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Conception Proposal and Tested Method for Genetic Characteristics of Geotechnical Materials

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Abstract: Due to inherent natural reasons, the fundamental properties of geotechnical materials always exhibit varying degrees of spatial variability. Thus, it is challenging to describe the global traits of geotechnical materials based on very limited test data, and the differences in the values of their characteristic parameters have a significant impact on the determination of geotechnical engineering stability and related engineering design results. To solve this issue, the concept of genetic characteristics of geotechnical materials was proposed for describing the overall characteristics of specific rock (soil) material belongings within a certain spatial range, and the definition of genetic characteristics and their basic attributes were given in this paper. Moreover, it gave that the notion of utilizing big data theory to statistically analyze the geotechnical material parameter data identified in numerous actual projects and search its genetic characters is presented. Besides, a software system has been developed for big data management and analysis of genetic characteristics of geotechnical materials, which can achieve the tasks of collecting, transmitting, classifying, screening, managing, and analyzing the big data of geotechnical materials. Eventually, based on more than 80,000 pieces of standard geotechnical material preliminary data in Chongqing City, the genetic features of typical geotechnical materials in the region can be analyzed to obtain the corresponding gene maps. The attained findings in this paper can offer a reliable guidance for the selection of geotechnical material parameters, engineering construction, and prevention of geological disasters.

Keywords: geotechnical materials; genetic characteristics; big data; statistical analysis; bayesian estimation.

1. Introduction

With the development of science and technology, different theories and models of geotechnical mechanics have been improved with diversified computation methods (Andreev et al., 2016; Boldini et al., 2019). Moreover, numerious advanced theories and approaches have been productively applied to realistic engineering, offering a robust theoretical foundation and technical support for solving geotechnical engineering issues and also significantly promoting the progress of geotechnical engineering disciplines (Brom and Natonik, 2017; Cai et al., 2016; Chen et al., 2019; Contreras and Brown, 2019). Yet, a key factor is still limiting the application of many advanced geotechnical mechanics theories in real engineering, which can obstruct the fast development of geotechnical engineering, and this factor is the understanding of fundamental physical and mechanical properties of geotechnical materials. More specifically, it is to precisely establish the basic physical and mechanical parameters of geotechnical materials. Generally, the application of any theory and method of geotechnical mechanics must be based on the correct understanding and accurate identification of the basic physical and mechanical parameters of geotechnical materials (Shahri and Naderi, 2016; Wang et al., 2017b) (Papaioannou and Straub, 2017). Otherwise, no matter how advanced the theory or how accurate the calculation is, the results will possibly have distortions or errors that cause theoretical research and numerical calculations findings meaningless. However, geotechnical materials always exhibits substantial spatial random variability and uncertainty because of their own inherent special genetic characteristics. Besides, the geotechnical engineering involves a fairly large spatial area. How to properly assess the physical and mechanical features of different rock (soil) materials in the area and how to attain the true and reliable physical and mechanical parameters of rock and soil materials in a certain space area is a very important and hard problem (Goharzay et al., 2017; Shepheard et al., 2019; Wang et al., 2017a). Currently, the common practice in the engineering community of world is to attain the test values of geotechnical material samples at several test points during the engineering survey. After simple statistical analysis, physical and mechanical parameters reflecting the overall belongings of the geotechnical material can be proposed and used for guidance engineering design. From the restrictions of the test samples, this approach perceptibly has larger deficiencies, causing people doubt the authenticity, reliability and representativeness of the acquired parameters (Lv and Zhou, 2020; Oladotun et al., 2019). Material parameters are the foundation and core of engineering design. Moreover, improper parameter selection will not only increase the risk of engineering accidents, but also enlarge the investment in engineering construction, resulting in potential waste of construction investment, and there is no way to evaluate this waste (Hu and Wang, 2019; Prastings et al., 2019). It can be found that the study of the essential physical and mechanical characteristics of geotechnical materials is not only very important, but also very necessary, which should be paid great attention by researchers and engineers in the field of geotechnical engineering.

According to the above issues and inherent spatial variability and uncertainty characteristics of the physical and mechanical characteristics of geotechnical materials, a new "geotechnical material gene characteristics" is proposed to describe the fundamental physical and mechanical characteristics of geotechnical materials over a certain area, with the combination of the geological genesis and structural conditions of geotechnical materials in different regions. The purpose of this paper is to apply data statistics to search basic physical and mechanical common traits of specific geotechnical material groups (or geotechnical material lithology categories) in a certain spatial area, and to establish a corresponding database of basic geotechnical materials parameters, the big data analysis method was used to identify and extract gene features. Meanwhile, the continuously supplemented test data of geotechnical materials can supplement and improve the database, and gradually modify the acquired genetic features. Thus, the description of the genetic characteristics gradually becomes more accurate, and the modified genetic attributes can in turn guide the value of geotechnical material characteristic parameters, thereby providing the reliable basic data for the application of geotechnical mechanics theory and geotechnical engineering design..

2. Proposing the notion of genetic characteristics of geotechnical materials

The term "gene" is originated in biology and refers to the rudimentary substances with genetic factors that exist in biological populations (Behdad et al., 2020). Similarly, although the geotechnical medium is a non-biological substance, it also has the internal micro-materials and its structural characteristics. Micro-fine particles and other media have formed geotechnical materials of today through hundreds of millions of years of physical and chemical action. Influencing factors such as specific material substance components, specific structural forms, and specific generation environments (temperature, pressure, etc.) give the geotechnical material group specific genetic characteristics, and can be expressed with specific physical and mechanical characteristics.

The concept of genetic characteristics of geotechnical materials can be defined as: common fundamental physical and mechanical features of the same geotechnical material group within a certain spatial area. According to this definition, the genetic characteristics of geotechnical materials should have three attributes: (1) Regionality: Because of the influence of the origin of geotechnical materials, only the same type of geotechnical materials formed under basically the identical conditions have the equivalent or similar genetic characteristics. The impact is great, so there are also large differences in gene characteristics, which limits the regionality of gene characteristics; (2) Grouping: Geotechnical materials with different rock (soil) properties have dissimilar micro-component materials, diverse structural forms, different generation environments, and naturally have different genetic characteristics. Therefore, they must be distinguished when researching them, and they cannot mix each other; (3) Convergence: The genetic characteristics of the identical group in the same region refer to their representative commonalities or convergence characteristics, and this is a statistical concept that does not rule out small differences in the sample indicators of individual points. Therefore, the identification or the test must be based on a sufficient number of sample data, and a representative common characteristic index can be obtained through statistical analysis.

3. Role and significance of researching genetic characteristics of geotechnical materials

At this stage, most of these research results on the fundamental physical and mechanical characteristics of geotechnical materials are from the study of a particular parameter index of a specific geotechnical material of a certain project, such as strength index, deformation index, permeability index or timeliness index, etc. The systematic and normative research is relatively absent. The concept of genetic characteristics of geotechnical materials covers a wide range of basic intrinsic properties of geotechnical materials in a broad sense, and is more uniform and standardized in description. More importantly, this notion not only contains and expands the connotation of basic physical and mechanical belongings of traditional geotechnical materials. It is a macro-statistical consequence according to the results of traditional experimental research, which can reflect the macroscopic properties of the same group of geotechnical materials in a specific range. The experimental data attained from the space points is not only the data source of regional statistics, but also the revision and supplementary information of the statistical outcomes of existing gene characteristics. Meanwhile, the existing genetic characteristics can also verify and compare the data acquired from each test, and urge people to analyze the occurrence of some strange data to search the cause, to circumvent human error or system error during the test and ensure the reliability and authenticity of data.

It can be concluded that the significance of learning the genetic characteristics of geotechnical materials is: Currently, relevant scientific and technical personnel cannot illuminate the overall features of the basic physical and mechanical properties of geotechnical materials in a certain area with a high degree of correctness. The data measured at the points to characterize the geotechnical material characteristics of an area is biased. Thus, based on statistical analysis of relevant big data under specific conditions, the findings attained are more reliable from a probabilistic perspective than the relevant data obtained from specific experiments, and they are more representative of the regional physical and mechanical belongings of geotechnical materials.

The investigation of genetic characteristics of geotechnical materials can comprehensively and systematically analyze the fundamental genes of different rock (soil) groups in diverse spatial regions, create corresponding gene databases, and draw corresponding gene maps. Also, with further systematically and comprehensively analysis the impacts of various genetic elements on the physical and mechanical characteristics of geotechnical materials, the sensitivity and correlation of the corresponding effects can be derived. From the analysis consequences and the actual requirements of the project, these genetic elements are modified and interfered to enhance the performance of geotechnical materials in certain aspects to satisfied the necessities of engineering construction. Thus, this work can be referred to as genetic modification or genetic modification of geotechnical materials.

4. Approach for establishing genetic traits of geotechnical materials

The means for acquiring the genetic characteristics of geotechnical materials is to employ the existing physical and mechanical parameters testing device of geotechnical materials to test various fundamental parameters, including indoor testing and field testing. The test content contains the material composition, structure and physical and mechanical characteristics of geotechnical materials in diverse regions and groups. The critical and difficult point of the problem is that there must be a sufficient amount of test data to statistically analyze the genetic characteristics of a group of rock and soil bodies and disclose their genetic characteristic values.

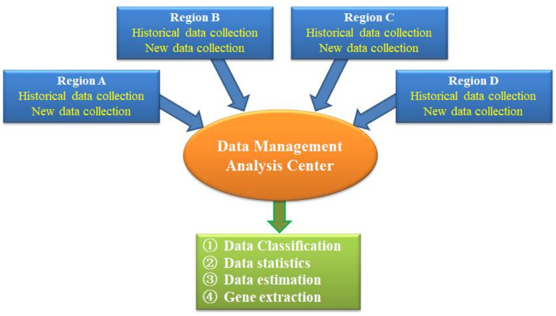

Figure 1. Schematic method for determining genetic characteristics of geotechnical materials.

Nevertheless, a phenomenon unnoticed by the researchers of universities and research institutes is that countries conduct an enormous number of engineering constructions in dissimilar regions every year. Engineering construction must be inseparable from the geological assessment of the construction site (such as low-cost bearing capacity, deformation characteristics, stability). To complete these estimations, massive site surveys must be accomplished, and the corresponding physical and mechanical parameters of geotechnical materials must be offered to satisfy the design requirements. Yet, these huge amounts of data have fulfilled their historical mission after the implementation of each project, and the repeated utilization rate is very low. From the perspective of an engineering project alone, after the project is completed, these data are indeed no longer useful, but if viewed from the perspective of studying the genetic characteristics of geotechnical materials, the value of these data will be extremely valuable. If you have the ability to collect these huge amounts of data, sort them according to factors such as geographic area, stratum structure, rock and soil groups, genetic elements. Statistical analysis is performed according to the big data method, and the genetic characteristics of specific geotechnical material groups will be obtained. It can be seen from Fig. 1 for the establishing approach of genetic characteristics of geotechnical materials.

It is particularly critical that the acquisition and update of geotechnical material parameters is a dynamic process. For every year, enormous data is supplemented to the corresponding database, and the original genetic characteristics of geotechnical material parameters are continuously revised. Thus, it can be imagined that after years or decades of data accumulation, the genetic characteristics of each geotechnical material group will become more and more clear and accurate, which will also apparently increase the safety and economics of engineering construction.

5. Initial exploration of genetic characteristics of geotechnical materials

Chongqing, a well-known mountain city in China, has notable characteristics of topography, geomorphology and geological structure, with the significant regional features of the basic lithology. To analyze the genetic characteristics of typical geotechnical materials in Chongqing, the following research work will be conducted in this paper.

5.1 Founding data collection and analysis management system for geotechnical materials

According to multiple geotechnical material test centers and using internet technology, a set of "geotechnical material data collection and analysis management system" was built, which can collect, transmit, classify, filter, manage and statistically analyze the detection data of different data collection points in real time. With Bayesian theory, combined historical data characteristics and field detection results can be combined to estimate parameter values of specific projects.

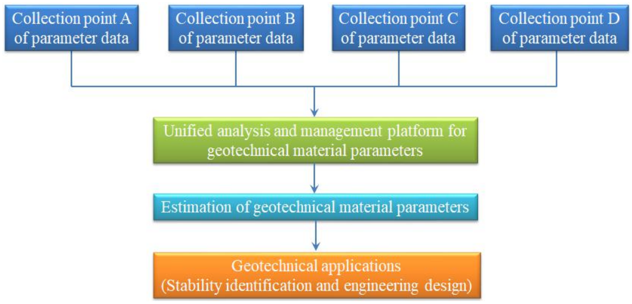

Figure 2. Flow chart of statistical analysis of big data for geotechnical parameters.

The big data statistical analysis process of geotechnical parameters and its platform interface are shown in Figs. 2, respectively. Currently, more than 80,000 pieces of physical and mechanical parameters of numerous geotechnical materials tested in Chongqing have been collected in the past 3 years, and the rudimentary characteristics of each data have been described and stored in the corresponding database for use in big data statistical analysis.

5.2 Analysis of genetic characteristics of geotechnical materials with mathematical statistics

From the relevant conditions set by the system, the data in the database can be classified and filtered based on regions, groups, and rock (soil) and physical and mechanical indicators, and eligible valid data can be extracted for statistical analysis. The rudimentary physical and mechanical characteristics or genetic features of the existing data can be attained as the prior information for the estimation of genetic traits of geotechnical materials. Figs. 3 and 4 are histograms of two intensity indicators randomly displayed in Yuzhong District, Chongqing, and gene characteristic maps of specific parameters of sandstone lithological materials in diverse districts and counties of Chongqing.

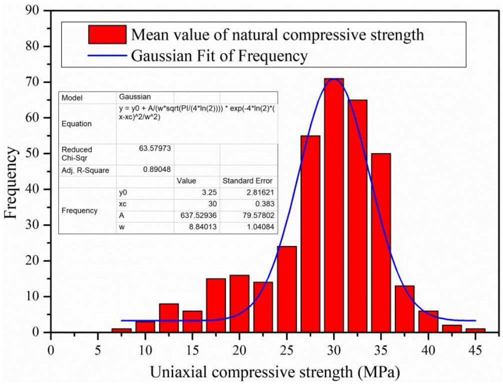

Figure 3. Natural statistical characteristics of natural uniaxial compressive strength of sandstone in Chongqing.

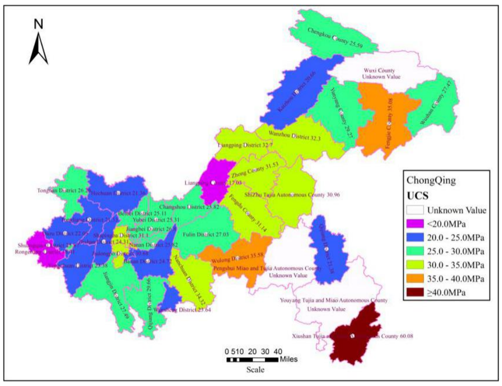

Figure 4. Gene map of natural uniaxial compressive strength of sandstone in Chongqing.

5.3 Design parameters of geotechnical materials from Bayesian estimation

Based on priori gene characteristics of the specific geotechnical material group offered by the system statistical analysis, combined with the parameter test values obtained from the specific engineering detection, the Bayesian estimation method can be applied to compute the geotechnical parameter design value for engineering design with taking the experimental value as the posterior parameter feature.

For the parameters of rock and soil strength that follow the normal distribution, that is $x \sim N(\mu,\sigma^2)$, where x represents the geotechnical strength parameters, (μ,σ^2) are the mean and variance of normal distributions subject to strength parameters, which fully reflects the random distribution characteristics of rock and soil strength parameters. Briefly, it is a manifestation of rock and soil strength parameter genes. For a specific project, the (μ,σ^2) corresponding to the cohesion c and the internal friction angle φ is unknown. How to scientifically establish (μ,σ^2) becomes the key to whether the value of the rock and soil strength parameter is reasonable. The conventional method is based on a set of results from field sampling experiments, statistics, point estimation method to infer (μ,σ^2). The unbiased point estimator of the mean of the field sample is the overall mean μ, and the variance of the field sample is the unbiased point estimator of the overall variance σ^2, namely:

$$\begin{cases} \mu\wedge = \bar{x} \\ \sigma^2\wedge = s^2 \end{cases} \quad (1)$$

Where, x is the sample mean of geotechnical strength index， s^2 means the sample variance of geotechnical strength index，$\mu\wedge$ is a point estimator for the population mean μ， and $\sigma^2\wedge$ gives the unbiased point estimator of variance σ^2.

Yet, since the number of on-site samples is generally very limited, normally only 6 to 8, this is a small sample problem in statistics, thereby leading to the characteristics of rock and soil strength parameters determined by formula (1) have greater uncertainty.

Consequently, from the theory of Bayesian statistics, (μ,σ^2) is proposed to obey a two-dimensional joint prior distribution, expressed as:

$$\pi(\mu,\ \sigma^2)=\pi(\mu|\sigma^2)\ \pi(\sigma^2) \quad (2)$$

Where, $\pi(\mu,\ \sigma^2)$ — Joint prior distribution of (μ,σ^2)

$\pi(\sigma^2)$ — Prior distribution of σ^2

$\pi(\mu|\sigma^2)$ — Prior distribution of μ prior distribution under σ^2;

Also, consider that $\mu|\sigma^2$ and σ^2 obey normal distribution and inverse gamma distribution, respectively:：

$$\mu|\sigma^2 \sim N(\mu_0, \sigma^2/\kappa_0) \quad (3)$$

$$\sigma^2 \sim IGa(\upsilon_0/2, \upsilon_0\sigma_0^2/2) \quad (4)$$

Where μ_0, κ_0, υ_0 and σ_0^2 are the hyperparameters to be determined.

Thus, the prior distribution of (μ,σ^2) can be name the normal-inverse gamma distribution. On the basis of the prior distribution, according to the Bayesian formula, the posterior distribution under the field sample condition (μ,σ^2) can be obtained with the Bayesian formula. From the theory of conjugate prior, the prior distribution and the posterior distribution belong to the same family distribution, correspondingly :

$$\pi(\mu,\ \sigma^2|x) \propto (\sigma^2)^{-(\upsilon_n/2+3/2)} e^{-\frac{1}{2\sigma^2}[\upsilon_n\sigma_n^2+\kappa_n(\mu-\mu_n)^2]} \quad (5)$$

Where: $\pi(\mu,\ \sigma^2|x)$ — posterior distribution of (μ,

σ^2);

$\mu_n = \frac{\kappa_0}{\kappa_0 + n}\mu_0 + \frac{n}{\kappa_0 + n}\bar{x}$; $\kappa_n = \kappa_0 + n$; $\upsilon_n = \upsilon_0 + n$;

$\upsilon_n \sigma_n^2 = \upsilon_0 \sigma_0^2 + (n-1)s^2 + \frac{\kappa_0 n}{\kappa_0 + n}(\mu_0 - \bar{x})^2$;

x — On-site sample mean;
s^2 — On-site sample variance;
n — On-site sample number;

With the maximum posterior estimate as the parameter estimator, the maximum posterior estimate table for (μ,σ^2) is:

$$\begin{cases} \mu_{MD} = \frac{\kappa_0}{\kappa_0 + n}\mu_0 + \frac{n}{\kappa_0 + n}\bar{x} \\ \sigma_{MD}^2 = \frac{\upsilon_0 \sigma_0^2 + (n-1)s^2 + \frac{\kappa_0 n}{\kappa_0 + n}(\mu_0 - \bar{x})^2}{\upsilon_0 + n + 3} \end{cases} \quad (6)$$

Where, μ_{MD}, σ_{MD}^2 — the maximum posterior estimate of (μ,σ^2);

$\mu_0, \kappa_0, \upsilon_0, \sigma_0^2$ — the hyperparameters can be determined for the prior distribution from historical data;

Thus, based on the formula (6), the historical data or genetic characteristics are scientifically synthesized from the field data to attain a more reasonable estimated value of the random distribution characteristic parameters of the rock and soil strength parameters. According to this algorithm, the Bayesian estimation of rock and soil strength parameters is implemented on a rock and soil big data platform.

5.4 Instances of geotechnical parameter estimation

With the approach proposed above, the strength parameters of geotechnical materials were assessed for a slope project in Chongqing, and the outcomes of the estimation were compared and analyzed. Table 1 indicates the historical gene characteristics, field test data, and Bayesian estimation results of the rock and soil strength parameters of the project. Meanwhile, from the characteristics of the three parameters in the table, the respective evaluations of slope stability are attained, and a comparative analysis was performed. The acquired outcomes suggest that there is a certain gap between the strength parameters of geotechnical materials from the genetic characteristics of geotechnical materials and the real testing data with Bayesian estimation and the strength parameters of geotechnical materials analyzed via only the actual testing data. Thus, this directs that the influence of genetic features of geotechnical materials on the parameter values of actual engineering cannot be overlooked.

Table 1 Bayesian estimation outcomes and comparison of rock and soil strength parameters of a slope project

Parameter type	Statistical characteristics	Field data	Historical data	Bayesian estimation
Natural cohesion	Mean value	33.225	23.180	27.028
	Variance	5.472	6.940	27.760
	Coefficient of variation	0.070	0.114	0.195
	Standard value	31.644	22.955	23.468
Natural friction angle	Mean value	9.487	14.500	11.450
	Variance	1.106	13.760	3.840
	Coefficient of variation	0.108	0.255	0.171
	Standard value	8.776	14.182	10.124
Stability coefficient	Natural state	1.810	1.650	1.500

From Table 1, it can be found that there exists a large difference between the field data of the cohesion and internal friction angle acquired by the natural fast shear of the slope project, and the historical data of the region. The assessed value attained via Bayesian estimation lies between field data and historical data. As for the stability coefficient, since it is influenced by both cohesion and internal friction angle and the sensitivity of the stability coefficient to cohesion and internal friction angle is different, the value of the stability coefficient is not necessarily in historical data and on-site data. Also, the stability coefficient of the slope in the example is smaller than the field data and historical data. Meanwhile, the magnitudes of the remaining sliding forces corresponding to the four strips of the slope under historical data, field data, and Bayesian estimates are shown in Fig. 5. From the figure, it can be concluded that the remaining sliding forces estimated by Bayesian are less than on-site and historical data, and this instance suggests that there may be large differences between the field data and history data. At this moment, it is not scientific and rational to simply assess from field data or historical data. Consequently, the conditional distribution of the random distribution of the characteristic parameters under the conditions of field sample occurrence can be acquired by Bayesian inference. Next, the maximum posterior estimate can be attained from the conditional distribution to get a standard value of the intensity parameter that is more practical in probability, which is perceptibly more scientific and reasonable.

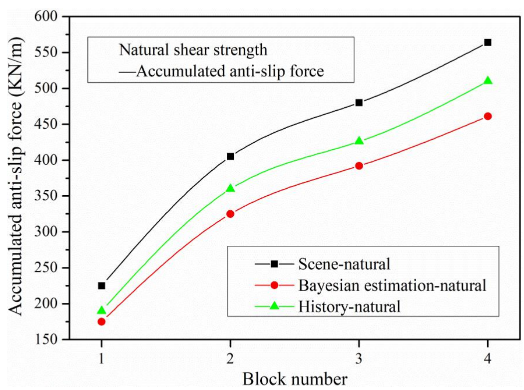

Figure 5. Bayesian inferred interface for strength parameters of rock and soil.

5. Conclusions

(1) The notion of biological genes was borrowed to propose the concept of genetic characteristics of geotechnical materials. The fundamental physical and mechanical characteristics of the same group of geotechnical materials within a certain geometrical space are homogeneously described by the genetic characteristics of geotechnical materials.

(2) Gene features are characteristic values that follow a certain distribution and can be acquired via statistical analysis of a large amount of such samples. As the quantity of samples remains to increase, the description of fundamental characteristics of rock and soil mass by genetic characteristics will be more and more precise.

(3) The notion of statistical analysis of genetic characteristics of geotechnical materials with massive practical engineering test data was presented, and a corresponding data collection, transmission, classification, screening, management, and analysis software platform can be established with internet technology and big data analysis means, which can achieve the analysis of the genetic characteristics of typical geotechnical materials in a certain area and their preliminary genetic characteristic maps can also be gained.

(4) From the statistical maps of typical geotechnical materials in Chongqing, Bayesian estimation theory can be employed to assess the strength parameters of geotechnical materials in practical engineering with the combination of data acquired from specific landslide engineering examples.

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