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Development of Regional Soil Shear Strength Database and Its Application in Probabilistic Analysis of Slope Stability

C.L. Chan[1], L.A. Wong[1], W.W.C. Leung[1], P.W.K. Chung[1],
M.K. Lo[2] and Andy Y.F. Leung[2]

[1]Geotechnical Engineering Office, Civil Engineering and Development Department,
The Government of Hong Kong SAR, Hong Kong SAR, China.
E-mail: clchan@cedd.gov.hk
[2]Department of Civil and Environmental Engineering,
The Hong Kong Polytechnic University, Hong Kong SAR, China.
E-mail: man-kong.lo@polyu.edu.hk

Abstract: Characterization of uncertainty in soil parameters constitutes an essential key aspect of probabilistic analysis in geotechnical engineering. While it is desirable to depict the soil variability for a specific site under a particular project, it is often difficult to obtain the site-specific probability distribution of soil properties mainly due to a lack of data. A pragmatic alternative to characterize the soil variability is to collect a large number of data for the same soil type from different sites across the region. This regional database would be useful for a preliminary reliability analysis of a site, or it could be served as prior knowledge to enrich the probability distribution of limited site-specific data. This study formed a database of over 3,000 data of shear strength parameters for various soils in Hong Kong. These data were derived from triaxial tests on soil samples retrieved from slopes in Hong Kong. The data have been compiled to form probability density functions of Mohr-Coulomb effective shear strength parameters (effective cohesion, c' and effective friction angle, ϕ') for different types of soils that are commonly encountered in the territory. Although the data were from various projects, the ground investigation field works and laboratory testing procedures are consistent as they follow the standard local practice. The application of these probability density functions is demonstrated through a case study of reliability analysis of a soil cut slope utilizing the Monte Carlo Simulation. The results of the reliability analysis incorporating the regional database are discussed against that undertaken based on limited site-specific data to articulate the differences in the calculations. Potential applications of the regional database are also discussed.

Keywords: Soil shear strength; Material variability; Triaxial test; Slope reliability; Monte Carlo simulation.

1 Introduction

To evaluate the stability of soil slopes, understanding the shear strength of soils is crucial. A common way to obtain this information is to retrieve site-specific soil samples for laboratory triaxial testing. In practice, the number of soil samples for a site are usually limited mainly due to various site- and project-constraints. The data would usually be sufficient for designers to determine the design values of soil shear strength for slope stability analysis, using either a global factor of safety approach or a partial factor of safety approach. However, the limited data render that the shear strength of soils cannot readily be characterized by an appropriate probability density function (PDF) and meaningful site-specific statistics (ISSMGE-TC304, 2021). This limitation has impeded the practical use of probabilistic analysis in slope engineering projects. As a result, many meaningful information regarding the reliability of the slope design could not be obtained.

Although the soil data for a site is usually limited, the knowledge of the soil properties can be enriched by compiling the data from many sites of similar geological conditions. Provided that sufficient test data are present, a regional database that generates distributions of shear strength parameters in the territory can be formulated. The regional distribution is considered equivalent to the averaged soil shear strength. This is particularly achievable in Hong Kong, where the ground investigation field works and laboratory testing procedures are consistent as they follow the standard local practice(e.g. GEO, 2017a; GEO 2017b). With the regional soil shear strength database, further refinement can be made to create PDFs which are more relevant to the soil types and stress conditions for a particular slope. It also enables an assessment of the approximate reliability of slope where adequate site-specific ground investigation and laboratory testing results are not available. The regional distribution could also facilitate the development of a hybridized distribution by considering it as the prior knowledge of the soils (Wang *et al.* 2016; Ching and Phoon 2020).

2 Development of a Regional Soil Shear Strength Database

2.1Sources of data

Since the establishment of the Geotechnical Engineering Office (GEO) by the Hong Kong Government in 1977, slope upgrading works have been systematically carried out on substandard slopes to reduce landslide risks through the pre-2010 Landslip Preventive Measures Programme and the post-2010 Landslip Preventive and Mitigation Programme. These projects involve ground investigation field works and laboratory tests to understand the properties of soils constituting the slopes to facilitate slope stability analysis. The data are stored in Geotechnical Information Unit for public access.The GEO also maintains a web-based geographic information system application called the Geotechnical Information Infrastructure (GInfo), which contains pertinent information on man-made slopes registered in Hong Kong and such other information related thereto. This application serves as a database for slope and ground investigation data collected from past projects, giving geotechnical engineering professionals an access to the critical information for performing their duties (GEO, 2021).

In this study, a territory-wide database of shear strength parameters of soils typically encountered in Hong Kong with the associated probabilistic distribution was formulated. These soils include superficial deposits: colluvium (COLL), fill (FILL); and in-situ soils: completely decomposed granite (CDG), completely decomposed volcanics (CDV) and residual soil from granitic origin (RS granitic) and volcanic origin (RS volcanic). The parent rocks of CDG mainly include fine-grained, medium-grained and coarse-grained granite. Fine ash and coarse ash tuff and rhyolite lava constitute a majority of the CDV parent rock types. The database contains soil shear strength data obtained from more than 3,000multi-stage consolidated undrained (CU) triaxial compression tests with pore water pressure measurement (GEO, 2017b) conducted on soil samples retrieved from more than 200 sites distributed over the territory of Hong Kong under the above-mentioned slope stabilization projects. Only soil samples collected with the highest sampling quality that is suitable for shear strength determination (GEO, 2017a) were selected to form the database.

2.2Data preparation and processing

In each of the multi-staged CU triaxial tests, the soil specimen was subjected to three consolidation and compression stages conducted in a consecutive manner. In each stage, the specimen was saturated and then consolidated at a fixed effective confining pressure and sheared until the failure criterion, which is defined as the maximum effective principal stress ratios (σ_1'/σ_3'), was reached. After that, the specimen would be re-consolidated at a higher effective confining pressure and then subjected to shearing again. The Mohr-Coulomb's shear strength c'-ϕ'parameters of the soil were then determined by linear regression of the triaxial test data under these three stages in the same multi-stage triaxial test. This approach has an advantage over fitting aset of c'-ϕ'parameters using several single-stage triaxial test results because the single-stage triaxial test specimens are separate specimens carrying different engineering properties and stress history to various extent, thus it requires careful examination on the specimens and the ground investigation results to obtain shear strength parameters representative to the specimens. In the regional database. the test conditions and results have been carefully reviewed and only reliable data are included. For example, only those tests with effective confining pressures less than or equal to 200 kPa were taken into account. This stress range matches the typical stress range of slope stability analysis in Hong Kong. Also, those tests with irregularities were neglected. These irregularities include:

1.Data resulted in exceptionally high effective cohesion;

2.Discrepancy in the weathering grades of in-situ material specimens observed from the split specimens' photographs taken after the triaxial compression test, as compared to the logged weathering grade in the field;

3.Exceptionally high Standard Penetration Test (SPT) N-values adjacent to the sample from which the laboratory specimens are taken; and

4.Exceptionally low coefficient of determination (R^2) in linear regression of the best-fit line, whereas most data show high R^2 (> 90%).

2.3Results

Statistical analyses of these parameters were conducted and continuous probability distributions were generated. A summary of the sample number, slope number, the shear strength parameters' mean, standard deviation and correlation coefficient representing the cross-correlations of the shear strength parameters of these soil types is shown in Table 1.

A large number of shear strength data in the database allows the generation of representative and meaningful continuous probability distributions of shear strength parameters for different soils. In general, effective cohesion follows gamma distribution, whereas effective friction angle follows normal distribution. A summary of best-fit continuous PDFs of c' is also given in Table 1 by the two gamma distribution parameters: shape parameter α and rule parameter β. Kolmogorov Smirnov goodness-of-fit tests have been applied to each of these best-fit curves. The null hypothesis was not rejected at 5% significant level. Compared to statistics quoted in literature such as Lumb (1974) where COV values for c_u(clays) and $tan\phi'$(sands) are between 20% to 50% and 5% to 15% respectively, the data collected in this study show higher variability, which is not unreasonable due to the vast number of slopes.

Table 1. Statistics of the soil shear strength database.

Soil Type	Number of Samples	Number of Slopes Involved	Cohesion (c')				Friction Angle (ϕ', $tan\phi'$)			Correlation Coefficient of c'-ϕ' and c'-$tan\phi'$
			Mean (kPa)	Standard Deviation (kPa)	COV	Gamma Distribution α, β	Mean	Standard Deviation	COV	
CDG	750	200	11.9	7.6	0.641	2.0, 6.8	37.6°, 0.781	5.2°, 0.152	0.137, 0.194	0.105, 0.123
CDV	650	200	11.4	7.4	0.652	2.5, 4.8	35.1°, 0.708	4.5°, 0.121	0.127, 0.170	-0.136, -0.120
RS Granitic	300	100	7.6	5.1	0.666	2.1, 4.1	32.4°, 0.641	4.6°, 0.114	0.142, 0.178	-0.471, -0.451
RS Volcanic	150	60	9.4	6.6	0.708	1.6, 6.6	32.8°, 0.651	4.9°, 0.123	0.150, 0.189	-0.329, -0.302
Fill	650	200	6.6	5.5	0.832	1.3, 5.0	34.1°, 0.684	5.0°, 0.130	0.147, 0.190	-0.183, -0.159
COLL	800	300	7.9	6.1	0.771	1.8, 4.6	34.2°, 0.685	4.7°, 0.123	0.138, 0.179	-0.212, -0.189

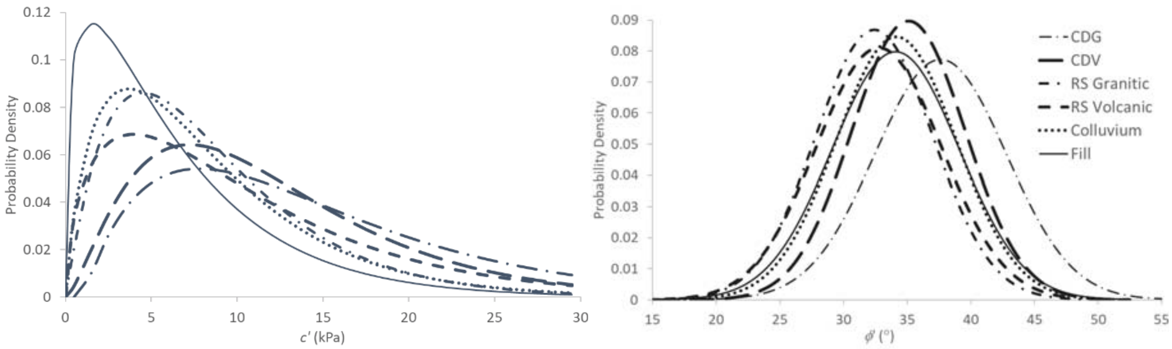

Figure 1. Continuous distributions of c'-ϕ'soil shear strength parameters for different soils.

3 Probabilistic Analysis of a Landslide Case

The regional database PDF has been applied to study a historical landslide case in Hong Kong. The case was subjected to a detailed landslide investigation so that there is a wealth of data e.g. ground investigation, laboratory testing of soil shear strength parameters, etc. to support the probabilistic analysis. The results have been compared to that of a parallel probabilistic analysis adopting the site-specific data.

3.1 Background of the landslide case

The landslide occurred on a cut slope at Ching Cheung Road, Hong Kong in 1997. The slope height varies from 12m to 47m, with a slope gradient of about 45° to 50°. HAPL (1998) reported the details and findings of the landslide investigation. The probable cause of the failure is the adversity of groundwater conditions brought by the surface water infiltration and groundwater recharge from the upslope natural terrain during an intense rainstorm. The rainstorm took place in less than a month after an initial failure of the slope that resulted in ground deformation and disruption of the surface drainage channels. The major failure involves a volume of mobilized soil material of 2,000 m^3.

The dominant material of the failed slope is completely decomposed medium- to fine-grained granite. Ground investigation and laboratory testing on soil shear strength were conducted on the landslide site and adjacent area. Persistent basalt dykes were encountered in several boreholes dipping sub-parallel to the ground surface. With notably lower permeability, the basalt dykes act as aquitards that inhibit downward movement of groundwater.

25 sets of CDG shear strength data were obtained from the ground investigation. A site-specific probability distribution of shear strength parameters of CDG was formulated. The mean and standard deviation of c' are 15.8 kPa and 7.8 kPa respectively, and the mean and standard deviation of ϕ' are 36.3°(0.740 for tan ϕ') and 3.4°(0.090 for tan ϕ') respectively. Both c' and ϕ'follow normal distribution, judging from the KS goodness-of-

fit test. Correlation coefficients of c'-ϕ' and c'-$tan\phi'$are-0.242 and -0.237 respectively. As a part of the landslide investigation, deterministic sensitivity analyses have been conducted to investigate the theoretical groundwater table at failure, which is about 17 m to 19 m above the persistent basalt dyke.

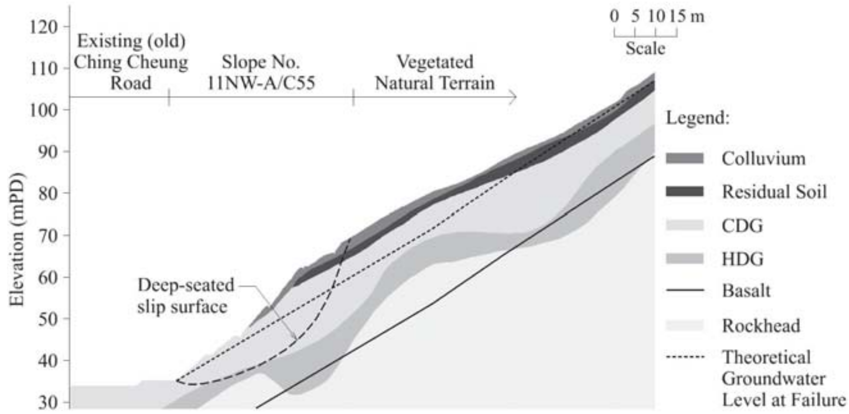

Figure 2. Ground model of the landslide case (right) (After HAPL, 1998).

3.2 Probabilistic analysis

The probabilistic analysis was based on limit equilibrium analysis using GeoStudio's SLOPE/W, where the Morgenstern-Price method was adopted. As the dominant material of the concerned slope is CDG, only the CDG shear strength data, which adopts the form of c'-ϕ' parameters of Mohr-Coulomb failure criterion, were sampled by Monte Carlo Simulation (MCS). Fixed c'-ϕ' parameters were adopted for residual soil, colluvium and highly decomposed granite in the slope stability analysis. The groundwater table is assumed at 18 m above the basalt dyke, i.e. within the range of the theoretical groundwater table at failure as suggested in the landslide investigation report. Fully specified slip surfaces were drawn to estimate the theoretical FoS of the slope under different CDG shear strengths as detailed in the following paragraphs.

Two sets of CDG probability distributions, i.e. the site-specific CDG data and the regional CDG data, were incorporated in two separate probabilistic analyses through Monte Carlo Simulation (MCS). The MCS operation was also performed in SLOPE/W. The simulation size of MCS was 4,000, which gave a stabilized probability of failure and mean FoS. Cross-correlation between the shear strength parameters have been taken into account for both probability distribution.SLOPE/W evaluated the FoS distribution separately for each slip surface. The probability of failure of the slope as a whole, i.e. the system reliability considering all failure modes, was calculated by extracting the FoS values for each slip surface for post-processing. The post-processing was conducted in the following way: first, the minimum FoS among all slip surfaces for each combination of shear strength random variables, i.e. each MCS sample, was evaluated; second, the minimum FoS values from all MCS samples were grouped to calculate the overall probability of failure. By combining the minimum FoS for all MCS samples, the distribution of FoS was obtained. The system probability of failure is defined by the number of MCS samples having a minimum FoS value smaller than 1.0 divided by the total number of MCS samples. In this study, each failure mode is defined as a potential critical slip surface within the slope, similar to that of Jiang *et al.* (2015). Failure modes can be defined differently in other studies. For rock slopes, each failure mode can refer to a completely different failure mechanism.

By separately applying the PDF of the shear strength of CDG using the site-specific and regional shear strength parameters in two probabilistic analyses, two distributions of FoS were obtained and presented in Figure 3. The mean FoS, standard deviation of FoS and the failure probability of the two analyses are shown in Table 2.

The results obtained based on the regional database and the site-specific data both give a mean FOS less than 1.0 and a system failure probability of about 0.7, suggesting the the slope has a high chance of failure at that time. As shown in Figure 3, both FoS distributions are nearly symmetrical with one peak. Minor skewness to the lower FoS value can be found in the distribution for the regional database data. The mean FoS for the regional database is slightly lower than the site-specific data. The FoS distribution of the regional database CDG has a larger coefficient of variation (19%) while that for site-specific data is smaller (11%). This could be a result of the smaller COV in c' (49%) of the site-specific data than that of the regional database (64%), as well as the negative cross-correlation of the shear strength parameters in the site-specific data, which inhibits sampling of extreme values of shear strength. With a smaller coefficient of variation of FoS distribution in the site-specific CDG data case, there are more MCS samples leading to a FoS value lower than 1.0, resulting in a higher system failure probability.

4 Discussion

4.1 Potential application of regional database

As indicated by the above case study, the regional shear strength distribution can produce comparable mean FOS and system failure probability as those using a large amount of site-specific data. The shear strength distributions produced from the regional database allow the reliability of slopes be approximated when adequate site-specific ground investigation and laboratory testing results were not available. Moreover, quantitative methods such as Bayesian analysis can be adopted to integrate the regional distribution with site-specific data, where the prior distribution of shear strength parameters will be updated to a posterior distribution, through incorporating site-specific data in the likelihood. In such case, the regional distribution could also facilitate the development of a hybridized distribution by considering it as the prior knowledge of the soils. The hybridisation approach, implemented by probabilistic graphical model, can rationally incorporate regional database and site-specific data to produce a hybrid PDF. Conceptually, with very limited site-specific data, the hybrid PDF would largely resemble the regional PDF; on the other hand, it would approach the site-specific PDF with increasing amount of site-specific shear strength data.

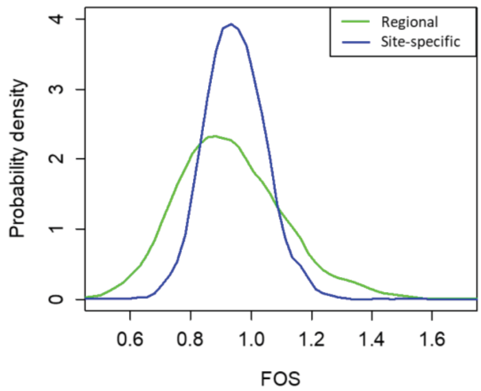

Figure 3. FoS distributions of probabilistic analysis based on regional database and site-specific shear strength of CDG for the 1997 Ching Cheung Road landslide.

Table 2. Comparison of the results of probabilistic analysis based on regional database and site-specific shear strength of CDG for the 1997 Ching Cheung Road landslide.

CDG Shear Strength Parameters	Mean FOS	S.D. FOS	System Failure Probability
Regional database data	0.932	0.176	0.677
Site-specific data	0.946	0.101	0.712

4.2 Further classification for refined probability density function

With the regional database, the probability density function of soil shear strength can be further refined by categorizing the data according to different basic soil properties, such as particle sizes and dry density. The refined PDF may be useful for sites where the soils are of similar nature. An illustration of such refinement is discussed in the following using the CDG database based on the classification of particle sizes. Based on the ground investigation fieldwork reports, each soil can be classified as gravel, sand, silt or clay based on the classification standard given in GEO (2017c). Here, only two groups of soil types i.e. “Coarse Soils” (i.e. gravel and sand) and “Fine Soils” (i.e. silt and clay) were considered to differentiate the soils with lower fines content (Coarse Soil) from that with higher fines content (Fine Soil). By categorizing the shear strength data according to this classification, the results presented in Table 3 show distinctive characteristics of CDG shear strength for different fines content. Further classification considering different index properties can produce different shear strength probability distributions, so that the PDF can be refined to match the characteristics of the soil in a particular slope, thus the confidence of extrapolating the data to other slopes can be enhanced.

4.3 Limitation of regional shear strength database

Although the shear strength database can produce continuous probability density functions passing the goodness-of-fit test for different soils, the system bias and uncertainty of data should be noted. Examples include sampling bias of the test data to the mass characteristics of the ground in concern (i.e. the inherent variability of the materials encountered, the possible existence of weaknesses), the appropriateness of test methods in relation to the field conditions and the limit states being considered, sample disturbance andthe inherent limitations of multi-stage consolidated undrained triaxial compression test . It is critical that the user of the database appreciates that the importance of the mass shear strength specific to the site in concern may not be adequately represented in the regional shear strength PDF. Caution should also be exercised in adopting the database for saprolites of parent rocks other than those from which the database was derived.

Another limitation of the regional database is that it may not represent the site-specific conditions accurately. Recently there are researches which focus on assimilating the regional database with site-specific data,where the regional database serves as the prior knowledge of the soil shear strength for cases which the site-specific data are insufficient. A case study of this further application of the regional database is presented in a companion paper by Lo et al. (2022).

Table 3. Characteristics of CDG shear strength categorized according to particle size of laboratory samples.

		Coarse Soils	Fine Soils
Cohesion (c')	Mean (kPa)	12.4	8.6
	Standard Deviation (kPa)	7.9	5.2
Friction Angle (ϕ', $tan\phi'$)	Mean	38.5, 0.831	33.5, 0.668
	Standard Deviation	4.8, 0.134	4.4, 0.113
Correlation Coefficient of c'-ϕ' and c'-tanϕ'		0.125, 0.156	-0.225, -0.185
Sample Proportion		82%	18%

5 Conclusion

In this study, the probability density functions of shear strength parameters of various types of soils commonly encountered in Hong Kong have been produced using triaxial test results of soils sampled across the territory. The database contains basic soil properties such as particle sizes and dry densities so that generalised shear strength parameters can be derived from the database for further analyses. With the possibility of including more index properties and adding more past and future laboratory testing data, the confidence in extrapolating the data to other sites with similar material types could be enhanced. In a case study presented in this paper, this regional soil shear strength database has been deployed into the probabilistic analysis of slope stability, which shows comparable results with those using site-specific shear strength data. Further probabilistic analyses of more cases would be useful to demonstrate the applicability of this regional database.

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References

Ching, J.,and Phoon, K. K. (2020). Constructing a site-specific multivariate probability distribution using sparse, incomplete, and spatially variable (MUSIC-X) data. *Journal of Engineering Mechanics*, 146 (7), 04020061, DOI: 10.1061/(ASCE)EM.1943-7889.0001779.

GEO(2021). Civil Engineering Library - Public Services (Information Note 10/2021). *Geotechnical Control Office, Hong Kong*

GEO (2017a). Guide to Site Investigation (Geoguide 2) (Continuously updated e-version released on 18 December 2017). *Geotechnical Engineering Office, Hong Kong*, 349 p..

GEO (2017b). Model Specification for Soil Testing (Geospec 3) (Continuously updated e-version released on 29 August 2017). *Geotechnical Engineering Office, Hong Kong*, 340 p.

GEO (2017c). Guide to Rock and Soil Descriptions (Geoguide 3) (Continuously updated e-version released on 29 August 2017). *Geotechnical Engineering Office, Hong Kong*, 78.

Halcrow Asia Partnership Ltd. (1998). Report on the Ching Cheung Road Landslide of 3 August 1997 (GEO Report No. 76). *Geotechnical Control Office, Hong Kong*, 142 p.

ISSMGE-TC304 (2021). State-of-the-art review of inherent variability and uncertainty in geotechnical properties and models. *International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) – Technical Committee TC304 'Engineering Practice of Risk Assessment and Management'*, March 2nd., 2021. DOI: 10.53243/R0001

Jiang S.H., Li, D.Q., Cao, Z.J., Zhou, C.B,, and Phoon, K.K. (2015). Efficient system reliability analysis ofslope stability in spatially variable soils using Monte Carlo simulation. *Journal ofGeotechnical and Geoenvironmental Engineering*, 141(2), 04014096.

Lo, M.K., Leung, Y.F., Chan, C.L., and Sze, E.H.Y. (2022). Reliability of a soil-nailed slope considering regional shear strength information. *In Proceedings of 8th International Symposium on Geotechnical Safety and Risk (ISGSR 2022), Newcastle, Australia*.

Lumb, P. (1974). Probabilistic Solutions in Geotechnics. *Chapter 3 in Soil Mechanics-New Horizons, ed. By I.K. Lee*.

Wang, Y., Akeju, O.V., and Cao, Z. (2016). Bayesian equivalent sample toolkit (BEST): an Excel VBA program for probabilistic characterization of geotechnical properties from limited observation data. *Georisk*. 10 (4), 251-268.