Research Progress of Freezing Sinking Theory and Technology

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Abstract. Freezing method has been applied in underground space development because of its high safety and reliability, good anti-seepage performance, wide application range and green environmental protection. This paper reviews the basic principle of freezing method and its research status in subway tunnel and underground space, summarizes the theory and application of freezing wall design of shaft in deep alluvium and water-rich soft rock stratum, analysis the shaft wall structure type and high-strength and high-performance concrete shaft wall material and design theory, and puts forward the prospect of practical engineering application of freezing method, in order to provide reference for further application of freezing method.

Keywords: freezing method; underground space; freezing wall; shaft wall

1 Introduction

In the process of hydraulic tunnel construction, complex geological structure is often encountered, which leads to the construction can not continue. The saturated loose siltstone stratum is extremely rare in underground engineering construction. Once encountered, it will bring great difficulties to engineering construction. Especially in the process of TBM tunneling, due to its characteristics of high water content and poor stability, the cutter head panel is in close contact with the surrounding rock of the working face, or the minimum torque value of tool starting can not be reached during TBM tunneling, which leads to tool wear and destruction. In addition, a large number of engineering practices show that using advanced reinforcement methods, such as mixing pile, grouting and rotary grouting, the pile body will often break during construction, and even induce water gushing and sand gushing. The construction principle of freezing method is that chemical refrigerating substances such as liquid nitrogen or Freon are used to continuously circulate through salt water medium to reduce soil temperature, and the water in rock and soil around the underground space to be excavated is frozen and cemented with rock and soil to form a high-strength freezing curtain structure, which is used to resist water and soil pressure and isolate groundwater, so as to carry out underground engineering construction under the protection of the curtain structure. Compared with mixing pile, grouting and rotary grouting, it has the ad-

K. Yuen et al. (eds.), *Proceedings of the 2025 International Conference on Engineering Management and Safety Engineering (EMSE 2025)*, Advances in Engineering Research 267,
https://doi.org/10.2991/978-94-6463-780-9_27

vantages of strong construction adaptability, high strength, good uniformity, excellent anti-seepage performance and "green" environmental protection [1]. Yan et al. [2] Taking the freezing construction at the exit of the main canal tunnel of the first phase of Tao Diversion Project in Gansu Province as an example, based on the phase change theory of thermal analysis and using the finite element software Ansys, studied the temperature field distribution, the intersection time of freezing pipes and the development of freezing curtain thickness during the active freezing period of double-row horizontal freezing construction of diversion tunnel, and discussed the numerical simulation accuracy of this method. Qi et al. [3] analyzed the feasibility and difference of the combined freezing reinforcement method of diaphragm wall + horizontal freezing back sealing in different water pressure strata by model test, and verified the feasibility of this support method. In order to solve the problem of no dewatering in the construction of foundation pit in water-rich stratum, Zhang et al. [4] put forward a "combined freezing method" which combines traditional suspended water-stop curtain with horizontal frozen soil water-stop curtain, and verified the feasibility of the combined freezing method through model test. Chen [5-7], in order to master the freezing design and construction technology of deep-buried stratum, combined with engineering practice, studied the engineering geological characteristics of extremely soft rock, as well as the key technologies such as "vertical freezing method" design, temperature field, refrigeration system and construction, which filled the blank of "vertical freezing method" technology for deep-buried hydraulic tunnels above 200.0 m in China and pioneered the "freezing method" construction technology for deep-buried hydraulic tunnels in China. Zhou et al. [8] compared and analyzed three analytical formulas of elastic design theory of shaft frozen wall, showed two methods of solving mechanical model based on interaction between frozen wall and surrounding rock by superposition principle in graphic way, and revealed the law of outer edge load of frozen wall changing with thickness and stiffness of frozen wall. Wang [9] According to the 22 km water conveyance tunnel of Shenmu County Water Supply Project, through comparative analysis of five construction schemes, it is recommended that the shaft construction scheme adopt the large section freezing method, while the flat tunnel construction scheme adopt the partial section expanded section mining method. Wang et al. [10] combined with the support engineering practice of unconsolidated sandstone layer in deep buried water conveyance project, analyzed the freezing construction process of unconsolidated sandstone layer, the evolution of soil mechanical properties after thawing and the combined stress mechanism of surrounding rock support, revealed the deformation law of surrounding rock and the evolution characteristics of support force under freezing and thawing process by finite element method, and put forward the design concept and support scheme of freezing construction and step-by-step combined support of unconsolidated sandstone layer. Xu et al. [11] In order to explore the formation process and mechanical characteristics of frozen soil curtain during freezing construction of diversion tunnel in water-bearing loose sandstone stratum, three-dimensional numerical simulation was carried out on freezing construction and excavation process of diversion tunnel. Combined with field monitoring data, the temperature change law of frozen soil and the formation mechanism of frozen soil curtain during freezing process were analyzed, and corresponding measures and suggestions were put forward.

This paper reviews the basic principle of freezing method and its research status in subway tunnel and underground space, summarizes the theory and application of freezing wall design of shaft in deep alluvium and water-rich soft rock stratum, analyzes the safety status of freezing pipe fracture and shaft lining destruction in freezing shaft, puts forward shaft lining structure type and high-strength and high-performance concrete shaft lining material and design theory, and puts forward the prospect of freezing method application, in order to provide reference for further application of freezing method in underground space development.

2 Principle and Application of Freezing Method

Artificial freezing method originated in England, and engineers used it to reinforce soil in building foundation in 1862. In 1880, Poetch, a German engineer, introduced the principle of freezing method for the first time in the world, and successfully applied this technology to Albarid coal mine in 1883, and built a shaft with a depth of 103 m. With people's understanding of this construction method, artificial freezing method has been widely used in tunnels, foundation pits and mines in the following decades[12].

2.1 Principle of the Freezing Method

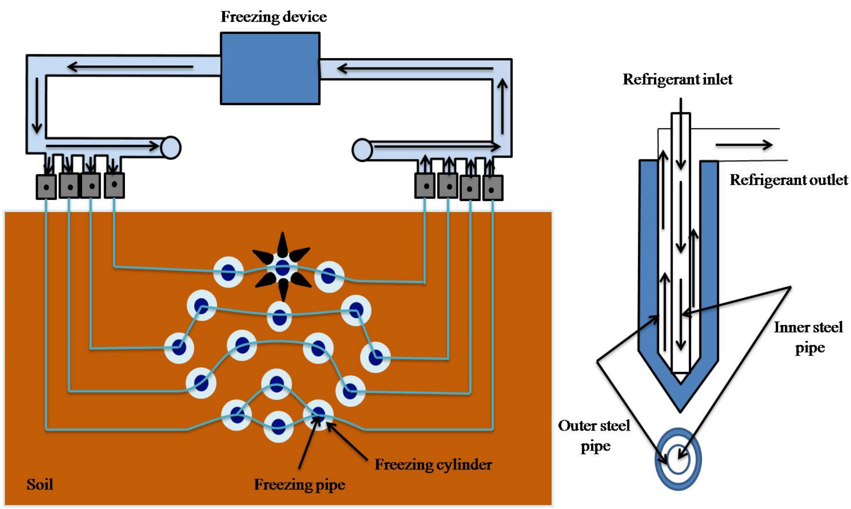

Fig. 1. Basic principle of freezing method.

The fundamental principle of the artificial freezing method involves creating a low-temperature environment within the soil through specific technical means, thereby reinforcing the soil. Specifically, low-temperature refrigerants, such as saltwater or liquid nitrogen, are utilized and circulated through the freezing tube after passing through the freezing device. Freezing pipes typically consist of two nested seamless steel pipes. As the low-temperature refrigerant circulates within the freezing tube, it exchanges heat with the surrounding soil, as illustrated in Figure 1. As the heat exchange process progresses, the soil's temperature gradually drops below the freezing temperature, causing the water in the soil to begin condensing into ice. The initial form of ice is a frozen cylinder, which continuously expands outward. Over time, adjacent frozen cylinders intersect with each other, ultimately forming a sealed frozen wall. Once the frozen wall attains a certain thickness, it can offer effective temporary support for underground engineering, significantly enhancing the safety and stability of construction.

2.2 Application of Freezing Method in Underground Space

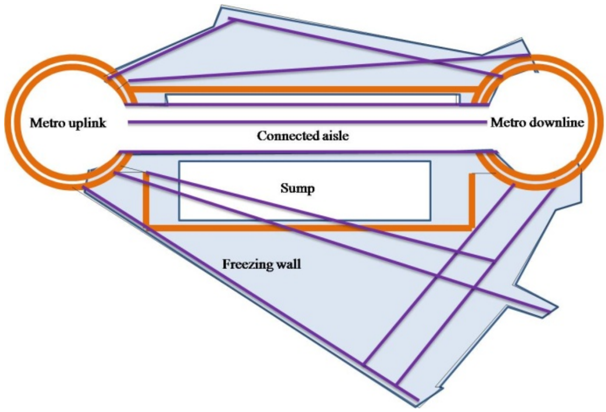

Fig. 2. Freezing method in underground space.

Dangerous situations such as sand gushing and water inrush sometimes occur in the construction of subway tunnels. Previously, the method of "rerouting and repairing" was often used, but this method has great drawbacks, which may lead to the construction not being completed on schedule and cause extra costs. In order to solve such problems smoothly, safe and efficient freezing method is often applied to the emergency repair process of subway tunnels, which is called "original repair", as shown in Figure 2. For example, when Guangzhou subway tunnel crosses the fracture zone during construction, there is a sudden danger of flowing sand, and then freezing method is adopted to reinforce it, and the damaged part is repaired smoothly. During the excavation of the connecting passage in a section of Shanghai Rail Transit Line 4, sediment poured into the tunnel, which caused the tunnel to collapse and the ground surface to settle. After that, the tunnel was repaired by freezing reinforcement. Many experts and scholars carry out comparative experiments on the two restoration methods to judge which method has better restoration effect. Water inrush occurred during the construction of a river tunnel in Changshu. By comparing the freezing method with the traditional temporary plugging wall, it is found that the freezing method is more controllable and safe. During the construction of the connecting passage of a section of

Shanghai Rail Transit Line 4, the danger of sudden water gushing and quicksand occurred, which affected the local traffic and caused huge economic losses. After demonstration by the expert group, considering the comprehensive factors such as difficulty and economy, the "in-situ repair method" of freezing reinforcement and underground excavation docking was selected to ensure the smooth construction.

2.3 Current Situation of Liquid Nitrogen Freezing Technology

The traditional freezing method is to absorb the heat of soil through brine and transfer the absorbed heat to liquid ammonia. After compression, part of the heat of ammonia is absorbed by cooling water, so that the unfrozen water in soil freezes to achieve the freezing effect. However, when the construction site is limited or the construction period is tight, the traditional freezing method cannot achieve the expected effect. The liquid nitrogen freezing method as a green, easy to operate and not limited by the construction site technology compared with the traditional freezing method has more advantages. Compared with traditional freezing technology, liquid nitrogen technology has lower boiling point and better freezing effect, so when the freezing effect of traditional freezing method can not meet the expectation, liquid nitrogen freezing method is often used. In a certain section of Shanghai Rail Transit Line 11 branch line, due to an unexpected accident during construction, the segment capping block fell off, and a large amount of silt poured into the tunnel. In order to complete the repair work as soon as possible, the liquid ammonia freezing technology is considered to work in the semi-circular section of 5 m on both sides of the center line of the downward tunnel, and after the freezing operation is completed, temporary supports are set at the repair position to prevent the tunnel from deforming. In order to plug the abnormal water gushing in the construction process, Wang Zhenwei and others put forward the method of plugging water gushing with liquid nitrogen on the background of secondary freezing water sealing with liquid nitrogen in tunnel. The results show that in case of sudden accidents such as water gushing, the liquid nitrogen freezing method is fast and safe, which can make the construction completed on schedule and ensure the construction quality. Hangzhou Metro Line 1 is located in a complex section. In order to reduce the impact on surrounding buildings and complete the construction within the specified time limit, liquid nitrogen freezing method was selected for construction. Because of the low temperature of liquid nitrogen, in order to ensure the uniformity of freezing, an air outlet is set every 1 m to discharge nitrogen. After 6 days of freezing, the thickness of freezing wall reaches the design requirements. In order to study the phase change heat conduction of liquid nitrogen freezing temperature field, Li Fangzheng and others took a section of Shanghai rail transit as the research object, and established a model to analyze the temperature field of liquid nitrogen freezing tunnel by using ADINA large-scale civil engineering numerical simulation software. The obtained results improved the relevant theory and technology.

2.4 Research Status of Freezing Wall and Temperature Field

Due to the continuous development of underground space in China, the freezing depth is also increasing, and the corresponding stratum situation is becoming more and more complex. Therefore, in order to ensure the safety of construction when using artificial freezing method, it is necessary to determine whether the freezing wall is safe or not. If the frozen wall is safe, it can ensure the strength and stability of the frozen wall, and then ensure the smooth progress of the construction. And the strength and stability of the frozen wall depends on the temperature of the frozen wall, so experts have adopted the numerical simulation method to study the temperature field of the frozen wall. The development of temperature field is the key of freezing method construction, and the law of temperature changing with time in the process of freezing is mainly studied. However, in the research of temperature field, the traditional two-dimensional model can not accurately reflect the condition of frozen wall compared with the three-dimensional model, so the safety of freezing construction can not be guaranteed. Although a lot of research has been done on the measurement of freezing temperature field, there is still a lack of research on the whole process of temperature change from freezing to thawing and the whole process of temperature development in deep soil. To sum up, temperature field is a very important aspect in freezing construction. At present, it is very extensive to use numerical simulation method to analyze the frozen wall and temperature field. Using this technology combined with mathematical model to calculate the weak area of frozen wall thickness, so as to ensure the stability of frozen curtain and add a guarantee for construction safety.

3 Design Theory and Application of Freezing Wall

3.1 Freezing of Vertical Shaft in Deep Alluvium

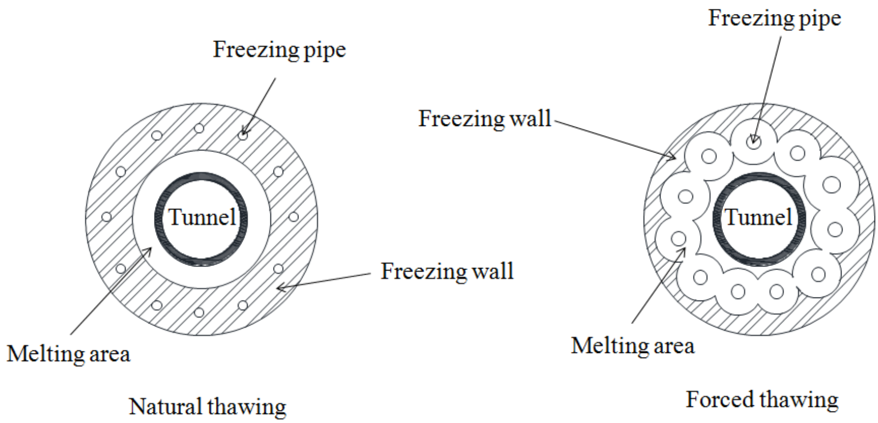

Fig. 3. Schematic diagram of tunnel freezing wall.

Frozen wall design theory is one of the basic theories of freezing sinking, and it has been a hot and difficult point for engineers and technicians in this field. In history, there have been mixed use of various theories, different implementation effects and profound experiences and lessons; There are even one construction organization design, and there are countless cases in which various calculation theories are used at the same time. Based on the full summary and research of the past experience and lessons of frozen wall design and application (Figure 3), many scientific and technological workers put forward a theoretical system of frozen wall design combining theory with experience[13].

3.2 Freezing of Vertical Shaft in Water-Rich Soft Rock Stratum

With the development of coal resources in western China, freezing method is widely used in sinking wells in soft and water-rich rock strata in western China, and has created the deepest record of freezing depth in the world. It is the key technology to calculate the thickness of freezing wall of deep vertical shaft in soft and water-rich rock stratum in western China, and it is obviously unscientific to simply apply the design theory of freezing wall of deep alluvium; However, only the design method of sealing water and freezing has the problems of high construction risk and unsafety. Therefore, many scholars have made useful explorations.

4 Design and Application of Shaft Lining Structure with High Bearing Capacity

4.1 Shaft Lining Structure Type

Whenever the thickness of alluvium or freezing depth of the shaft passes through a big leap, what kind of structure and strength of shaft lining is adopted in the freezing section of the shaft has become a difficult and hot spot in peer research. Engineering practice shows that reinforced concrete-plastic sandwich composite shaft lining has strong "vitality", can better adapt to the stress and waterproof requirements of shaft lining in freezing section, and has become the main structural type of shaft lining in freezing section of deep alluvium.

The suitable shaft lining structure of frozen shaft in water-bearing soft rock stratum should still be double shaft lining. Some research units have tested and applied new single-layer shaft lining structure, but in view of the harsh and complex conditions of underground construction and the difficulty in implementing complex construction technology, the comprehensive technical and economic effects of test application need to be further summarized and improved[13].

4.2 High Strength and High Performance Concrete Shaft Lining Material and Design Theory

The preparation technology of C80 ~ C120 high-strength and high-performance concrete for freezing shaft lining developed by the "Twelfth Five-Year Plan" national science and technology support project "Research and Application of High-performance Concrete for Freezing Kilometers Deep Shaft in Deep Alluvium" can control the maximum thickness of shaft lining in freezing section of 700 ~ 1000 m alluvium within 2.5 m, which has far-reaching technical progress, making it possible to apply freezing sinking technology in 700 ~ 1000 m deep alluvium, overcoming the bottleneck of freezing sinking technology in deep alluvium due to excessive thickness of shaft lining, and providing technical support for freezing sinking technology in deeper alluvium.

However, the existing codes lack more than C80 high-strength concrete shaft lining design specifications or regulations, so it is necessary to study and solve the technical problems such as reasonable selection of shaft lining design load, design value of physical and mechanical parameters of concrete materials, design calculation of bearing capacity and design method when C80~C120 high-strength and high-performance concrete is used in deep shaft freezing shaft lining design. Others put forward a formula for calculating the standard value of horizontal load-freezing pressure of outer shaft lining in the design of deep alluvium sinking shaft lining with thickness greater than 500 m according to the measured research of freezing pressure of deep shaft in China; And put forward some suggestions on the strength growth performance of cast-in-place concrete. Other design loads of shaft lining can be taken according to the current regulations. Whether the design value of axial compressive strength of concrete is reasonable or not directly affects the application benefit of high-strength concrete. If the design value of axial compressive strength is too low, the potential of high-strength and high-performance concrete cannot be brought into play; If it is too high, it will affect the safety of the design structure. Based on the comprehensive study of concrete design codes at home and abroad, research achievements of domestic scholars and verification tests carried out for this purpose, the author puts forward some suggestions on the design and standard values of axial compressive strength, axial tensile strength and elastic modulus of C80 ~ C100 concrete (see Table 1), and suggests that Poisson's ratio should be 0.2; If the shaft deformation design and scientific research should be carried out, the elastic modulus and Poisson's ratio parameters should be determined through experiments; Suggestions are put forward on the values of relevant parameters when C80 ~ C100 concrete is used to calculate the bearing capacity of shaft lining in design, such as the influence coefficient of concrete strength β_c in the calculation of shear bearing capacity of inclined section of shaft lining, the eccentric compression bearing capacity of normal section of shaft lining and the relevant coefficients of steel bar configuration (α_1, β_1, π_b) (see Table 1); In order to improve the bearing capacity of steel bars in reinforced concrete structures and to better match the high-strength performance of high-strength concrete, high-strength steel bars should be adopted when C80 ~ C100 concrete is used in shaft lining design, and the minimum reinforcement ratio limit value should be increased. The minimum reinforcement ratios are 0.75%, 0.70% and 0.65%, respectively, with strength grades of 400, 500 and 600 MPa, which provides a basis for the formulation of technical specification and the formation of technical system for the application of C80 ~ C100 concrete in shaft lining design of freezing sinking.

Table 1. The parameter design values of C80~C100 concrete.

Index		Concrete strength grade				
		C80	C85	C90	C95	C100
Standard value of axial compressive strength f_{ck}/MPa		50.2	53.5	56.7	59.9	63.1
Design value of axial compressive strength f_c/MPa		35.9	38.2	40.5	42.8	45.1
Standard value of axial tensile strength f_{tk}/MPa		3.11	3.18	3.22	3.28	3.30
Design value of axial tensile strength f_t/MPa		2.22	2.27	2.30	2.34	2.36
Elastic modulus E_c/GPa		38.0	38.3	38.7	39.0	39.3
Elastic modulus tensile compressive strength ratio f_t/f_c		1/16.17	1/16.83	1/17.61	1/18.29	1/19.11
Influence coefficient for inclined section bearing capacity β_c		0.800	0.778	0.755	0.735	0.716
Calculation coefficient of equivalent rectangular stress diagram β_1		0.74	0.73	0.72	0.71	0.70
Calculation coefficient of equivalent rectangular stress diagram α_1		0.94	0.93	0.92	0.91	0.90
Compression zone height ξ_b	400 MPa rebar	0.463	0.453	0.444	0.435	0.426
	500 MPa rebar	0.429	0.420	0.411	0.403	0.394
	600 MPa rebar	0.396	0.386	0.380	0.371	0.363

5 Application Prospect of Freezing Method

With the development of the times, any construction method will expose problems. Considering that the freezing method is environmentally friendly and efficient, it is suitable for soft soil areas, but it will have adverse effects on surrounding buildings and underground pipelines. From the technical point of view, although freezing sinking method is a mature special construction method, it is an indisputable fact that related basic research, design theory, construction technology and technology lag behind engineering practice due to the changes of geological conditions, shaft depth and other factors, so it is urgent to carry out relevant research to meet the actual needs of engineering[14].

(1) Under the theoretical framework of frozen soil physics, the theoretical and experimental research on the coupling problems of temperature field and moisture field and the coupling problems of temperature field, moisture field and stress field in frozen stratum of artificial deep alluvium with multi-circle pipes is carried out, the corresponding coupling calculation model is established, the coupling mechanism of water and heat is revealed, and the simplified analytical calculation method with engineering significance is given; By means of theoretical analysis, numerical simulation and field measurement, the deformation and mechanical characteristics of frozen wall under excavation conditions are emphatically studied.

(2) By systematically analyzing the temperature field, freezing pressure and hydrological variation of frozen deep wells in China in recent years, the distribution law of freezing pressure in deep wells of typical strata (clay and sand layers) in the region is

obtained, and the semi-theoretical and semi-empirical formula for calculating freezing pressure with regional representative significance is established.

(3) Study the new high-strength freezing shaft lining structure and its design theory, reveal the interaction mechanism between freezing wall and shaft lining structure, analyze the actual stress state of freezing pipe, and innovate the construction technology of freezing pipe from many aspects such as low-temperature physical performance of freezing pipe, joint structure and welding technology.

(4) The thawing characteristics and laws of temperature field in each area of the frozen wall under multi-circle pipe freezing are studied, and the thawing time ratio of multi-circle pipe is obtained, which provides theoretical basis for scientifically determining the grouting time behind the wall to prevent wellbore from producing water.

(5) Study the dynamic response law of surrounding rock of deep shaft (700~1000 m) connecting chambers under complex geological conditions to construction sequence, excavation and support mode, etc., and obtain the inherent universal law between natural geological factors and human factors and the stability of surrounding rock of deep shaft connecting chambers, so as to solve the safety problems of deep shaft connecting chambers during construction and operation.

6 Conclusions

(1) As a reinforcement method of underground space, freezing method has been very mature, especially for soft soil stratum with high water content, its superiority is more obvious. At present, freezing method has played a very good role in reinforcement, emergency repair and emergency rescue of subway connecting tunnels. In the future, this method can also play an important role in the fields of roads, bridges and water conservancy.

(2) At present, the design and calculation system of frozen wall in deep alluvium has been established, which solves the theoretical problem of frozen wall design within 800 m. However, dozens of formulas for calculating the thickness of frozen walls based on different boundary conditions and constitutive relations are still necessary for further study. The design and calculation method of frozen wall in water-bearing soft rock needs to be further summarized and condensed in engineering practice.

(3) The research and development of special C80~C120 high strength and high performance concrete for the inner and outer layers of freezing well provides technical support for controlling the shaft wall thickness of freezing sinking in 700~1000 m deep alluvium within 2.5 m. But how to establish the technical specification of applying C80~C120 concrete in freezing shaft on the basis of the existing regulations of shaft lining is an urgent task; Especially, the design load and load separation criterion of inner and outer shaft lining in freezing section of deep alluvium (>600 m) need further study.

(4) Although freezing sinking is a mature and special construction method, it is an indisputable fact that related basic research, design theory, construction technology and technology lag behind engineering practice due to the changes of geological conditions,

shaft depth and other factors, so it is urgent to carry out relevant research to meet the actual needs of engineering.

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