Study on geotechnical engineering investigation method of strong karst deep backfill area in mountain area

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Abstract: Guizhou Province is characterized as mountainous with few flat lands. It also features undulating terrains; widespread karst strata; large karst troughs; karst depressions and falling water caves; and well-developed underground karst caves, karst pipelines, and underground rivers. In such mountainous areas, large-scale construction of karst sites requires large-scale excavation and backfilling. The study site comprises several backfilled layers of 5–50 m thickness and features complex components and large thickness variations. The influence of the long-term seepage of surface water and groundwater is also apparent. However, the study site also exhibits an uneven settlement of deep backfilled layers and unstable karst foundation. The conventional survey method cannot identify effectively and comprehensively existing problems in engineering geology and hydrogeology according to the problems found in the investigation of large-scale building areas, municipal roads, urban rail transit, and university campuses. Through the combination of building engineering methods, such as new and old topographic and geomorphologic contrast methods, on-site geological surveys, karst hydrogeological surveys, borehole layout principle, drilling method, effective physical exploration test, field in-situ test, and indoor test, the scale and characteristics of karst development in the study site, changes in backfill thickness and material composition, and physical and mechanical properties of rock and soil mass are determined. The results provide comprehensive geotechnical data for the type selection, arrangement, and foundation scheme selection of structures. Through comprehensive analysis and summary, this work establishes a set of comprehensive geotechnical investigation methods for strong backfilled karst areas in mountainous regions. The results are expected to be applicable to other similar sites.

Key words: Strong karst stratum in mountain area; deep and thick backfill area; karst foundation stability; uneven settlement; seepage influence; exploration method

0 Introduction
Guizhou is a mountainous area with a wide distribution of karst strata, surface karst hills, karst troughs, large karst depressions, and falling water caves. It also comprises underground hall-type karst caves, large karst pipelines, and isolated-type karst caves. This area is mainly characterized as having an uneven surface and numerous underground caves. With the continuous development of Guizhou’s economy in recent years, construction activities have taken off rapidly. In particular, a large number of earth-rock construction projects have excavated and discarded ballast continuously, thereby backfilling the low-lying troughs, depressions, and falling water holes. As construction projects progress, previously backfilled and waste areas have become new construction sites characterized by flat fields. With these changes, Guizhou is now described as a special construction site whose “lower part is the karst development area and the upper part is the deep backfilled area.” Two problems need to be
solved in the geotechnical engineering investigation of deep backfilled zones in strong karst strata: karst collapse and the uneven settlement of deep backfilled zones. At present, no systematic research at home and abroad has focused on the investigation of deep backfilled sites. The main investigation methods employed are geophysical prospecting and drilling methods. High-density seismic mapping is used to explore backfilled refuse pits in a shield-driven approach; the method can accurately reflect and distinguish the shapes of bad underground geological bodies, and it can be integrated with exploration hole data for the quantitative analysis of bad geological bodies[1]. The geological radar technique is used to determine the specific position, buried depth, and distribution range of rocks in a rock fill site[2]. On the basis of the study of core drilling technology for deep sand and cobble beds of riverbeds in western hydropower industries, researchers put forward an air down-the-hole hammer drilling technology, which can realize synchronous core drilling and is suitable for sand and gravel cover in hydraulic engineering; for this technology, a type of vegetable gum flushing liquid with strong wall protection is used[3]. Current exploration methods for backfilled strata mainly adopt single geophysical prospecting or geophysical prospecting with exploration. However, no comprehensive survey method has been reported. Moreover, the research on deep burial and the fluctuation of backfilled bottom boundaries, stage backfill, the lower part of strong karst strata, and other multibody characteristics in site exploration remains limited. In the current work, deep backfilled areas in strong karst strata in mountainous areas are investigated and analyzed in detail. The results are expected to be of guiding significance to similar engineering investigations.

1 Basic Geological Conditions

1.1. Topography and geomorphology
Following the characteristics of Guizhou’s topography and geomorphology, most large-scale engineering construction projects are located in the controllable region characterized by a 0–100 m elevation difference and 5–30 topography gradient. This region is a low Zhongshan karst basin, a large karst trough, a large karst depression, and a denudation–planation landform with a relatively large relief.

1.2 Formation lithology
Arranged from the most recent to the oldest one, the general lithological characteristics of the deep and thick backfilled layers in the strong karst area of the mountainous region of Guizhou are as follows:

(1) Overburden
1) Recently backfilled soil (Qm2): Plain backfilled soil, which is filled with crushed stones and clay in the process of leveling the construction site. The thickness ranges from 5 m to 20 m, the structure is loose, some of the broken stones are overhead, and the uniformity is poor.
2) Early backfilled soil (Qml): Plain fill, mainly composed of building debris, clay, and crushed stone. It is loose and locally dense.
3) Quaternary relict clay bed (Qedl): Light yellow and yellow clay with crushed stone. Its thickness ranges from 2 m to 18 m, and its part is 30 m. It is mainly distributed in depressions, solution troughs, and gentle slopes.

(2) Underlying bedrock
Most of the limestone, dolomitic limestone, dolomite, and limestone dolomite formations are highly soluble.

1.3 Geological structures
Mountain areas are developed not only by faults of various sizes but also by unloading fractures, large-scale corrosion fractures, and steep dipping and gently dipping fractures developed in different directions. Filling clay, calcite, the extension length of 2~10m, a small part of extension 30~50m.

2 Characteristics of Karst Development
Limestone, dolomite, and dolomitic limestone outcrops, which are affected by faults, corrosion fissures, and the development of sinkholes, provide the necessary migration and storage space for the surface and
groundwater activities of the site. Hence, they create favorable geological conditions for the development of surface and underground karstification. The morphological characteristics of surface and underground karstification are as follows:

2.1 Morphological characteristics of surface karst
The main features of areas with widely distributed and well-developed strong karst strata, karst depressions, karst trough valleys, and karst caves are as follows:
1) Karst depressions and sinkholes: Located in the low-lying areas of the site, most of these formations are round and oval in shape, with diameters ranging from 100 m to 1,000 m. One to five sinkholes develop at the bottom of depressions, which serve as collecting and discharging channels for surface water during flood season.
2) Karst trough valley: It is a strip-shaped valley with a width of 100–300 m and a length of 500–1,000 m. The bottom is often accompanied by a sinkhole, and the end is mostly connected to a karst depression, which serves as a drainage channel for collecting surface water during flood season.
3) Karst cave: It is mainly a large-scale karst cave, which is located in the middle and bottom of the steep wall of the mountain. It is the location of the underground karst pipe. The diameter of the cave varies from 2 m to 10 m, and the length of the cave is more than 500 m. Such a cave is typically detected manually.
4) Solution ditch and solution trough: They are mostly developed along dominant cracks, and their surface width ranges from 0.5 m to 5.0 m, more filled clay, local non-filling.

2.2 Morphological characteristics of underground karst
Extensive karst investigations and geological data analyses in the geotechnical engineering investigation of karsts reveal that underground karst morphology can be divided into isolated, beaded, hall-type, karst pipeline, and karst underground river according to scale. Their characteristics are as follows:
1) Isolated small karst cave: This type of karst cave is small in scale and is generally distributed in the shallow layer of rock mass. The diameter of this cave is 1–5.0 m, and it is not typically connected to the cave. This type of cave mostly develops along fissures and is mainly filled with clay; in some cases, it is not filled or is semi-filled.
2) Beaded karst cave: This formation mainly has 2–4 layers along a steep fault and fissure structure. The distance between the upper and lower layers is 3–5.0 m, and the diameter of the cave is 2–5.0 m. It is beaded, the upper part is mostly unfilled, and the lower part is filled with soft plastic and flowing plastic clay.
3) Hall cave: It is relatively large in scale, with its height ranging from 5 m to 20 m. It measures 30–40 m long and shows no filling, as shown in Figure 1.
4) Karst pipe: It generally develops along the fault, its length is more than 500 m, and the hole diameter is 3–10.0 m. It has no water flow, and most of the bottom part has karst accumulation, as shown in Figure 1.
5) Karst underground river: Its morphological characteristics are basically the same as those of karst pipelines, but its development position is relatively low. It is usually near the base level of groundwater discharge and has long flowing water.
3 Groundwater Recharge, Drainage, and Runoff Conditions

The karst area generally has two types of groundwater: quaternary pore water (aeration zone water) and karst phreatic water.

(1) Quaternary pore water is mainly distributed in quaternary loose deposits, which are widely distributed and highly permeable. This groundwater is mainly supplied by atmospheric precipitation and is drained by evaporation and seepage to the lower bedrock. The amount of water is small, more than the upper layer of stagnant water type exists, by the surface and atmospheric precipitation recharge greater influence, water level change is also greater.

(2) The foundation rock of the site is soluble limestone, the karst is strong, and the joints and fissures are well developed. After a long period of erosion and weathering, the fissures in the limestone have become a system and channel for the storage and transportation of groundwater and the formation of karst fissure water and karst groundwater. It is characterized by large cross-section changes, flow that is not concentrated and is unobstructed, slow flow speed, and small hydraulic gradient. Its supply source is the same as that of the stagnant water in the upper layer. Its discharge is mainly seepage discharge; lateral discharge is the auxiliary form. Therefore, the site is characterized by the obvious seasonal characteristics of groundwater.

(3) Groundwater runoff: The direction of groundwater runoff is mainly to the lowest river and reservoir base level near the project area through the fissure dense zone, underground karst pipeline, and underground river.

4 Exploration Methods

Strong karst strata in mountainous areas show surface karst depressions, falling water caves, karst ditches and karst troughs, large underground karst caves, karst pipelines, and underground rivers. Hence, this work focuses on geotechnical engineering methods for exploring the varying properties of these formations, the extremely uneven composition of rock and soil, and the complex foundation conditions in the field.

4.1 Comparison of new and old geomorphologic landform characteristics

Prior to any field work, 1/1,000 or 1/500 topographic map surveying and mapping should be carried out. Existing topographic and geomorphologic features can be fully reflected in a map. However, with the passage of time and the continuous development of national engineering construction, the existing geomorphologic features and the original geomorphologic features may greatly vary. In any geotechnical investigation, one must understand the changes occurring over a certain time period, and early
Geomorphologic data should be used for analysis and comparison. At present, most parts of China have 1/50,000 and 1/0,000 topographic maps from the early 1990s. Through the analysis and comparison of new and old topographic data, the change process of topographic features, the original karst geological conditions, and the backfilling conditions can be preliminarily understood. (Figure 2). The specific contents of the comparison are as follows:

1) The original and present topography, which can be used to compile the geological section for the analysis of the original topography and geomorphologic features and present conditions;
2) The boundary of the backfilled layer and the change of thickness;
3) The distribution range and boundary condition of the karst depression;
4) The location and scope of the cave of falling water determined preliminarily from the lowest depression zone of the original topographic map.

Through the analysis and study of these four aspects, the original and existing topographic and geomorphological features of the whole site and the preliminary formation of the spatial structure can be transformed. A series of data and mapping software may be employed to generate the corresponding 3D models, which can then be used as basis for geotechnical engineering investigations and for the selection of the next investigation scheme and workload layout.

4.2 In-situ geological mapping

In-situ geological surveying and mapping is an important task. However, in geotechnical engineering investigation, the control over the site scope often results in incomplete geological survey and mapping and reduced attention to the task. The impact of these drawbacks is minimal on plain areas but prominent on mountainous terrains. Serious problems such as collapse, landslide, debris flow, water gushing, and antifloating failure occur in the later stage of a construction project. These issues are related to the geological environment around the project area, the geological boundary conditions, and the insufficient karst hydrologic investigation. A 1/1,000 topographic map of the survey area and 1/10,000 topographic map of a large area should be utilized to survey and map engineering geology and hydrogeology. Moreover, any change in geological environment conditions from the scope to the surrounding area may influence engineering construction. Geological mapping involves the following.

(1) Lithology investigation of site and surrounding strata: Geological mapping is conducted starting from the site and then to the surrounding mountains. The detailed investigation covers exposed strata lithology and rock and soil type distribution range. The 1/10,000 topographic map of the site and the surrounding mountains can be used for supplementary geological survey when the existing topographic map does not adequately cover the area.

(2) Geological structure: Site activities and the passage of large faults can be ascertained by finding out the occurrence, development scale, character, and distribution area of unfavorable structural planes, such as faults and joints (or fissures), all of which may affect the stability of the slope.

(3) Karst investigation: This investigation is mainly aimed at identifying the morphological characteristics and development scale of karst caves, karst depressions, karst ditches and karst troughs, etc.

(4) Hydrogeological investigation: The investigation and statistical analysis are carried out on the site and the surrounding water bodies, rivers, streams, and springs that may influence the project so as to determine the direction of surface runoff discharge, the water level, and the change of water volume during the dry
flood season. For the site in a low-lying area, the area of surface water conflux should be identified to provide basic data for water gushing and antifloating.

(5) Investigation of adverse geological phenomena: The main adverse geological phenomena of construction sites in mountainous areas are collapse, landslide, and debris flow, which are generally distributed in higher terrains around the sites. The site investigation should be based on topographic conditions, the position of the distribution of the loose soil layer, the attitude of the stratum, the geological structure, the unfavorable structural plane, and the surface water conflux of the mountain valley. The distribution location and scale of possible collapse, landslide, and debris flow should be delineated to provide data for the analysis and evaluation of adverse geological hazards.

4.3 Geophysical testing

In all types of geotechnical investigation in the field of engineering construction, the main method used is physical exploration and testing. This approach can provide a basis for preproject planning, site selection, route selection, and engineering investigation and evaluation in the construction period. However, many other methods are available, and they entail different requirements depending on the environmental conditions, geological conditions, test depths, and suitability of the site and its surroundings. These methods have different effects. The current study mainly explores mountain terrains, strong karst strata, deep backfilled layers, and the problems that must be solved and the methods adopted under the geotechnical engineering investigation code. Geophysical testing mainly involves the following.

(1) Shear wave test: This test is also called the surface wave or shear wave test. It is a method of site classification for natural soil layers, backfilled layers as foundation bearing layers, or sites with thick soil layers. This classification is necessary for the seismic design of buildings. The test can be used to judge the thickness, depth, and compactness of the new and old backfilled layers and the original soil layer.

(2) Microvibration test: This test method applies to microwave groups with natural vibration sources (wind, wave, traffic, etc.) whose amplitude is $10^{-6}$–$10^{-7}$ m and whose frequency is 0.5–20 Hz. It mainly provides a site’s predominant period and microvibration amplitude for the seismic and vibration isolation design of buildings. It also serves as a supplementary certification method for site classification. The data for this method are rich, but the environmental requirements are high. Generally, no source is located within the 150 m radius of a survey point.

| Predominant period T (s) | Type of venue |
|--------------------------|---------------|
| <0.1                     | I (Bedrock)   |
| 0.1–0.4                  | II (Primary soil) |
| 0.4–0.8                  | III (Loose soil) |
| >0.8                     | IV (Abnormally loose soil) |

(3) Shallow seismic method: This method is highly accurate for testing the thickness variation and depth of overburden. It is also used to determine the interface between the backfilled layer and the primary soil layer, bedrock, and soil layer. It has been widely used in practical work. Using this method to test the depth of overburden in mountainous terrains yields positive and highly reliable results.

(4) High-density resistivity method: This method is widely used in geotechnical investigation, and it can be employed to determine the thickness of site overburden, the locations of superficial karst caves, and the distribution of fault fracture zones. However, it has many restrictive conditions and a limited test depth. Hence, it is not ideal to use in testing the karst caves and faults in deep backfilled layers, shallow groundwater levels, and bedrock fluctuations.

(5) Magnetotelluric method (EH4): This method is widely used in the initial exploration of underground water levels; large karst caves (generally more than 5.0 m in diameter); large karst pipelines buried in rivers; and the distribution of large fault structures in railways, highways, water conservancy and other tunnel projects, and watershed areas on both sides of reservoirs. The method is suitable for mountainous terrains, and its testing depth is large; however, the accuracy is poor. The geophysical EH4 testing method is included in this work mainly because the testing depth of other methods is limited and the error is relatively large. EH4 can preliminarily determine the groundwater level, possible large-scale water falling caves,
large-scale beaded caves, and possible karst collapse areas caused by the development of large-scale karst pipelines. Through this test, we can determine the location and scale of karst development and provide a theoretical basis for the arrangement of ground structures and detailed exploration work.

(6) Interhole CT detection method: It is also known as the cross-hole tomography detection method. This method has relatively high test accuracy, but the requirements for the distance between test holes and the depth of holes are strict. The effect is generally favorable when the spacing is less than 30 m and the effective test hole depth is more than 1.5 times that of the spacing. Therefore, its survey workload, especially for the detailed survey stage, is relatively large when identifying the specific locations of karst caves and their development scale.

For the preliminary exploration stage, 1) the site shear wave and microvibration tests should be completed as required by the code; 2) the shallow seismic method and high-density resistivity method can meet the requirements for determining site backfill thickness, and one of them can be selected according to specific conditions; 3) geophysical EH4 is relatively effective in testing deep and large karst caves in deep backfilled layers and strong karst development areas in mountainous regions. In the detailed exploration stage, the CT detection method can be used to investigate and demonstrate the large karst cave identified in the preliminary exploration stage, including their specific locations and development scale.

4.4 Layout principles and drilling methods of exploratory boreholes

4.4.1 Principles of layout of exploratory boreholes

For geotechnical engineering investigations in strong and deep backfilled karst areas, the arrangement of boreholes is important. At present, states, industries, and localities have corresponding regulations, specifications, and requirements, which are universal but not highly targeted. In completing the arrangement of boreholes, the following problems should be considered:

(1) According to the field geological mapping data, the distribution range and property characteristics of backfilled layers and primary soil layers of a site, the karst development characteristics, and the hydrogeological conditions should be determined comprehensively. Drilling holes are encrypted in the complex section.

(2) For engineering geology and hydrogeology problems on site, the problems that need to be identified through investigation and drilling should be targeted.

(3) The distribution position, scale, characteristics, load size, and distribution form of ground structures should be established. The requirements for bearing capacity and foundation deformation should also be met.

(4) The foundation form to be adopted for the construction should be identified.

(5) The geophysical test for the verification of suspected large karst cave drilling should be based on the principle of identifying development location, scale, and direction.

(6) Borehole depth control: In the initial stage of drilling, the possibility of large-scale karst collapse should be considered within a range of not less than 40 m below the bedrock surface. The depth of boreholes in the detailed survey stage should be determined according to the foundation form to be adopted. The depth of boreholes in the foundation with a backfilled layer and an undisturbed soil layer as the holding layer should be no less than 5.0 m below the bedrock surface. The drill hole of the pile foundation should pass through the dissolution fracture zone and karst cave and enter the relatively complete and stable bearing layer of rock mass. Given the influence of strong karst development and later construction control, the drill hole control depth of not less than 7.0 m should be at the bottom of the foundation.

4.4.2 Drilling method

In view of the current drilling operation market for engineering exploration, most drilling methods are relatively independent. Even though many complex sites have various rock–soil combinations, the drilling operation mode of one drill to the end is still adopted. However, this method has weak relevance and low core recovery rate. Given the impossibility of judging the properties and material composition of backfilled and soil layers and the nonideal coring of broken rock mass, which seriously affects the quality of exploration, the drilling methods and working methods should be studied comprehensively, and corresponding effective measures should be adopted.
(1) Double-pipe single-action drilling method: Deep backfilled zones are characterized by a complex composition of rock and soil and differently sized particles. In improving the core recovery rate, the double-pipe single-action drilling method is preferred. Through field tests, the core recovery rate can reach over 80%. The method is suitable for backfilled layers and broken rock mass, and the effect is satisfactory.

(2) Barrel percussive drilling method: The main principle of this method is to use the weight of the barrel itself to enter the soil layer, drill, and take the core after falling freely at a certain height. This method is suitable for hard plastic, plastic, and soft plastic soil layers of red clay. Years of practice have proved that this method causes little disturbance to the soil layer and that it has a high coring rate.

(3) Rotary drilling method: This method is suitable for drilling bedrock with relatively good underlying integrity. However, it is not applicable to strong weathered layers, corrosion-affected zones, and broken rock mass.

The analysis shows that the double-pipe single-motion drilling method can be used in deep backfilled zones, strong weathering zones, corrosion zones, and broken rock mass areas. The tubular percussive drilling method can be used in clay layers. The return drilling method can be used for bedrock with relatively intact rock mass. The drilling method can be selected according to the illustration in Figure 3.

Fig. 3 Section diagram of comparison and analysis of engineering exploration drilling methods

4.5 In-situ testing

For deep backfilled zones, the long backfill time and the great changes in backfill composition result in considerable differences in compactness, particle gradation, inhomogeneity, etc. Suitable in-situ tests can be used to ascertain the physical and mechanical properties of landfills and provide reasonable geological parameters for the design of structural layout, type selection, and foundation treatment. However, they are not suitable for long-term excavation and backfilling in the Guizhou mountainous area. Hence, a well-targeted and effective testing method should be adopted. Years of practice have proved that the following methods are most applicable.

(1) Dynamic penetration test (DPT): DPT is a widely used and effective method for testing the compactness and character division of backfilled layers in backfilled zones. Its compactness, material composition, and grain gradation are also quite different. The type of DPT should be fully considered. Three methods can generally be used in equipment selection: 1) light dynamic sounding can be used for loose layers of 0–8.0 m, backfilled layers of −10 cm, and backfilled layer with less than 40% crushed stone content; 2) heavy dynamic sounding can be used for slightly dense backfilled layers of 8.0–20 m, backfilled layers of 5–20
cm, and backfilled layers with similar content of crushed stone and clay; 3) overheavy dynamic sounding can be used for backfilled layers of more than 20 m with long backfill time, good compactness, and crushed stone and clay content measuring 10–50 cm. This method can determine the compactness and deformation characteristics of most backfilled layers, but it is not suitable for backfilled sites with a particle size of more than 50 cm and content of more than 60%.

(2) Standard penetration method: For the distribution area of primary and secondary red clay layers, the standard penetration method can be used to test the physical and mechanical properties and state characteristics of the soil layer. It can also be used to analyze the nonuniform settlement deformation of foundations and the stability of mountain slope soil foundations. It is one of the important means to obtain the physical and mechanical parameters of soil layers.

(3) Plate loading test method: This method is the most effective approach to studying shallow backfilled areas, the physical and mechanical properties of surface layers, and deformation characteristics. The measuring points can be arranged at the surface layer of the backfill elevation and the two parts below 5.0 m. The pressure–settlement curves of backfilled layers under different conditions and depths are measured by non-immersion and immersion test methods, as shown in Figures 4 and 5, respectively. These curves are an important index of foundation design and treatment.

(4) Density detection method: Through density detection, the density index of backfilled layers can be determined, the main material composition of the site can be understood, and the parameter index can be provided for the calculation of the settlement and negative friction of the backfilled area.

(5) Particle testing method: This method can directly determine the material composition, particle size change, and percentage of backfilled layers. It can also provide the geological parameters for basic type selection and construction, and it is an important method for the on-site testing of backfilled areas. The parameters obtained by the test are shown in Figure 6.
4.6 Indoor testing
Mainly through the field sampling of rock, soil, water physical mechanics and corrosion of the conventional test, no special, according to the relevant rules and regulations can be implemented. Emphasis should be placed on the corrosion test of backfilled layers. As a result of the considerable changes in the composition of landfill materials in different periods and regions, corrosion problems may differ in severity. Hence, in the course of investigation, we should employ the sub-area and sub-depth sampling method according to the changes of the materials in backfilled layers to determine the corrosivity of each material.

5. Conclusion
This work focuses on the geotechnical investigation of a large-scale housing construction area, municipal road, rail transit, university park, etc. in the strong and deep backfilled karst layer in the mountainous area of Guizhou Province. The goal is to address the problems of the settlement and deformation of deep backfilled layers and karst collapse of underlying strong karst strata through a suitable and targeted geotechnical engineering investigation method. Such method should serve as the basis for ascertaining all engineering geological problems and hydrogeological conditions. On the basis of the analysis and summary of previous surveys, this work forms a set of favorable geotechnical engineering survey methods to guide future work and improve the quality of survey products.

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