Probabilistic Modeling of Settlement Risk at Land Disposal Facilities – 12304

Kevin C. Foye* and Te-Yang Soong*
*CTI and Associates, Inc., Wixom, Michigan 48393

ABSTRACT

The long-term reliability of land disposal facility final cover systems – and therefore the overall waste containment – depends on the distortions imposed on these systems by differential settlement/subsidence. The evaluation of differential settlement is challenging because of the heterogeneity of the waste mass (caused by inconsistent compaction, void space distribution, debris-soil mix ratio, waste material stiffness, time-dependent primary compression of the fine-grained soil matrix, long-term creep settlement of the soil matrix and the debris, etc.) at most land disposal facilities. Deterministic approaches to long-term final cover settlement prediction are not able to capture the spatial variability in the waste mass and subgrade properties which control differential settlement. An alternative, probabilistic solution is to use random fields to model the waste and subgrade properties. The modeling effort informs the design, construction, operation, and maintenance of land disposal facilities. A probabilistic method to establish design criteria for waste placement and compaction is introduced using the model.

INTRODUCTION

Landfill engineers widely recognize that the slope of final cover systems must be selected to ensure drainage and cover integrity throughout the design life of the facility, especially under the action of settlement. Accordingly, the prediction of final cover settlement is a necessary activity in assessing potential designs. Designers also recognize that differential settlements, not absolute values of settlement are the most pertinent to this problem. In particular, the creation of local depressions in final cover systems for landfills prevents them from draining properly and minimizing infiltration through the liner system [1]. Therefore, designs of these systems must be engineered to limit the negative impact of these differential settlements. Unfortunately, existing measures to predict and limit differential settlement of final covers at Department of Energy waste disposal facilities are not sufficient and better design and evaluation tools are needed [2][3][4].

Settlement of final cover systems is due to compression of both the landfill foundation and the landfill waste mass. This compression is a function of the compressibility of the materials and the loads imposed on them. Differential settlements therefore arise from differences in loading and differences in compressibility. Engineers assess differences in loading directly through consideration of the design embankment geometry and composition. In contrast, a complete assessment of differences in compressibility is impossible due to a nearly limitless number of differences in material composition, stress history, density, etc. The existence of local variations in compressibility is recognized by engineers, but is excluded mathematically from most settlement analyses. This problem is exacerbated for waste materials, which generally exhibit greater heterogeneity than soils.

Foye and Soong [5] introduced a methodology to simulate the differential settlement of waste using random fields in conjunction with a simple isolated column settlement model. In this methodology, random fields are generated to simulate the variation of subgrade compressibility. The columnar settlement model, using the random field compressibility values as input, computes the settlement at discrete points throughout the plan area of the final cover. This calculation results in a post-settlement final cover topography. The post-settlement slope between the discrete points is then calculated. Finally, the frequency of occurrence of various post-settlement slopes is counted. This process is repeated for multiple realizations of the random field in order to generate a large population of post-settlement slopes.

The simulation methodology summarized above also requires a design criteria that connects the results of the model to the quality control of waste placement in the field. Because differential settlement is caused by the spatial variability of waste compressibility, the design criteria are necessarily statistical controls on the range of physical waste properties allowed in-place.

CALCULATION METHODOLOGY

The analysis is concerned with differential settlement of final cover systems over landfills. In the development of the proposed probabilistic design evaluation technique, the following analysis methods were used to model total settlement and calculate differential settlement from this model.

Isolated column compression model

The settlement of the final cover system is computed at several discrete points throughout the final cover plan area. Foye and Soong [5] proposed an analysis methodology where the settlement at each of these discrete points is modeled as the compression of an isolated column. Fig. 1 illustrates the concept of the column compression model. For the following examples, the compressibility of each column i is modeled using an equivalent elastic modulus E, and initial column height (waste thickness) h,

$$= - h \qquad \text{(Eq. 1)}$$

The pressure applied to each column is denoted p. The resulting settlement, s, leads to a change in the post-settlement final cover elevation,

$$_{,} = \ _{,} - \qquad \text{(Eq. 2)}$$

Where e is the final cover elevation above the column – subscripts f and 0 denote final and initial elevations, respectively. The difference in the change in final elevation between columns is differential settlement. Accordingly, the post-settlement slope w_f can be computed between two adjacent columns using the following equation:

$$_{,} = \frac{\ _{,} \quad _{,}}{} \qquad \text{(Eq. 3)}$$

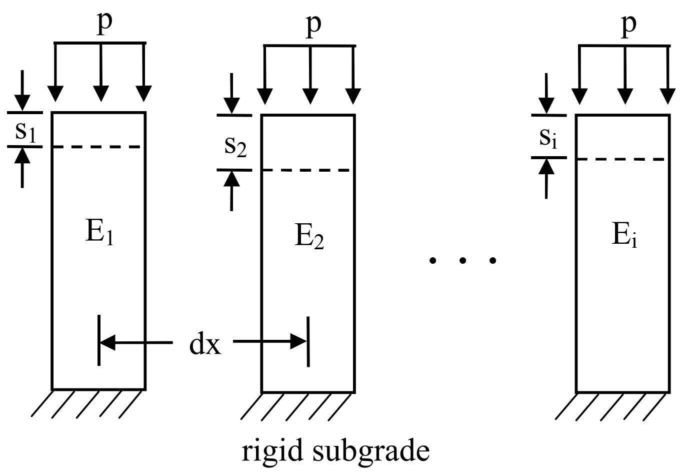


Fig. 1. Isolated column model for settlement calculation.

For waste comprised primarily of granular soils, the compressibility E of each column can be related to the relative density of the soil in-place through the following relationships. Relative density can be determined with field tests performed on granular wastes as they are being placed and compacted. Accordingly, it is a possible field quality control measure during waste placement – an important consideration that will be revisited in the design evaluation procedure outlined in the sections below.

First, following from the work of Schmertmann et al. [6][7], the equivalent elastic modulus E in Eq. 1 can be related to the cone penetration test (CPT) tip resistance q_c:

$$= 2.5 \qquad \text{(Eq. 4)}$$

Tip resistance q_c is a function of relative density and confining stress – often expressed as effective lateral earth pressure σ'_h [8]. Confining stress for a given point within the waste mass can be estimated from the waste depth and bulk unit weight. The relationship between q_c and D_R(%) can be expressed [8]:

$$— = 1.64 \quad [0.1041 \quad + (0.0264 - 0.0002 \quad) \quad] \; — \qquad \text{(Eq. 5)}$$

Where p_A is reference stress 100 kPa and ϕ_c is the critical state friction angle for the granular material (taken here for example as 30 degrees).

In the following examples, relative density D_R(%) is a random variable, uniformly distributed between an upper and a lower quality control acceptance bound. The procedure to select values of D_R(%) for each column is discussed in the random field generation section below. Following the selection of a D_R(%) value for each column, Eq. 5 and Eq. 4 are used to calculate equivalent elastic modulus E. Settlement and post-settlement slopes are calculated for each column using Eq. 1, Eq. 2, and Eq. 3. The effect of the selection of the D_R(%) quality control bounds on differential settlement and the performance of the final cover system is discussed below.

Random field generation

Because the exact distribution of relative density $D_R(\%)$ values throughout the waste mass is not known in advance of waste placement, it is necessary to simulate possible distributions to establish the $D_R(\%)$ quality control acceptance criteria. Random fields are the ideal mathematical tool to model this distribution because they enable simulation according to probabilistic rules resembling the quality control acceptance criteria and observations of spatially varying phenomena in nature.

Random fields are generated using Local Average Subdivision, following the procedure developed by Fenton [9]. In this example, random values of $D_R(\%)$ must be selected according to the uniform distribution discussed above. The first step is to generate random values according to a normal distribution that observes a spatial correlation rule. Similarly to Fenton et al. [10], the spatial correlation is modeled using the following correlation function:

$$\rho(\tau) = \exp\left(-\frac{2|\tau|}{\theta}\right) \quad \text{(Eq. 6)}$$

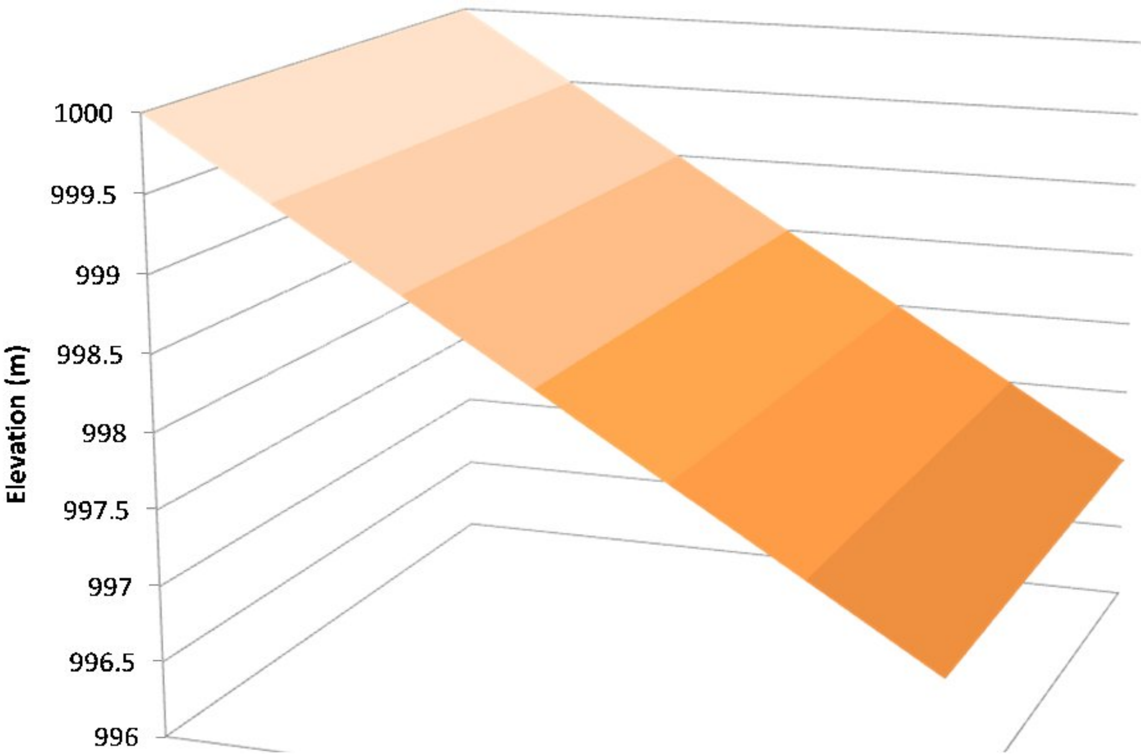
where ρ is the correlation coefficient, $|\tau|$ is the absolute distance between two points being modeled (“the lag distance”), and θ is the scale of fluctuation. Scale of fluctuation θ can be understood as the distance at which field values are no longer significantly correlated.

Considering differential settlement under a landfill’s final cover modeled with vertical columns, a 2-dimensional random field simulation is used to model the heterogeneity of $D_R(\%)$ and, hence, waste compressibility over the plan area of the landfill. Accordingly, a different value of $D_R(\%)$ is assigned to each of the model columns under the final cover in the 2-dimensional random field. Foye and Soong [5] proposed an interim technique to determine values of θ to generate random fields for the columnar settlement model. Based on this technique, $\theta/h_0 = 256$ was proposed as a viable definition for use in conjunction with the columnar settlement analyses.

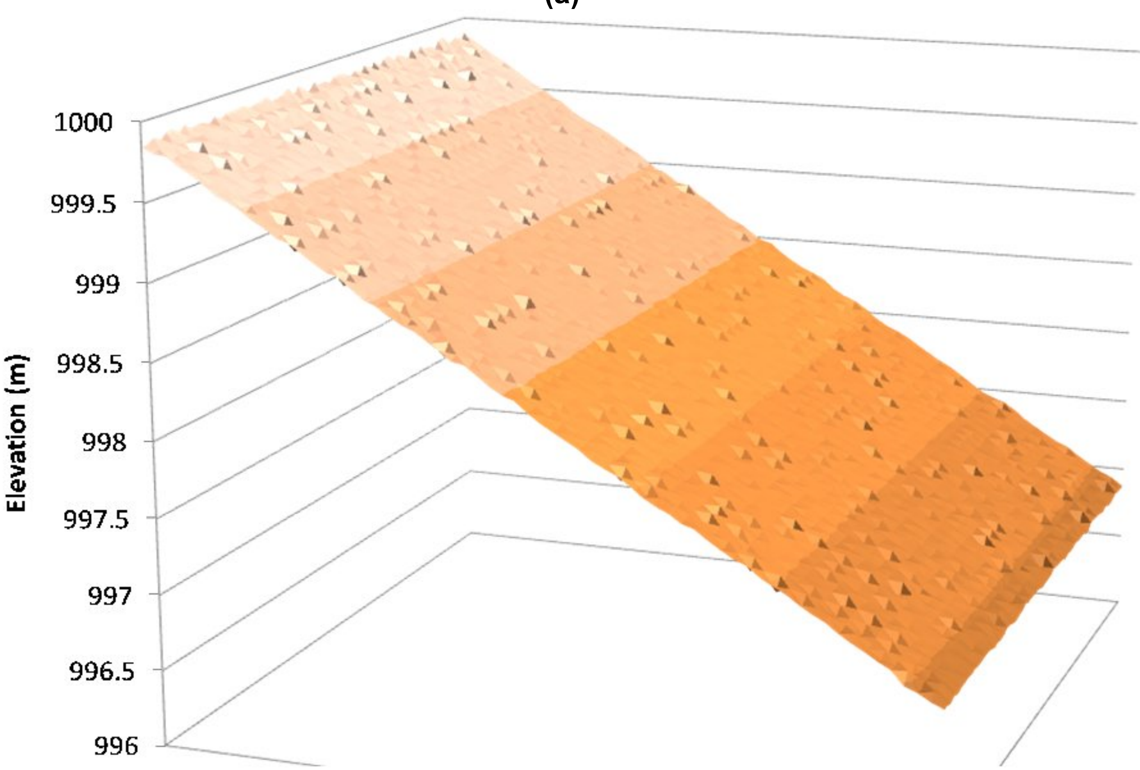
Following generation of a set of normally-distributed random values obeying the correlation function Eq. 6, these values are transformed to a uniform distribution according to its cumulative distribution function. The resulting values of $D_R(\%)$ are then used to calculate settlement, as explained above. The next section discusses how this calculation methodology can be applied to an example final cover system.

EXAMPLE FINAL COVER DESIGN EVALUATION

In this example, the random-field-based settlement calculation methodology is used to simulate several different post-settlement final cover topographies. Fig. 2(a) shows an example initial final cover topography with a design slope of 10%. Fig. 2(b) shows a resulting post-settlement elevation simulation when allowable $D_R(\%)$ values are between 50% and 100%. Fig. 3 is a histogram of the post-settlement slopes computed for the simulation depicted in Fig. 2. Using this histogram, it is possible to count the number of slope segments above or below a particular target value.



(a)



(b)

Fig. 2. Shaded View of 10% Design Slope Final Cover Surface: a) Pre-Settlement and b) Post-Settlement.

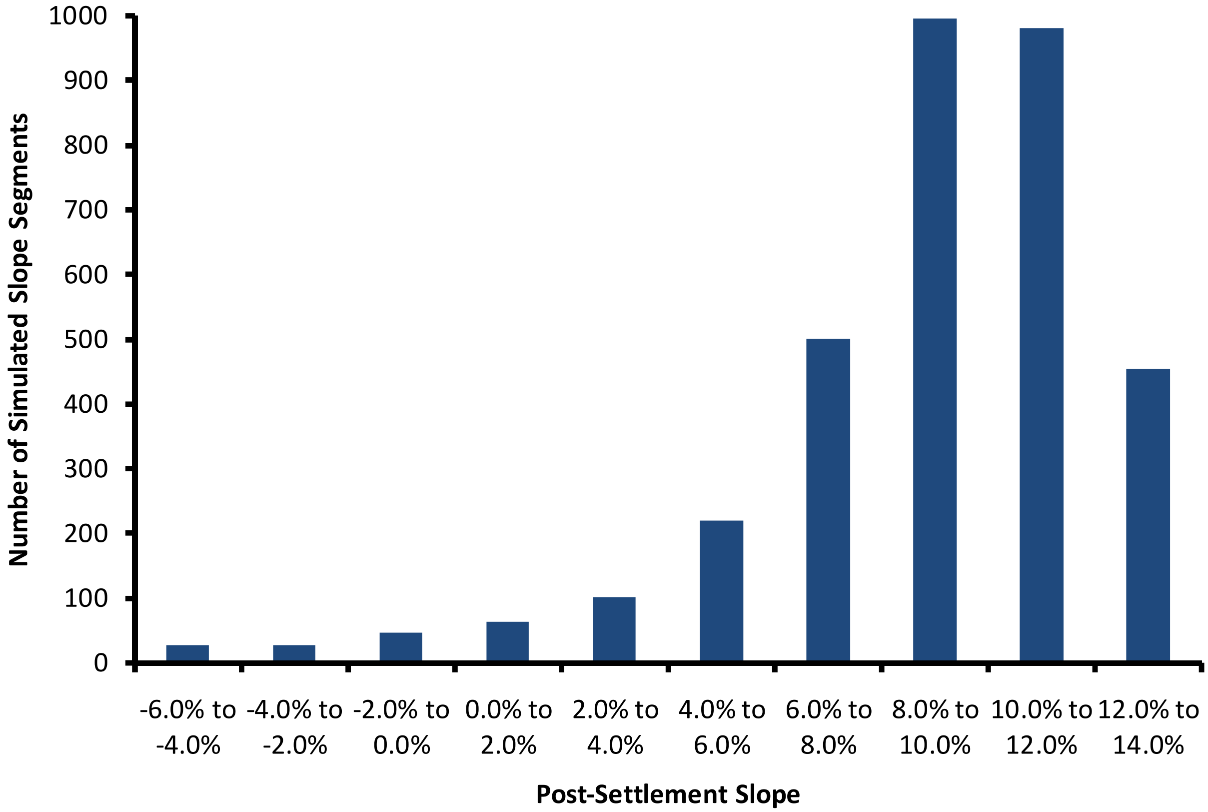


Fig. 3. Histogram of Post-Settlement Slopes for the 10% Design Slope, 50%<D_R<100% Simulation of a 30-m Deep Granular Waste Landfill.

For this example, an absolute minimum post-settlement slope value of 0% is selected, corresponding to the case of "positive drainage." Accordingly, the percentage of the final cover area exhibiting positive drainage is calculated

$$_{\%} = \frac{\quad}{\quad}\% \qquad \text{(Eq. 7)}$$

Where n is the number of segments – subscripts "w>0%" and "total" denote positive drainage and total segments, respectively. It is expected that, because probabilistic analyses supporting design consider extreme as well as common events, acceptable values of $a_{w<0\%}$ may be greater than 0%. The exact value of $a_{w<0\%}$ that is acceptable for a given design will be established from site-specific design criteria.

Following this procedure, a new set of post-settlement final cover elevations and corresponding values of $a_{w>0\%}$ are calculated for each initial design slope and for each D_R(%) acceptance criteria. A comprehensive design evaluation is therefore performed by conducting multiple simulations for many values of initial final cover slope and ranges of acceptable D_R(%) values. Fig. 4 illustrates the results of an example design evaluation using this procedure. Once an acceptable post-settlement positive drainage performance criterion is selected (i.e., maximum

$a_{w<0\%}$ value), the designer can select an optimal combination of initial design slope and achievable relative density quality control criteria for waste placement. It is expected that site-specific design evaluations, tailored to specific landfill conditions and anticipated waste types will be needed for each design.

Fig. 4 shows that as the initial design slope is increased, the proportion of the final cover that does not exhibit positive drainage decreases. Also, as the range of acceptable D_R(%) values is decreased, the proportion of the final cover that does not exhibit positive drainage also decreases. If a probabilistic design criteria of minimum 98% area exhibiting positive drainage ($a_{w<0\%}$ = 2%) is selected, acceptable D_R(%) ranges vary from 22% to 82% for initial design slopes between 5% and 25%. The specific combination of design slope and D_R(%) acceptance criterion depends on site-specific economics as well as other design constraints on landfill geometry.

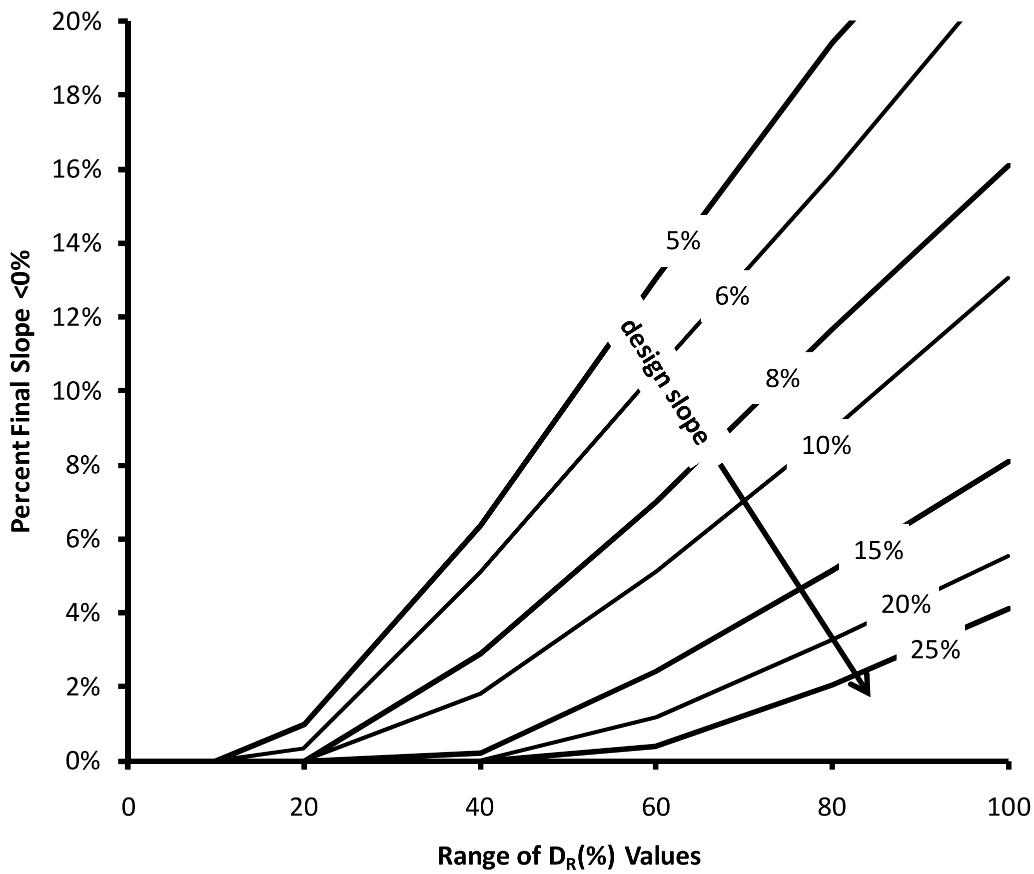


Fig 4. Example design evaluation – a plot of post-settlement slope area not exhibiting positive drainage versus varying initial design slopes and relative density acceptance criteria.

CONCLUSION

Random fields are ideally suited to problems of differential settlement modeling of highly heterogeneous foundations, such as waste. Random fields model the seemingly random spatial distribution of a design parameter, such as compressibility. When used for design, the use of these models prompts the need for probabilistic design criteria. It also allows for a statistical approach to waste placement acceptance criteria.

An example design evaluation was performed, illustrating the use of the probabilistic differential settlement simulation methodology to assemble a design guidance chart. The purpose of this design evaluation is to enable the designer to select optimal initial combinations of design slopes and quality control acceptance criteria that yield an acceptable proportion of post-settlement slopes meeting some design minimum. For this specific example, relative density, which can be determined through field measurements, was selected as the field quality control parameter for waste placement.

This technique can be extended to include a rigorous performance-based methodology using other parameters (void space criteria, debris-soil mix ratio, pre-loading, etc.). As shown in this example, each parameter range, or sets of parameter ranges can be selected such that they can result in an acceptable, long-term differential settlement according to the probabilistic model. The methodology can also be used to re-evaluate the long-term differential settlement behavior at closed land disposal facilities to identify, if any, problematic facilities so that remedial action (e.g., reinforcement of upper and intermediate waste layers) can be implemented.

Considering the inherent spatial variability in waste and earth materials and the need for engineers to apply sound quantitative practices to engineering analysis, it is important to apply the available probabilistic techniques to problems of differential settlement. One such method to implement probability-based differential settlement analyses for the design of landfill final covers has been presented. The design evaluation technique presented is one tool to bridge the gap from deterministic practice to probabilistic practice.

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