consideration over the past few decades as it offers a rational framework to include and quantify uncertainties in the parameters associated with the problem (Christian et al. 1994; Duncan 2000; Sia and Dixon 2012). In particular, the reliability based analysis for landfills has shifted from conservative limit equilibrium techniques to a more comprehensive finite difference or finite element methods. In this regard, Monte-Carlo simulations (MCS) within the framework of a finite difference/ finite element numerical methods have gained widespread attention (El-Ramly et al., 2005; Babu et al, 2012; Sia and Dixon 2012; Reddy et al, 2013) since it is much simpler and easier to carry out and the statistical response can be expressed in the form of reliability index (β), probability of failure (P_f) and probability of occurrence ($1-P_f$) (Baecher and Christian 2003).

There is a need for reliability-based analyses to investigate the variability associated with major MSW properties and their influence on the performance of bioreactor landfill subjected to coupled hydro-bio-mechanical processes. Recently, Reddy et al. (2017b) formulated a coupled hydro-bio-mechanical model to predict the MSW behavior in bioreactor landfills and simultaneously examined the influence of the MSW behavior on the interface shear response of the geosynthetics in composite liner system. However, the study by Reddy et al. (2017b) did not consider the spatial variability associated with the MSW properties and evaluated the bioreactor

landfill performance for a single set of values representing the waste properties. This paper is aimed to be a companion study that evaluates the performance of bioreactor landfills considering random-fields of spatially variable geotechnical properties of MSW to simulate the heterogeneity and uncertainty in the values of the MSW properties across the landfill. The resulting performance of the landfill is quantified in terms of the probability of occurrence and reliability indices, as the performance indicators, based on the statistical analysis of the output parameters obtained from several Monte-Carlo simulations (MCS) performed in this study.

In this study, the coupled hydro-bio-mechanical numerical model built in FLAC, a finite difference code, was used to determine the overall performance of bioreactor landfills with randomly varied sets of geotechnical properties for MSW. The input geotechnical properties of the MSW namely the initial saturation, initial porosity, unit weight, saturated hydraulic conductivity, anisotropy, shear strength parameters, were accounted as log-normally distributed random field variables (Limpert et al. 2011). Several Monte-Carlo simulations (MCS) were performed to obtain the statistical response of the output parameters including the wetted area (i.e., the MSW area with degree of saturation $\geq 70\%$), the ratio of pore water pressure (PWP) to the total overburden stress, total MSW settlement, and induced shear stress and shear displacement of the interface between smooth HDPE geomembrane and nonwoven geotextile in a composite liner system at different period of leachate injection durations. Finally, the statistical response for each performance measure was presented in terms of reliability index and the probability of occurrence.

Methodology

Coupled Hydro-Bio-Mechanical Model

A coupled hydro-bio-mechanical model is used that integrates a two-phase flow hydraulic model, a first order decay biodegradation model and a plane-strain formulation of the Mohr-Coulomb mechanical model to predict the MSW behavior and examine the interface shear response of composite liner system under the influence of coupled hydro-bio-mechanical processes (Reddy et al. 2017b). In particular, the two-phase flow hydraulic model simulates the flow/transport of each fluid phase (liquid and gas) through Darcy's law and is extended to unsaturated fluid flow using the relative permeability functions given by van Genuchten (1980). A schematic of the numerical framework is presented in Reddy et al. (2017b) and the same is shown in Fig. S1. This numerical framework is implemented in FLAC, a finite difference code. A detailed explanation on each of these models and the entire numerical framework is presented in Reddy et al. (2017b). This coupled hydro-bio-mechanical model is validated with large-scale laboratory and field-scale pilot studies (Reddy et al. 2017c) and the effects of system variables (e.g. landfill configuration, leachate recirculation system layout and mode of leachate injection) are also assessed (Reddy et al. 2017d).

Landfill Configuration

A 2D bioreactor landfill cell with a total width of 120 m and a depth of 35.5 m was created in FLAC to perform the numerical simulations. This landfill cell geometry is based on a typical landfill in Illinois, USA, and is presented in Reddy et al. (2017b). The composite liner system consists of a 1V:2H side slope liner and 85 m wide bottom liner placed at a depth of 15 m from the ground level (GL). The composite liner system is made of 1 m thick compacted clay overlain by 1.5 mm smooth HDPE geomembrane and overlain by a 0.4 kg/m² non-woven geotextile. A

flat 3 m wide anchor was provided to secure the geomembrane and geotextile in place (Sharma and Reddy 2004). A 0.5 m thick high permeable drainage layer was overlain on the top of geotextile to simulate the leachate collection and removal system (LCRS). The same landfill cell configuration is shown in Fig. S2.

The total initial waste height was selected to be 30 m and was divided into 10 layers, each of 3 m thick. A total of four 1 m x 1 m horizontal trenches (HTs) are simulated such that two HTs are located in the shallow layers and the other two HTs are located in deep layers of landfill (Fig. S2). The two leftmost HTs are placed at a lateral distance (i.e., setback) of 30 m away from the MSW face slope to maintain the stability of landfill slopes. The HTs within the shallow MSW layers are situated 10 m vertically below the top of MSW landfill surface. Moreover, the horizontal and vertical spacing between successive HTs are 30 m and 10 m, respectively. This represents the typical layout of HTs employed in bioreactor landfills (Giri and Reddy 2015; Haydar and Khire 2005). Continuous leachate operations in bioreactor landfills are performed through injecting leachate in all four HTs at an injection pressure of 100 kPa. The injection pressure is selected based on the injection pressures reported in previous literature (Xu et al. 2011). The final cover system has a 1V:3H MSW face slope and 70 m wide horizontal portion. In addition, the final cover system is comprised of 1 m thick erosion (vegetative soil) layer underlain by 0.4 kg/m² non-woven geotextile and 1.5 mm smooth HDPE geomembrane. The geomembrane is underlain by a 1 m thick infiltration layer made of compacted clay (refer Fig. S1).

Material Properties

The geotechnical properties of the landfill soils and interface materials that consist of the smooth HDPE geomembrane and non-woven geotextiles are taken from previous studies (Reddy et al. 1999; USEPA, 1994) and are reported in Table S1. The statistical range of the selected MSW properties and their variation (mean and standard deviation) obtained from published field data is shown in Table 1. The mean value of MSW unit weight was varied along the depth using Zekkos et al. (2006) model, while the mean value of saturated vertical hydraulic conductivity of MSW was varied based on Reddy et al. (2009). Moreover, the mean value of the initial porosity and initial saturation of the MSW were varied with landfill depth using the mass-volume relationships. This was done in order to represent realistic field conditions (i.e., heterogeneous MSW with varied geotechnical properties along the depth). The shear strength parameters and the stiffness of MSW were assumed to be the same throughout the landfill and the initial values of these properties were generated randomly based on the mean value and coefficient of variance (CoV) obtained from previous studies. Furthermore, these parameters varied with time due to waste degradation based on the coupled hydro-bio-mechanical formulation. The biochemical methane potential (BMP) was assumed to be 100 m³/Mg (Faour et al. 2007) for all the MCS performed. The MSW unsaturated hydraulic properties ($\alpha = 1.18 \text{ kPa}^{-1}$, $n = 1.33$, $\theta_r = 0.03$) were taken from the experimental study performed on U.S. MSW by Breitmeyer and Benson (2011). The variability of unsaturated properties of MSW was not considered due to the limited evidence of its statistical variation in the literature. The variability associated with geotechnical properties of MSW namely, unit weight, porosity, saturation, cohesion, friction angle, saturated hydraulic conductivity, and anisotropy was accounted based on log-normal distribution as shown below:

$$k(x_i) = \exp\{\mu_{ln k} + \sigma_{ln k} \cdot G_i(x)\} \quad (1)$$

Where, $k(x_i)$ is the geotechnical property at a spatial position (x_i); $\mu_{ln k}$ and $\sigma_{ln k}$ are lognormal mean and lognormal standard deviation; and $G_i(x)$ is uncorrelated randomly distributed number based on standard Gaussian distribution (mean = 0, standard deviation = 1).

Monte-Carlo Simulations

The reliability based performance assessment was carried out by performing MCS considering the MSW properties as log-normally distributed random field variables. The CoV of each of the input MSW geotechnical properties is obtained based on previous field data (Table 1). The large data sets derived from the previous studies were considered to determine the CoV for each input parameter and large variations were observed for most of these input parameters. Consequently, it is clear that the available field data contains a lot of uncertainties, and therefore, a reliability-based performance evaluation of the bioreactor landfills is critical.

The log-normal mean (μ_{ln}) and log-normal standard deviation (σ_{ln}) were computed using the normal mean (μ) and the normal standard deviation (σ) as shown below:

$$\mu_{ln} = \ln \left(\frac{m}{\sqrt{1 + \frac{\sigma^2}{m^2}}} \right) \quad (2)$$

$$\sigma_{ln} = \sqrt{\ln \left(1 + \frac{\sigma^2}{m^2} \right)} \quad (3)$$

The log-normally distributed random numbers for each spatially variable input parameter in each MCS were generated using equation (1).

It is important to estimate the number of simulations that are required to achieve reasonable accuracy in the obtained results. As outlined by Sia and Dixon (2012) that the probability distribution associated with low number of MCS tends to ignore different sets of field situations that may take place in landfills. In contrary, large runs of MCS need additional

computational time and efforts, which could be expensive and require significant output storage capacity. In spite of that, the results based on probabilistic framework approximately tend to provide a range of the total number of realizations needed to improve overall accuracy, which can be further added to enhance the overall quality of the numerical results. In this regard, for each MCS, the computational time taken for simulating large-scale coupled hydro-bio-mechanical interactions and attaining the waste stabilization is time-consuming. In this study, a total of 400 simulations were performed due to the large number of uncertainties associated with many of the input geotechnical properties of MSW. In addition, MCS were performed by setting an upper and lower bound for the geotechnical properties of the MSW based on the typical values reported in literature to avoid having unrealistic values assigned to MSW properties. The number of simulations performed was found adequate as there was no significant change in the variance of the estimated mean of output parameters (wetted area, settlement, maximum interface shear stress and shear displacements) towards the end of 400 simulations.

The numerical analysis was carried out for each realization of MCS by simulating continuous leachate injection through the four HTs at a constant injection pressure of 100 kPa until the waste attained stabilization. In this study, the waste stabilization time is defined as the leachate injection time at which the difference of obtained maximum landfill settlement (any location on the final cover system) between any two consecutive years is less than 5%. The output results in terms of the MSW wetted area, the ratio of pore water pressure (PWP) to the total stress at the deeper trench locations, total landfill settlement, and the maximum interface shear stress and maximum interface shear displacement for the bottom liner and side slope liner are obtained at the end of 1 year, 5 years, 8 years, 10 years, and the MSW stabilization period. In the probabilistic framework, the statistics for the output results can be presented by evaluating

the reliability index (β), and the probability of occurrence (%). Meanwhile, the probability of occurrence ($100\% - P_f$) is also known as reliability, which in itself is the complement of the probability of failure (P_f). The statistical response of the output results (β , and $1 - P_f$) obtained for different leachate injection durations is calculated as follows:

The probability of failure (P_{f_wa}) to achieve wetted area after k^{th} year (W_{a_k}) is expressed as:

$$P_{f_wa} = \frac{\sum_{i=1}^N I(W_{a_k} < W_{a_target})}{N} \quad (4)$$

where, N = total number of random samples generated during MCS, and W_{a_target} = target wetted area proposed to achieve after k^{th} year.

The number of unsuccessful simulations to achieve after k^{th} year (W_{a_k}) is calculated using the indicator function, $I(g(x) < 0)$; $g(x)$ is the performance criterion. For a given random sample, $I(W_{a_k} < W_{a_target})$ is taken as the value of 1.0 when $W_{a_k} < W_{a_target}$ occurs and 0 when $W_{a_k} \geq W_{a_target}$ occurs.

The pore water pressure ratio (R_u) is the ratio of PWP to the total stress at the deeper trench locations. The probability of failure (P_{f_Ru}) to achieve PWP ratio after k^{th} year (R_{u_k}) out of target value of PWP ratio achieved after k^{th} year (R_{u_target}) is expressed as:

$$P_{f_Ru} = \frac{\sum_{i=1}^N I(R_{u_k} < R_{u_target})}{N} \quad (5)$$

The probability of failure (P_{f_Ws}) to achieve waste settlement after k^{th} year (W_{s_k}) out of targeted value of waste settlement (W_{s_target}) can be expressed as:

$$P_{f_Ws} = \frac{\sum_{i=1}^N I(W_{s_k} < W_{s_target})}{N} \quad (6)$$

The interface shear stress ratio along the bottom liner (SSR_{BL}) is defined as the ratio of shear stress (SS_{BL}) to the maximum shear stress achieved after stabilization time ($SS_{BL_{max}}$) among all the MCS performed. The magnitude of $SS_{BL_{max}}$ is observed as 42 kPa during MCS. The probability of failure ($P_{f_SS_{BL}}$) to achieve shear stress after k^{th} year (SS_{BL_k}) out of targeted value of shear stress ($SS_{BL_{target}}$) can be expressed as:

$$P_{f_SS_{BL}} = \frac{\sum_{i=1}^N I(SS_{BL_k} < SS_{BL_{target}})}{N} \quad (7)$$

The interface shear displacement ratio along the bottom liner (SDR_{BL}) is defined as the ratio of shear displacement (SD_{BL}) to the maximum shear displacement achieved after stabilization time ($SD_{BL_{max}}$) among all the MCS performed. The magnitude of $SD_{BL_{max}}$ is found to be 14 mm. The probability of failure ($P_{f_SD_{BL}}$) to achieve shear displacement after k^{th} year (SD_{BL_k}) out of targeted value of shear displacement ($SD_{BL_{target}}$) can be expressed as:

$$P_{f_SD_{BL}} = \frac{\sum_{i=1}^N I(SD_{BL_k} < SD_{BL_{target}})}{N} \quad (8)$$

Similarly, the interface shear stress ratio along the side slope liner (SSR_{SL}) is defined as the ratio of shear stress (SS_{SL}) to the maximum shear stress achieved after stabilization time ($SS_{SL_{max}}$) among all the MCS performed. The magnitude of $SS_{SL_{max}}$ is found to be 52 kPa. The probability of failure ($P_{f_SS_{SL}}$) to achieve shear stress after k^{th} year (SS_{SL_k}) out of targeted value of shear stress ($SS_{SL_{target}}$) can be expressed as:

$$P_{f_SS_{SL}} = \frac{\sum_{i=1}^N I(SS_{SL_k} < SS_{SL_{target}})}{N} \quad (9)$$

The shear displacement ratio along the side slope liner (SDR_{SL}) is defined as the ratio of shear displacement (SD_{SL}) to the maximum shear displacement achieved after stabilization time ($SD_{SL_{max}}$) among all the MCS performed. The value of $SD_{SL_{max}}$ is found to be 21.2 mm. In

addition, the probability of failure ($P_{f_SD_{SL}}$) to achieve shear displacement after k^{th} year (SD_{SL_k}) out of targeted value of shear displacement (SD_{SL_target}) can be expressed as:

$$P_{f_SD_{SL}} = \frac{\sum_{i=1}^N I(SD_{SL_k} < SD_{SL_target})}{N} \quad (10)$$

Subsequently, the reliability indices to achieve targeted values of wetted area (β_{W_a}), PWP ratio (β_{R_u}), waste settlement (β_{W_s}), shear stress on bottom liner ($\beta_{SS_{BL}}$), shear displacement on bottom liner ($\beta_{SD_{BL}}$), shear stress on side slope liner ($\beta_{SS_{SL}}$) and shear displacement on side slope liner ($\beta_{SD_{SL}}$) for different injection periods are obtained using the following equation:

$$\beta = \Phi^{-1}(1 - P_f) \quad (11)$$

where, Φ is the standard normal distribution and P_f is the probability of failure. The probability of occurrence can be obtained as $100 - P_f$ in percentage.

Results and Discussion

Monte-Carlo Simulation Results

The mean maximum value for the output parameters (W_a , R_u , W_s , SS_{BL} , SD_{BL} , SS_{SL} , SD_{SL}) was calculated by dividing the cumulative sum of the values of an output parameter for a specific number of MCS by the corresponding number of MCS. Fig. 1a and 1b shows the plot for the mean maximum wetted area and mean maximum landfill settlement for all the MCS performed, respectively, at different leachate injection periods. The simulation results are based on the coupled hydro-bio-mechanical response of MSW under continuous leachate injection operations until the waste stabilization time. As shown in Fig. 1a, the MSW wetted area is found to increase

with leachate injection as the waste achieves higher levels of saturation over time. The mean maximum wetted area ranged from 1650 m² to 2015 m² at the end of waste stabilization. Moreover, the mean MSW wetted area shows no significant change in the variance of the mean MSW wetted area towards the end of 400 simulations and hence the number of simulations performed was found adequate. Similarly, the mechanical response in terms of the mean maximum landfill settlement is plotted in Fig. 1b for all the MCS observed at different leachate injection periods. The landfill has higher settlement with time primarily due to the enhanced waste degradation. The mean maximum landfill settlement varied between 5.6 m and 8.7 m at the end of the MSW stabilization time. Furthermore, the number of simulations performed was found adequate to capture the variability in observed settlements as the mean maximum landfill settlement showed no significant variation towards the end of 400 simulations.

Fig. S3a and S3b shows the mean maximum induced interface shear stresses for both bottom liner and side slope liner interface, respectively, for all the MCS observed at different leachate injection periods. In Fig. S3a it is observed that the interface shear stress for the bottom liner increases with the leachate injection period. This is mainly due to increased unit weight of MSW, caused by the settlement of waste and biodegradation, which exerts higher overburden stress on the bottom liner over time. The mean maximum shear stresses for bottom liner interface ranged from 18.5 kPa to 28 kPa at the end of waste stabilization. However, the interface shear stresses along the side slope liner were found to decrease with time as shown in Fig. S3b. This could be due to the reduced stiffness of MSW representing a more compressible waste over time. The overburden stress applied by the MSW could possibly be absorbed by the degrading waste (because of low stiffness and high compressibility) and may not get transferred to the interface and thereby the shear stresses are not mobilized along the side slope interface. Moreover, the

friction angle of the waste is assumed to reduce with degradation which influences the shear strength of waste and thereby the waste and liner interaction. The mean maximum shear stresses for side slope liner interface ranged widely from 18 kPa to 39 kPa at the end of waste stabilization.

Fig. S4a and S4b shows the mean maximum interface shear displacement for both bottom liner and side slope liner interface, respectively, for all the MCS observed at different leachate injection periods. As shown in Fig. S4 the observed interface shear displacements for side slope liner, in general, were relatively much higher than the shear displacements along base liner. This result is in congruence with several other studies that reported similar observations for the shear displacements along the side slope liner interface (Sia and Dixon, 2012; Jones and Dixon, 2005; Reddy et al. 1996). Moreover, the shearing along the side slope and the mobilization of shear stresses along the side slope is more probable due to increasingly high normal stresses imposed by the overlying MSW and its draw down along the side slope. The large shear displacement along the side slope liner is attributed to the low interface friction angle (smooth HDPE geomembrane and nonwoven geotextile). Nevertheless, the trend of the mean maximum shear stresses and shear displacements towards the end of all simulations (Fig. S3 and Fig. S4) shows that the number of MCS performed were adequate to quantify the variability in interface shear response.

Reliability Assessment

Wetted Area

The performance of the bioreactor landfill (Fig. S2) subjected to the coupled hydro-bio-mechanical processes is assessed in terms of wetted area, ratio of pore water pressure to total stress at the deeper trench locations, landfill settlement, and interface shear stress-displacement in the liner system (interface between smooth HDPE geomembrane and nonwoven geotextile). The reliability measures namely, the reliability index (β) and the probability of occurrence ($1 - P_f$) are used to quantify the output from the MCS. Fig. 2 shows the influence of variability in MSW properties on the reliability index (β_{w_a}) and the probability of occurrence ($1 - P_{f_w_a}$) of attaining a specific MSW wetted area (relating to moisture distribution) at different periods of leachate injection. The wetted area increases with the continuous leachate injection, representing higher levels of moisture within the waste. A reliability index (β_{w_a}) of 3 (which signifies the above average performance of the landfill) can be obtained corresponding to the MSW wetted area of approximately 8%, 13-20%, 16.5-24%, 21-28.5%, and 23-31% of the total landfill area after leachate injection of 1 year, 5 years, 8 years, 10 years, and at the end of waste stabilization (Fig. 2a). It is worth mentioning that a large set of results for certain specific wetted area show negative reliability index ($\beta \leq 0$), representing more than 50% probability of failure corresponding to those higher percentages of wetted area. This is because, the high variability of hydraulic conductivity limits adequate moisture distribution despite having a continuous leachate injection and this is reflected reasonably well in the results shown in Fig. 2. Similar observations were made by Reddy et al. (2013), who showed that a large variation in the saturated hydraulic conductivity reduces the increase in overall degree of saturation and consequently the MSW wetted area, considerably. The effect of variability in MSW parameters on the probability of occurrence of a wetted area after a particular time of leachate injection is plotted in Fig. 2b. The probability of occurrence ($1 - P_{f_w_a}$) represents the chance of a positive outcome and a 95% or

higher probability of occurrence was observed for the MSW wetted area of about 225-700 m², 375-925 m², 475-1125 m², 600-1250 m², and 675-1300 m² at the end of 1 year, 5 years, 8 years, 10 years, and waste stabilization time, respectively. Furthermore, the probability of occurrence ($1 - P_{f_{wa}}$) is reduced significantly when a large wetted area is anticipated to be achieved during any given leachate injection period. A comparison of the results of wetted area in this study with a deterministic analysis (Reddy et al. 2017b) performed on the same landfill geometry with similar waste and leachate operating conditions yielded a maximum wetted area of 2600 m², which according to the reliability estimate and has a low probability of occurrence. Hence, a design based on such deterministic analysis would result in over-prediction of the hydraulic performance of the LRS leading to ineffective leachate injection operations.

Pore-Water Pressures

The overall stability of a bioreactor landfill must be carefully analyzed for the development of excessive pore-water pressures during the period of leachate injection. In addition, it is also possible to develop artesian conditions where the pore pressures exceed the overburden stress by MSW and can even promote lateral seeps from side slopes. Therefore, the ratio of maximum developed pore water pressure (PWP) at the deeper trench location to the total stress (R_u) was evaluated and the effect of spatial and temporal variability of the geotechnical properties of MSW on R_u was investigated. The landfill is considered to be stable when $\text{PWP/Total stress} \leq 1$ and this was the case in all the MCS for the landfill configuration considered in this study. However, a high value of R_u would indicate a condition for potential seeps. Therefore these results are helpful in guiding one in deciding the operating pressures for leachate injection based on a known overburden stress at the trench location. It can be seen in Fig. 3 that the values of the R_u decreased with leachate injection over time. The ratio (R_u) was found to vary from 0.3 to

0.47 at the end of waste stabilization. This variation is attributed to change in the overburden stress as the unit weight of MSW was found to increase with degradation thereby decreasing the ratio of PWP to total stress. Note that a decrease in this ratio does not indicate that the slope wouldn't fail as the stability is still influenced by changes in the shear strength of MSW due to biodegradation. Fig. 3a and 3b shows the variation of reliability index (β_{R_u}) and the probability of occurrence ($1 - P_{f_{R_u}}$) for a particular value of R_u for any given leachate injection period, respectively. A relatively good reliability index (β_{R_u}) of 3.0 was observed when the ratio R_u was approximately 0.37, 0.34, 0.32, 0.30, and 0.29 after 1 year, 5 years, 8 years, 10 years, and at the end of stabilization time, respectively. The ratio, R_u remained below 0.61 at all times, and therefore the landfill analysed in this study should be considered adequately stable. The deterministic analysis (Reddy et al. 2017b) had a R_u value of 0.3, 0.27, 0.26, 0.25, and 0.24 after 1 year, 5 years, 8 years, 10 years, and at the end of stabilization time, respectively. The deterministic analysis under-predicts the possibility of potential seeps and instability due to excess pore water pressures leading to unsafe design.

Landfill Settlement

The influence of variability in MSW properties on the landfill compression (settlement) subjected to coupled hydro-bio-mechanical processes is shown in Fig. 4 for different leachate injection periods. The total landfill settlement ranges approximately between 5.3 m to 11 m, corresponding to a vertical compressive strain of 17.6% to 36.6% at the end of waste stabilization period. Similar to the wetted area, the reliability index (β_{W_s}) was found to decrease significantly for higher values of landfill settlements at any leachate injection period. The probability of occurrence of a total landfill settlement greater than 6 m (at the end of waste

stabilization) was less than 95%. As shown in Fig. 4a, a relatively high reliability index (β_{w_s}) of 3.0 was observed when the total landfill compression was approximately 3.9 m, 4.4-4.5 m, 4.8-4.9 m, 5-5.2 m, and 5.3-5.5 m, at the end of 1 year, 5 years, 8 years, 10 years, and the MSW stabilization time, respectively. A similar trend was seen in the case of probability of occurrence ($1 - P_{f_{w_s}}$) as shown in Fig. 4b. A 95% and higher probability of occurrence was found for a total landfill compressive strain of 13-14.3%, 14.6-17.6%, 16-18.6%, 16.6-19% and 17.6-20% at the end of 1 year, 5 years, 8 years, 10 years, and after MSW stabilization time, respectively. A deterministic analysis (Reddy et al. 2017b) performed on the similar, landfill and leachate operating conditions shows a total landfill settlement of 4.9 m, 7.4 m, 8.2 m, 9.8 m, and 10.8 m at the end of 1 year, 5 years, 8 years, 10 years, and the MSW stabilization time, respectively. This shows that the deterministic analysis over predicts the landfill settlement as a result of which can cause disruption in the planning and management of final cover operations while having its implications on other landfill activities thereby leading to ineffective waste management.

Geosynthetic Interface Performance of Composite Liner System

A typical response of the variation of interface shear stresses and shear displacements along the bottom and side slope liner for the landfill geometry analysed is presented in Reddy et al. (2017b). The influence of variability in MSW properties on the interface shear stress and shear displacements along the bottom liner evaluated at different leachate injection periods is shown in Fig. 5 and Fig. 6, respectively. The maximum interface shear stress and shear displacement along the bottom liner was found to be 42 kPa and 14 mm, respectively. In this study, the interface shear stresses and shear displacements are normalized with the maximum shear stress and

maximum shear displacement (maximum value among all the MCS), respectively, so as to quantify the shear stress and shear displacement observed in each MCS. Therefore, the normalized interface shear stress (SSR_{BL}) and normalized interface shear displacement (SDR_{BL}) along the interface was evaluated for the reliability assessment.

As shown in Fig. 5, the reliability index ($\beta_{SS_{BL}}$) and the probability of occurrence ($1 - P_{f_{SS_{BL}}}$) decrease with an increase in the anticipated interface shear stress along the bottom liner with time. Although the interface shear stresses along the bottom liner increases with time due to increased unit weight, there were quite a large number of MCS with a high interface shear stress but with a low probability of occurrence. Therefore, a very limited MCS showed a high reliability index ($\beta_{SS_{BL}}$) of 3 corresponding to the normalized shear stress (SSR_{BL}) of about 13.1%, 19-21%, 25-26.2%, 28.5-30%, and 31-32%, at the end of 1 year, 5 years, 8 years, 10 years and MSW stabilization period, respectively. Based on the probability of occurrence ($1 - P_{f_{SS_{BL}}}$) greater than 95% the interface shear stress along the bottom liner interface (SS_{BL}) is more likely to reach a value of 5.5-7 kPa, 8-11 kPa, 10.5-15 kPa, 12-16.5 kPa, and 13-17.5 kPa after 1 year, 5 years, 8 years, 10 years and end of MSW stabilization, respectively.

The interface shear displacement along the bottom liner (SD_{BL}) as shown in Fig. 6 investigated while accounting for the variability in the MSW properties showed a similar trend as that of interface shear stress. The shear displacement along the bottom liner interface (SD_{BL}) increased with leachate injection and was observed to be in the range of 4.4 mm to 14 mm at the end of waste stabilization time. A large set of shear displacement results (for shear displacements greater than 9 mm) showed a negative reliability index value representing less than 50% probability of occurrence for those values of interface shear displacements along the bottom liner interface. A reliability index ($\beta_{SD_{BL}}$) value of 3 (Fig. 6a) is obtained for the normalized shear

displacement (SDR_{BL}) of about 13%, 21-23%, 27-28.5%, 28.5-30%, and 31.5%, respectively, after 1 year, 5 years, 8 years, 10 years, and the end of MSW stabilization. For the same results, it is observed that there is more than 95% probability of occurrence (Fig. 6b) of interface shear displacements (SD_{BL}) with a value of 1.8-2.2 mm, 3-4 mm, 3.8-5.3 mm, 4-5.6 mm, and 4.4-5.8 mm after 1 year, 5 years, 8 years, 10 years and at the end of MSW stabilization, respectively. The results from a deterministic analysis performed on the same landfill configuration, interface properties, waste and leachate injection conditions resulted in a maximum interface shear stress and maximum interface shear displacement of 34.5 kPa and 13.5 mm, respectively. These values which are over predicted in the deterministic analysis leads to a conservative design. However, on a large scale implementation such as landfill, using these values in the design would lead to uneconomical decisions.

Fig. 7 and Fig. 8 show the results of the influence of variability in MSW properties on interface shear stress and shear displacement along the side slope liner, respectively. The interface shear stress along the side slope liner (SS_{SL}) is found to decrease over time. The maximum interface shear stress at the end of MSW stabilization period is found to vary between 5 kPa to 52 kPa. As mentioned earlier, the decrease in interface shear stress along the side slope interface is mainly attributed to changes in MSW shear strength and MSW stiffness with degradation. The soft (relatively compressible) MSW representing low stiffness is found to possibly reduce the transfer of overburden stress into the interface leading to reduced mobilization of shear stresses. Similar observations in the variation of interface shear displacements with MSW stiffness is reported in previous (Reddy et al. 1996; Sia and Dixon, 2012). The values of reliability index ($\beta_{SS_{SL}}$) and probability of occurrence ($1 - P_{f_{SS_{SL}}}$) are found to decrease with the increase in interface shear stress along the side slope liner. It is

important to note that, high values of interface shear stress are predominant in side slope liner. A reliability index value ($\beta_{SS_{SL}}$) of 3 (Fig. 7a) is obtained when the corresponding normalized shear stress for side slope liner (SSR_{SL}) is approximately 2-4%, 4-8.6%, 5.8-9.6%, 7.7-10.6%, and 9.6-12.5% at the end of 1 year, 5 years, 8 years, 10 years, and MSW stabilization time, respectively. In this regard, from the results shown in Fig. 7b, the interface shear stresses (SS_{SL}) corresponding to more than 95% probability of occurrence are 1-7.5kPa, 2-10.5 kPa, 3-12.5 kPa, 4-13.5 kPa, and 4.5-13.5 kPa at the end of 1 year, 5 years, 8 years, 10 years and MSW stabilization, respectively.

Fig. 8 shows the influence of variability in MSW properties on the interface shear displacement along the side slope liner (SD_{SL}). The interface shear displacement was observed to be in the range of 2.6 mm to 21.2 mm, towards the end of waste stabilization time. Clearly, the shear displacements along the side slope liner interface are larger than the shear displacements observed along the bottom liner interface. In addition, the interface shear strength (adhesion and interface friction angle) considered was relatively lower as they were for the smooth HDPE geomembrane and nonwoven geotextile. Therefore, large interface shear displacement can be expected along the side slope liner for such interfaces. Similar results were obtained by Sia and Dixon (2012), who reported a large shear displacement of side slope liner interface (textured geomembrane and nonwoven geotextile) under the high stiff waste conditions. A reliability index ($\beta_{SD_{SL}}$) of 3 (Fig. 8a) was observed for normalized shear displacement (SDR_{SL}) corresponding to 5-24.5%, 6.6-24%, 8.5-23.6%, 10.4-24.5%, and 12-25.5% at the end of 1 year, 5 years, 8 years, 10 years and MSW stabilization, respectively. Likewise, more than 95% probability of occurrence (Fig. 8b) was found corresponding to interface shear displacement (SD_{SL}) of 1-7 mm, 1.4-8.4 mm, 1.8-8.8 mm, 2.2-9 mm, and 2.6-9.8 mm at the end of 1 year, 5 years, 8 years, 10

years and end of MSW stabilization, respectively. A deterministic analysis for the same landfill conditions and leachate injection operations it is observed that the maximum interface shear stress and interface shear displacement along the side slope liner interface were 37.1 kPa and 15.8 mm which in comparison to the reliability estimates in this study are higher. This can potentially lead to over estimation of the need for stiffer and thicker geosynthetics to be installed in the composite liner system.

Conclusions

Reliability-based analyses provide greater insight into the accuracy of predicting the performance of bioreactor landfills when subjected to the coupled processes during leachate injection operations, and especially when the uncertainties associated with MSW properties are large. In this study, reliability based assessment using Monte-Carlo simulations was carried out to investigate the effects of spatial variability and uncertainties in the geotechnical properties of MSW on the overall performance of bioreactor landfills. The key landfill performance measures were quantified by the means of reliability index and the probability of occurrence as performance indicators. A total of 400 realizations of MCS were performed and were found to be adequate to predict the performance of bioreactor landfills for the selected site-specific conditions. The modeling results clearly indicate that variability of input geotechnical MSW properties such as unit weight, shear strength parameters, saturated hydraulic conductivity, anisotropy, degree of saturation, initial porosity, and unsaturated hydraulic parameters significantly influence the performance of bioreactor landfills in terms of moisture distribution,

development of pore water pressure, total landfill settlement, and in-plane shear behavior of composite liner system.

Based on the selected bioreactor landfill conditions, it is found that achieving a MSW wetted area (a measure of moisture distribution) close to 31% of the total landfill area, and the MSW compression as high as 18-20 % is highly likely to occur towards the end of waste stabilization. In addition, these results are further supported by a good reliability index (β) of 3 which represents the above average performance of landfill. Similarly, the in-plane shear behaviour (shear stress-displacement) of the bottom liner and side slope liner system were quantified with reliability indices and the probability of occurrence to assess the performance of bioreactor landfills with respect to liner integrity. For the selected site-specific conditions, it is highly likely to observe an interface shear stress as much as 17-18 kPa and an interface shear displacement about 4-6 mm along the bottom liner interface at the end of waste stabilization time. More importantly, the observed shear displacements along bottom liner interface are relatively smaller compared to the shear displacements along the side slope liner interface and therefore may not become a huge concern for integrity in liner system.

Likewise, it is highly likely to observe an interface shear stress of about 14 kPa and the interface shear displacement nearly 10 mm along the side slope liner at the end of waste stabilization. Such values of shear displacements could possibly compromise the integrity of the liner for the interface analysed. The parameter variability with degradation, especially the waste stiffness, seems to have profound impact on the observed shear displacements. However, it is hard to quantify the exact stiffness values that could cause increase or decrease in shear displacements. In addition, the shear response largely depends on the landfill geometry and

boundary conditions as well and hence site specific landfill conditions and landfill configuration needs to be accounted to obtain the accurate results pertaining to those boundary conditions.

Owing to the highly heterogeneous and anisotropic behavior of MSW it is essential to quantify the spatial variability in MSW properties and predict the performance of the bioreactor landfill unlike assigning a single set of values for the MSW properties, which may result in unrealistic performance as discussed with the values predicted in a deterministic analysis. Most of these values were found to have a lower probability of occurrence based on the reliability analysis performed in this study. Hence, a probabilistic approach that considers the spatial variability is most desirable for an effective design of bioreactor landfills.

It should be noted that the estimates on the spatial variability of the MSW properties in the field should be considered with utmost importance as the reliability assessment is always only as good as the data used for the analysis. Field investigations and observations on the variability of the data needs to be accounted accurately to obtain higher confidence in the reliability estimates. Some of the limitations of the current study include the inability of the numerical model to account for the biochemical reaction kinetics (the leachate characteristics) and the influence of the temperature and other factors on the biodegradation of waste. The continuous leachate injection simulated in this study represents aggressive leachate recirculation conditions as opposed to the intermittent injections with periodic resting times. This was done as a simulation of worst case scenario so that the resulting evaluation and design implications are conservative. A parametric evaluation involving the effect of intermittent injections will also be performed. In addition, the composite liner interface of the geosynthetics considered in this study needs to be modeled to follow a strain softening behavior in order to examine the shear response

under the influence of coupled processes and thereby evaluate the stability and integrity of the liner system accurately.

Acknowledgements

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1 **Table 1.** Statistical range of variability in MSW parameters based on published field and laboratory studies

2

3

Mean Values					Co-efficient of Variation		
Layers	Density (kg/m ³) ¹	Sat. Vertical Hydraulic Conductivity (k _v , cm/s) ²	Initial Porosity (%) ³	Initial Saturation (%)	Variable	CoV	Source
10 (Top)	811	9.1 x 10 ⁻⁴	53	36	Density	25%	Babu et al. (2012); Reddy et al. (2009, 2013, 2015);
9	882	6.8 x 10 ⁻⁴	49	37	Cohesion	80%	
8	934	3.1 x 10 ⁻⁴	46	38	Friction Angle	25%	
7	974	1.5 x 10 ⁻⁴	44	39	Sat. Vertical	165%	
6	1006	9.5 x 10 ⁻⁵	42	40	Hydraulic Conductivity		
5	1032	8.0 x 10 ⁻⁵	40	41	Initial	20%	Benson and Wang (1998); Haydar and Khire (2005); Kazimoglu et al. (2006); Breitmeyer and Benson (2011); Stoltz et al. (2012); Nastev (1998) Abichou et al. (2013); Koerner and Soong (2000); Stoltz et al. (2012); Nastev (1998)
4	1053	4.3 x 10 ⁻⁵	39	42	Porosity		
3	1070	2.5 x 10 ⁻⁵	38	43	Initial		
2	1085	1.5 x 10 ⁻⁵	37	44	Saturation	20%	
1 (Bottom)	1098	9.3 x 10 ⁻⁶	36	45	Anisotropy	50%	Based on estimates using field data

4 ¹Zekkos et al. (2006); ²Reddy et al. (2009); ³Calculated based on mass-volume relationship

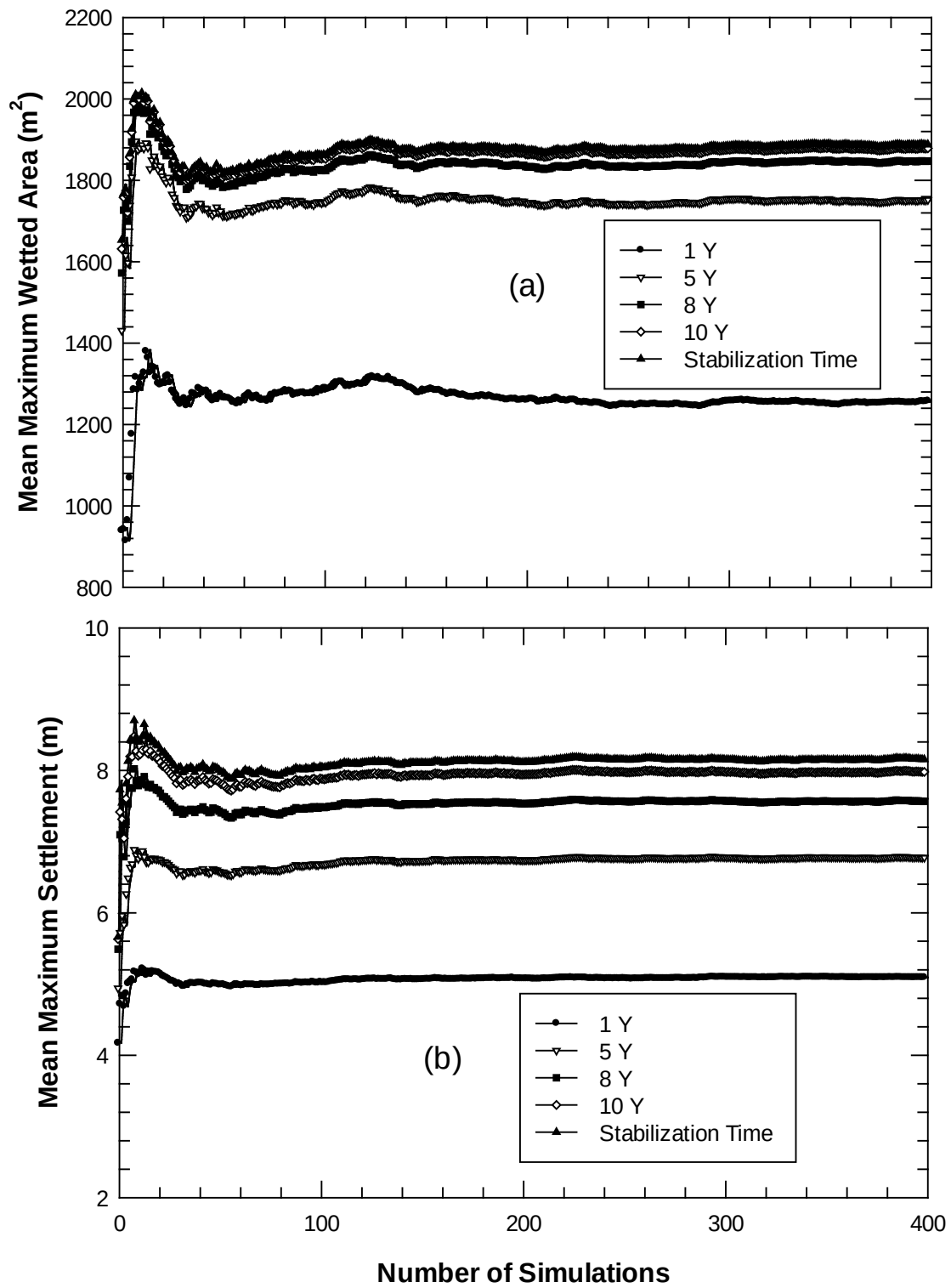
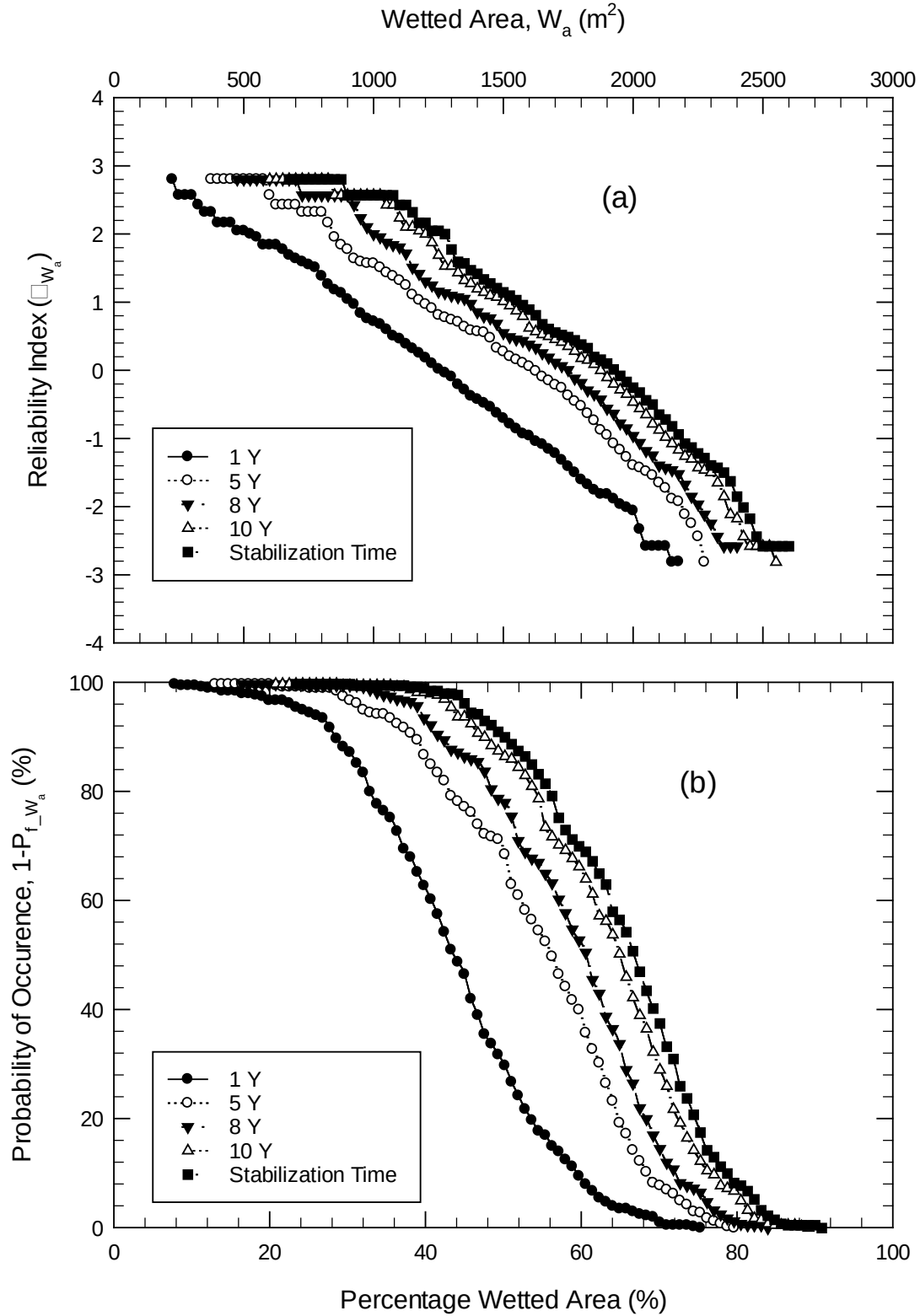


Fig. 1. Monte Carlo simulations: (a) mean maximum wetted MSW area (b) mean maximum total landfill settlement, for different leachate injection durations.



9
10 **Fig. 2.** Variation of (a) reliability index vs. wetted area (W_a), and (b) probability of occurrence
11 vs. MSW wetted area (W_a), for different leachate injection durations

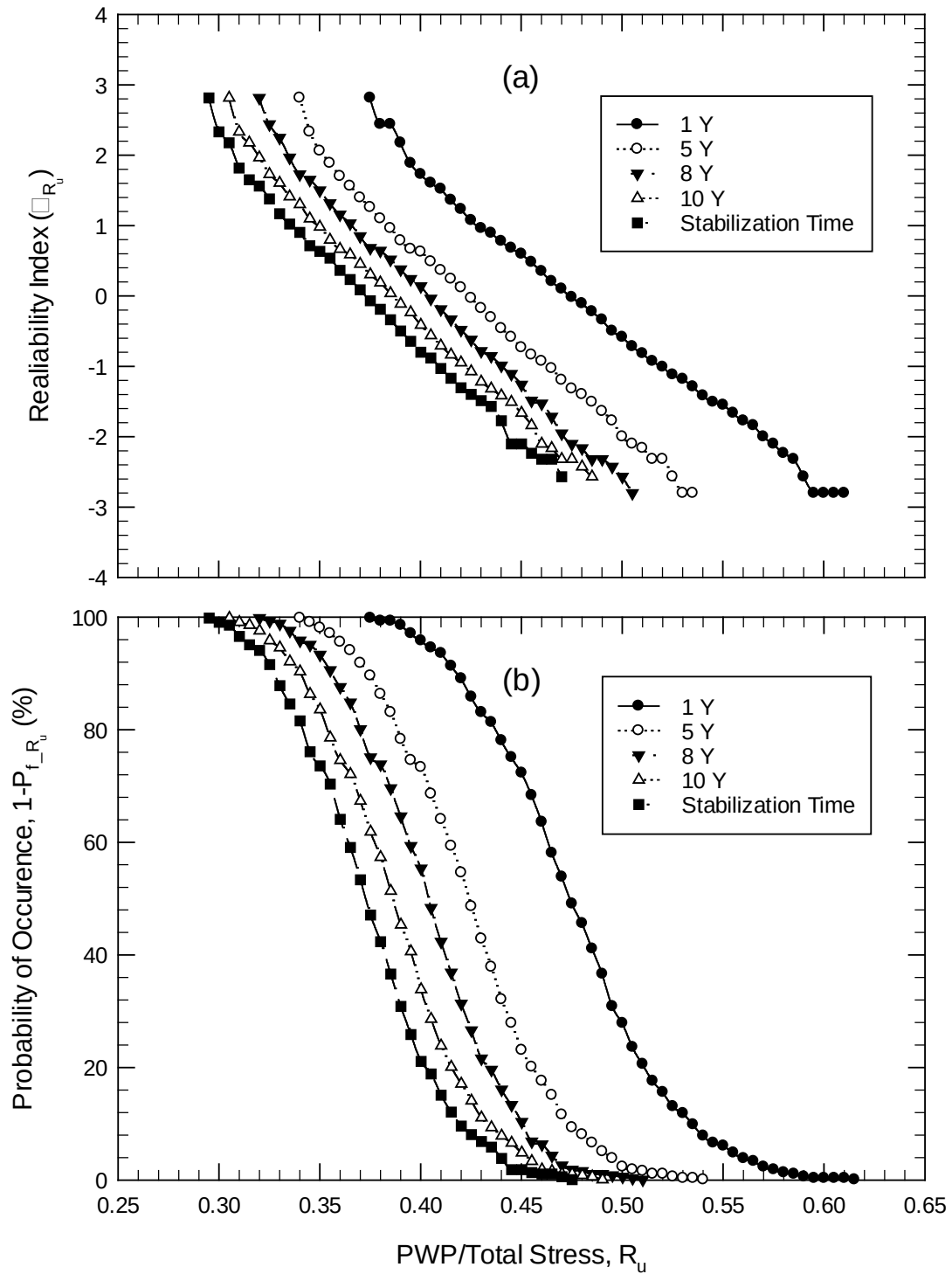


Fig. 3. Variation of (a) reliability index vs. the ratio of pore-water pressure to total stress (R_u), and (b) probability of occurrence vs. ratio of pore water pressure to total stress (R_u), at the deep horizontal trench locations, for different leachate injection durations

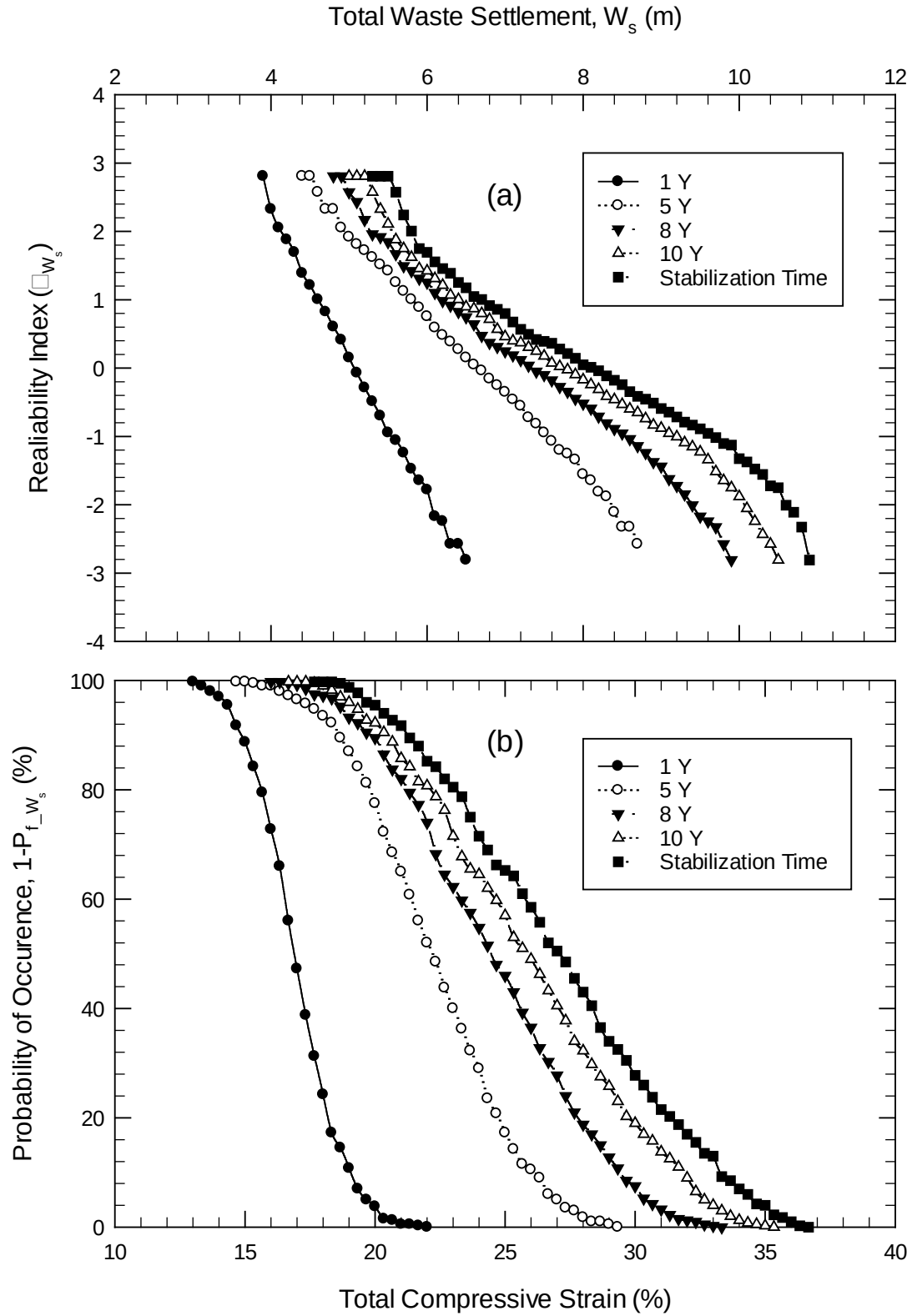


Fig. 4. Variation of (a) reliability index vs. total waste settlement (W_s), and (b) probability of occurrence vs. total compressive strain (%), for different leachate injection durations

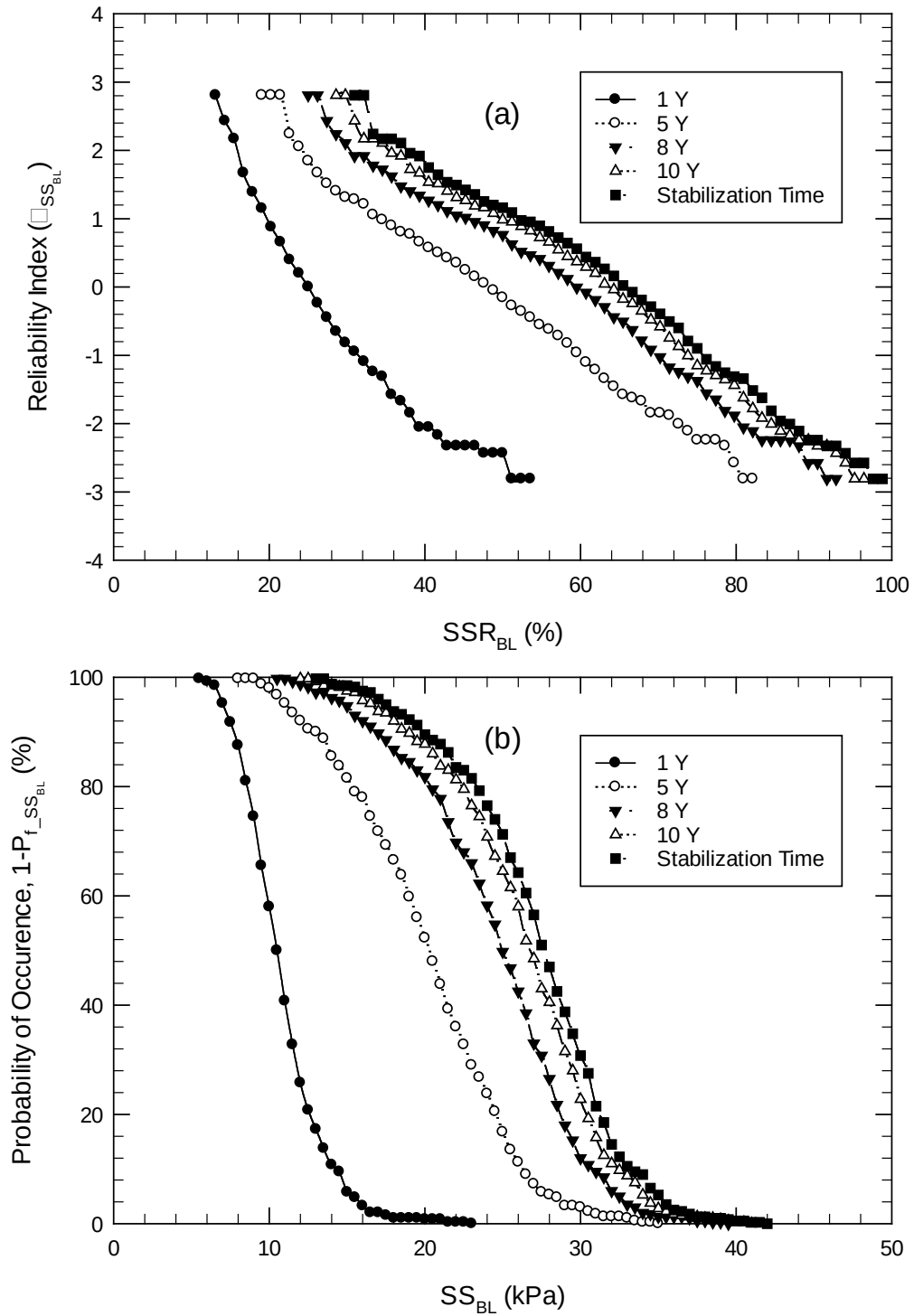


Fig. 5. Variation of (a) reliability index vs. shear stress ratio for the bottom liner interface (SSR_{BL}), and (b) probability of occurrence vs. the induced interface shear stress for the bottom liner interface (SS_{BL}), for different leachate injection durations

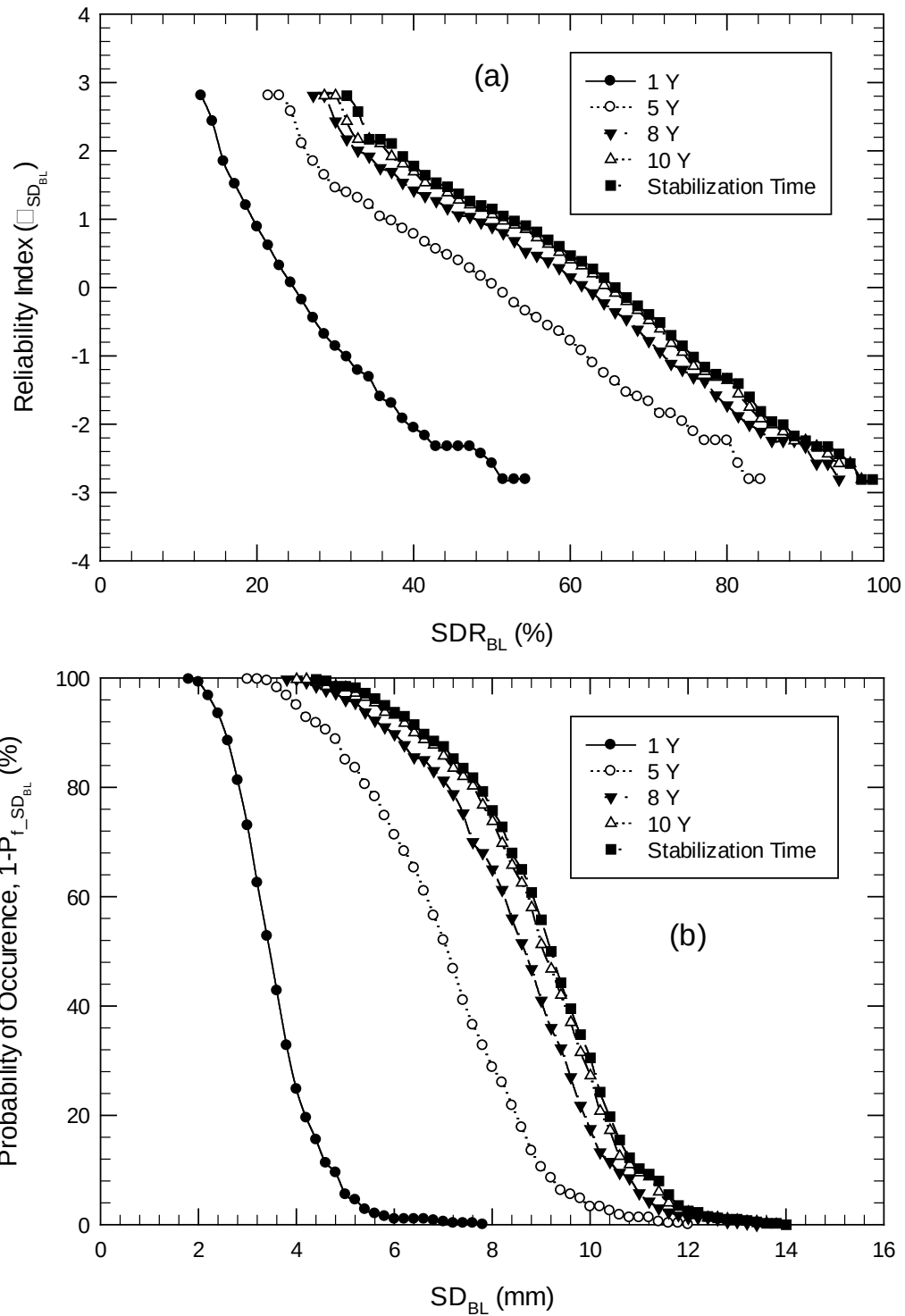


Fig. 6. Variation of (a) reliability index vs. shear displacement ratio for the bottom liner interface (SDR_{BL}), and (b) probability of occurrence vs. the interface shear displacement along the bottom liner (SD_{BL}), for different leachate injection durations

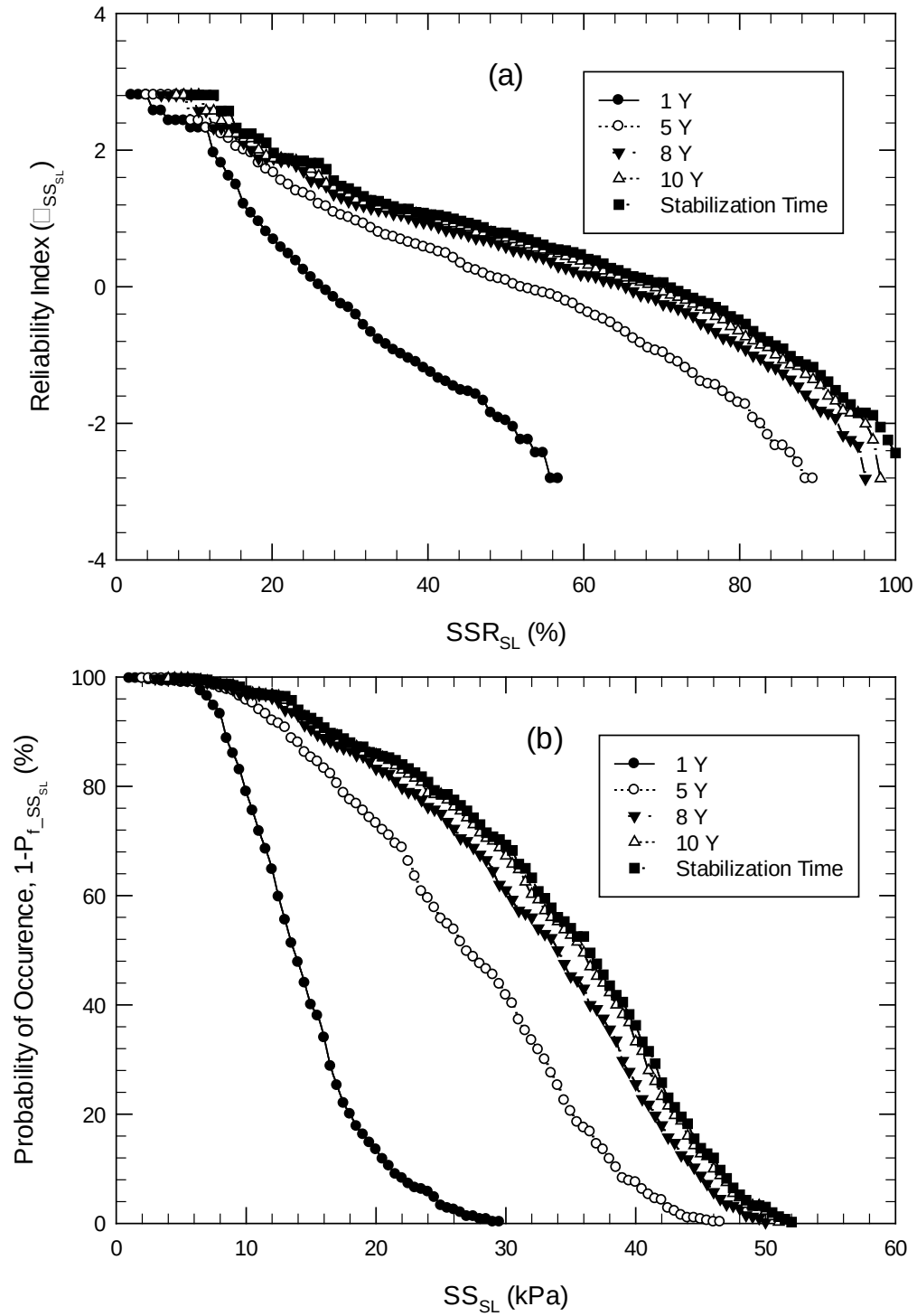


Fig. 7. Variation of (a) reliability index vs. shear stress ratio for the side slope liner interface (SSR_{SL}), and (b) probability of occurrence vs. the induced interface shear stress for the side slope liner interface (SS_{SL}), for different leachate injection durations

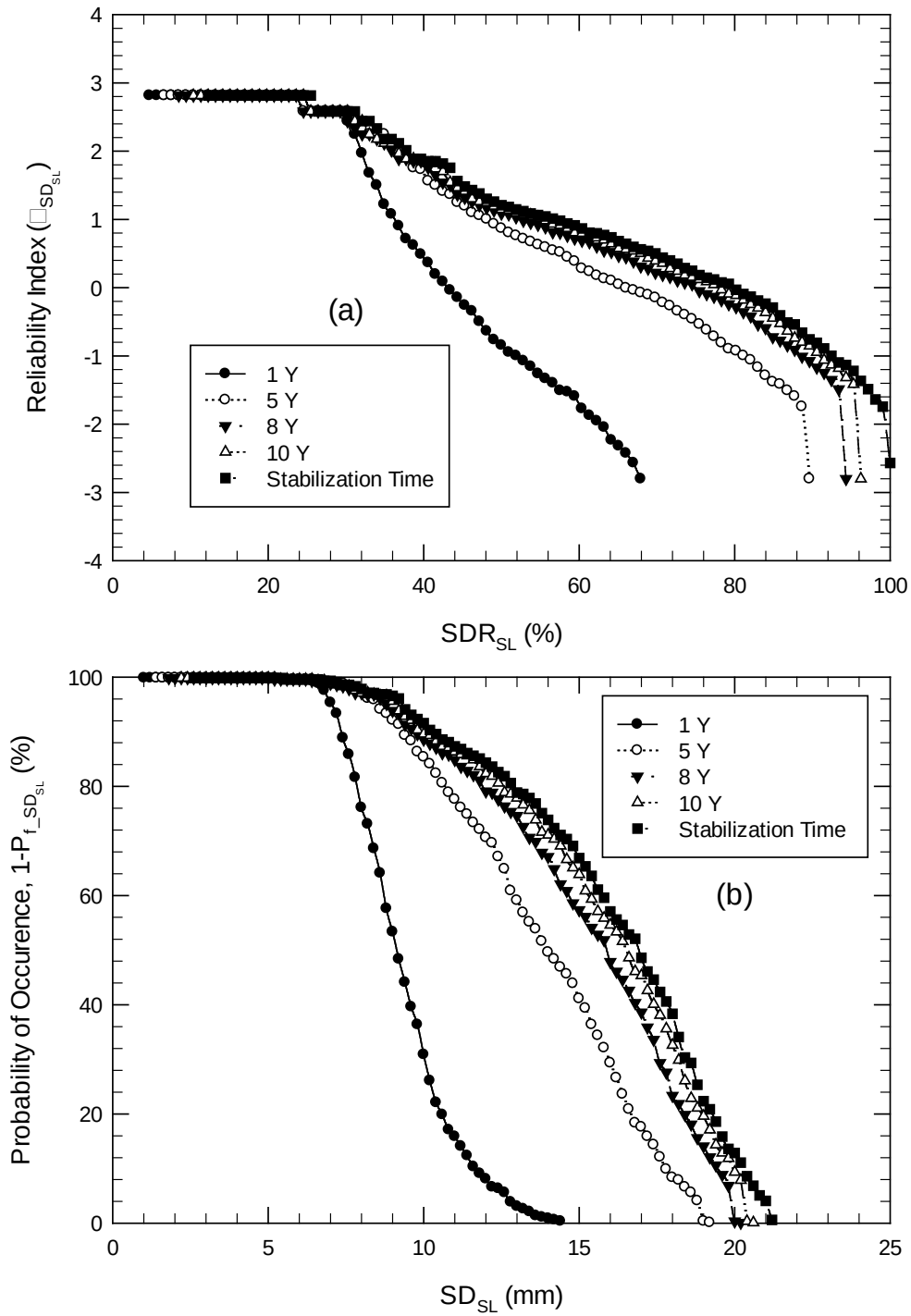


Fig. 8. Variation of (a) reliability index vs. shear displacement ratio for the side slope liner interface (SDR_{SL}), and (b) probability of occurrence vs. the induced shear displacement along the side slope liner (SD_{SL}), for different leachate injection durations

SUPPLEMENTAL INFORMATION

Table S1. Material properties for landfill liners and final cover systems

Properties	Native Soil	Compacted Clay	Drainage Layer	Vegetative Soil	Interface between smooth HDPE geomembrane and non-woven Geotextile
Density (kg/m ³)	2100	2030	1835	1835	-
Cohesion (kPa)	80	48	0	72	2*
Friction Angle (Deg)	0	0	32	0	14*
Bulk Modulus (Pa)	2 x 10 ⁸	1 x 10 ⁸	3 x 10 ⁸	9 x 10 ⁷	-
Shear Modulus (Pa)	1 x 10 ⁸	6 x 10 ⁷	2 x 10 ⁸	6 x 10 ^{7†}	-
Total Porosity (%)	43.7	41.3	45.7	43.7‡	-
Normal Stiffness (Pa)	-	-	-	-	3 x 10 ^{7§}
Shear Stiffness (Pa)	-	-	-	-	3 x 10 ^{6§}

*Wasti and Özdüzgün (2001)

†Reddy et al. (1999)

‡HELP Manual USEPA (1994)

§Jones and Dixon (2005); Sia and Dixon (2012)

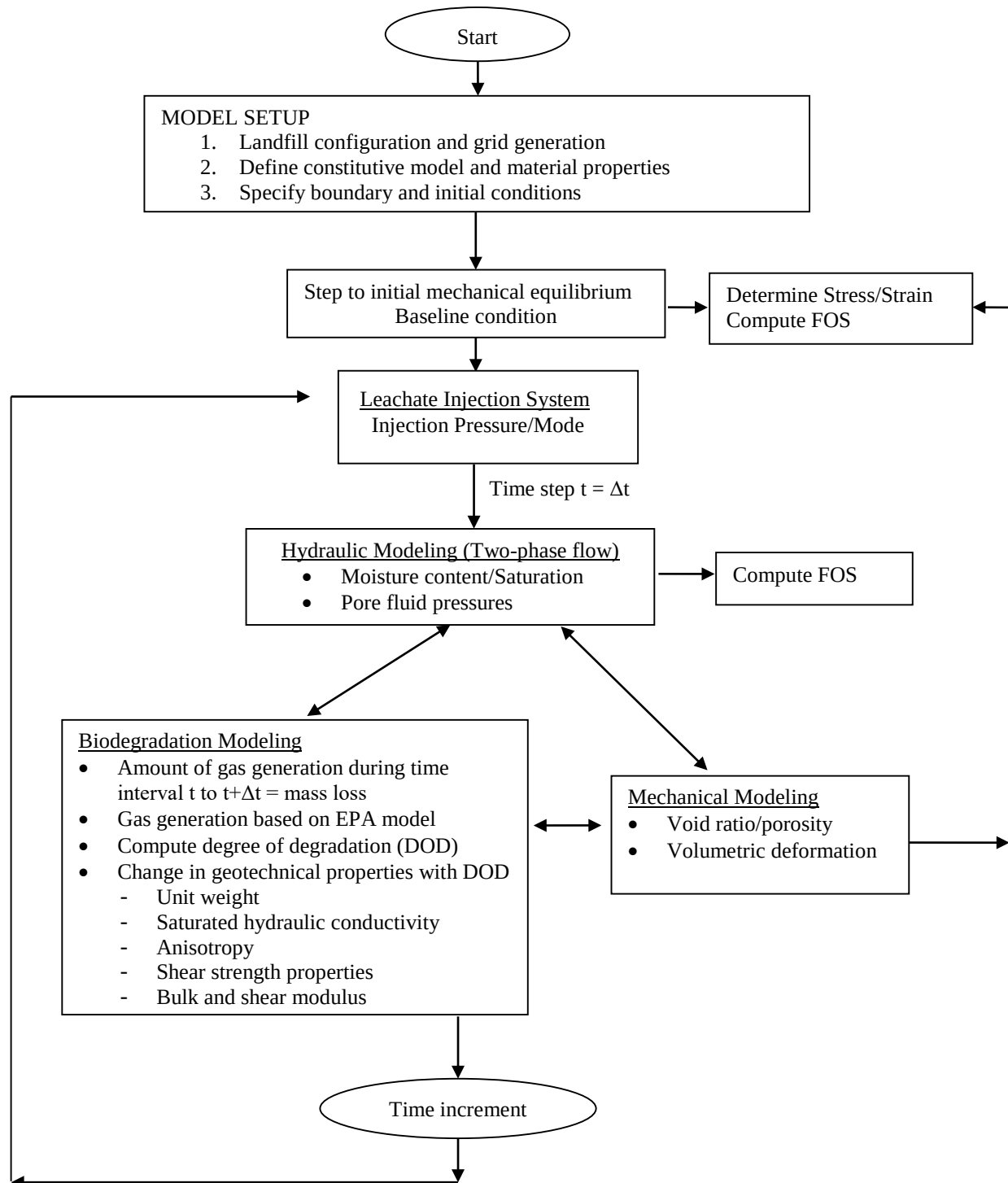


Fig. S1. Coupled hydro-bio-mechanical modeling framework

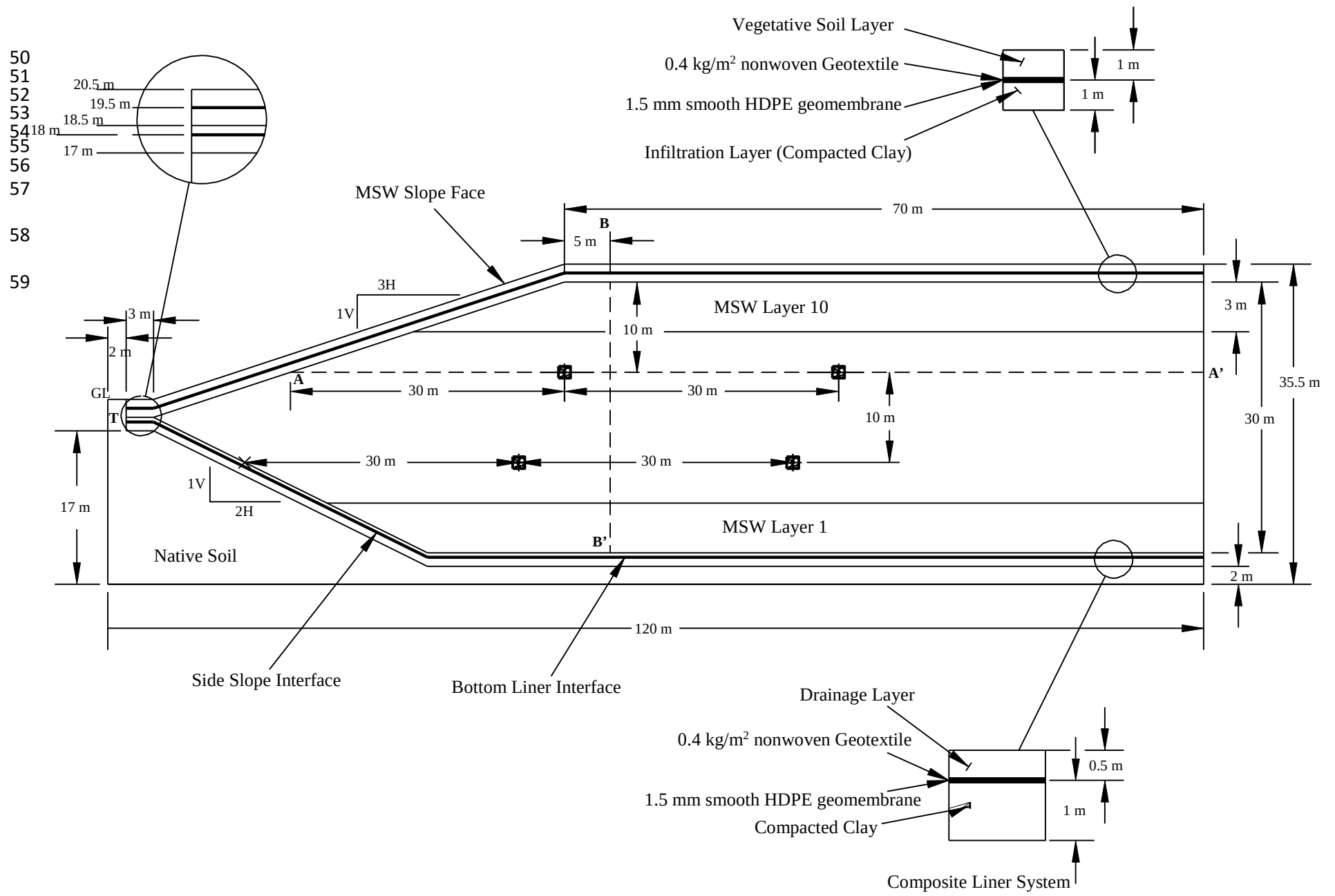


Fig. S2. Typical bioreactor landfill configuration along with its various components selected for numerical simulations

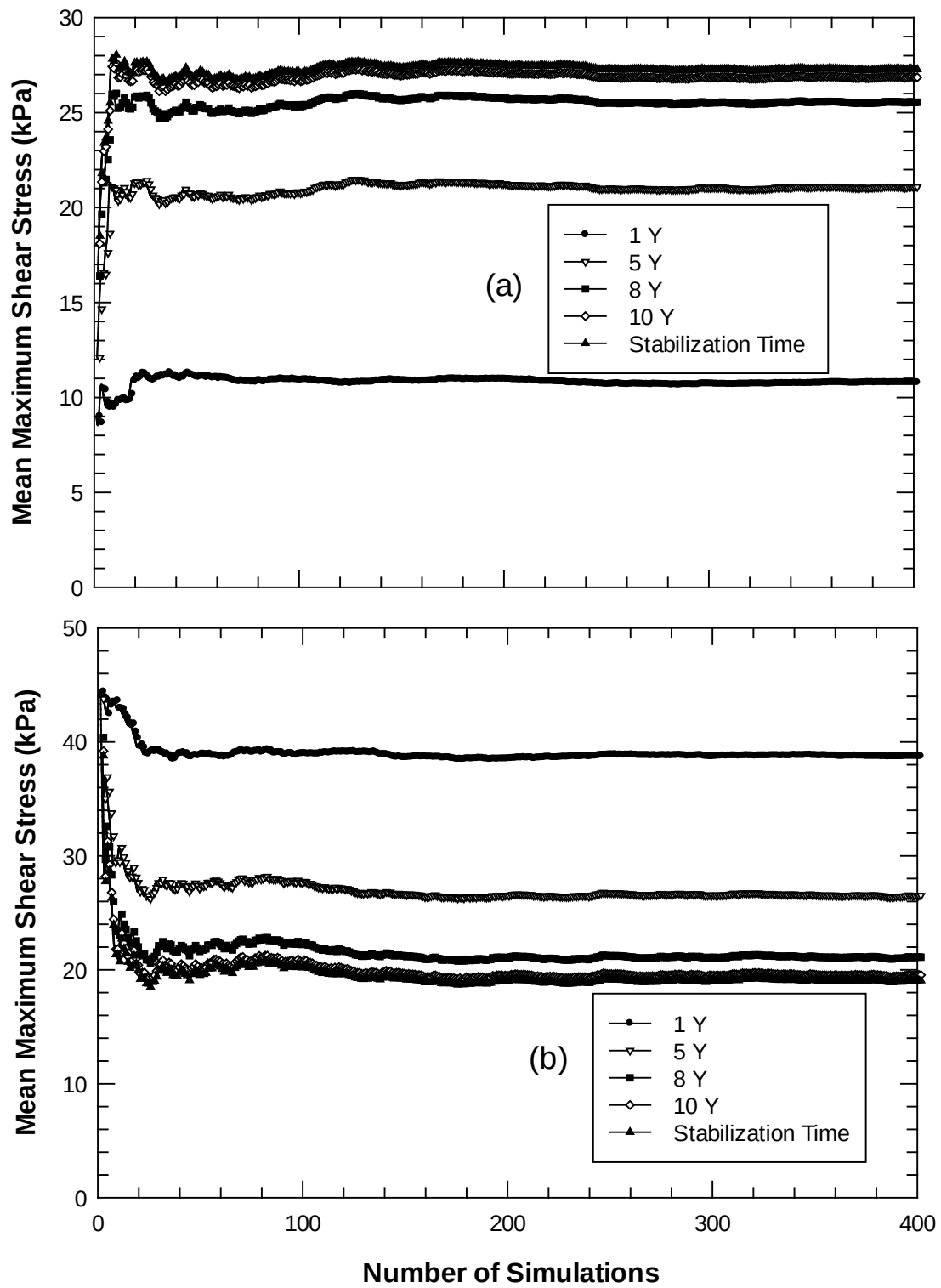


Fig. S3. Monte Carlo simulations for mean maximum interface shear stress in (a) bottom liner interface (b) side slope liner interface, for different leachate injection durations

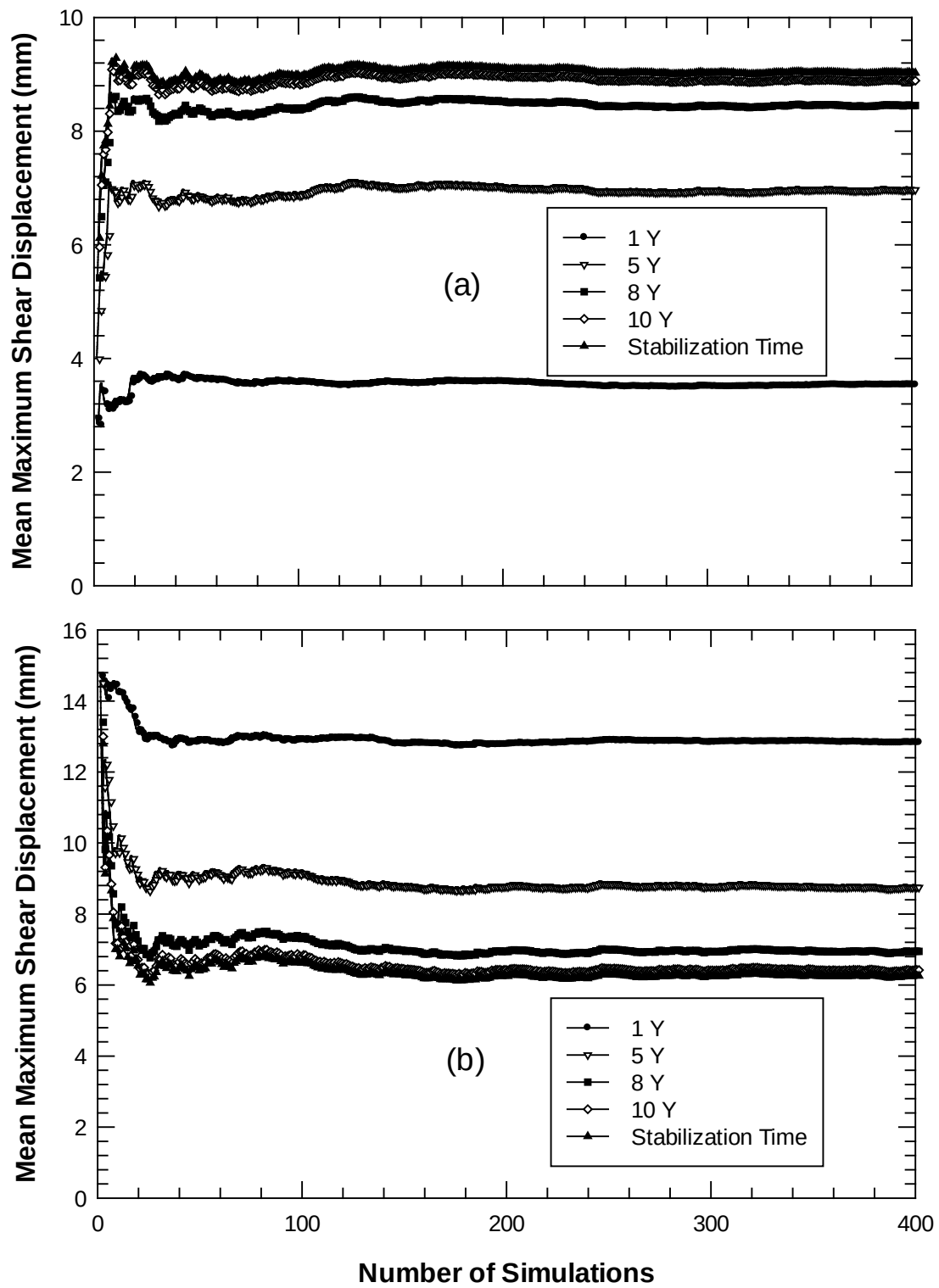


Fig. S4. Monte Carlo simulations for mean maximum interface shear displacement in (a) bottom liner interface (b) side slope liner interface, for different leachate injection durations