# Influence of Soil Spatial Variability on Embankment Deformation Reliability Analysis Using the Random Finite Element Method

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**Abstract.** When dealing with practical engineering problems, the uncertainties associated with soil are a major limiting factor in terms of defining the subsurface characterization and the input parameters used for design considerations in computational analysis. These uncertainties are mostly associated with the fact that soil is a natural material, formed by different geological processes that entail inherent variability. The increasing use of CPTu for site investigations allows geotechnical engineers to obtain reliable data to describe the spatial variability of soil. In this study, a geotechnical engineering situation is presented, in which the deformation of an embankment section is analyzed. On-site investigations are provided by CPT profile data, which are used to estimate soil parameters using well-known correlations from the literature. The inherent spatial variabilities in soil geotechnical properties along the profile are described using the decomposition method by a smoothly varying trend function and residuals components. Then, the random finite element method (RFEM) is applied to compare the results with homogeneous layer probabilistic analysis. The results obtained show that consideration of spatial variability can lead to almost identical average displacement values compared to homogeneous layer probabilistic analysis, but with tighter distribution of the findings.

**Keywords:** Soil Spatial Variability, Random Finite Element Method, Embankment Deformation.

## 1 Introduction

Variability analysis importance is increasingly being recognized by geotechnical engineers as reliability-based methods of varying degrees of sophistication, contributing for the improvement of design codes world-wide (Uzielli et al. [1]). As a natural material formed by geological process soil parameters vary along the tri-dimensional space, which is the source of great uncertainty to stress-strain behavior affecting stability evaluation. Most design codes such as Eurocode, Canadian Foundation Engineering Manual (CFEM), British Standards (BS), Japanese Geotechnical Society (JGS) Recommendations, incorporate soil deformation criteria to ensure structures and foundation performance.

Stress-Strain components can be calculated by finite element method computer programs, that in most cases allows users to input soil as a material composed by homogeneous simplified layers, without considering the spatial variability. Then probabilistic analysis can be performed varying homogeneous soil parameters according to a mean and standard deviation obtained by the site investigations results. The main output of a probabilistic analysis is a probability of failure, that can be calculated by the number of failures obtained (Ziesmann [2]). It can be interpreted as the relative frequency of an event or a degree of belief (Phoon [3]).

To incorporate soil spatial variability to Finite Element Method (FEM), Fenton and Griffiths [4] proposed the Random Finite Element Method (RFEM), which considers the material's variability through Local Average Subdivision (LAS) (Fenton and Vanmarcke [5]). According to Jha and Ching [6], RFEM is capable of capturing the effect of soil spatial variability well, and is able to simulate complex failure mechanisms.

This paper presents a comparison between a probabilistic analysis performed in a road embankment of the South Brazilian highway BR-470, which is over a soft clayey soil foundation, considering both homogeneous soil layer and a spatial characterized soil layer, in order to understand the impact of that consideration in the section deformation results and reliability based-design. The soil profile is characterized by site investigations using Cone Penetration Tests (CPT). However, CPT is not sensible enough for obtaining clayey soil deformation parameters (Schnaid and Odebrecht [7]), it provides ideal data for assessing inherent soil variability because a large volume of near-continuous data can be collected in a cost-effective way (Uzielli et al. [1]).

# 2 Probabilistic Approach

## 2.1 Probabilistic Analysis

Probabilistic analysis applied to geotechnical context is frequently used to determine the probability of failure of a certain section, by incorporating the soil parameters characteristic variation to the numerical analysis and computing the results for each random parameter try. In the context of Finite Element method, the failure is associated to a concentrated shear strain zone (Matsui and San [8]), or high slope deformations. The Finite Element Method (FEM) can be used in combination with the Point Estimate Method, Monte Carlo simulation and the Random Finite Element Method (Dyson and Tolooiyan [9]), in order to access reliability-based conclusions.

The calculation of the probability of reaching a certain outcome is a powerful tool, because it can help in risk assessment in the context of soil engineering, since the parameters affecting the outcome are properly obtained and characterized.

## 2.2 Random Field Characterization

To guarantee the analysis maintains a good level of accuracy, soil spatial variability should be properly characterized regarding the natural in situ conditions. It is more common to characterize the soil spatial variability in the vertical direction, primarily because vertical profiles provide valuable insights about the subsurface characteristics as soil layers are penetrated, offering information about several different depths. In counterpart, horizontal spatial variability implies in more complex and resource intensive survey, because it requires extensive soil samplings along the area being studied.

To incorporate those variations as inputs to numerical calculation model, a mathematical approach is needed. One of the alternatives is to use the decomposition method (Campello et al. [10]), where the 'real' value of a geotechnical property in a specific direction $\xi(z)$ is decomposed into a smoothly varying trend function $t(z)$ and a fluctuation component $w(z)$ representing the inherent soil variability (Uzielli et al. [1]):

$$\xi(z) = t(z) + w(z)$$

The fluctuation component $w(z)$ is associated to statistical properties such as mean $\mu$, standard deviation $\sigma$, and correlation length $\theta$. According to Alamanis and Dakoulas [11], various algorithms have been proposed to produce random fields corresponding to different levels of accuracy, being the most important among them Moving Average, Fast Fourier Transform, Turning-Bands method and Local Average Subdivision (LAS) method. In this work LAS, proposed by Fenton and Vanmarcke [5] is used. LAS can create soil random fields with the fluctuation component associated to the statistical properties mentioned above, in a particular way that in random field local subdivisions, the global parameters average is preserved.

# 3 Materials and Methods

This study aimed to evaluate the effect of the variability of the foundation soil on the deformations of an embankment. Two methodologies for implementing variability were compared, referred to in this paper as homogeneous fields and random fields. In the analysis considering homogenous material (homogenous fields) a set of Monte Carlo simulations are performed using in each simulation a unique value of the considered soil parameter, while in the random field the parameter also varies according location.

The procedures for implementing random fields in Abaqus was developed by Ziesmann [2] and a more detailed explanation can be found in his study. Initially, it is necessary to perform a statistical analysis of the parameter to be taken into account for random field generation. Then, the field was generated by the LAS methodology using the RFEM software by Fenton and Griffiths [4]. The random field generated in the previous step was then entered into the Abaqus software through a table considering coordinates.

### 3.1 Study Site

The embankment under study, denominated km 30+460, was part of the duplication work of the BR470 highway, between the municipalities of Navegantes and Indaial (68.6 km), in the state of Santa Catarina, Brazil. The choice of the site was based on the studies developed by Cordeiro [12] and Ziesmann [2], who initiated the analysis of the region.

The section, presented in Figure 1, is composed of two road embankments (old embankment, built in the 1970s and 1980s and the new embankment of the duplication) and a balancing berm supported on homogeneous soft soil, characterized by Cordeiro [12] and Ziesmann [2] as a very soft dark grey clay. The goal was to verify the magnitude of the deformations taking into account a quick loading due to the construction of the duplication embankment and, therefore, in an undrained condition.

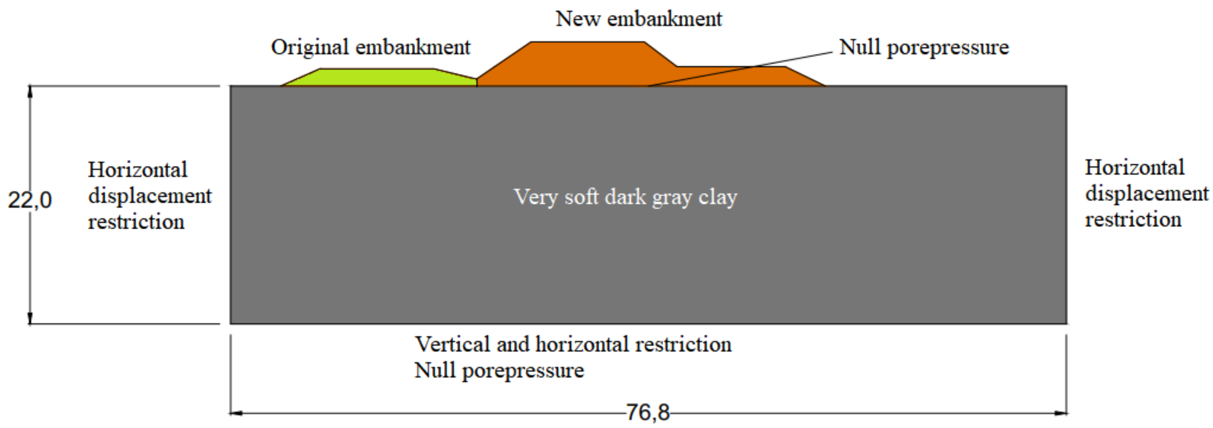



Figure 1. Section geometry and boundaries conditions (in meters) (Adapted from Ziesmann [2])

Figure 1 also shows the dimensions of the clay foundation, with a thickness of 22.0 m and a cross-sectional length of 76.8 m. There are also indications of the boundary conditions considered in the model, with restriction of horizontal displacement on the sides, since it is a bidimensional model, and restriction of horizontal and vertical displacement in the bottom region.

Table 1 identifies the values assigned to the embankment and foundation soil properties and are referenced to Cordeiro [12] and Ziesmann [2]. The Mohr-Coulomb failure criterion was used for both the embankment and the foundation. Although a Cam Clay type of model is more appropriate for modeling soft soil deformations, the Mohr Coulomb model was considered in the present work as an extension of the analysis performed by Ziesmann [2] which evaluated the variability of the undrained strength (Su), resolution is a probability of failure of 0.54%. The modeling was performed with a 4-node quadratic mesh with bilinear deformation and pore pressure (CPE4P). A structured mesh was applied for the soft clay foundation and a free mesh for the embankment. The dimensions of the quadratic element used in the simulations was about 1.0 m x 1.0 m.

Table 1. FEM input values

| Parameter | Embankment | Foundation | Unit |
|---|---|---|---|
| Specific Weight | 20 | 16 | kN/m³ |
| Friction Angle | 35 | 0 | ° |
| Cohesion | 5 | 26 | kPa |
| Young's Modulus | 25 | Random or Homogeneous Field | MPa |
| Poisson's ratio | 0.3 | 0.45 | - |

### 3.2 Variability Analysis

The variability analysis of the foundation soil of this embankment was performed by Ziesmann [2] and the main points are presented in the sequence. The piezocone test was used as representative for the analysis of variability in depth, given the number of readings per vertical profile; it was considered that there were no reading or equipment errors and that the variability coming from the test readings reflects the inherent variability of the material; and it was sought to characterize the variability of the basic readings in order not to introduce model errors and or transformation.

First, the adherence between the histogram of the readings and probability density functions was analyzed. Figure 2a shows the histogram of qt and Figure 2b the Q-Q graph, whose theoretical distribution that proved to be more adherent was the lognormal.

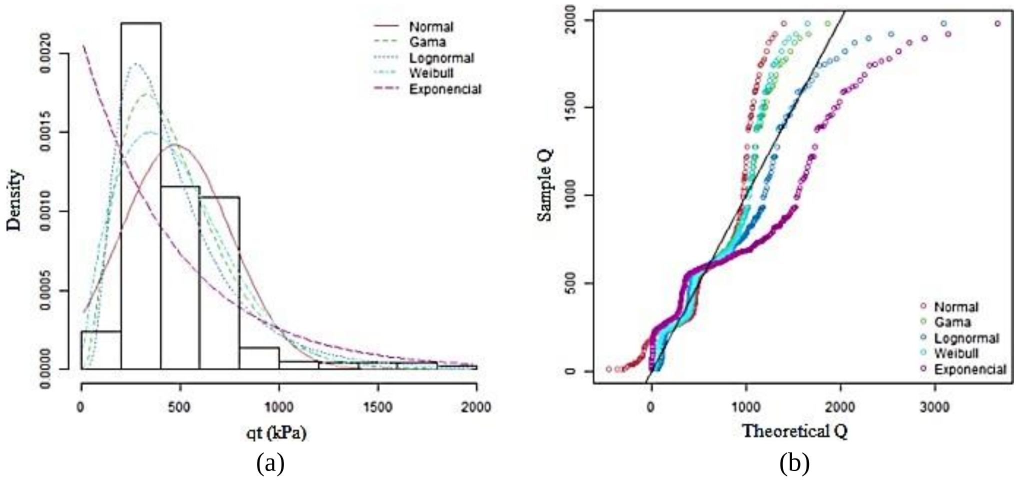



Figure 2. Theoretical distribution adjustments (a) Histogram and (b) Q-Q Graph (Adapted from Ziesmann [2])

The vertical fluctuation scale adopted was 0.34 m, obtained through Vanmarcke's Expedited Method for qt readings. The horizontal fluctuation scale used to generate the random field was equal to 10.0 m.

Through the field and laboratory tests, Cordeiro [12] and Ziesmann [2] found the average value of parameter E for the soft soil layer as 1300 kPa, with no account for the evolution of stiffness with depth. Assuming that the covariance obtained by Ziesmann [2] for the Su parameter (0.072) also applies to the E parameter, the standard deviation used in this research was 93.6 kPa.

## 4 Results and discussions

It was decided to use 5000 simulations to evaluate the effect of parameter E on the displacements of the embankment, a number higher than the 1000 that is recommended in the literature (Wang et al. [13]; Griffiths; Huang; Fenton [14]). Considering that there are no cases of failure when considering the variability of E, the probability of failure was not affected by the variation of this parameter. In this sense, the analyzes that follow were focused on determining the distribution of vertical and horizontal displacements at points of interest on the landfill.

Maximum displacements (Figure 3) stabilized around 595 mm for the analyses using random fields and 596 mm for the homogeneous field. It is observed that this value was reached around the 1500 simulation, which demonstrates the need for simulations beyond the minimum presented by the literature.

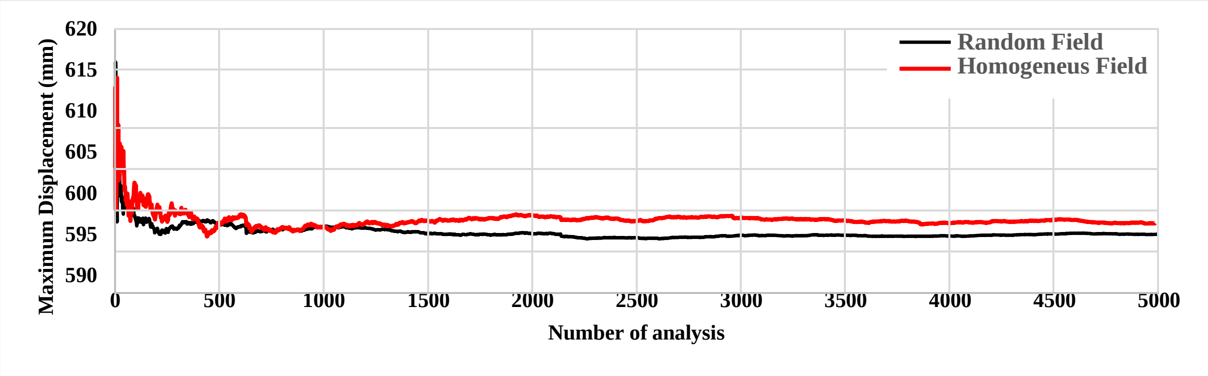
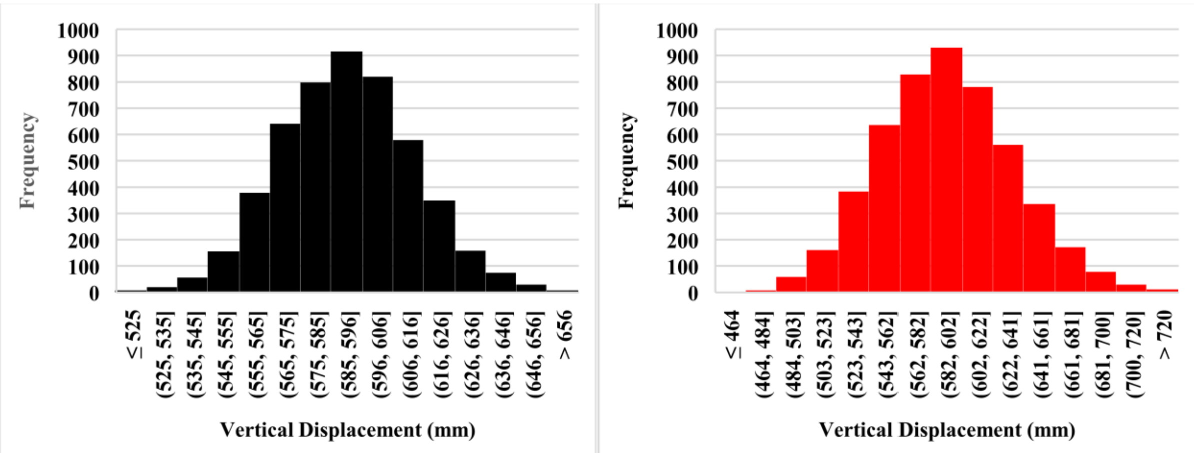



Figure 3. Maximum displacements convergence

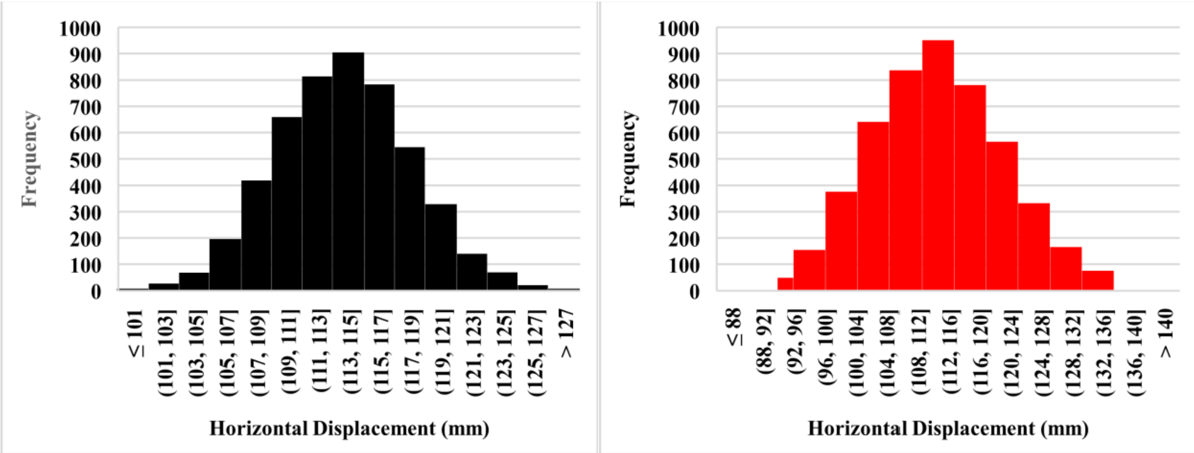
Figures 4 to 7 present the histograms of the displacements in the embankment, both for random and homogeneous fields, obtained for the 5,000 simulations. Figures 4a and 4b present the distribution of vertical displacements at the top of the embankment, while Figures 5a and 5b show the horizontal displacements at the toe of the embankment. In addition, Figures 6a and 6b present the vertical displacements at the intermediate embankment and Figures 7a and 7b the horizontal displacements in the same region.




(a) (b)

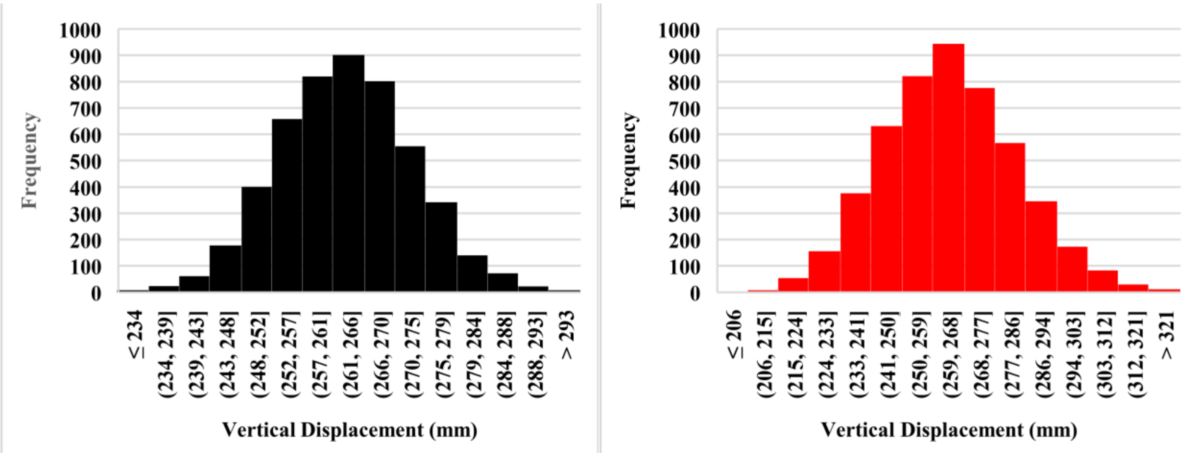
Figure 4. Embankment top vertical displacements: (a) Random Field and (b) Homogeneous Field

In all the analyses, the average values remained almost constant between the two types of fields, but with greater dispersion in the results for the homogeneous field. The average value of the vertical displacement of the top of the embankment was 590 mm for the random field analysis and 592 mm for the homogeneous layer. The horizontal displacement at the foot of the embankment was 114 mm in both analyses. In the intermediate embankment, on the other hand, the average values were close to half of the overall analysis, with 263 mm of vertical displacement and 55 mm of horizontal displacement for the random field analysis and 264 mm and 55 mm, respectively, for the homogeneous layer analysis. Covariance was used as a measure of the dispersion of the results, and values between 0.037 and 0.039 were found for the random field model, while for the homogeneous layer model the range obtained was 0.072 to 0.075.



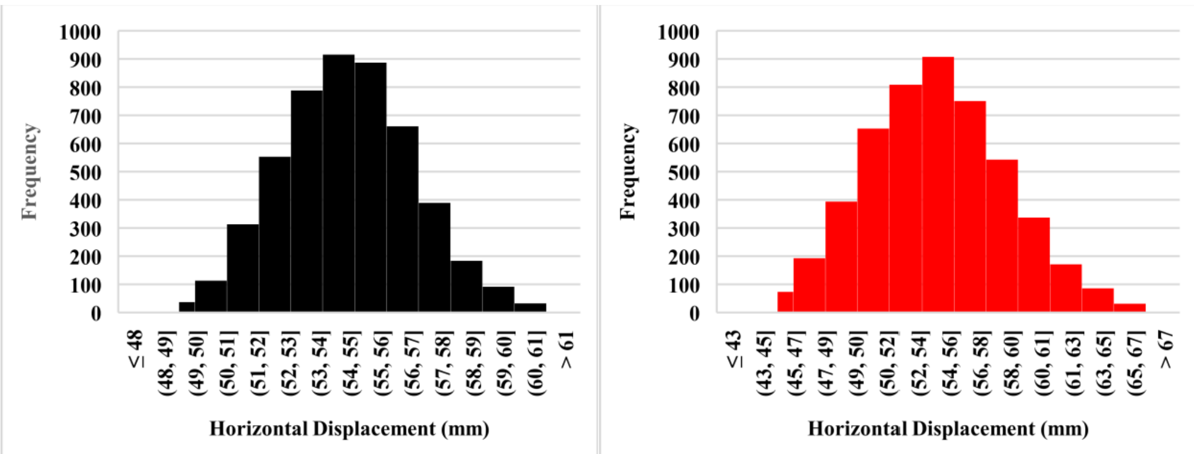

(a) (b)

Figure 5. Embankment foot horizontal displacements: (a) Random Field and (b) Homogeneous Field




(a) (b)

Figure 6. Intermediate embankment vertical displacements: (a) Random Field and (b) Homogeneous Field




(a) (b)

Figure 7. Intermediate embankment horizontal displacements: (a) Random Field and (b) Homogeneous Field

# 5 Conclusions

In this article, a comparison was conducted between the result distribution of probabilistic analysis for a homogeneous layer and random fields characterized layer in determining displacements in a road embankment. Soil parameters were obtained through field and laboratory tests, and a statistical analysis was performed on CPTu tests to capture the spatial variability of the material. Random fields generated using RFEM were exported to Abaqus, and the same model was processed 5000 times with different samples of Young's modulus distribution for the soil layer of the foundation. The results obtained demonstrate that accounting for spatial variability can yield displacement values that are nearly identical to those obtained from homogeneous layer probabilistic analysis, albeit with a more tightly constrained distribution of findings.

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