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► **To cite this version:**

Humberto Yáñez-Godoy, Sidi Mohammed Elachachi. Effects of Spatial Soil Heterogeneities on Structural Behavior of a Steel Sheet Pile. 12th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP12, Jul 2015, Vancouver, Canada. hal-01213425

HAL Id: hal-01213425

<https://hal.science/hal-01213425>

Submitted on 8 Oct 2015

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Effects of Spatial Soil Heterogeneities on Structural Behavior of a Steel Sheet Pile

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ABSTRACT: This article aims to introduce spatial variability effect on the behavior of extended structures as the sheet piles. The importance of these aspects can provide elements of response to experts in charge of the standards of design for these structures. Two main problems are identified, the first one is about the most appropriate way to model the variability of soil and its interaction with the sheet pile. The second one is to take into account the uncertainties and their propagation through a model. A 2-D mechanical model of the sheet pile has served to propagate the soil variability and the system-parameter uncertainties and allowed to study the response of the different structural elements of the structure. The spatial soil heterogeneities show clearly its effect on the behavior of the structure. This analysis has opened up new possibilities to advance in researches on longitudinal aspects for these structures.

1. INTRODUCTION

A large proportion of structural damages to extended structures, as sheet piles, can result from three factors:

- the partial and or the lack of knowledge of geotechnical characteristics (behavior of soil-structure interaction),
- the variability of soil (properties and mechanical characteristics),
- the non-inclusion of longitudinal dimension in standard codes and design guidelines.

In this way, for the design of sheet piles, NF EN 1997-1, (2014) considers only the cross-section for the ultimate and serviceability limit states and neglects then the effect of the redistribution of the internal strains of the structure due to longitudinal differential displacements. On the other hand, the approach considered by standards is quasi-deterministic and nonetheless incomplete. Some studies can cover these kinds of limitation and play a

practical complementary role in design situations not covered by standards (see for example Low and Phoon, (2015)). Furthermore, a probabilistic approach seems to be more suited to integrate both soil uncertainties and spatial variability (Ahmed and Soubra (2012)).

With regard to sheet piles, although several studies (e.g. Wang, (2013), Low and Phoon, (2015)) have dealt with both soil uncertainties and spatial variability by considering a combination of probabilistic approach and limit equilibrium method (method often used for a preliminary design), we note very few studies in which numerical models as finite-element methods or subgrade reaction methods take into account spatial soil variability.

Furthermore, some studies are divided on the question of taking into account the interaction soil-structure. For example, (Schweiger et al, (2001)) shows that geotechnical uncertainties not taken into account can result in undersized structures. In contrast, (Schweckendiek et al., (2007)), notes that the

effect of soil variability is negligible but it would require being associated to other factors such as corrosion. Both of these studies don't consider spatial soil variability.

In this article a first exploratory 2-D approach to introduce spatial soil variability for the sheet piles is performed. The physical model of the interaction soil-structure together with a stochastic model characterizing the variability of the soil is then developed. A 2-D mechanical finite-element model of the sheet pile serves to propagate the soil variability and the system-parameter uncertainties and allows to study the response of the different structural elements of the structure.

A variability effect analysis is then done using the direct Monte Carlo numerical simulation method in order to evaluate both a confidence interval of the bending moment along the sheet pile and a probability of exceeding a reference value. A discussion is then given on the comparison of the results obtained by considering two different scenarios: homogeneous soil (uncertain model parameters as input data are considered, this is unstructured variability) and heterogeneous soil (random fields to represent spatial variability are considered, this is structured variability).

2. STRUCTURAL COMPUTATIONAL MECHANICS OF A STEEL SHEET PILE SEAWALL

2.1. Mechanical modeling description

The example adapted from the one presented in Boéro et al. (2012) is representative of quay walls and considers a structure with U shaped piles, anchored through one level of passive tie rods. A recapitulation of the principal geometrical and nominal mechanical characteristics of the quay is shown in Figure 1. We assume here that the soil correlation along x is negligible after 20 meters and that the sheet pile can be modeled with a 2-D model. We therefore consider the stability of a sheet pile 2 meter wide, the distance between tie-rods. A load q of 50kPa is applied to the quay. The water

level of sea is equals to groundwater table. The construction phases of the quay are not taken into account. The steel (present in the main wall, the pile anchorage and the tie-rods) is assumed to behave in an isotropic and linearly elastic manner. We consider in this paper to use a mechanical finite-element model that let to take into account the interaction soil-structure by a Mohr-Coulomb model. The model (see Figure 2) has been developed within the CAST3M finite element computer code (<http://www.cast3m.cea.fr>) developed by the Atomic Energy Commission (CEA).

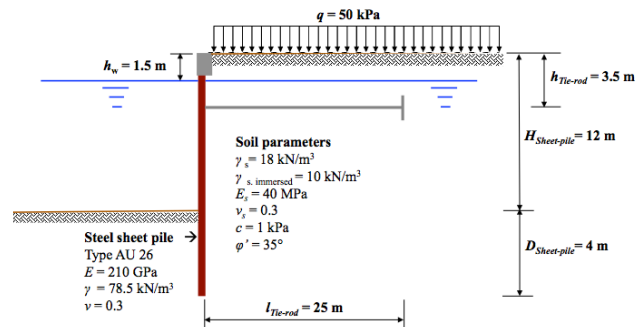


Figure 1: Geometrical and mechanical characteristics of the steel sheet pile seawall.

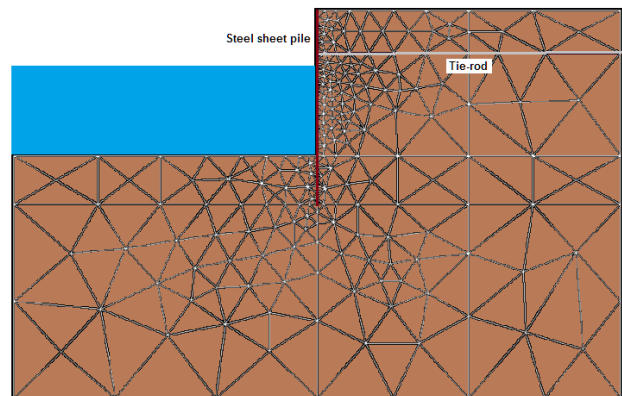


Figure 2: Finite element mesh used.

2.2. Soil-structure model

The soil (non cohesive soil type) is modeled as a homogeneous powder material in one case (see 2.3 and 4.1) and as a heterogeneous powder material by taking into account spatial variability

in a second case (see 4.2) and behaves in a perfectly elasto-plastic manner (Mohr-Coulomb criterion). The friction angle φ' is considered as a random variable for the first case and as a random field for the second case. The elements of interface, laid out around the main wall, are described by the Coulomb friction criterion. The angle of the interface is approximately equal to $2/3 \varphi'$ (this angle varies then in function of φ' value), and the contact cohesion is negligible. The resistance of the tension elements in the interface soil-sheet pile is zero, which allows for relative movement between the nodes of the various interfaces.

2.3. Deterministic computations

The deterministic computations are carried out for 3 different values of φ' : 24° , 35° and 40° . In fact, these values correspond respectively to minimum, most likely and maximum values for a sand soil (Rackwitz et al. (2006)).

First at all, in order to obtain reference values to compare to the probabilistic analysis presented in section 3, the influence of deterministic values of φ' on the wall bending moment is analyzed. Figure 3 shows the results. The lowest value of φ' (24°) makes the wall more flexible. Indeed, the maximum moment at over -10 m (this is the permanent immersion zone) is 2 times higher than bending moment for $\varphi' = 35^\circ$. The bending moment at the level of the passive tie-rods is also increased by a factor of 2.5 times in rapport to the other values.

These different situations corresponding to three nominal values are not certainly a confidence interval of the possible mechanical stress on a structure for a given problem. In fact, by knowing a priori the most likely value of the nominal value of φ' (that supposes a good knowledge of intrinsic properties of the embankment soil) we can then introduce the random nature of soil (random variables, random fields) in the mechanical model by taking into account the available information.

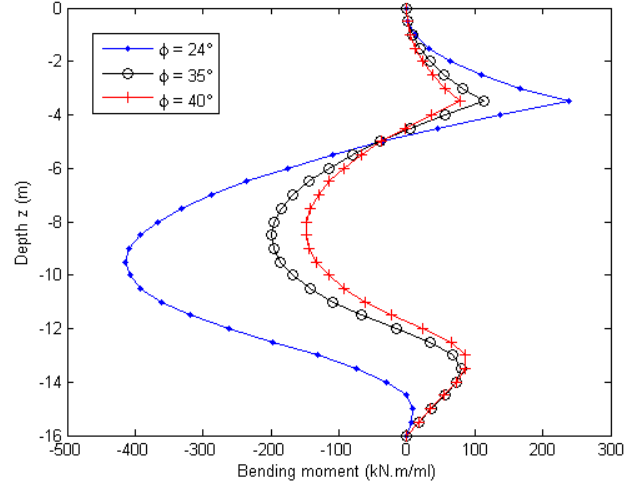


Figure 3: Bending moment in the steel sheet pile seawall.

3. MODELLING OF UNCERTAIN PARAMETERS AND SPATIAL VARIABILITY IN SHEET PILES

3.1. Uncertain model parameters

The only variable geotechnical parameter considered in the probabilistic analysis presented in this study is the friction angle φ' . In fact, this parameter is a dominant random variable as shown in Boéro et al. (2012) or Cherubini (1998).

The values considered for the mean μ and the coefficient of variation COV are respectively: $\mu_{\varphi'} = 35^\circ$ and $COV_{\varphi'} = 10\%$ (indicative minimum value for φ' , drained soil, according to Rackwitz et al. (2006)). The scenario proposed for modeling φ' is a beta probability distribution constructed under the constraints defined by the available (published) information (MaxEnt principle): $\min_{\varphi'} = 24^\circ$, $\mu_{\varphi'} = 35^\circ$ and $\max_{\varphi'} = 40^\circ$. The beta probability distribution is written as (see Desceliers et al. (2013)):

$$B_{\varphi'} = (\max_{\varphi'} - \min_{\varphi'})Z + \min_{\varphi'} \quad (1)$$

where Z is a beta random variable with values in $[0, 1]$ and with parameters a and b defined by:

$$a = \frac{m_Z^2}{\sigma_Z^2} (1 - m_Z) - m_Z \quad (2)$$

$$b = (1 - m_Z) \left(\frac{m_Z(1-m_Z)}{\sigma_Z^2} - 1 \right) \quad (3)$$

in which the mean value m_Z and the variance σ_Z^2 of random variable Z are written as $m_Z = (\mu_{\varphi'} - \min_{\varphi'}) / (\max_{\varphi'} - \min_{\varphi'})$ and $\sigma_Z = \sigma_{\varphi'} / (\max_{\varphi'} - \min_{\varphi'})$. A random sample of the beta probability distribution of φ' is shown in Figure 4.

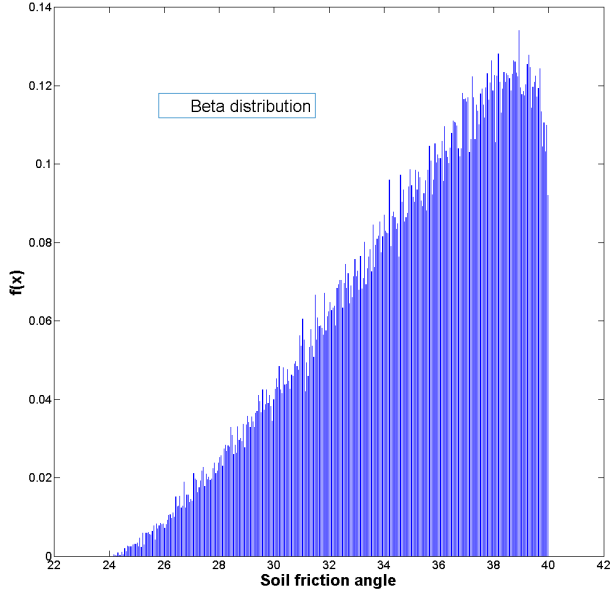


Figure 4: Probability distribution function of friction angle.

3.2. Variability of soil

In order to represent the variability of a homogeneous soil the friction angle φ' is modeled as a 1-D normal stationary random field (through the soil depth) by using the spectral approach that takes advantage of the Fast Fourier Transform technique (Yang, (1972)). This random field is characterized by its mean $\mu_{\varphi'}$, variance $\sigma_{\varphi'}^2$, and correlation function $\rho(\tau)$, where τ is the lag. A single exponential correlation function is used:

$$\rho(\tau) = \exp\left(-\frac{2\tau}{\delta}\right) \quad (4)$$

where δ is the correlation length (CL) of φ' . Concerning the fluctuation values of CL, they

depend on the soil type, the geotechnical parameter and the direction of variability (vertical or horizontal) (Phoon and Kulhawy, 1999). Concerning vertical fluctuation, it appears generally that vertical CL is around a few meters. We will also focus on higher values to study their influence on the behavior of the structure.

In order to introduce the continuous random field profile on the nodes of the finite element mesh (see Figure 2), we discretized it into N vertical elements. This approach let us to maintain continuity in the random field over the total depth z . Indeed, for M realizations of random field, the $\varphi'_{j=1}^M$ values for each vertical element is obtained by a polynomial of order l :

$$\varphi'(z_{i=1}^N)_{j=1}^M = a_{0j} + \sum_{k=1}^l a_{kj} z_i^k \quad (5)$$

An example for one realization of a continuous random field and its discretized profile by polynomial interpolation is shown in Figure 5.

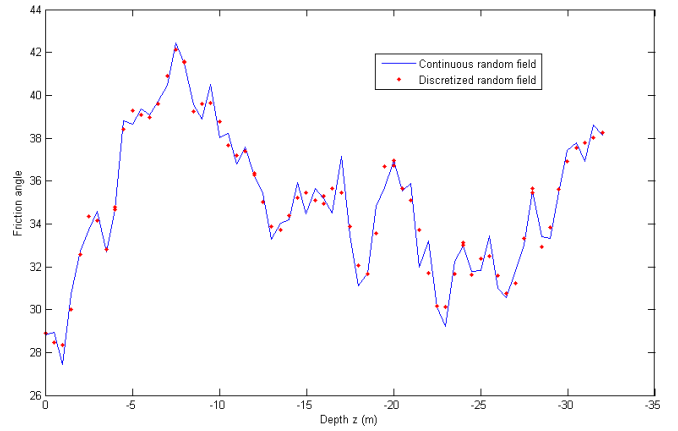


Figure 5: One continuous simulated realization and one profile discretization of the normal random field of φ' over the total depth of the soil: $\mu_{\varphi'} = 35^\circ$, $COV = 10\%$, correlation length $CL = 10$ m, single exponential correlation function.

3.3. Propagation of uncertainty

The propagation of uncertainty via the finite element model developed within the CAST3M finite element computer code (see section 2.1) is performed by direct Monte-Carlo numerical simulation method using the MATLAB Statistics Toolbox. Figure 6 shows the flowchart of

propagation of uncertainty using the coupling system MATLAB-CAST3M.

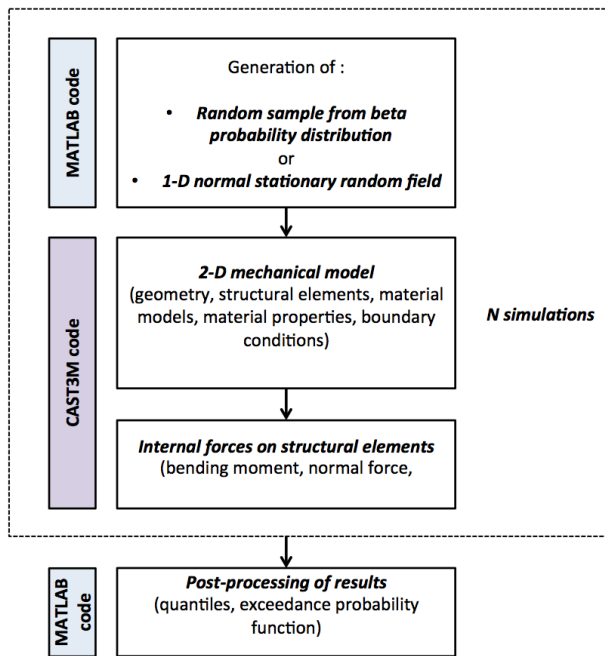


Figure 6: Coupling system MATLAB-CAST3M.

For a homogeneous soil a random sample is generated from beta probability distribution of friction angle using MATLAB, and is then introduced into the mechanical model.

For a heterogeneous soil with spatial variability several realizations of a Gaussian random field of friction angle are generated using the spectral approach (implemented in MATLAB) discussed in section 3.2 and are then introduced into the finite element model.

4. PROBABILISTIC ANALYSIS OF THE STRUCTURAL BEHAVIOUR

4.1. Case 1: Homogeneous soil

The effect of input variable identified in section 3.1 on the mechanical model is now studied by analyzing the output distributions for a homogeneous soil. Direct simulations are made with the finite element numerical model and with random variable φ' . 1000 simulations are carried out and for each one a vector of the bending moment in the steel sheet pile is computed.

Results, sorted in quantiles (2.5%, 50%, 97.5%), are shown in Figure 7, where a beta probability distribution of φ' is considered. We have retained for this scenario a COV = 10%. Confidence interval at the permanent immersion zone, notably at -9 m, is proportionally larger than the one at the level of the passive tie-rods, at -3.5 m. Indeed, maximum bending moment for quantile 2.5% at -9 m is about 100% more important than median value. On the other hand, we can see this same rate for maximum bending moment for quantile 97.5% at -3.5 m with respect to median value. We also note that the asymmetry in these results, quantiles 2.5% and 97.5%, against quantile 50% can be explained by the nature of beta distribution.

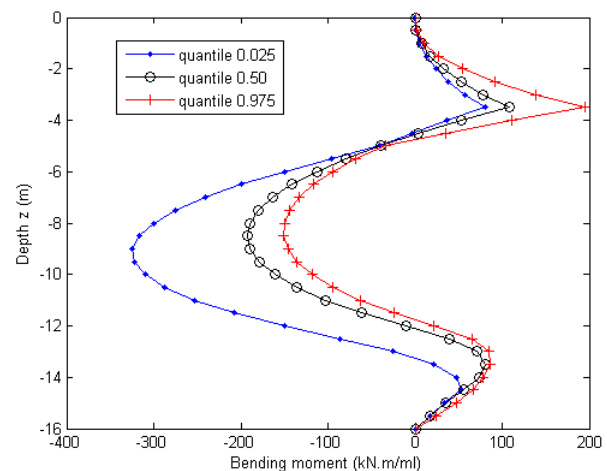


Figure 7: Bending moment in the steel sheet pile seawall for a homogeneous soil: beta probability distribution of friction angle, $N = 1000$ simulations, COV = 10%.

4.2. Case 2: Heterogeneous soil with spatial variability

In order to appreciate the influence of spatial variability, we limit the study to the normal random field. Direct simulations are made with the finite element numerical model and with the random field of φ' . 1000 simulations are carried out and for each one a vector of the bending moment in the steel sheet pile is computed.

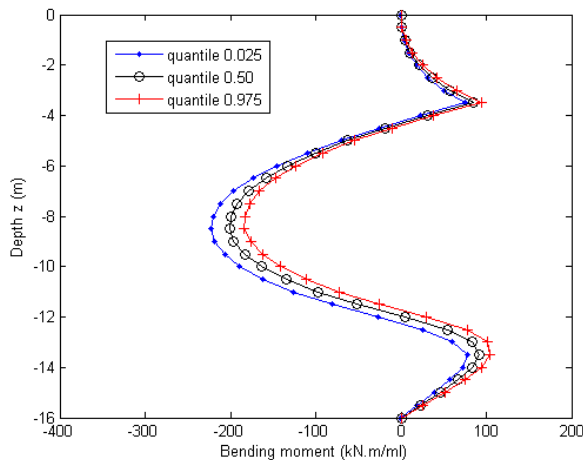
Results, sorted in quantiles (2.5%, 50%, 97.5%), are shown in Figure 8, where four different correlations lengths, CL, of φ' are considered: 1 m (Figure 8(a)), 10 m (Figure 8(b)), 16 m (Figure 8(c)) and 100 m (Figure 8(d)). We have retained for these four scenarios a COV = 10%.

A high sensitivity is observed for the maximum bending moment M_{\max} at -8.5 m in relation to deterministic computation presented in Figure 3 ($M_{\max} = -199$ kN.m/ml for $\varphi' = 35^\circ$). Indeed, for interval LC = [1 m; 10 m] (Figure 8(a) and 8(b)), quantile 2.5% indicates a significant increase of the moment from 12% to 30%. Nonetheless, for higher values than LC = 10 m (Figure 8(c) and 8(d)), we observe that differences in relation to CL = 10 m are smaller.

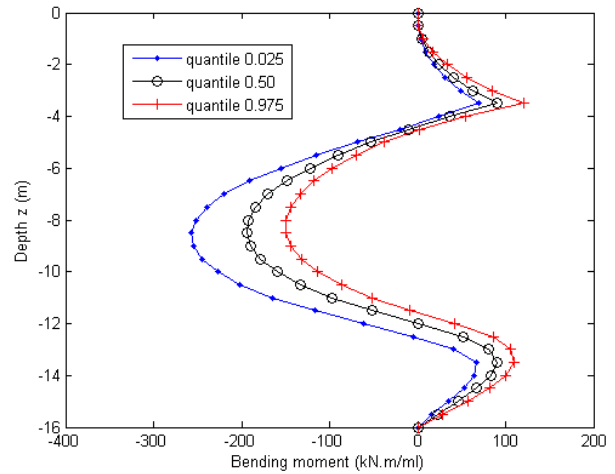
Concerning quantile 97.5%, for interval LC = [1 m; 10 m] (Figure 8(a) and 8(b)) we note a decreased value of the maximum bending moment, in relation to deterministic value, from 8% to 25%. We also notice smaller differences for higher values than LC = 10 m in relation to CL = 10 m (Figure 8(c) and 8(d)).

The same observations, with regard to the evolution of the confidence interval at the level of the passive tie-rods for the four values of CL, can be drawn from these made for the maximum bending moment.

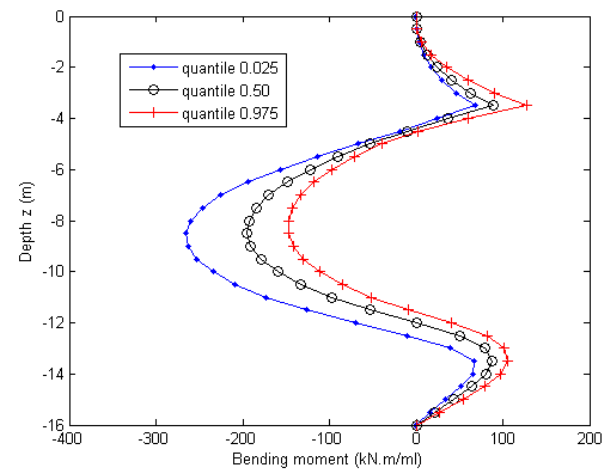
The influence of these soil heterogeneities on the structural behavior are presented in section 5.



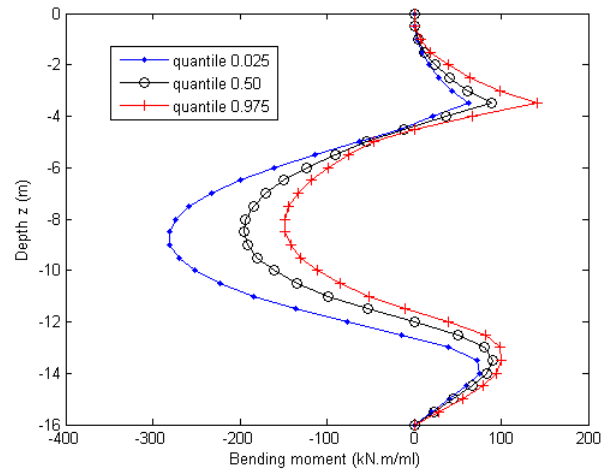
(a)



(b)



(c)



(d)

Figure 8: Bending moment in the steel sheet pile seawall for a heterogeneous soil: random field of

friction angle, $N = 1000$ simulations, $\mu_{\varphi'} = 35^\circ$,
 $COV = 10\%$, (a) $CL = 1$, (b) $CL = 10$, (c) $CL = 16$,
 (d) $CL = 100$.

| | | | | |
|-------|-------|-------|-------|-------|
| 0.443 | 0.608 | 0.443 | 0.447 | 0.454 |
|-------|-------|-------|-------|-------|

5. VARIABILITY EFFECT ASSESSMENT

5.1. Exceedance probability function

We are interested in compare the probability of exceeding a reference value along the sheet pile. More precisely, we consider this reference value as the maximum bending moment, $M_n = 199$ kN.m/ml, corresponding to the nominal value $\varphi' = 35^\circ$ (see Figure 3) at the permanent immersion zone. The probability P_r is calculated as:

$$P_r = P(M_{max}(\mathbf{A}) > M_n) \quad (6)$$

where $M_{max}(\mathbf{A})$ is the computed maximum bending moment according to the random variable $\mathbf{A} = \{\varphi'\}$ for a homogeneous soil and according to the random field $\mathbf{A} = \mu_{\varphi'} + \{\varphi'(z)\}$ for a heterogeneous soil with spatial variability. The purpose to compute these probabilities is to know the order of magnitude with respect to a deterministic computation when one considers the random character and spatial variability of sensitivity parameters as the angle of friction.

5.2. Influence of spatial soil variability

Results of computed probabilities with Eq. (6) are shown in Table 1. Spatial variability when $CL = 1$ m, shows to have a greater influence on the bending moment than the other cases. We observe a smoothing effect for $CL = 10, 16$ and 100 , compared to $CL = 1$ m, indeed, these values remain very close to the one of beta distribution.

Table 1: Probabilities computed for the different cases, $COV = 10\%$.

| <i>Homogeneous soil</i> | <i>Heterogeneous soil</i> | | | |
|--------------------------|--|-----------|-----------|------------|
| $A = \{\varphi'\}$ | $A = \mu_{\varphi'} + \{\varphi'(z)\}$ | | | |
| | <i>CL</i> | | | |
| <i>Beta distribution</i> | <i>1</i> | <i>10</i> | <i>16</i> | <i>100</i> |

6. CONCLUSIONS

We have presented in this paper the effects of soil variability on sheet piles in order to study its global behavior. This structural behavior is random in nature due to the interaction of the structural system and its environment (soil-structure interaction) and implies a significant number of uncertainties. We have limited our study to only one geotechnical parameter. The angle of friction is a parameter very sensitive and a first deterministic parametric computation presented in this paper has confirmed this assumption.

We have then introduced the soil variability by considering two approaches: uncertain model parameters (unstructured variability) and random fields (structured spatial variability). The two cases of application let us to estimate a confidence interval, which allowed to appreciate the sensitivity of the maximum moment, notably at the permanent immersion zone and at the level of the passive tie-rods. The vertical correlation length for the values between 1 m and 10 m seemed to be more sensitive on the effect of the maximum moment than the values beyond 10 m. This last observation is verified in the computation of the exceedance probability function, being the spatial variability influence for the vertical correlation length equals to 1 m more important than the others. We have then showed that spatial variability associated to sheet piles can be not negligible for specific parameters as the friction angle φ' .

The effect of spatial soil heterogeneities open up new possibilities to advance in our researches on longitudinal aspects such as, for example, the longitudinal differential displacements which could impact sensitive structural elements as the tie rods. These future researches can provide elements of response to experts in charge of the standards of design for these structures.

7. ACKNOWLEDGMENTS

The first author would like to thank the AUGC (Association Universitaire de Génie Civil – France) for its funding contribution.

8. REFERENCES

- Ahmed A. and Soubra A.-H. (2012). “Probabilistic analysis of strip footings resting on a spatially random soil using subset simulation approach”. *Georisk*, 6(3), 188-201.
- Boéro J., Schoefs F., Yáñez-Godoy H. and Capra B. (2012). “Time-function reliability of harbour infrastructures from stochastic modelling of corrosion” *European Journal of Environmental and Civil Engineering*, 16(10), 1187-1201.
- Cherubini C. (1998). “Probabilistic approach to the design of anchored sheet pile walls”. *Computers and Geotechnics*, 26, 309-330.
- Desceliers C., Soize C., Yáñez-Godoy H., Houdu E. and Poupard O. (2013). “Robustness analysis of an uncertain computational model to predict well integrity for geologic CO₂ sequestration” *Computational Geosciences*, 17(2), 307-323.
- Low B.K. and Phoon K.-K. (2015). “Reliability-based design and its complementary role to Eurocode 7 design approach”. *Computers and Geotechnics*, 65, 30-44.
- NF EN 1997-1 (2014). *Eurocode 7 : Geotechnical design*. Norme française. Afnor.
- Phoon K.-K. and Kulhawy F.H., (1999). “Characterization of geotechnical variability”, *Canadian Geotechnical Journal* 36, 612-624.
- Rackwitz R., Denver H., and Calle E. (2006). *JCCS Probabilistic Model Code, Section 3.7: Soil properties*, Updated version 2006. Joint Committee on Structural Safety.
- Schweckendiek T., Courage W.M.G. and Van Gelder P.H.A.J.M. (2007). “Reliability of sheet pile walls and the influence of corrosion: structural reliability analysis with finite elements”. *Proceedings of the European Safety and Reliability Conference (EREL 2007)*, Stavanger, Norway, 25-27 June. ISBN 9780415447867.
- Schweiger H.F., Thurner R., and Pöttler R. (2001). “Reliability Analysis in Geotechnics with Deterministic Finite Elements - Theoretical Concepts and Practical Application”. *International Journal of Geomechanics*, 1(4), 389-413.
- Wang Y. (2013). “MCS-based probabilistic design of embedded sheet pile walls”. *Georisk* 7(3), 151-162.
- Yang J.-N. (1972). “Simulation of random envelope processes”. *Journal of sound and vibration*, 21(1), 73-85.