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Study on the Protective Effect of Viscous Buffering Device under Explosive Load

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Abstract

In recent years, with the complex and changeable international situation, local wars and conflicts abroad have occurred frequently, which seriously threaten the safety of human life and property. Against this background, high-precision and high-intensity strikes against key targets such as enemy command posts and ordnance reserves have become the norm in modern warfare. As the undercard of national security, the security and protection capabilities of underground military facilities are of great importance. Underground structures not only play the role of emergency evacuation of personnel to avoid air and missile attacks, but also the core of the combat command system, where key facilities such as military underground factories and warehouses are located. The security of these facilities has a direct bearing on the outcome of a war and even the fate of a country. In view of this, taking effective measures to improve the explosion resistance, durability and survivability of underground protective structures has become an important research topic in the field of military engineering in various countries. Under the action of the explosion of conventional weapons at a certain distance, the underground protective structures can be damaged due to insufficient resistance. The powerful shock wave generated by the explosion, with its huge kinetic energy and impact force, will cause a large vibration acceleration ring inside the structure, which is very easy to cause casualties and equipment damage within the structure, thus posing a serious threat to the safety of underground engineering. In order to improve the anti-explosion performance of the protective structure under the action of blast impact load, the underground protection engineering structure has been continuously upgraded and optimized, among which the layered protective structure has been widely used because of its relatively excellent protection effect. The layered protective structure realizes a relatively effective protection system through a well-designed camouflage layer, a bullet shielding layer, a dispersed layer and a main structure. However, although significant progress has been made in the optimization of three-layer materials, the defects such as the unstable state of the dispersed layer and the possibility of reducing the overall protection performance with time or external conditions are still an urgent problem to be solved. This system is designed to replace or partially replace the traditional dispersed layer, which is not only designed to effectively absorb and dissipate the blast wave energy transmitted by the bomb shielding layer, but also fundamentally solve the problem of the reduction of protection effect caused by the change of the state of the dispersed layer. In this study, the simulation technology will be used to deeply explore the structural dynamic response of the protective structure after the addition of buffer energy dissipation device under the blast impact load, and the key factors affecting the protection effect will be systematically analyzed, the simulation parameters will be accurately set, and the protection effect under different parameter combinations will be simulated, so as to find an optimal parameter configuration scheme. This study not only helps to deepen the understanding of the anti-explosion performance of underground protection structures, but also provides valuable theoretical basis and practical guidance for the design and construction of underground protection projects in the future.

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Keywords

Protective Structure; Dispersion Layer; Simulation Technology.

1. Background of the Research Topic

The dynamic impact kinetic energy of the explosion impact load on the underground engineering is large, the impact force is large, the peak spectrum is high and the frequency domain range is narrow, the pressure or suction load is large for the underground engineering, and the vibration is caused by the underground engineering and the upper overlay, which seriously threatens the stability of the underground structure and endangers human safety. The layered protective structure originated in the early 20th century and is a type of protective structure that emerged with the development of conventional ground-penetrating weapons. A typical layered protective structure is usually composed of four parts: camouflage layer, bullet shielding layer, dispersion layer (also called distribution layer) and main structure. Among them, the bomb shield layer mainly causes the projectile body to buckle, stalemate, deflect and fragment, so as to force the high-speed penetrating projectile body to explode in the bomb shield layer without directly contacting or penetrating the main structure. However, with the development of more sophisticated and high-speed ground-penetrating weapons, the impact effect of the explosion will pose a huge security threat to the main structure. In order to ensure that the main body of the project is not damaged and how to reduce the strong vibration generated by the explosion to a range that can ensure the safety of personnel and equipment, a dispersed layer is laid between the bomb shield layer and the main structure. The specific functions of the dispersion layer are: to improve the energy proportion of the downward propagation of the explosion wave and extend the propagation path; Rapid dispersion of local loads in the spatial dimension; Through the irreversible plastic deformation of the dispersion layer itself, it can quickly absorb and digest the shock wave [1]. At this stage, the dispersed layer filling material is mainly used in the commonly used ordinary sand [2] . Conventional sand and soil materials have the ability to consume the blast wave, and the material is convenient and low-cost. Considering the material characteristics, construction technology and cost, there is still a lot of room for improvement in the quantity, size and layout of the dispersed layer material. However, in harsh environments such as salinity, consolidation, precipitation and ice, ordinary sand will change the state of the dispersed layer and reduce the protection effect. The impact protection effect is insufficient and unstable; These dispersed layers are difficult to protect and repair. Therefore, a new form of dispersed layer structure is needed to make it better to resist impact loads, and it is not affected by groundwater, and has higher durability and maintainability. After the introduction of layered protective structures, people have never stopped researching dispersed layers, from filling materials to structures, and continuously improving the performance of resistance to blast waves. With the increasing requirements for protection, the idea of replacing the dispersion layer with an air interlayer was proposed[3]. Liyong[4] When studying the anti-explosion performance of hybrid sandwich panels, it is found that the anti-explosion performance of sandwich panels is the best when there is no filler, and the total energy absorption of the structure is the largest. However, the air interlayer faces the support problem in the process of use, and the construction is also relatively difficult, and the structural stability cannot be guaranteed.

Qiaanqihu错误!未找到引用源。 In the study of the design of the seismic isolation system, it is proposed that the structure is supported by seismic isolation elements. Nonlinear seismic isolation elements have air springs, liquid springs, etc., with greater damping, and can better absorb energy during action, China's explosion-resistant seismic isolation structure has studied a variety of seismic isolation elements such as wire rope seismic isolators, which play a role in energy dissipation buffering in the protection system. The United States uses transverse shock

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absorbers and hydropneumatic spring buffers to isolate the missile launchers inside the silos, and the underground civil defense headquarters built in Sweden is also built on spring isolation supports. If the buffer energy-dissipating bearing is applied to the air interlayer of the protective structure, whether the bearing can give full play to the anti-explosion performance, whether it affects the performance of the air interlayer itself, and when its height is what needs to be considered, a series of issues such as affecting the stability of the protective structure need to be studied.

2. Significance of the Research Topic

The dispersed layer in the layered protective structure can quickly disperse the local load and quickly absorb the blast wave energy, so the relevant research on the dispersed layer can improve the anti-explosion performance of the protective structure. After the air interlayer replaces the dispersed layer, the impact of the explosion wave is improved, but there are still support problems and construction problems to be solved. The application of the buffer energy dissipation bearing to the air interlayer of the protective structure can solve the drawbacks of the air interlayer; There will also be a lot of room for research on the head engineering against foreign enemies and the seismic isolation of silos. This research field is not very perfect at present, and this research can affect the performance of the buffer energy dissipation bearing itself, the influence on the air interlayer, and the effect on the stability of the protective structure. The underground protective structure is related to the security of national property, and the in-depth study of the protective structure is a major breakthrough for the dispersed layer, which solves the disadvantages of the air interlayer at the same time, and strengthens the protective effect of the dispersed layer. Second, it provides a theoretical basis for relevant researchers and contributes to national security.

3. Research and Development Status at Home and Abroad

3.1. Research History at Home and Abroad

The research on dispersed layers has evolved from material selection to combining structural forms to improve the protective effectiveness of dispersed layers. The research process on dispersed layer filling materials and structures, protective structures, and buffer supports is as follows:

Research on dispersion layer filling materials: In 2003, Wang Yonggang et al. [6] studied the propagation characteristics of shock waves in foam aluminum through experiments and numerical simulation; In 2006, Liu Fei et al. [7] conducted impact tests on several typical dispersion layer materials, such as foam concrete, loess and sand, and compared their performance; In 2007, Zhao Kai [8] conducted SHPB impact tests on several major engineering protective materials, such as concrete, loess, sand, foam concrete, and layered composite specimens composed of them, and found that foam concrete has a more obvious dissipation effect on waveform under complex stress conditions; In 2014, Li Xuyang [9] designed a hollow shell particle material with triple hole isolation effect using a closed cell silicon aluminum foam ceramic material as the parent material, and applied it to layered protection engineering; In 2015, Ren Xinjian [10] and other designers carried out three types of chemical explosion tests, which verified the strong wave dissipation and energy absorption characteristics of foam hollow sphere materials. In 2016, Xu Chang [11] found that polyurethane foam dispersion layer has good performance in dissipating explosive energy, and the increase of its thickness will further enhance the dissipation of explosive energy; In 2017, Sun Xiaowang et al. [12] developed a new type of hollow shell particles lined with PVC shells and wrapped with foam ceramic shells as the distribution layer of civil air defense structures. In the same year, Wang et al[13]; Ye Zhongbao et al. [14] demonstrated that the new type of hollow shell particle

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composite material not only has a very significant attenuation and dispersion effect on explosion waves, but also has the ability to withstand multiple impacts.

In 2019, Huang Xu [15] proposed the application method and measures to be taken for the layered protective structure of polyethylene PEF buffer layer, providing a method and approach to fully utilize the advantages of the buffer layer material and the energy dissipation and load reduction function of the buffer layer; In 2021, Hiroyoshi Ichino [16] incorporated expanded polystyrene (EPS) boards into the soil layer to mitigate explosions. Research has shown that there is an optimal ratio of sand layer thickness to EPS board thickness for reducing and dispersing explosion pressure; In 2022, Hiroyoshi Ichino [17] studied the influence of the density of expanded polystyrene foam (EPS) on the effectiveness of the explosion mitigation system. The duration of the explosion pressure at the bottom of the explosion becomes shorter with the increase of EPS density, and the relief system becomes shorter; In 2022, HooMinLee [18] studied composite sandwich structure and evaluated the influence of porous foam surface pattern on composite sandwich structure stability and weight reduction. We conducted impact hammer and mass drop tests to study the vibration reduction and damping performance of composite material structures. The simulation verification experiment results were conducted based on the finite element method (FEM). In 2023, Xu Hang [19] proposed that polyurethane foam materials can be combined with the main structure to reduce the size of the main structural members and avoid "fat beams and columns"; In 2024, Jianwei Cheng [20] discovered that the performance of explosion suppression materials has a significant impact on controlling the spread of explosions. Bentonite has a large surface area and rich pore structure, which can adsorb free radical reactions during explosion processes. And propose three schemes to improve the spatial suspension performance of bentonite.

Research on dispersed layer structure: In 2004, Jiang Shuide proposed the air sandwich structure, which consists of a top layer structure (blast resistant layer), an air sandwich layer, and a bottom layer structure (collapse isolation layer). Research has found that the anti explosion local damage ability of air sandwich structures is 5.8 times higher than that of conventional reinforced concrete structures. In 2006, Wu Jianqiang [21] pointed out that air interlayers can effectively prevent the transmission of explosive compression waves from the top structure to the collapse isolation layer, resulting in the collapse isolation layer only receiving small compression waves and concrete debris impacts. The air sandwich structure is a structure with strong explosion resistance and plays an extremely important role in important building structures and civil defense structures. In 2007, Zhao Yuetang [22] stated that the thickness of the dispersion layer has a significant impact on the dynamic response of the main structure, and increasing the thickness of the dispersion layer appropriately can effectively weaken the dynamic response of the main structure; In 2008, Yan Haichun [23] adopted measures such as setting steel mesh inside the slab or pasting steel plates on the back surface of the roof to address the impact of collapsed fragments of the shielding layer on the roof structure under the condition of dispersed air interlayer; In 2012, Yan Haichun [24] discovered that by controlling the thickness of the air layer, the damage caused by explosive impact loads could be effectively reduced, providing a new design concept.

Continuous exploration of protective structures: In 1987, Joseph W. Tedesco [25] proposed that "layered structures" could provide a feasible alternative to traditional hardened structures; In 2018, Luo Weiming[26] proposed a layered aluminum honeycomb sandwich structure. By conducting drop hammer impact tests at two different energy levels, the local impact response results of different combinations of specimens were obtained. The research results can provide reference for the application of layered aluminum honeycomb sandwich structures in protective engineering; Liu Zheng [27] proposed a layered protective structure of "granite (air) sand concrete" and conducted numerical calculations to study the failure characteristics and energy distribution of the structure under ultra high speed impact. Vertical impact kinetic

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energy is transmitted laterally in the shielding layer and distribution layer. Increasing air barriers can reduce the penetration depth of structural layers, the proportion and absolute value of energy distribution among structural layers; In 2019, LijuanSu [28] applied closed cell foam aluminum to the structural design of high-speed railway tunnel damping layer for the first time. Closed cell foam aluminum based on pure aluminum is used for the design and manufacture of tunnel lining damping layer. The results show that the closed cell foam aluminum layer has a certain weakening effect on the dynamic response of the tunnel lining, and the shock absorption performance changes with the change of load conditions; In 2024, Sobhan Pattajoshi [29] proposed a novel multi-layer composite protective structure and studied the dynamic behavior of multi-layer composite materials under impact loads; WenyiBao [30] introduced a new type of protective structure, which adopts a bowstring design and a bent sandwich panel with a folded core as the core to improve the blast resistance of the protective structure; HangZhou [31] proved that the compression and energy absorption performance of foam polymer with larger thickness and lower density is improved due to the increase of its pore number through a typical test device. The transmission and reflection stress waves of the "hard soft hard" layered structure are influenced by the wave impedance of adjacent media.

The research status and application of seismic isolation bearings: In 2006, JianchengTao [32] found that increasing damping effect reduced the resonance peak and seismic isolation performance in the "isolation zone". This article investigates the effect of viscous damping on force transmission rate. In 2018, Yongfeng Cheng [33] introduced a new type of cylindrical electrical equipment isolation device, which is composed of circular lead alloy isolation units installed at the bottom of the equipment. In 2023, ZhenlinLiu [34] proposed a design and performance characterization method for a combined seismic isolation system to improve the seismic performance of slender electrical equipment in interconnected circuit systems. This scheme is based on a novel combination application of bolt type seismic isolators and support blocks, which achieves seismic isolation function by reducing the bending stiffness of slender equipment. In 2024, Li Xiaodong [35] proposed an electromagnetic suction cup friction pendulum composite seismic isolation bearing based on electromagnetic force and combined with traditional friction pendulum. In 2024, Wen Runqiu [36] proposed to use modular layers in parallel with rubber bearings as the main body, combined with multi-stage U-shaped dampers and pin type wind resistant devices to form a composite isolation layer. In 2024, ZeMo [37] proposed a new type of air spring lead rubber bearing (AS-LRB), a three-dimensional seismic isolation device with horizontal and vertical seismic resistance functions. In 2024, ZeMo [38] proposed a large deformation spring type vertical isolation device to address the poor isolation performance of traditional rubber vertical isolation devices, and introduced the compressed air isolation device (ASVSID) using air spring type vertical isolation. In 2024, Liang Qiuhe [39] proposed a new type of circular spring rubber three-dimensional seismic isolation bearing. In 2024, Li Baoyu [40] found that installing rubber seismic isolation bearings between the upper and lower structures can fully utilize the function of the isolation layer, consume seismic energy, reduce building resonance and horizontal stiffness, and keep the building stable after the earthquake. In 2023, Longwen Fan [41] studied the seismic response of asymmetric large-span suspension and the asymmetric parameter combinations of various control objectives of viscous dampers. It was found that the parameters of the viscous dampers on both sides of an asymmetric long-span suspension bridge can balance the overall bridge force and improve the absorption effect of the impact dampers.In recent years, the research on dispersed layer materials has been mainly reflected in the solidity in the early stage. Later, natural materials or industrial waste were used for reuse. Then he began to improve the properties of the materials, studied the stability and durability of the filler materials, and slowly ventured into composite materials and smart materials. In short, the research process of dispersed layer

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filling materials for underground protective structures is a process of continuous innovation and development, which provides important technical support for improving the safety and reliability of underground protective structures. The development of the dispersed layer structure gradually tends to synergize with the main body of the underground protective structure to achieve the best protection effect. The research on air interlayer is mainly listed here, which provides an important theoretical basis for the next research and provides important technical support for improving the safety and reliability of underground protective structures. The research on layered protective structures is still innovating and expanding. Researchers continue to explore new materials and structural forms to improve protection and reduce costs. In recent years, the research on seismic isolation bearings mainly includes the influence of viscous damping on the force transmission rate, the continuous development of composite bearings, the composition of springs and traditional bearings, and the evolution of three-dimensional seismic isolation bearings, which play an increasingly important role in seismic isolation.

3.2. Development of

For the material-filled dispersed layer, it mainly relies on the irreversible deformation of the material itself to consume and absorb energy. The protective principle of the air interlayer is different, firstly, to give full play to the function of the bomb shielding layer, the bullet shield layer has more space to deform to consume energy more effectively; Second, from the perspective of the propagation characteristics of the stress wave in the medium, the existence of the air dispersion layer makes the waveform disperse to the surroundings, thereby prolonging the distance and time of the explosion wave propagation, so that the explosion wave can be more fully dissipated and weakened in the dispersion layer. However, in the practical application of this structure, there are still problems such as construction difficulties and long-term stability of the structural form. With the continuous development of ground-penetrating weapons, the requirements for protective engineering are also increasing. The support problems, construction problems and structural stability problems faced by the air interlayer in the process of use still need to be further studied. At present, little is known about the application of buffer energy-dissipating bearings to air interlayers, and it is necessary to further adopt numerical simulation methods, and at the same time propose a variety of structural forms and support parameter types to select the optimal parameter combination through calculation.

3.3. Basic Theory of New Dispersion Layer

The explosion-proof buffer energy dissipation bearing is installed in the air interlayer, which can just solve the disadvantages faced by the air interlayer in the use process. The explosion-proof buffer energy-dissipating bearing is a buffer + hydraulic speed energy-absorbing energy-absorbing protection device, which is composed of a viscous damper and a spring recovery force device, which provides static load support with a spring and provides reciprocating motion stiffness in the process of high explosion and vibration; Damping parts are used to absorb part of the explosion impulse and buffer energy dissipation. By studying the working performance and effect of the bearing, a better optimization scheme is proposed Viscous dampers are suitable for some fast-vibrating loads such as earthquake windmill flow loads, which can play a role quickly and reduce the dynamic response of the structure. Moreover, the viscous damping material is less affected by environmental factors, easy to maintain and has good durability. The bearing is installed in the air interlayer, which can solve the problem of no support in the air interlayer, and can greatly reduce the peak stress of the stress wave in the support compared with the ordinary column, and the bearing has self-determined damage resistance and self-recovery ability, and can withstand multiple explosion impacts. So as to solve the protection problems of some fortifications with high requirements for protection performance. Its function is to carry out damped free vibration under the condition of initial

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huge impulse impact, and its conceptual design covers two ideas: First, the protection function is composed of two processes (buffer process and energy dissipation process), the buffering process refers to the explosion wave acting on the viscous damper, the cushioning effect of the spring and the downward movement of the piston interact with the viscous damping material, and the energy dissipation process refers to the flow of the viscous damping material inside the cylinder through the damping hole, the pressure difference between the two sides, and the damping material flows through the damping hole to produce damping force. The force transmitted by the vibration of the structure is dissipated, and the effect of the vibration is reduced[42]. In the process, the vibration amplitude of the protection system is gradually reduced, and the vibration is dampened in a few vibration cycles. The realization of the buffer process is based on the principle of equal impulse, and the realization of the energy dissipation process is based on the principle of equal energy. Second, the buffer energy-absorbing device is composed of two types of devices (buffer energy-absorbing device and energy-absorbing device). This is shown in Figure 3. This design combines a buffer energy absorber and a energy absorption device into one, and is called an "impact-resistant buffer energy absorber".

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