Study of the Limestone Strength Weakening Mechanism at the Eastern Margin of the Kangdian Palaeouplife in Southwest China

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Abstract. The limestone of the South China Lower Permian Qixia & Maokou Group usually features high purity, high strength, and poor weathering, while the limestone of the Qixia & Maokou Group at margin of the Chuan-Dian Paleouplife of southeast China is characterized by obvious strength weakening. The weakening of limestone strength leads not only to excessive errors in the estimation of useful material reserves in the limestone quarry, but also increases the engineering slope support cost in the limestone distribution area on the eastern margin of the Kangdian Paleouplife. In order to ascertain the cause mechanism of the strength weakening of the limestone in the stockyard, we take the stockyard in the dry valley as an anatomical point. The strength weakening of limestone is comprehensively analyzed by means of drilling, large-section excavation, site investigation, sampling, and physical mechanics tests. The main findings are as follows: (1) The limestone area of the Qixia & Maokou Formation near the Kangdian Paleouplife generally contains terrigenous fine-grained materials and mud iron; (2) The weakened rock masses are divided into two types of weakening: deep dissolution type and deep strong weathering type. The uniaxial compressive strength of the deep weakened rock mass is only 2.5-25 MPa, which is 70%-90% lower than that of the fresh rock mass. Compared with the natural state, the compressive strength of the saturated rock mass is reduced by 60%-90%. The deep weakened rock mass has the characteristics of weakened strength and is softened by water; and (3) The dissolution type rock mass is weakened as a result of the dissolution of the high-level exposed broken spring along the east-west fracture zone; the formation mechanism of the strong weathering rock mass weakening is that under the conditions of tectonic shear, terrigenous muddy interlayer and dry-heating condition. The buried depth of groundwater is large, the hydrodynamic force is weak, and the coupling of water and rock under long-term infiltration environments makes the limestone body softened and argilized.
in situ, leading to a significant decrease in the strength of the rock mass.

**Keywords:** Terrigenous material of limestone; Fractured rock mass; Dry-hot valley; Limestone strength weakening

1. Introduction

The Yangtze platform, which is located on the eastern margin of the Kangdian Paleouplift in Southwest China, contains the Lower Permian Qixia & Maokou Formation (P_l g+m) limestone [1, 2]. This type of limestone has specificity in its petrology, sedimentology [3] and geochemistry [4] and shows high compressive strength and poor weathering [5-7]. In recent years, a strength weakening phenomenon of the rock mass has been observed at the eastern margin of the Kangdian paleouplifit, which is similar on both banks of the Xiaojiang River, where this limestone is widely distributed. The Hangudi quarry of Baihetan Hydropower Station, provides conditions for the study of the weakening mechanism from preliminary exploration to excavation.

The 935 × 10^4 m³ volume of coarse and fine aggregates that were required for the dam for the Baihetan Hydropower Station are all sourced from the Hangudi quarry in Qiaojia County (hereinafter referred to as ‘the quarry’). A preliminary survey revealed that the lithology of the quarry consists of thick layered limestone of the Permian Qixia and Maokou Groups, and the physical and mechanical indexes and limestone reserves can meet the quality requirements of the concrete aggregate used to construct the Baihetan dam. After excavation, a rock strength weakening phenomenon was found. Unexpectedly, the normal weakly weathered layer contains not only deep dissolvable weathering features, such as karst caves and dissolved collapse breccia, but there are also intense undissolvable weathering phenomena, such as saccular, lenticular, circular, and banded weathering. These phenomena are widely distributed at depths greater than 100 m and are controlled by multiple factors. These two types of weathering have caused the minable and eligible limestone quantities of the quarry to be much lower than the estimated values [8,9].

The adverse engineering geological effects caused by the strength weakening of the deep limestone body in the Hangudi quarry area of Qiaojia County are representative in northeastern Yunnan, in particular: (1) Insufficient understanding of the deep strength weakening mechanism has led to an overestimation of the useful material reserves of the dam, and it has to be re-examined, surveyed, and adjusted for expansion; (2) In areas with weakened strength, engineering slopes have poor self-stability, and design considerations such as strong support and increased grading coefficient are required; (3) These factors have guiding significance for the future resettlement, tunnel excavation, and school construction in the limestone area of Qiaojia County. Therefore, research into its strength weakening mechanism has important scientific value.

2 Methodology

This study aims to obtain a comprehensive understanding of the causes, types, and distributions
of weakened limestone through field surveys and drilling, and to determine the hydrogeological conditions in the quarry area. Then, samples of deeply buried weakened rock mass and normal weathered rock were sent to the Nanjing University of Technology for chemical analysis, X-ray diffraction analysis and petrographic analysis, and were also sent to the College of Earth Sciences, Chengdu University of Technology for thin-section analyses to understand the mineral compositions, structural characteristics and chemical composition changes of the weakened limestone. Natural and saturated uniaxial compressive strength tests were carried out separately to determine the strength weakening characteristics of the deep, strongly weathered rock masses. Finally, the faults and fissures in the area were catalogued, and plan layout and trend rose diagrams were drawn to understand the nature, scale and dominant position of the structural plane of the rock mass.

3 Characteristics of the weakened rock mass

3.1 Geological background of the quarry

The quarry is located in Hangudi village, which is upstream of the Baihetan Hydropower Station and is on the right bank of the Jinsha River, north of Qiaojia County, is approximately 31 km away from the hydropower station site. The quarry zone shows a large slope dip to the NW, and the southern and northern slopes have steep cliffs. The south cliff is 40–60 m high, below which there is the perennial anhydrous Dawanzi Gully; the north cliff is 40–50 m high and below it is the Xiaohongyan Gully, which is narrow with seasonal running water; the Zhongliangzi Gully is located in the middle and occasionally has running water (Fig. 1). The strata consist of the compact bioclastic limestone of the Lower Permian Qixia and Maokou Formations (P$_{q+m}$) and shows great thickness, with dips of N0°–15°E, NW 15°–25° that contain a muddy interlayer.

The Quaternary residual slope sediments (Q$_{e+dl}$) consist of maroon clay scattered on the surface. The Zemuhe fault, Xiaojiang fault, and a fracture zone intersection at the Daliangshan site are located in the quarry and are sinistral active strike-slip faults [10]. The activity of the Xiaojiang fault is the most intense, with the largest seismic events being as high as magnitude 8. The quarry area is mainly affected by the eastern boundary of the Sichuan-Yunnan rhombic block and the northern end of the active control of the NNE Xiaojiang fault (Fig. 2).
Figure 1. Location and lithology distribution of the quarry

Legend: I Xiaohongyan Gully, II Zhongliangzi Gully, III Dawanzi Gully, I Dalongtan, and 2 Xiaolongtan

Legend: I Bayanrola block, II South China block, III Sichuan-Yunnan block, IV Qiangtang block, V South Yunnan block, VI West Yunnan block, F₁ Longmenshan-Jinpinshan block, F₂ Xianshui River-Anqing River-Zemu River fault, F₃ Xiaojiang fault, F₄ Lijiang-Xiaojin River fault, F₅ Jinsha River-Hong River fault, F₆
Lancang River fault, and F; Shizhi fault

Figure 2. Main faults in the region

3.2 Type and distribution of weakened rock masses

The primary area of the planned quarry is approximately $22.5 \times 10^4$ m$^2$, its volume is approximately $1650 \times 10^4$ m$^3$, the mining elevation ranges from 1340 to 1620 m, the height difference is 280 m, and the weakening types of rock masses exposed in the deep part of the quarry mainly include two types: dissolvable weathering and undissolvable intense weathering limestone.

3.2.1 Dissolvable weathering and weakening of rock mass

The field surveys and drilling data indicate that dissolvable weathering is the main type. The intense dissolution is mainly concentrated in the intersection area between north yard faces B and AB, has a banded configuration, and an EW (240°) extension (Fig. 3). The top of the intersection area of faces A and B is the Zhongliangzi gully, its flow direction is 252°, and two perennial springs are exposed: Dalongtan and Xiaolongtan (Fig. 1). Dalongtan is a fault spring, located at the source of the Zhongliangzi gully, with a flow rate of 108 L/min; Xiaolongtan is located at the junction of the Zhongliangzi gully and top face of the quarry, with a flow rate of 10 L/min. Face B is relatively moist and there are several water outlets.

There are 8 karst caves in the quarry. They are distributed between elevations of 1405 to 1465 m, their widths are approximately 2 m, and their heights are approximately 10 m. Of these, 63% (5 places) are located in the area where plane B is located. The No. 4 karst cave is wet but the rest are dry caves. The cave distribution shows a significant spatial regularity and is entirely banded and distributed along the near EW part of the quarry. The types of dissolvable weakened rock masses in the quarry can be divided into karst cavities, weakly cemented filling by heterogeneous materials, and collapsed breccia (soil-like).

Figure 3. Distribution map of the karst caves in the quarry
3.2.2 Undissolvable intense weathering with large burial depths

The weathering degree of the rock mass in the quarry is controlled by the lithological composition and faults. The surface rock layer follows a normal distribution sequence of full-strong-weak-micro weathering. From the surface to the inside of the rock mass, the weathering degree changes from deep to shallow. Grooves and ridges are alternately distributed as zigzag patterns and the burial depths of the grooves are up to 16 m. Beneath the weak weathering, strong weathering can be found, which has a clearly uneven distribution. Most of the deeply buried weathered rock masses are earthy yellow, while part of the rock mass is wet and partially covered by weakly weathered rock blocks that retain the original dark gray or grayish white color. Based on the weathering type and distribution, the weathered rock with large burial depths can be roughly divided into four types: cystic weathering, lenticular weathering, ring island-like weathering and strip weathering.

Cystic weathering: Strong cystic weathering can be observed at different elevations below the excavated surface of the slope. According to the drilling and geophysical data, strong cystic weathering can still be seen even below an elevation of 1250 m (the design elevation of the bottom of the quarry is 1340 m). The zone of strong cystic weathering is mainly developed along fault intersections, and a dense zone of joints and fissures have developed at different scales, which generally range from a few meters to more than ten meters in width (Fig. 4).

Lenticular Weathering: On the central and southwest sides (elevation 1435~1465 m) of face A, lenticular weathering can be seen and is mostly distributed along extensional faults. The lens sizes are controlled by the scale of the extensional faults, and the axis direction is parallel to the fault dip. The long axis of the strongly weathered lens is approximately several meters to several tens of meters, while the short axis is approximately ten centimeters to several meters (Fig. 5).

Ring island-like weathering: The ring island-like strong weathering zone formed in the inlaid structure where the joints and fissures densely cut the rock mass, and its width is generally from tens of centimeters to a few meters and weathering occurs around the joints and fissures. The soil-yellow, strongly weathered limestone is wrapped with gray-black weathered breccia with diameters of approximately 5~10 cm, which form gray-black, weakly weathered limestone. The weathered breccia looks like dissolution breccia. These weakly weathered breccia are sporadically distributed, the edges are rounded, and a circle of weathering strips can be seen, which indicated that the breccia finally disappeared due to the weathering process from the slope surface to the interior. After that, the rock mass became strongly weathered rock (Fig. 6).

Strip-shaped weathering: This weathering type is mainly developed in areas where the joints and fissures are relatively large and sparse and the surrounding rock masses have good integrity. Strong strip weathering generally occurs when the thickness is not large and extends to different lengths. Depending on the crack lengths, the strip lengths are approximately 0.5~0.4 m, and the thicknesses are approximately 0.1 ~ 0.8 m. Striped weathering can be seen in the weak weathering that is present along mining cracks in quarries and usually exists in conjunction with the other three types of weathering. Some of the striped and strongly weathered limestone has a
laminated layer thickness of 0.1~0.5 cm. For example, at the 1435 m platform, microcrystalline limestone changed to marlstone stripes under strong weathering. Under the shear action of the structural bedding, interlaminar wrinkling is often produced and after weathering it shows a cystic appearance (Fig. 7).

![Figure 4. Cystic weathering](image)

![Figure 5. Lenticular weathering](image)

![Figure 6. Ring island-like weathering](image)

![Figure 7. Interlaminar wrinkling stripe weathering](image)

3.3 Characteristics of the weakened rock masses

3.3.1 Mineral composition and structural features

X-ray diffraction analysis and lithofacies analysis were conducted on 15 groups of samples. Strongly weathered limestone mainly consisted of $\leq 120 \mu m$ calcite, and approximately 90% of the area was severely rusted and localized. Patchy areas of 30~800 $\mu m$ in size with rust stains were found (Fig. 8). Compared with the weakly weathered rock masses, the strongly weathered rock masses in areas with rust stain and their mineral compositions, which still mainly consist of calcite, changed little. The strongly weathered rock mass has stripes and clumps of rust stain, and the area with rust stains accounts for 90% of the total. Meanwhile, a few areas with microcrystalline quartz and iron ore were also found. (Fig. 9)
Figure 8. Calcite in the non-rusted and rusted areas in strongly weathered limestone

Figure 9. Calcite, microcrystalline quartz, iron ore, and rust in weakly weathered limestone

Seventeen limestone samples were selected for thin-section analyses. The lithology of the material field is a whole argillaceous micritic-microcrystalline bioclastic limestone material that is mainly composed of 95% calcite and <5% mud iron. The structural components include micrite-microcrystalline calcite, intraclasts, bioclasts, arenes, terrigenous clasts, and mud iron. The intraclast content is 10%~50% and the structure is micrystal-microcrystalline. The bioclastic content is approximately 12%~42%. Some schivags can be seen in some sections. When cut by calcite veins with widths of approximately 0.16~2 mm, the fissures are filled with clean crystalline calcite and multiple stages of crushing and filling are present. The terrigenous clast content is 1% and is composed of feldspar, quartz, and other microcrystalline particles. Compared with the weakly weathered rock masses, the argillaceous content of the strongly weathered rock masses increases by approximately 4%. The iron minerals in the rock mass have also caused limonitization due to weathering. Some of the strongly weathered thin sections show pseudobedding structure characteristics that were formed by weathering in the late stage, which are similar to laminae.

3.3.2 Chemical composition characteristics

According to Table 1, the CaO quality in the strongly weathered limestone decreases slightly compared with weakly weathered limestone and it can be determined that the loss of Ca$^2+$ in the weathered limestone at deep burial depths is small or there is almost no loss. The results show that the deep weathered limestone is in the process of desilication and aluminum-ferric enrichment, which is manifested by the softening and mudding of rock mass in situ rather than the leaching process of calcium carbonate.

Table 1. Chemical compositions of limestone in the quarry
### 3.3.3 Compressive strength characteristics

In horizontal comparison, the uniaxial compressive strength of the deep, strongly weathered rock mass is reduced by 74%–84% compared to the fresh rock mass and 65%–68% compared with the weakly weathered rock mass, under natural conditions; in the saturated state, the uniaxial compressive strength of the deep, strongly weathered rock mass is reduced by 92%–97% compared to the fresh rock mass, and 86%–96% compared with the weakly weathered rock mass. It can be seen that the integrity of the deep, strongly weathered rock mass is destroyed, and the compressive strength of the rock mass is greatly reduced. Longitudinal comparison shows that the uniaxial compressive strength of the deep, strongly weathered rock mass in the saturated state is only a few MPa, a decrease of 60%–90% compared to the natural state. However, the compressive strength of weakly weathered and fresh rock masses decreases by 20%–40% and 3%–18%, respectively. It can be seen that the deep strongly weathered rock mass has obvious characteristics of water softening. (Table 2).

**Table 2. Compressive strengths of limestone with different weathering degrees**

| Rock statue | Deep bury strongly weathered | Weakly weathered | Fresh |
|-------------|------------------------------|------------------|-------|
| Natural     | 18–25 MPa                    | 73–86 MPa        | 98–110 MPa |
| Saturated   | 2.5–7 MPa                    | 51–58 MPa        | 90–95 MPa |

### 4 Analysis of the weakening mechanism
4.1 Control factors

4.1.1 Lithology

At the beginning of the Permian, due to the extension of the continental margin, seawater began to invade the interior of southern China. The largest transgression occurred in the Middle Permian Qixia Period in the Late Palaeozoic, and nearly all of southern China was covered by seawater \textsuperscript{[11]}. The western margin had a small range and only a small section of the ancient Kangdian uplift remains, while the carbonate basin on the eastern side provided fine-grained terrigenous materials. In the Qixia-Early Maokou transgression period (TST), the study area mainly experienced deposition of bioclastic limestone and micrite with interbedded mudstones or lens bodies (Fig. 10 a). Late Maokou was a high-level period (HST) that inherited the ancient geographical and depositional patterns of the Qixia-Early Maokou (TST) as bioclastic marlstone (Fig. 10 b).

![Legend: 1. Continental boundary, 2. Old land, 3. Restricted platform, 4. Open platform, 5. Bioclastic limestone, 6. Bioclastic marlstone, 7. Limestone with interbedded dolomite, 8. Study area](image)

\textbf{Figure 10.} Palaeogeographic map of the first supersequence structure of the Permian-sequence lithofacies\textsuperscript{[11]}

Cheng (2017) believed that coarse-grained high-energy granular rock retained matrix pores and was easily eroded by karst water to form a high permeability layer. In contrast, the denser micrite and microcrystalline matrix pores were cemented and not conducive to the seepage of karst water and form a water barrier \textsuperscript{[12]}. The micritic and microcrystalline structures of the fine-grained limestone structures are closer in their properties, and the water in the integrated rock mass has difficulty in seeping. This is not conducive to deep dissolution of the rock mass...
and rapid expansion of caves, underground rivers and other karst phenomena; thus, water weakly infiltrates deep into the rock mass through structural fissures.

4.1.2 Geological structure

Thirty-four faults were found in the quarry with different scales (Fig. 11); the widths are usually 0.1~1.0 m and up to a maximum of 1~1.5 m, while the lengths range from 50 to 500 m and up to a maximum of greater than 600 m. The fault dip angles are generally 60° and greater while the faults are mainly tensional and torsional. The statistics revealed 20 E-W strike faults, which accounted for 59% of the total; 9 N-S strike faults, which accounted for 26%; and 5 NE strike faults, which accounted for 15% (Fig. 12). A typical area was selected to construct measuring windows in the mineral surface and footrill. The measuring window was then divided into 1 × 1 m units to carry out cataloging and determine the statistics of the rock fissures. The measured area was 179 m², 1469 fissures were found, and the density was 8.2 per square meter. The majority of fissures have extensional properties. Based on the statistical rose diagram, fissures with such occurrences, NS strikes, EW strikes and NNW strikes with steep dips and NS strikes with gentle dips are dominant. EW and SE strikes with steep dips account for 19.5% and 14.7%, respectively, of the total. (Fig. 13)

Figure 11. Fault layout map of the quarry
In short, there are developed faults, dense joints and fissures, and severely fractured rock masses in the quarry. Faults and fractures are mainly tensional and torsional, and are dominated by E-W, followed by S-N, deeply dipping groups.

Through the analysis of the regional geological structure, it is believed that the fissuring of the rock mass of the quarry is mainly caused by the Neotectonics and Qiaojia Basin pull-apart effect.

(1) Neotectonics: According to the regional GPS velocity directions \(^\text{[13]}\) and focal mechanism solutions \(^\text{[14]}\), the main stress direction of the quarry crustal stress is WNW. Sinistral strike-slip movement and the E-W strike fissure group occurred because the Xiaolijiang fault, with a NNW strike, was squeezed by the NW crustal stress.

(2) Qiaojia Basin pull-apart effect: The Qiaojia Basin \(^\text{[15]}\) formed because of the pull-apart effect that was induced by the Xiaojiang and Zemuhe faults. During the pull-apart process, the rock mass of the slope unloaded to the west, and the nearly east-west fissures were loosened due to the cutting and erosion of gullies.

4.1.3 Climate and hydrology factors

A dry-hot valley means high temperatures, drought and low humidity conditions \(^\text{[16,17]}\). Dry-hot valleys were created in the Qiaojia section of the Jinsha River Basin during the early Quaternary period because of regional uplift and intense valley incision. The annual average temperature is 20°C, the annual rainfall is 816 mm, and the rainfall in the rainy season is 737 mm, which accounts for 89% of the total rainfall. The rainfall in the dry season is 92 mm, which accounts for 11% of the total rainfall. The evaporation is 2529 mm per year. The climate is characterized by drought, high evaporation and low rainfall. The maroon clay present is a product of this climate.

The mineral area forms a slope, with a higher-elevation east side and lower-elevation west side. Six exploration drill holes were selected from east to west to analyse the groundwater
depths. The groundwater depths are consistent with the regional elevations and are high in the east and low in the west. The groundwater depth is usually greater than 110 m (Fig.14). Groundwater at great depths has a limited effect on limestone. The surface water is discharged quickly, and two high elevation springs can be found on the upper side of the Liangzi Gully, where the inner rock mainly consists of dissolvable rock masses.

![Groundwater depth diagram](image)

**Figure 14.** Groundwater depth diagram

### 4.2 Cause analysis

During the early Permian, the extension of the continental margin around the Xiaojiang fault and the eastern margin of the Sichuan-Yunnan block caused the mineral area to form a restricted platform in the Permian Qixia-Maokouan Period because of seawater intrusion. The quarry area began receiving deposits of shallow-sea, biological, thick micritic-microcrystalline bioclastic limestone. Then, the mineral area was uplifted in the Permian under the influence of the Kangdian Palaeouplift and iron mud and other land-based sources were deposited on the carbonate platform so that mud iron materials and lens bodies were present in Qixia-Maokou limestone.

The Late Indosinian movement after Yunnan terminated marine deposition and initiated the inland basin development phase \(^{[18]}\). Since the Himalayan movement, the Sichuan-Yunnan fault block has been wedged in a southeast-east direction. The eastern boundary fault, which is the northern part of the Xiaojiang fault, began sinistral strike-slip movement. The quarry is located on the eastern side of the northern end of the Xiaojiang fault. It not only inherits the northeast fault from the earlier period but also generates tensional fissures with EW strikes.

Since the Quaternary, the Qinghai-Tibet Plateau and Yunnan-Guizhou Plateau were uplifted rapidly, and the Jinshajiang River valley began to be cut intensely. The pull-apart effect occurred in the early Pleistocene-middle Pleistocene and led to the formation of a dry-hot valley, while the
groundwater depths on the right bank of the Qiaojia section of the Jinsha River decreased drastically. The development of structural fissures makes it possible to infiltrate deep water bodies; under the background of dry-hot and rainless climate, water infiltrates in the non-flowing form, resulting in weak hydrodynamic conditions that are unable to take away the products of deep weathering. These adverse factors created conditions for the decreased strength of the deeply buried rock masses.

During the rainy season, the surface water penetrated the slope along the fissures. The uneven distribution of cataclastic rock masses, repeated infiltration and softening, and seasonal fluctuations on the phreatic surface drive the corrosive carbon dioxide-containing water vapor to circulate in the fissures. In the infiltration state, the hydrodynamic conditions are weak and the weathering material cannot be carried away, and the rock mass is mainly softened and muddy in situ. As a result, a strip of strong weathering is formed where a single long crack is developed; a sac-like strong weathering is formed at the intersection of a dense crack zone and a fault; the fragmented rock mass is weathered inward from the edge of the rock block to form an island-like strong weathered breccia; and containing the interlayer muddy water-proof layer with concentrated mud and sand forms temporary upper stagnant water. After the action of water and rock, strong lenticular weathering with very low intensity is formed. At the intersection of the faces AB of the material yard, the fault spring exposed at a high position re-infiltrated the limestone rock mass, which changed the hydrodynamic conditions of water infiltration under dry-hot conditions. It continued to dissolve along the east-west fracture zone and exchange Ca$^{2+}$ in the limestone. With the formation of a large-scale karst pipeline, the roof collapsed to form a karst cave breccia zone with mud and rocks, resulting in the weakening of the corroded rock mass.

5 Conclusions

(1) Micritic-microcrystalline bioclastic limestone with dense grain structure and a high content of pelitic iron is exposed in the eastern margin of Kang-dian Palaeouplift. Due to the influence of multi-stage tectonic movement since the Mesozoic, the limestone develops fractures characterized by uneven spatial density.

(2) The weakening of the limestone can be divided into dissolvable weakening and undissolvable weakening. The former consists mainly of karst cavities, weak cementation filling of heterologous materials, and dissolution-collapse breccia. The latter mainly consists of cystic weathering, lenticular weathering, ring island-like weathering and stripe-shaped weathering rocks.

(3) The mineral composition of deep, strongly weathered limestone mainly consists of calcite. However, in the limestone, 90% of the area is banded and clumps of rust. Chemical composition analysis shows that the strongly weathered limestone is in the stage of desilication and rich in aluminum and iron, which indicates in-situ softening and mud. The uniaxial compressive strength of strongly weathered limestone is 2.5~25 MPa, and it has the characteristics of weakened strength and softened by water.
(4) The weakening mechanism of deep, strongly weathered limestone is that under the conditions of structural shear fracture, terrigenous argillaceous intercalation and dry-heat, and with the infiltration of surface water in the non-flowing form, the long-term water-rock coupling action occurs, which makes the limestone in situ continuously softened and argilized, resulting in a significant decrease in the strength of limestone. The mechanism of deep dissolution limestone weakening is that the fault spring exposed at a high position flows along the dense fissure zone, which breaks the hydrodynamic conditions for water infiltration in a dry-hot background then forms a large-scale karst pipeline. Later, the roof collapse and the filling of heterogeneous materials results in dissolution weakening.

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