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Analysis on the Characteristics and Laws of Tunnel Hydraulic Inrush in Karst Area

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Abstract: As highways are extended to deep mountains, high altitudes, and special geological conditions, tunnel construction becomes more and more challenging, especially the construction of tunnels in karst areas. Due to the particularity of the regional geological structure, karst is well developed in the southwest of our country, especially at areas where the problem of tunnel water inrush in karst areas is more prominent. To further ensure the safe construction and operation of tunnels, the characteristics of tunnels in karst areas is analyzed in this article.

Keywords: Karst area; Tunnel; Water inrush; Mechanics

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1. Introduction

According to research, there are four conditions that affect karstification: the solubility of rocks, the permeability of rocks, the fluidity of water, and the corrosivity of water. Karstification will occur if these four conditions are met.

With the extension of highway construction to deep mountains, high altitudes, and special geological conditions, tunnel construction is facing more and more technical challenges, especially the construction of tunnels in karst areas.

Due to the particularity of the regional geological structure, karst is well-developed in the southwest of our country, especially at areas where the problem of tunnel water inrush in karst areas is more prominent [1]. To further ensure the safe construction and operation of tunnels, the characteristics of tunnels in karst areas is analyzed in this article.

2. Main influencing factors of karst development

2.1. Lithology

Lithology is the material basis and the main factor controlling the development of karst. Different types of karst formations have different degrees of karstification. For example, the mud in the argillaceous limestone aquifer leads to the formation of thin-layer structures and fine cracks, which become seepage channels for the dispersion of groundwater in the mountain, so the karst development is scattered. Generally, a network of dissolution fractures is formed rather than a large cave system. Carbonic acid causes a "double erosion" effect, which can dissolve nearly 20% of the calcite of rock formations in volume [2].

It has been found that the diagenetic minerals of different soluble rock groups, the composition of trace minerals, and the organizational structure have an important impact on the four conditions of the aquifer: solubility, water permeability, self-erosion, and water movement. Lithology determines the mechanism and display strength of karst medium based on these four basic conditions.

2.2. Geological structure

Geological structure plays a leading role in the development of karst, it not only controls the direction of karst development, but also affects the scale of karst development.

Tensile fault zones are affected by tensile stress, and the width of the fracture zone is generally not large, but the degree of tension cracks is large, and the fault surface is rough and uneven. It is a favorable channel for karst water, so the degree of karstification is usually the strongest [3] .

2.3. Topography

The surface karst form is the surface trace of the underground river system, and depressions, funnels, and sinkholes are all input points of the underground river system. Large-scale input points such as depressions and underground extensions of underground river inlets are channels for high-level tributaries of underground rivers.

The development of karst is largely affected by surface water and seepage conditions, and these two are often affected by landform conditions, such as ground slope, cutting density and depth, water system distribution, etc., and the process of development is also different.

3. Characteristics of disasters and analysis of tunnel water inrush

The factors affecting karst water inrush are caused by geological factors and engineering factors, and it occurs when there are contradictions between to two factors. The reason of occurrence and influencing factors of water inrush determine the type of water inrush. In terms of geological factors, the karst water-bearing medium usually has great heterogeneity and diversity, and the water distribution is extremely uneven, where laminar flow and turbulent flow coexist, small fissures constitute the main water storage space and large water inrush channel. In terms of engineering factors, rock mass excavation and unloading, blasting disturbance and grouting failure, etc. are the main contributors to the hysteresis and uncertainty of water inrush [4].

3.1. Conditions for water inrush

Underground construction will inevitably destroy the concealed water-bearing structure, causing the aqueduct to be connected or quasi-connected with the excavation surface, and further disturbance will cause the groundwater or other water bodies that are hydraulically connected to the aqueduct (surface water, underground rivers and molten pools, etc.) to suddenly pour into the excavated area, causing water inrush. Therefore, from the perspective of system theory, certain conditions must be met for the occurrence of karst water inrush, namely the energy storage of water-bearing structures, karst hydrodynamic performance and energy release, and the stability of surrounding rocks.

3.2. Factors affecting of water inrush

In essence, karst water inrush is a phenomenon of dynamic instability caused by external interference of groundwater migration network or storage conditions. There many factors that influences the occurrence of water inrush, but it can be generalized into geological factors and engineering factors [5].

(i) Geological factors

In terms pf engineering factors, construction induces water inrush, but hydrogeological conditions are the main influencing factors of water inrush, and the hydrogeological conditions are controlled by the topographical conditions, stratum lithology, geological structure and karst hydrodynamic zoning conditions of the construction area, etc.

(ii) Engineering factors

The engineering factors affecting karst water inrush are mainly excavation and the vibration caused by blasting. During the construction of underground projects, the construction methods and techniques may induce karst water outburst, and even poor grouting may cause delayed water inrush disasters. However, according to the statistics, most of the water inrush occurred after construction blasting and excavation. Therefore, it is clear that excavation and blasting are the most important influencing factors among engineering factors.

3.3. Types of water inrush

There are many types of karst water inrush, but in terms of the specific attributes of the inrush prevention structure, water inrush can be divided into two types: geological defect type and non-geological defect type water inrush.

Water inrush can be divided into four grades according to the amount of water, as shown **Table 1**.

Table 1. Types of water inrush divided by water inrush volume

Level code	Water volume, Q (m^3/h)	Description
Grade A	>10000	Occurs instantly with a water pressure is greater than 0.5 MPa and lasts for a last time
Grade B	1000–10000	Transitional, with water pressure less than 0.5 MPa.
Grade C	100–1000	The water pressure is small, and the flow depends on the dynamic water pressure, which does not affect the construction.
Class D	10–100	The groundwater flows slowly, and the drainage requirements can be met during construction along the slope.

3.4. Water inrush method

There are a few ways in which water inrush can occur: instantaneous water and mud inrush, stable water inrush, and seasonal inrush. Instantaneous water and mud inrush: When the karst pipeline is exposed during the construction of a tunnel, groundwater or underground mud-rock will spurt from the pipeline mouth with huge pressure (1–3 MPa) in an instant, and its flow rate can reach thousands of cubic meters or even more than 10,000 cubic meters per hour. Stable water inrush: there is no significant change in the amount of water before and after construction even when the karst pipeline is exposed and the groundwater flows under the action of water pressure. Seasonal water inrush and gushing: When dry caves or water-filled caves with relatively large catchment areas are close to the tunnel, , the karst pipeline will be filled with water rapidly after continuous rainfall or a heavy rain, water inrush will occur, causing underground debris to flow along the pipeline [6].

3.5. Impact of water inrush

The impact of karst water inrush can be divided into three categories: serious loss, medium loss and slight loss. The most serious water inrush is categorized as grade A, where underground debris flow occurs, and the tunnel is forced to shut down for more than 3 months, causing huge economic losses, casualties, and other major accidents; the moderate inrush and mild inrush are categorized as grade B and C, respectively, in which the tunnel is forced to shut down for 1 month when during seasonal water inrush, causing a certain amount of property damage; the amount of water gushing with minor losses is grade C, D, and the tunnel is forced to shut down for 10 days [7].

3.6. Protrusion prevention structure

In terms of water inrush damage, karst water inrush can be divided into three types: geological- defect water inrush, non-geological defect water inrush, and combined water inrush. This form of categorization is closely related to the outburst prevention structure and water inrush channel, as shown in **Table 2**.

Table 2. Types of water inrush by failure mode

Water inrush type	Inrush prevention structure	Water inrush channel
Non-geological defect type	Complete surrounding rock (outburst prevention layer)	In the early stage, it is a network of fractures, and in the later stage, it is the rupture of the aquitard
Geological defect type	Filling medium	Cracks, faults, dissolved cavities and karst pipes, etc.
Modular	End core surrounding rock + filling medium	Different combinations of the above two water inrush channels.

For non-geological defect water inrush, that is, when there is no obvious geological defect between the tunnel surface and the nearby water-conducting structure, the water rushes in from the fault zone; for combined water inrush, if the geological defect that is hydraulically connected to the water-conducting structure does not intersect the tunnel, tunnel water inrush will not happen unless both of the filling medium and inrush prevention structure are unstable.

4. Analysis of basic mechanical characteristics of water inrush in tunnel

Water inrush in karst areas is essentially a dynamic damage, which is due to the drastic changes in the mechanical balance of the karst water-bearing medium, hydrodynamic system, and surrounding rock due to underground excavation, resulting in the instantaneous release of energy stored in the groundwater body. and the water gushes out of the ground at a high speed In terms of water-rock interaction mechanism, there are two processes to a karst water inrush: potential storage and instability. Potential storage is a gradual process, and it eventually turn into instability, which is an instant process, after some time.

4.1. Potential storage process of water inrush

Karst water inrush is a dynamic damage in which long-term water-rock interaction induces rock mass rupture, instability, and water inrush stimulated by external forces during a construction. The effect of water and water pressure on the softening, dissolution, and stress of rock mass takes long time.

(i) The softening and dissolution effect of karst water on fractured rock mass

Under karst water dissolution, the strength of rock under saturated water state and the strength of dry rock can be deduced according to the following relationship

$$\sigma_w = \eta K_w \sigma_0 \ (K_w > 1)$$

In the formula, η is the rock strength reduction coefficient within the safe thickness range, and its value is related to the degree of rock dissolution and the rock humidity of the water inrush surface; K_w is the rock softening coefficient, and its value mainly depends on the lithology of the rock.

(ii) Effect of karst water pressure on the stress of fractured rock mass

The mechanical effect of karst water pressure on fractured rock mass is mainly reflected in its effective stress and softening effect. Since these two effects are related, the comprehensive mechanical effect can be expressed by the following formula:

$$\Delta t = \sigma(\tan\varphi - \tan\varphi_w) + P_w \tan\varphi_w + CC_w$$

In the equation above, Δt is the reduction value of the shear strength of the fractured rock mass caused by karst groundwater; P_w is the karst water pressure; C and φ are the connection force and friction angle of the fractured rock mass before water immersion; C_w and φ_w are connection force and friction angle of post-fractured rock mass after water immersion. For the karst confined water in the tunnel floor, the influence of karst water pressure P_w on the strength of fractured rock is more significant due to the vertical pressure relief of the floor strata after excavation [8].

4.2. Instability characteristics of water inrush

Based on the diversity of the torrent-proof rock mass structure, karst water inrush has multiple failure modes. For water-bearing structures with obvious geological defects, such as fractured rock masses, faults, and filled karst pipelines, the water inrush channels are regular, and the instability and failure modes are relatively fixed. For fractured rock mass, there is hydraulic fracturing cause by the water inrush.

The erosion and expansion of the water flow on the water inrush channel is used in the water inrush of underground engineering. There is always a fixed initial channel at the moment of failure and instability for any type of water inrush, but the shape and boundary of the water inrush channel are different. However, with the further development of water inrush, the walls along the channel will be continuously destroyed and peeled off, thus increasing the volume of the water inrush channel. Microcracks or other geological defects that cause cracks can be described by the following model.

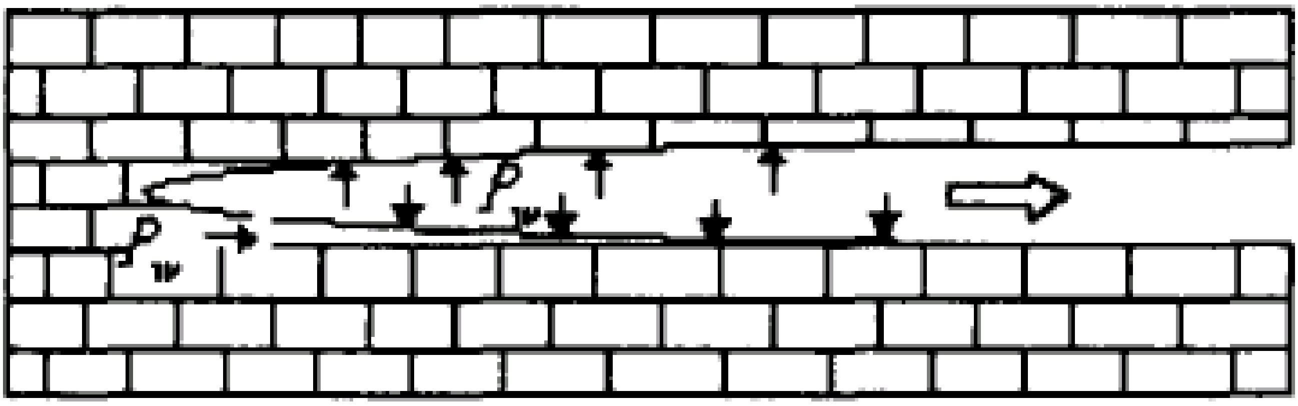

Figure 1. Calculation model of diameter expansion by water flow erosion

4.3. Analysis of source of water inrush

The driving force of water inrush can be divided into hydrostatic pressure water inrush and dynamic water inrush. Hydrostatic pressure water inrush occurs under the action of a large static storage water body, and as the inrush prevention of the structure gradually weakens, the water body will slowly become unstable and finally gush out. Dynamic inrush is where the body of water is impacted by an external force, which stimulates high water pressure, and instantly forms a water inrush channel. **Table 3** shows the difference between dynamic water inrush and hydrostatic pressure water inrush.

Table 3. Classification of water inrush sources

Type of water inrush	Hydrostatic pressure inrush	Power water inrush
Source of water	Aquifers, surface water, old empty water, etc.	Delaminated water
Aisle	Water-conducting fissure zones, faults, karst pipelines, etc.	Dynamic breakthrough zone
Precursory features	Increased water seepage on the wall surface, sediment discharge, etc.	No warning signs
Water inrush	Irregular, controlled by water pressure and channel etc.	The instantaneous water inrush is large and the decay is fast
Water inrush process	Similar to a water bottle with a loose cork turned upside down and water flowing out	Can be described as pressing against a hot water bag, causing the water burst out

Apparently, static water inrush is more common, and dynamic water inrush requires a certain power source.

The formation of water channels is mainly due to the action of dynamic damage and excess hydrostatic pressure, while the hydrostatic pressure inrush is mainly due to the hydrostatic pressure of the original aqueduct.

5. Conclusion

Through the analysis of the mechanical characteristics and laws of tunnel water inrush in karst areas, several conclusions can be drawn.

(i) Through the analysis of the characteristics and laws of tunnel water inrush, it is possible to preliminarily determine the high-incidence areas of and areas prone to tunnel water inrush.
(ii) In the process of tunnel construction in karst areas, various means such as TSP (tunnel seismic prediction), geological radar, transient electromagnetic, direct current, and infrared water detection can be used to carry out advanced geological prediction.
(iii) Through the analysis of tunnel hydraulic inrush characteristics, corresponding design parameter adjustments can be adopted to ensure construction and operation safety.

Disclosure statement

The authors declare no conflict of interest.

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