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Quantitative evaluation of stratigraphic properties based on composite binary structure

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ABSTRACT

In planning and developing urban underground space, it is vital to conduct regional engineering geological zoning for the Quaternary sedimentary layer. Simplifying and quantifying the stratigraphic characteristics for correlative and calculative analysis between strata in different regions and depths is necessary. Further, the simplified expression must represent the critical geotechnical properties of the stratum. This paper defines the concept of coarse layer ratio (CLR). Using the original drilling data, assigning and calculating the CLR of the formation from the perspective of composite binary structure, this paper realizes the quantitative description of the formation characteristic. The results show that the proposed method can genuinely reflect the objective situation and quantitatively express the nature of the spatial strata in the horizontal and vertical directions. Furthermore, it clearly shows the change in the stratigraphic properties in space. The results are promising to provide practical guidance for evaluating the engineering nature of urban underground space resources.

Keywords: urban underground space, quantitative evaluation method, formation properties, composite binary structure

1 INTRODUCTION

The utilization of deep underground space is becoming a trend in modern large cities, and describing and analyzing the engineering geological characteristics of deep underground strata is necessary. Currently, the dividing depth of deep underground space in China is mainly set at 30~40 m (Xin et al., 2019), the depth that most underground projects, such as subways and deep foundation pits, have yet to reach. Also, there is no standardized method for describing and analyzing geological characteristics in deep underground space engineering planning. Thus, it is a novel topic in the field of geotechnical engineering.

Furthermore, the study of deep engineering geological zoning in recent years mainly focuses on the evaluation of the engineering geological conditions and applicability of the engineering environment. The areas with sound or poor engineering geological conditions are divided according to soil type and engineering geological properties. The applicability evaluation and zoning of the engineering geological environment, which is especially relevant for deep foundation pit and tunnel engineering, are carried out based on the hydrogeological conditions and geotechnical properties (Sun, 2015; Shi et al., 2016).

In the existing traditional geotechnical engineering practice, it is necessary to carry out horizontal engineering geological zoning and vertical stratification for a specific area to meet the need for construction planning and engineering geological evaluation. The primary geological zoning is usually based on geomorphology, which is closely related to sediment characteristics. For example, four engineering geological areas exist in Shanghai according to the landform, namely, lacustrine plain area (I), coastal plain area (II), estuarine sand island area (III), and alluvial plain area (IV). Then, based on the primary zoning, the secondary level of zoning is carried out according to the characteristics of the engineering geological conditions, namely stratigraphic and geotechnical properties (Fang &Yang, 2002; Yan &Shi, 2006; Zhang &Shi, 2013). Based on the local Quaternary chronostratigraphy, the engineering geological layers are further distinguished according to the genetic type, crucial engineering geological characteristics, physical properties, and mechanical engineering properties, including lithology, density, shear strength, compression modulus, and foundation bearing capacity. Each layer is usually composed of a single soil layer of a particular type or a set of layers dominated by a specific soil type.

The existing traditional engineering geological zoning and deep engineering geological assessment have the following cons. First, they are relatively sketchy zoning methods, either the zoning method according to the sedimentary environment in the traditional engineering geological practice or the "superior or bad" classification proposed in recent years in the deep underground zoning. Then, it is a qualitative description of geological conditions. The classification and description of geotechnical properties in engineering geological surveys make the knowledge of horizontal changes in engineering geological conditions qualitative. Furthermore, the zoning method only highlights the differences and basic characteristics of different engineering geological areas in a city-level region. However, it cannot quantitatively analyze and describe the lateral changes of strata in a project area of a smaller scale of hundreds to thousands of meters.

This research explores a quantitative description of soil layer characteristics. The horizontal variation of geological characteristics will be quantitatively analyzed and used for more detailed engineering geological zoning for deep underground projects.

2 INDICES AND METHODOLOGY

2.1 Data source

A large number of geotechnical survey data have been accumulated in earth exploration activities, which provides convenience for the study of geological characteristics. Geotechnical survey data mainly include geological and geotechnical information, physical properties, and mechanical properties such as geological age, rock/soil type, density, shear strength, compression modulus, and groundwater level. Among them, the mechanical property is a quantitative index and can be directly used for quantitative analysis. Soil type is the most basic characteristic of geological strata, related to its geological origin and geotechnical engineering properties. Therefore, the characteristics of soil types are selected as a quantitative index. The pros of this method are that it not only retains vital geological features but also evaluates the geotechnical characteristics. The quantitative analysis method based on the mechanical properties of the soil layer will be discussed separately. Drilling data obtained by drilling technology can accurately describe the spatial distribution of engineering geological layers from a wide range of sources and thus be used in this study. The drilling data used in this study need to include position, stratification, lithology, and particle screening information.

2.2 Indices

Due to the lateral shifting of the sedimentary environment and the vertical change in the sedimentary cycle, sediment type has seemingly complex changes in both horizontal and vertical directions. However, the horizontal change will become more comparable and regular if the considered unit is a sedimentary cycle or a multi-layer combination of sedimentary cycles. Therefore, soil layers are dealt with in units of multi-layer composite to conduct the quantitative analysis. The most typical layer group is the binary structure of alluvial deposits, so this quantitative analysis method using multi-layer composite is also called "composite binary structure analysis."

According to the engineering survey, the soil layer is usually divided into a series of layers of certain specific soil properties, which are continuously overlapped underground. The interior of the single layer is regarded as uniform soil, and there are changes in soil properties only between different single layers. This single layer is the basic assignment unit.

First, the engineering geological layers are grouped into two major sets, coarse-grained and fine-grained layers, from the perspective of the composite binary structure. Coarse-grained soil includes gravel, sand, and silt. Fine-grained soil includes clay and mucky soil, clayey silt, and silty clay. It can be seen that these two groups of soil reflect the solid and weak hydrodynamic sedimentary environment, strong and weak mechanical properties, and permeability, respectively. The specific rules are described below.

0.075 mm is taken as the boundary particle size between coarse and fine soil. When a single layer is composed of more than 50% coarse soils, it belongs to the coarse-grained layer. On the contrary, when it is composed of more than 50% of fine soil, it belongs to the fine-grained layer.

To illustrate the distribution of coarse-grained and fine-grained layers in the layer group, this research uses two indices to describe the soil layer characteristics of the layer group, the thickness ratio of coarse-grained soil layer to fine-grained soil layer and the average particle size of the coarse-grained soil layer. The first index is the percentage of the thickness of all coarse layers in a layer group, with a range of 0~1, called the coarse layer ratio (CLR). For every single layer, if it belongs to fine-grained soil, the soil property value is zero; and if it belongs to coarse-grained soil, the soil property value is 1. The weighted average of the soil properties value of each layer in a composite layer group is defined as the CLR of the layer group, namely a composite binary structure. When all the soil layers are coarse, the CLR equals 1. When all the soil layers are fine, the CLR equals 0. When there are coarse and fine layers, the coarse-layer ratio is between 0 and

The second index is the average particle size of the coarse layer, which is the weighted average particle size in millimeters of all the coarse layers in the group. The corresponding nondimensionalized values are 0.1~1.0 and 1.0 for particle sizes of 0.01~2 mm and above 2 mm, respectively. In this way, a layer group consisting of 1~N single layers is described by two indices with values between 0-1, namely the ratio of coarse layers and the average particle size of coarse layers, after dimensionless, which is equivalent to a two-dimensional vector. The two indices obtained through information simplification can meet the needs of quantitative analysis and retain the basic information of geological origin and geotechnical engineering properties of sedimentary strata. The second index is not currently discussed in this study.

2.3 Methodology

The study is carried out in the following steps. Step 1 is drill hole data collecting and data cleaning. Step 2 is data analysis, statistics of the average thickness of engineering geological layers, soil types, and other characteristic data in the area. Step 3 is engineering geological layers classification. Step 4 is the study area vertical layering and coarse layer ratio calculation. Step 5 is calculating and visualization. Step 6 is the result analysis.

The study region was separated into layers based on layer thickness, and each layer's geographic distribution of CLRs was examined. The study layers can be divided into two ways. One is for actual construction projects, where underground structures are spatially distributed on a surface of the same elevation. As a result, the reference elevation is established, and the thickness of the corresponding research layer is determined by the size of the engineering construction at the time. The other one is for geological scientific study. The research layer is connected to the geographic location of the engineering geological layer, and the layer thickness is determined by the engineering geological layer's thickness. The weighted sum of the coarse layer ratio calculations for each engineering geological layer in the layer group is used to get the coarse layer ratio of the research layer.

The interpolation approach is applied in this study to forecast the unknown point data to obtain the overall assessment of the study area. Kriging interpolation, a technique for unbiased optimal estimation of regionalized variables in a finite area based on structural analysis and variational function theory, has recently gained popularity in scientific studies due to its effectiveness (Li et al., 2013). ArcGIS 10.7 is used to carry out this study.

3 CASE STUDY

3.1 Study area

The study area is located in the Nanshan District of Shenzhen's southern alluvial plain and reclamation area, a commercial hub in southern China. The drilling data is distributed in strips along the NO.2 metro line, as in Figure 1. Along the route, it passes through geological areas such as the Holocene lagoon deposit, the Upper Pleistocene marine deposit, the Lower Cretaceous Yanshanina IV hills, and artificial accumulation.

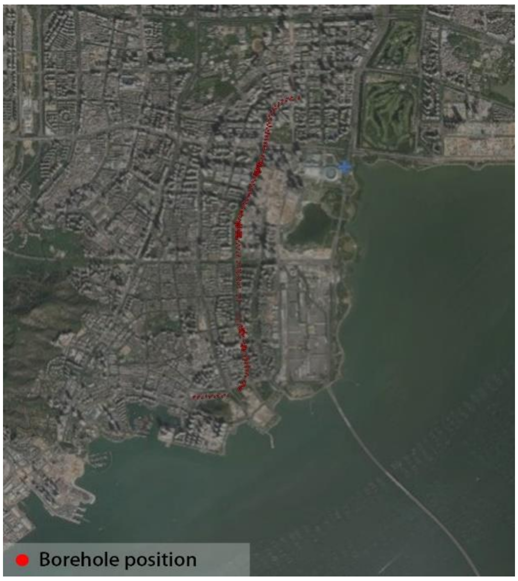

Figure 1. *The spatial location of drilling data*

3.2 Study layer dividing

According to data analysis, the artificial fill layer in the research region had an average thickness of 5.2 meters and an average elevation of 4.4 meters. The area below elevation -1 m was chosen as the study area. The soil layers were separated by 4 m as the layer thickness, with the first layer ranging from -1 m to -5 m, the second layer ranging from -5 m to -9 m, the third layer ranging from -9 m to -13 m, and the fourth layer ranging from -13 m to -17 m.

3.3 Meshing

The drilling data were dispersed in a strip along the metro line with a maximum section width of 100 m and an interval length of 5.6 km. The study area boundary was manually determined according to the drill geographical distribution, and the area was divided into a grid of 15m*15m squares, creating a total of 2979 grids. The average value of the CRL was used as the coarse layer ratio value of the grid inside each grid.

3.4 Classification of the geological layer

Eleven engineering geological layers are identified in the drill data in the study area, and the values were assigned according to 2.2.

4 RESULT

The case computation results are displayed in Figure 2. The result shows that soil layer characteristics are visually displayed, and based on the coordinate data, the coarse layer ratio of any point in the study area can be queried. For instance, the coarse layer ratio of the point (16225.000, 102263.000) under the independent coordinate system in Shenzhen is 0.047 in the interval of -1~-5m, meaning that the location of this point is a fine layer in the interval of elevation -1~-5m. On this foundation, we can do quantitative comparison analysis directly in all directions of horizontal space. For example, the coarse layer ratio in the first and second layers has less variation, reflecting the consistency of soil characteristics over a large area. In contrast, the third and fourth layers change relatively frequently, from which we can see changes in soil layers' characteristics at different depths.

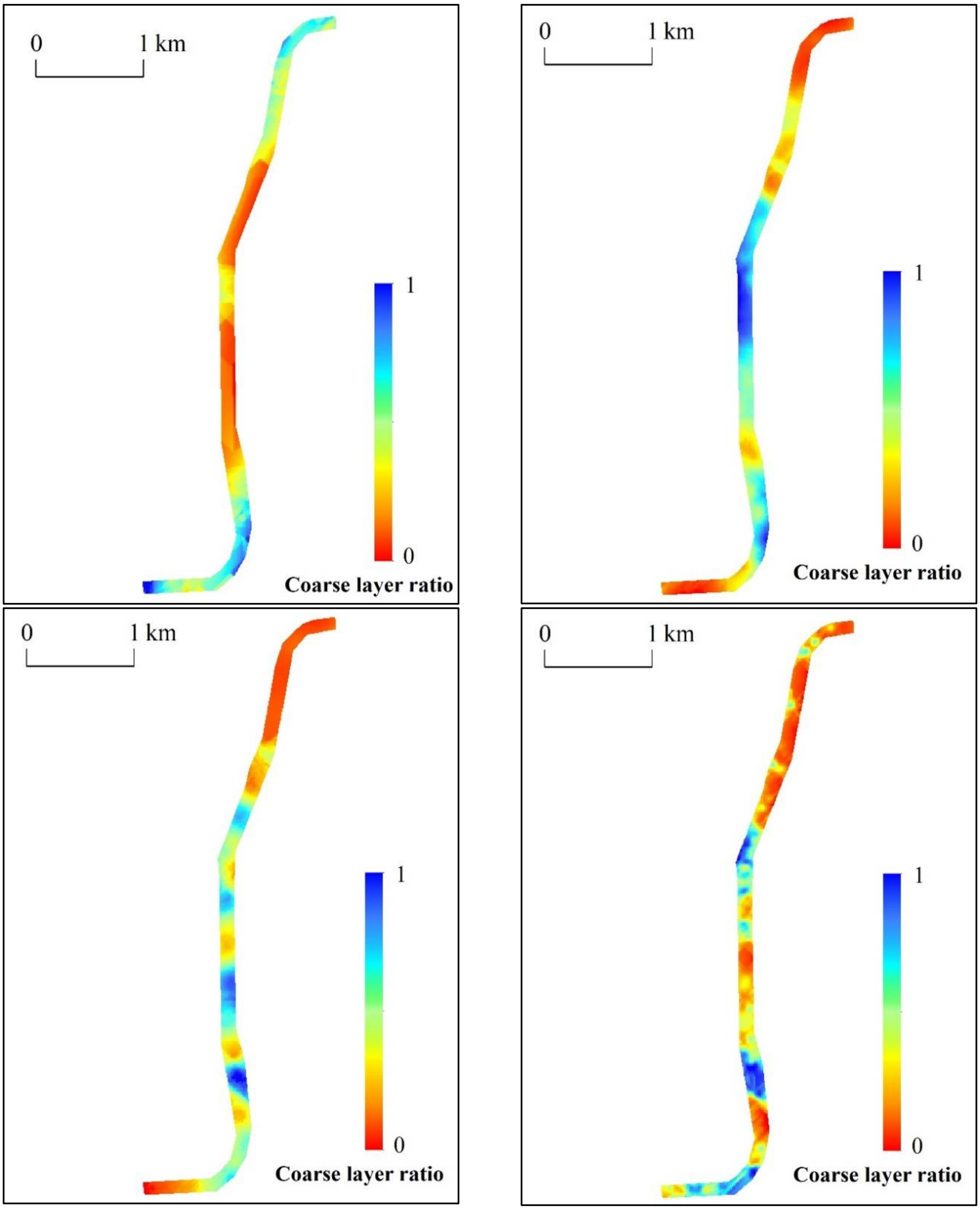

Figure 2. *Coarse layer ratio on the first layer (top-left), the second layer (top-right), the third layer (bottom-left) and the fourth layer (bottom-right).*

The research area's coarse layer ratio cloud map is loaded simultaneously with the geological map for comparison. In some unique geological regions, such as those with abrupt geological type changes, the change in coarse layer ratio exhibits a specific association with geological change. The coarse layer ratio exhibits a significant rate of change at the intersection of various engineering geological layers, as in Figure 3.

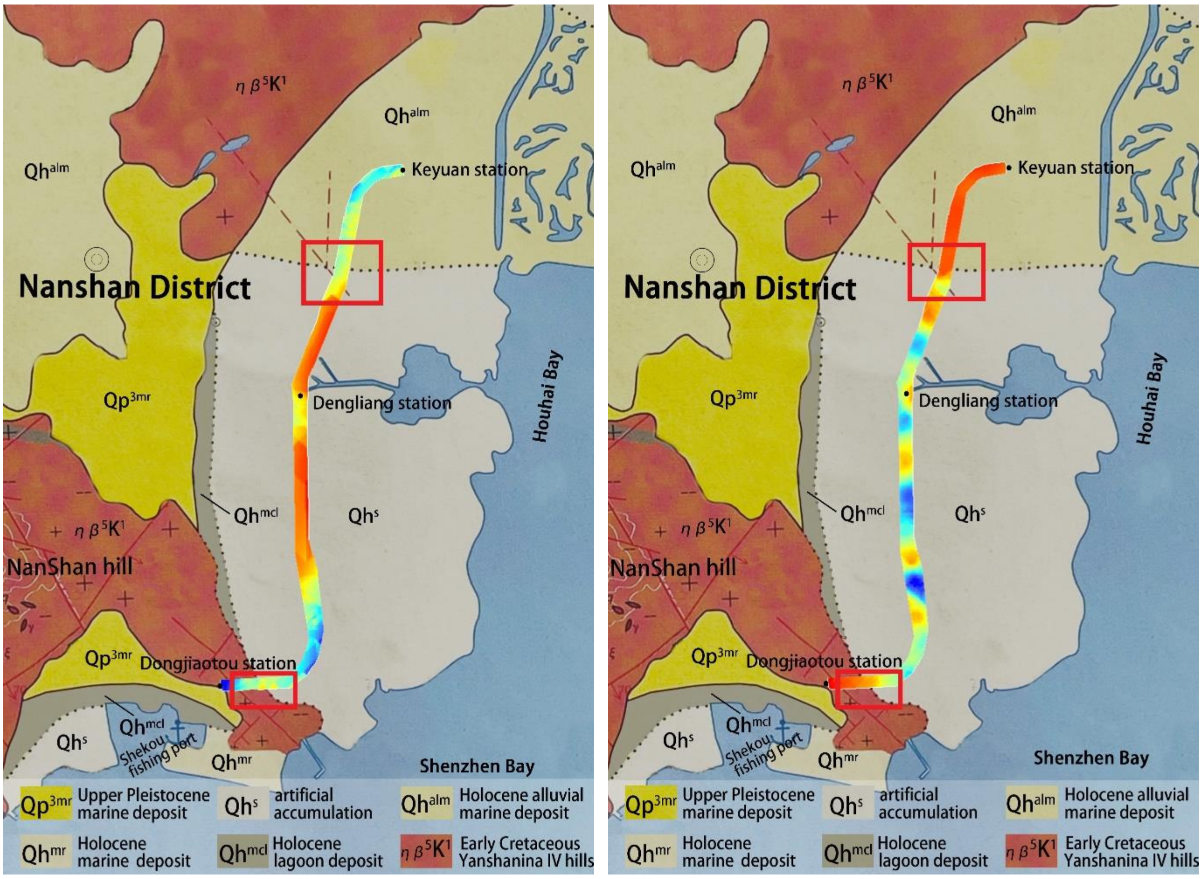

Figure 3. *Coarse layer ratio cloud map on the first layer (left) and third layer (right) compared to the geological map.*

5 DISCUSSION

To realize the quantitative description and analysis of geological features in the planning and development of deep underground space, the concept of "composite binary structure analysis" is proposed, and the quantitative expression of geological features is realized through the parameter of coarse layer ratio.

An essential presumption of this work is that soil layers can be divided into coarse- and fine-grained layers. The current system of classifying soils is based on the gradation of soil grains, and binary division research is still in its infancy. It is undeniable that precise classification of soils based on their granular composition is more convenient for earlier research; however, this approach cannot be used for spatial studies−−with distance, soil characteristics briefly alter. Binarization can be considered a macroscopic perspective that, when the study area is large, assures consistency of judging standards and relative correctness in the description of the soil layer.

In the process of quantitative study, a variety of quantitative indices have been tried in the previous study, which is affected by the three compositions, physical state, and structure of the soil, such as physical and mechanical indices (Li et al., 2013). As one of the three phases, solid particles affect the distribution of gases and liquids and can also reflect the soil structure and physical state. In this paper, the quantitative expression results are compared with the geological map, and the existence of a correlation is found. It is foreseeable that this method can use discrete drill data to predict particular geological phenomena.

6 CONCLUSIONS

The quantitative evaluation to describe and analyze geological characteristics is a new topic in planning and developing deep underground space. This study introduces the concept of coarse layer ratio, formulates the assignment and calculation rules of engineering geological layer, manually divides the grid and horizontal layer, and realizes the quantitative expression and analysis of the study area using the Kriging interpolation. Through the case study, it was discovered that in the expression of some unique geological phenomena, the research findings of this approach are associated with those of conventional geological categorization methods. As a result, the quantitative research method using the coarse layer ratio is workable and offers a novel perspective for continuing related research. With machine learning, the method of recognizing unique geological phenomena will be investigated in the following stage. It is also anticipated that a correlation between the mechanical and economic indexes of engineering construction will be established.

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