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Analysis of failure and optimization study of stoppage ring opening mechanism in sleeve valve casing material

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ABSTRACT

In the context of deep-buried sleeve valve construction, two significant challenges in grouting operations involve the material infusion and subsequent failure of the casing material's opening loop. This study combines indoor experiments and field studies to investigate the optimization strategies for sleeve valve construction by introducing aggregate additives. The research begins with a theoretical analysis of the weak formation of the stoppage ring, scrutinizing its failure causes under deep-buried conditions. It further delves into mechanism study on optimizing the opening loop mechanism of the stoppage ring post the addition of crushed stone aggregates. Simultaneously, indoor experiments focus on assessing the fracture characteristics of aggregate-casing materials. These findings are then applied to on-site grouting loop tests. The experiments demonstrate that the inclusion of aggregates not only enhances the intact opening probability and operational efficiency of casing materials but also disperses the impact of casing material aggregates within the stratum. This dispersion significantly reinforces the crushed stone-mud slurry framework within the stratum, ultimately contributing to improved stratum uniformity and stability. Through a comprehensive investigation into the casing material's opening loop mechanism, a clearer understanding of the causes of opening failure is achieved, leading to proposed optimization methodologies. These findings aim to provide both theoretical support and practical guidance for improving designs and optimizing fluid systems in diverse engineering contexts.

1. Introduction

The grouting technique is a pivotal auxiliary method in underground engineering construction, addressing weak and water-rich unfavorable strata. It has played a crucial role in reinforcing surrounding rocks, sealing underground water, and enhancing foundation bearing capacity[1]. As urbanization accelerates, limitations on urban surface transportation space have increased. Consequently, the frequency of grouting reinforcement techniques in underground engineering, such as subways, tunnels, bridge foundations, and building foundations, has steadily risen[2–4]. Sleeve valves, as key components in fluid control, play a critical role in reinforcing underground structures, increasing foundation stability, and enhancing engineering safety and reliability[5]. Additionally, sleeve valve grouting, compared to traditional foundation treatments, offers more convenience and flexibility. It enables operations in confined spaces or complex environments and allows customization of construction plans based on various engineering needs to meet

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specific requirements for grouting reinforcement at different depths. Therefore, it finds extensive application in urban foundation reinforcement.

In exploring grouting engineering, past research has mainly focused on material suitability and performance under diverse geological conditions. This involves optimizing factors like grout viscosity, fluidity, setting time, compressive strength, and its interaction with underground environments[3,6]. Advanced monitoring techniques assure real-time observation of parameters such as grouting material solidification, compactness of grouting areas, and structural stability, ensuring engineering quality and safety[7]. Due to geological complexity, grout diffusion varies across different geological settings[8]. Scholars have delved deeply into this; for example, Bantralexis, et al. [9] predicted cement suspension grouting performance in soil improvement and permeation projects using a novel sand grain aperture distribution model. However, a mature calculation theory and method for sleeve valve grouting are yet to be established. The investigation into the damage of the grouting ring in the casing during sleeve valve grouting processes often extends to models of uniform stress and non-uniform stress under the influence of ground stress for traditional cylindrical casings[10]. Consequently, classical yield criteria have certain limitations[11]. Building on this, Zhang, et al. [12] proposed the use of the non-associated flow rule within the plastic influence zone of the surrounding soil. They derived expressions describing the relationship among the initial radius of the slurry, the slurry radius, and the radius of the soil's plastic zone during the grouting process. The theoretical formula for calculating the grouting pressure was derived and applied to verify the on-site sleeve valve grouting process. Lei [13] conducted field experiments to improve sleeve valve grouting using coarse sand as the casing material. Acceleration and soil pressure response tests were performed during the grouting process, and an analysis of the excavated strata around the sleeve valve grouting was conducted to assess the reinforcing effectiveness of the improved casing material. Guo, et al. [14] established a theoretical calculation method for the open-loop pressure of the sleeve valve grouting, considering multiple factors through on-site experiments. They conducted in-depth research on the impact of the strength of the grouting ring material and the elastic modulus of the grouting ring material and the soil being grouted on the open-loop pressure. However, in the deep grouting construction process of sleeve valve pipes, there still exists a problem of long-distance clogging of casing material, and the local failure of the casing material grouting ring in the open-loop process, as well as the issue of uneven slurry seepage in a single direction, has not been effectively resolved.

In conclusion, the research, beginning with an exploration of the causes behind stoppage ring opening failure, initially introduces the concept of adding aggregates to casing material. Subsequently, starting from the optimization of the opening mechanism, both indoor and field experiments were conducted. The validation revealed that including aggregates not only enhanced the flowability of casing material but also refined the opening mechanism, elevating the probability of complete casing material opening. Simultaneously, it further reinforced the impact dispersion of aggregates into the formation, confirming the viability of the optimization approach. Furthermore, the study delved into the potential use of waste materials as aggregates for casing material [15]. The experimental results indicate that researching the failure mechanism and optimizing the open-loop system of the grouting ring holds significant importance for optimizing and improving sleeve valve grouting construction technology.

2. Experimental

Prior studies have primarily concentrated on sleeve valve grouting, yet there is a dearth of research concerning the casing material's opening mechanism. Through past research and on-site grouting, several issues have been identified regarding casing material utilization: (1) Under deep burial conditions, high-viscosity mixed casing material tends to obstruct conduits during the injection process. Air compressors exhibit poor performance in compressing high-viscosity materials over extended distances, resulting in inadequate material compaction and the formation of voids within the stoppage ring. Moreover, the burial depth of conduits makes them challenging to clean and clear, impacting construction efficiency. (2) Uneven cracking of the casing material stoppage ring causes unidirectional seepage of the slurry, leading to a dispersed injection range [16]. Increased voids within the ring intensify weaknesses, resulting in zoneal opening failure before reaching the standard injection pressure. Consequently, the slurry seeps unidirectionally from the weakened area, causing locally excessive injection effects, posing difficulties in meeting uniform and stable grouting reinforcement requirements.

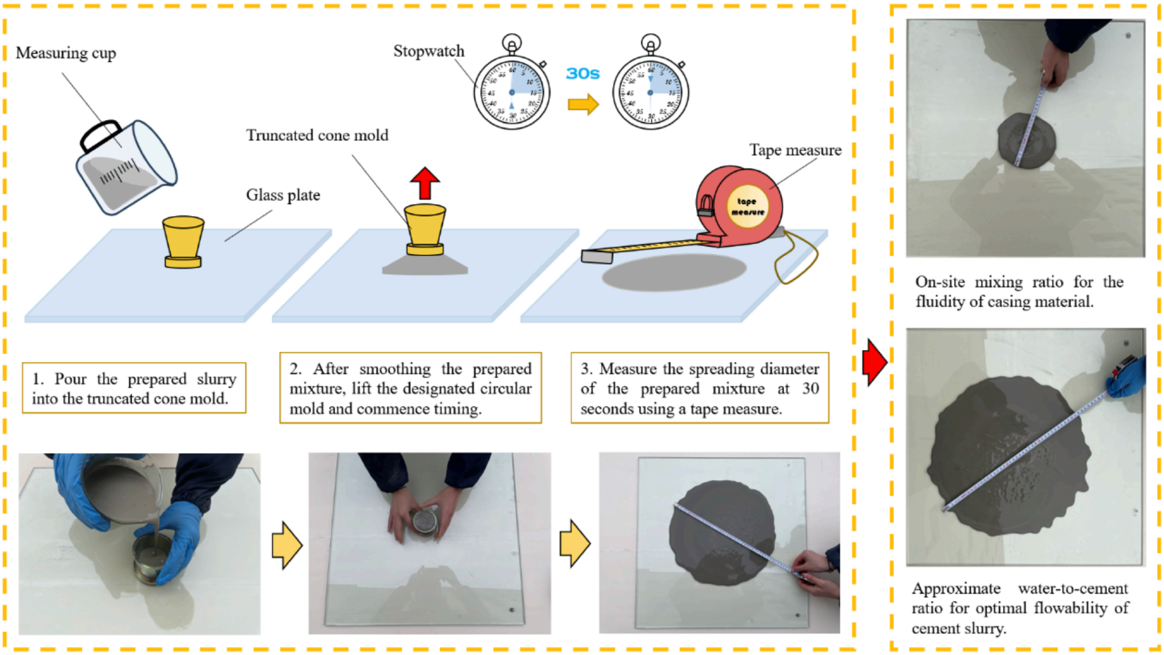
2.1. Casing material long-distance infusion blockage

At a construction site in Chongqing, the casing material infusion was conducted using an outer diameter 25 mm PVC conduit. The optimal mixture ratio of the casing material obtained during on-site construction comprised water, cement, and bentonite in a ratio of 2.3:1:1. Conduct a cement slurry flowability test according to the homogeneity test method (GB/T8077-2012). Swiftly pour the well-mixed slurry into a truncated cone mold and level it with a scraper. Lift the truncated cone mold vertically upwards, start the stopwatch, and let the slurry flow on the glass plate for 30 s. Measure the maximum diameter in two mutually perpendicular directions of the flowing part with a ruler, and take the average as the flowability of the cement slurry. Following the shell material ratio used at the construction site, i.e., water: cement: bentonite at 2.3:1:1, water-cement ratio at 2.3:2, approximate water-cement ratio at 1.15:1, we conducted a cement slurry flowability test with a water-cement ratio of 1.15:1 and the shell material ratio of water: cement: bentonite at 2.3:1:1 to compare the flowability of the two slurries. The maximum diameter of the indoor experimental shell material flowability test is approximately 13.5 cm, while the maximum diameter of the cement slurry solution with a water-cement ratio of 1 is approximately 43.0 cm. The flowability of the former is about 0.31 times that of the latter, indicating that the flowability of the shell material raw material is very low. The indoor flowability comparison test process is shown in Fig. 1(a).

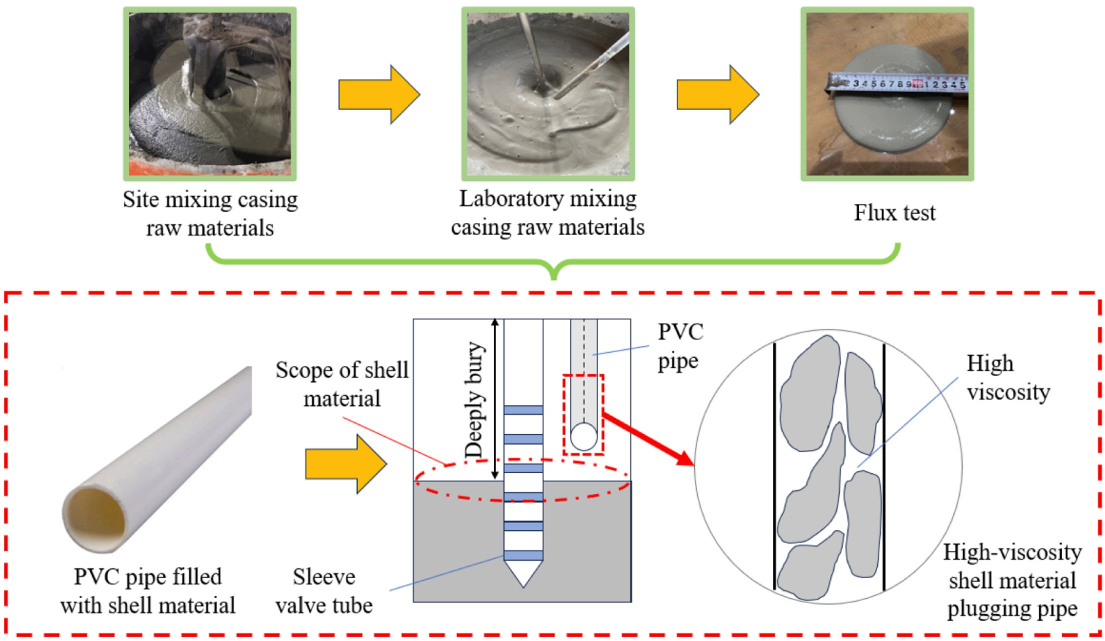
During the infusion process within the pipe, excessive burial depth led to an elongated PVC conduit, coupled with the high viscosity of the mixed casing material. Consequently, the material adhered to the walls of the PVC conduit, causing conduit blockage during the deep infusion process, as depicted in Fig. 1(b).

2.2. *Uneven opening of casing material seal ring*

To delve into the study of the open-loop grouting mechanism in sleeve valve pipes, an on-site analysis of the grouting cross-section



(a) Flow comparison test process diagram



(b) Schematic diagram of shell material infusion blocking

Fig. 1. Mechanism analysis diagram of shell material infusion blocking.

was conducted. The on-site grouting area comprised backfilled soil layers, with a grouting reinforcement depth of 10 m. The grouting employed a segmented approach from bottom to top, lifting the grouting pipe by 30 cm after each segment for the subsequent grouting. Galvanized pipe grouting tools and sleeve valve pipes with a diameter of 48 mm were used for the grouting process. Cement for grouting utilized P.042.5 cement with a water-cement ratio of 1.0 for cement slurry, and the shell material was proportioned at a ratio of water: cement: bentonite as 2.3:1:1. After 3 days of curing, grouting experiments were initiated. On-site monitoring indicated an open-loop pressure range of 0.8 MPa to 1.0 MPa, with a grouting pressure of 1.0 MPa. After completing the grouting, sleeve valve pipe grouting holes were excavated one day after curing. Fig. 2 (a) displays the diffusion of slurry at a depth of 1.6 m, forming stone bodies with the surrounding soil as depicted in Fig. 2 (b), (c), and (d). Simultaneously, the grout ring was not completely damaged but formed local cracks, as shown in Fig. 2 (e). The slurry flowed unidirectionally through the cracks, indicating the failure of the open-loop grouting of the grout ring. The flowing slurry did not form a uniformly circular stone body around the sleeve valve pipe in the surrounding soil.

During the on-site grouting process of the sleeve valve pipe, irregularities were observed in the open-loop grouting pressure, significant variations in grouting pressure peaks, and unclear abrupt drops in open-loop grouting pressure. The possible cause of these issues may be the greater depth of grouting, causing the bentonite shell material to adhere to the pipe wall during the long-distance infusion. This resulted in insufficient compactness of the overall shell material grout ring and even the formation of internal cavities, collectively weakening the strength of the grout ring. The grout ring gradually developed splitting cracks under the influence of slurry pressure. Due to the uneven formation of the grout ring, the open-loop grouting process prevented the complete destruction of the grout ring, and slurry pressed through the weak points, forming unidirectional flow. The inability to completely open the loop resulted in an ineffective grouting system. The defect mechanism of the shell material open loop is illustrated in Fig. 2 (f), (g), (h), and (i).

2.3. Optimization of opening mechanism

In addressing the aforementioned concerns, the design sought to improve the flow properties of the bentonite mixture by introducing crushed stones. This modification aimed to transition the original sliding friction between the casing material and the PVC conduit during the infusion process into rolling friction, significantly reducing their adhesive friction. During the opening phase, the escalating grouting pressure drove the grout to impact the crushed stone seal ring. This impact caused the stones on the seal ring to fracture and detach, continuously colliding with the grout to form a mixed solution, as illustrated in Fig. 3 (b) and (c). Compared to traditional casing materials, this combined impact and fracturing increased the efficiency of the opening process. Additionally, the circumferential stress on the crushed stone-bentonite casing material during the opening process became more evenly distributed, facilitating uniform grout diffusion and dispersion, effectively preventing unidirectional grout seepage. Furthermore, the crushed stones damaged by compression were pushed by the grout to the outer circumference of the sleeve valve conduit and integrated with the surrounding backfill soil layer. Under the influence of the grout, these stones formed a cohesive structure, resulting in a higher-strength crushed stone-cement grout framework compared to the original cement-grouted stratum, contributing to stratum reinforcement, as depicted in Fig. 3 (d).

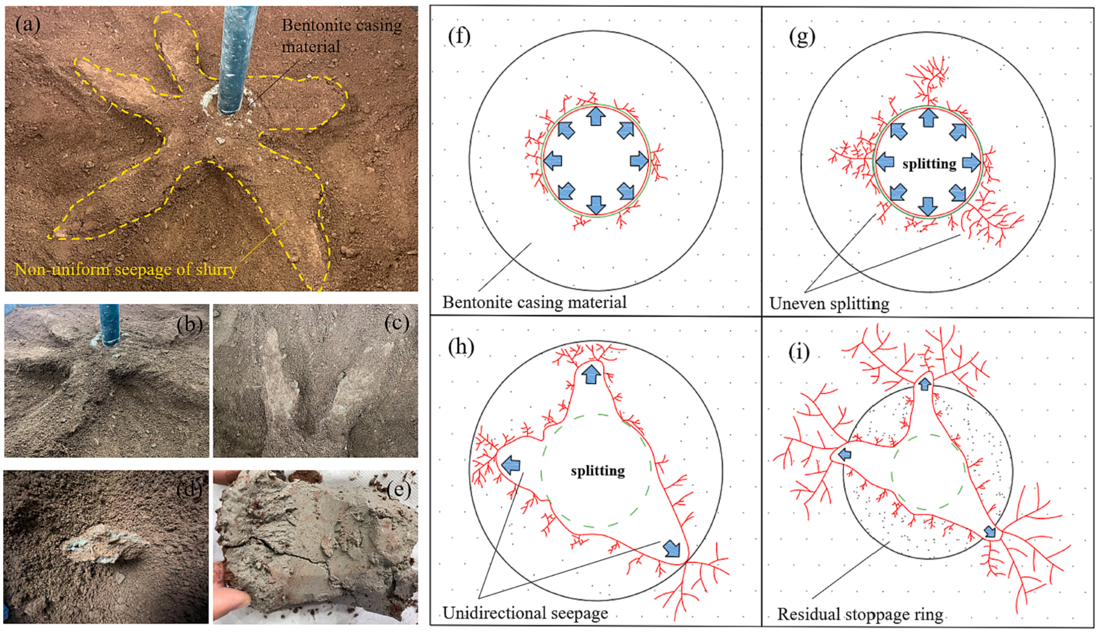


Fig. 2. Grouting cross-sectional analysis and diagram of bentonite grout ring open-loop mechanism.

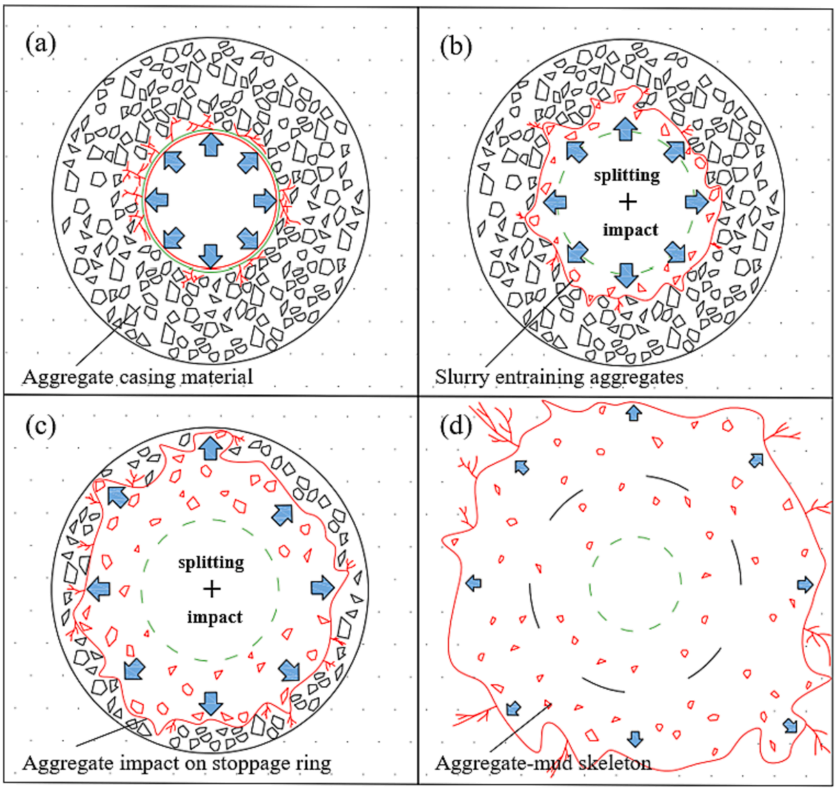


Fig. 3. Diagram depicting the mechanism of grout ring opening after the incorporation of crushed stone aggregate.

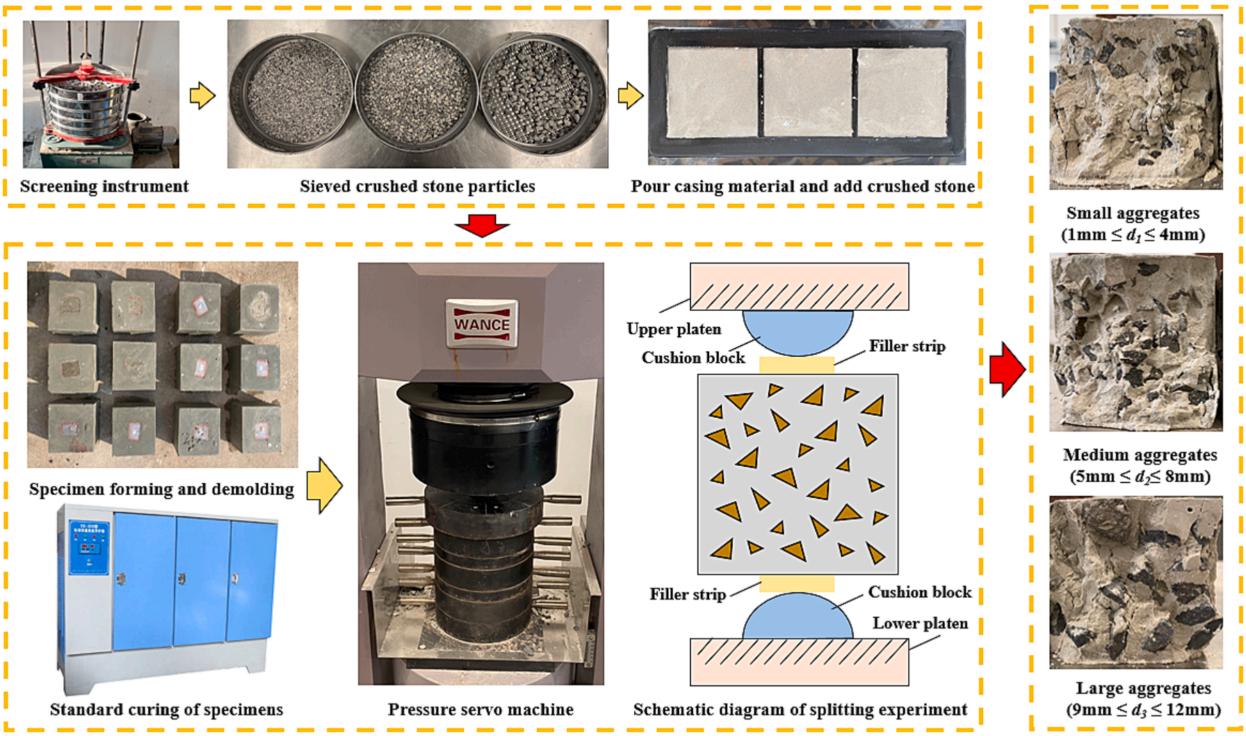


Fig. 4. Indoor mechanical test procedure diagram.

3. Results

3.1. Mechanical performance strength test

3.1.1. Aggregate impact on mechanical performance test plan

The initial study involves experimenting with four variables: the percentage of aggregate mass, types of aggregate material, aggregate particle sizes, and curing duration of the grout ring, aiming to understand their impact on the strength of casing materials. Considering the influence of different aggregate particle sizes on the strength of casing material and the challenge of aggregate transportation blockage, the experimental design classifies aggregate particle sizes into three ranges: 1 mm $\leq d_1 \leq$ 4 mm, 4 mm $< d_2 \leq$ 8 mm, 8 mm $< d_3 \leq$ 12 mm, corresponding to small, medium, and large aggregates. Initially, a vibrating sieve was employed to screen crushed stone aggregates, using stainless steel filter screens with square holes of 4 mm, 8 mm, and 12 mm aperture distribution. Employing a mix ratio of water: cement: bentonite as 2.3:1:1, the casing material ingredients were uniformly mixed with a small mortar mixer. Subsequently, the mixture was blended uniformly at proportions of 20 %, 30 %, 40 %, and 50 % of aggregate content, poured into molds to prepare 70.7 mm cubic specimens. The specimens were then placed in a standard curing box under standard curing conditions at a temperature of 20 °C and a relative humidity of 95 % for curing periods of 2 days, 3 days, and 4 days. After curing, the splitting tensile strength test was conducted to preliminarily evaluate the mechanical properties of the aggregate casing material. Initial experimental data suggesting marginal strength improvement with small-sized gravel prompts further investigation into 40 % and 50 % addition rates, exploring different aggregate types and particle sizes. Specifically, medium and large-sized crushed ceramic aggregates are chosen as comparative groups against crushed stone aggregates. The experimental procedure is outlined in Fig. 4.

3.1.2. Results and analysis of mechanical performance testing

Refer to Figs. 5 and 6 for the indoor experiment results. The preliminary findings suggest that the addition of aggregates does not notably enhance the strength of casing materials. The increase in strength due to curing time is approximately 2.6 % per day. Additionally, the largest observed strength difference between medium-sized ceramics and medium-sized crushed stones during the same period is 6.4 %. The hierarchy of influence on casing material strength is as follows: aggregate material type > curing duration > percentage of aggregate mass > aggregate particle size. This implies that adding aggregates can enhance the strength of casing materials. The introduction of aggregates leads to irregular splitting surfaces and a slight increase in splitting strength. However, in this experimental ratio, the higher water content in the bentonite-cement material weakens the bond between the bentonite-cement matrix and gravel, resulting in minimal overall enhancement in splitting strength. Consequently, the inclusion of crushed stone aggregates has a limited impact on the mechanical properties of bentonite casing materials. This benefits the open-loop process, as the addition of aggregate material does not significantly enhance the strength of the casing material. Since the splitting action plays a dominant role during the open-loop process, it can be inferred that the addition of aggregates has an optimizing effect on the open-loop process. Furthermore, it validates the potential use of waste materials as aggregates.

3.2. Field experiment

3.2.1. Experimental design plan

The experiment is divided into four zones: Zone 1 serves as the control group using traditional bentonite casing materials, Zone 2 employs small-sized crushed stone casing materials, Zone 3 utilizes medium-sized crushed stone casing materials, and Zone 4 adopts large-sized crushed stone casing materials. All zones have a 50 % incorporation ratio of crushed stones. The distance between two

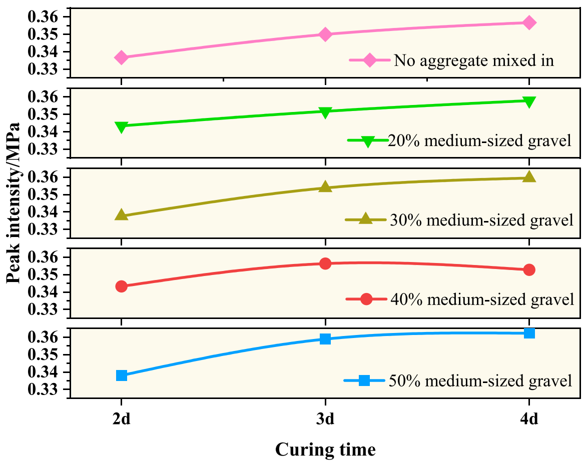


Fig. 5. Impact of different gravel ratios on strength over curing time.

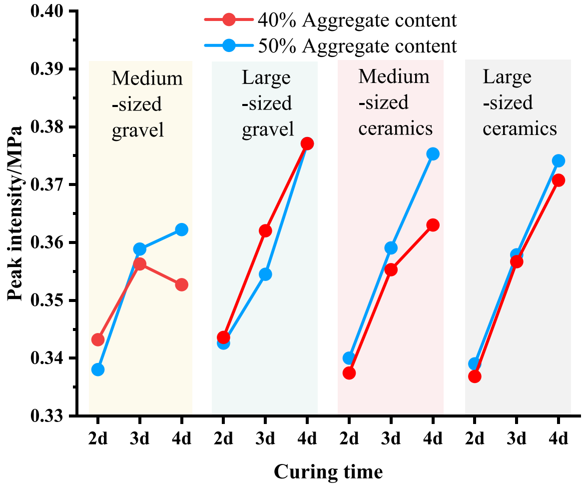


Fig. 6. Impact of different particle sizes and material ratios on strength over curing time.

grouting points horizontally and vertically is fixed at 1.5 m. Grouting is carried out to a depth of 20 m, with pressure monitoring for open-loop conducted at depths of 11 m, 14 m, and 17 m. The grouting process is segmented from bottom to top, with the grouting pipe lifted 30 cm after each segment to ensure even grouting effects. The lifting distance should not exceed the sleeve valve's operational range to maintain uniform grouting. Grouting ceases at a distance of 1.5 m from the ground surface. Core sampling is performed at 12 locations in each zone, positioned 0.6 m away from the casing's center. A total of 48 core samples are obtained in this experimental phase. The schematic representation of the field experiment design plan is depicted in Fig. 7.

To prevent the addition of aggregates from causing environmental pollution, toxicity tests were conducted on the adopted crushed stone, crushed ceramics, and casing material raw materials. This ensures that the construction materials used are below the heavy metal leaching standards[17–20]. Upon examination, all three construction materials tested were found to be below the relevant regulatory requirements. Therefore, these crushed stone and crushed ceramic materials can be employed as aggregates for ground reinforcement.

Based on the established coordinates of control points, calculate the coordinates of the guide hole position. Stake out the hole

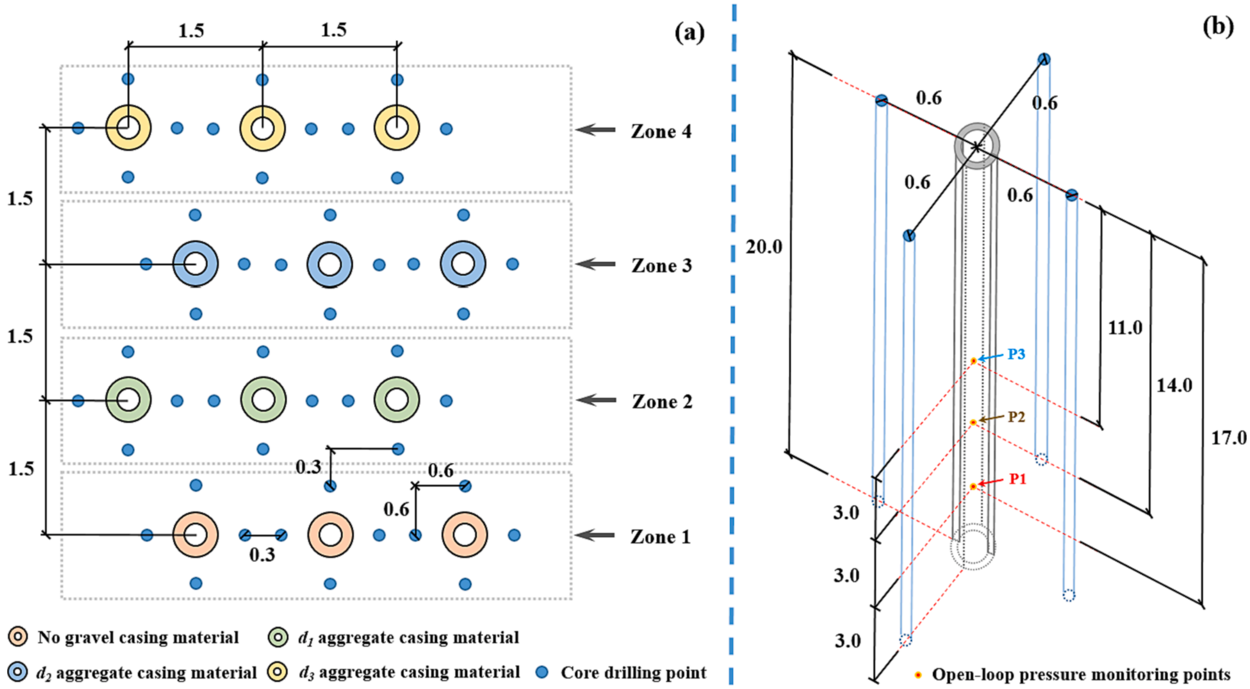


Fig. 7. Field experiment design; (a) Top view of pile locations for core sampling, (b) Isometric view of single pile core sampling in the south-west direction.

position using a total station and employ a level to measure ground elevation, confirming the guide hole depth. Utilize the casing protection water flush method for drilling to achieve the grouting consolidation section. Initially, connect the sleeve valve pipe based on the guide hole depth, with the upper end of the sleeve valve pipe exposed 20 cm above the ground. Seal the lower end of the connected sleeve valve pipe with a pointed bottom, then insert the sleeve valve pipe into the hole, ensuring it reaches the bottom. Clean the inside of the hole using high-pressure water to reduce sediment and mud density, followed by implementing the grouting work using a segmented grouting reinforcement method.

During the grouting process, changes in grouting pressure are monitored. The grouting pressure should display two distinct peaks: initially, there's a peak at the commencement of grouting as the casing material undergoes initial compression, followed by a rapid decline when the casing is crushed. After this initial pressure drop, the grouting pressure stabilizes within a certain range for approximately one minute. Subsequently, a second peak in grouting pressure occurs as the injected slurry fills the voids in the geological formation. The grouting action shifts from permeation and filling to fracturing and compaction of the formation. As this process unfolds, the grouting pressure gradually rises. The on-site construction is depicted in Fig. 8.

3.2.2. Analysis of field test results

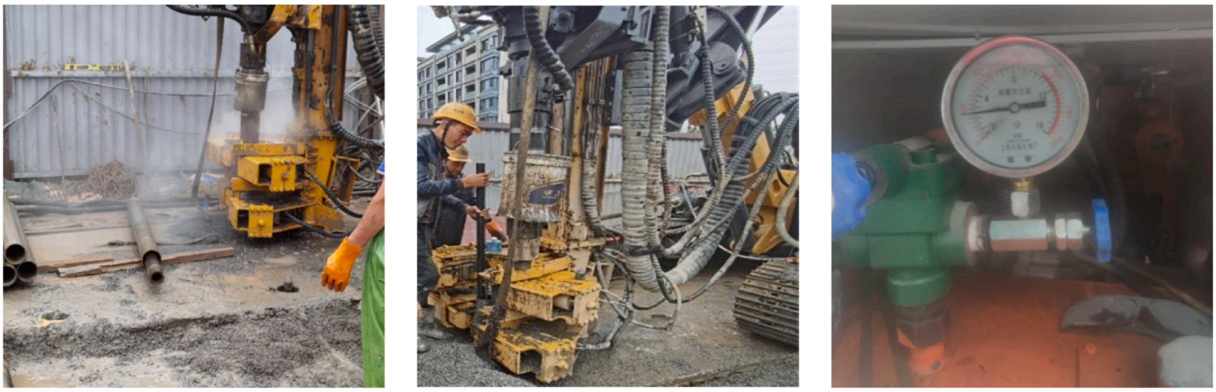
Following the addition of crushed stones on-site, the evaluation of optimized sleeve valve material indicated enhanced flowability. The burial time for traditional sleeve valve material notably increased by approximately 30 % compared to the original duration. The inclusion of crushed stones mitigated adhesion between the sleeve valve material and the infusion pipe. Previously, cleaning was required, on average, after each infusion hole; however, with crushed stones, it increased to an average of three infusions per cleaning. This inclusion diminished material adhesion and bolstered on-site construction efficiency.

The on-site aggregate and casing material test section recorded an open-loop pressure ranging from 0.8 to 1.1 MPa, while the traditional casing material exhibited an open-loop pressure between 0.7 and 1.2 MPa. The open-loop strength of the plugging ring with added crushed stone aggregates does not show significant differences compared to the traditional plugging ring strength. However, there is a concentration of open-loop pressures in zones 3 and 4, as illustrated in Fig. 9. The open-loop pressures at 36 points in the four test areas were collected, and the variance and standard deviation of open-loop pressures for each test area were calculated, as shown in Table 1. The experimental results indicate that the variance and standard deviation of open-loop pressures gradually decrease with the addition of crushed stone aggregates. Among them, the variance and standard deviation in test zone 4 are the smallest. Compared to test zone 1, the variance in test zone 4 has decreased by 31.5 %. The reduction in variance and standard deviation of open-loop pressures in the test areas implies a gradual decrease in the fluctuation of open-loop pressures, indicating that the addition of crushed stone aggregates has a promoting effect on the control of open-loop pressures.

The variance in open-loop pressures can be attributed to: a) the relatively high water content in the current mixture of expansive soil–cement materials, resulting in lower bond strength between the materials and crushed stones, aligning with conclusions drawn from laboratory experiments; b) while the addition of aggregates contributes to the enhancement of open-loop strength, it also facilitates the impact on the grout ring, reducing the difficulty of the open-loop through a combination of impact and fracture actions, aligning with the optimized open-loop theory.

Seven days after completing grouting, core sampling tests were conducted at 12 sites within each zone, resulting in 48 core samples for this phase. As illustrated in Fig. 10, cores obtained from identical locations in the four test zones displayed specific characteristics:

Zone 1, featuring lower cement content, experienced soil dispersion during sampling due to water flow, leading to ineffective grout consolidation. Enhanced grouting effectiveness was evident in Zones 2 and 3, with increasing cement content resulting in some cemented soil structures. Zone 4 exhibited cores with a higher cement block content, showing significant crushed stone-cement consolidated structures, leading to improved filling and reinforcement effects. The integrity of cement soil core samples notably improved. Analysis of core sampling outcomes across test areas indicates that incorporating crushed stone aggregates into sleeve valve material during grouting effectively contributes to ground filling. The utilization of crushed stone sleeve valve material ensures a more uniform grouting range, offering superior overall grouting effects compared to clay-based sleeve valve material.



(a) Installation of casing (b) Assembly of sleeve valve pipe (c) Monitoring of open-loop pressure

Fig. 8. On-Site experiment construction and monitoring.

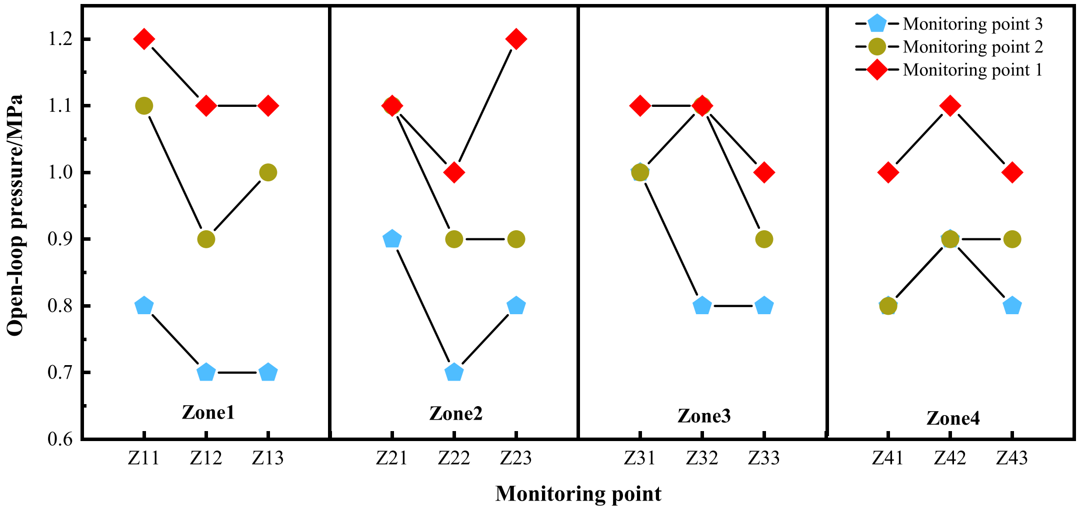
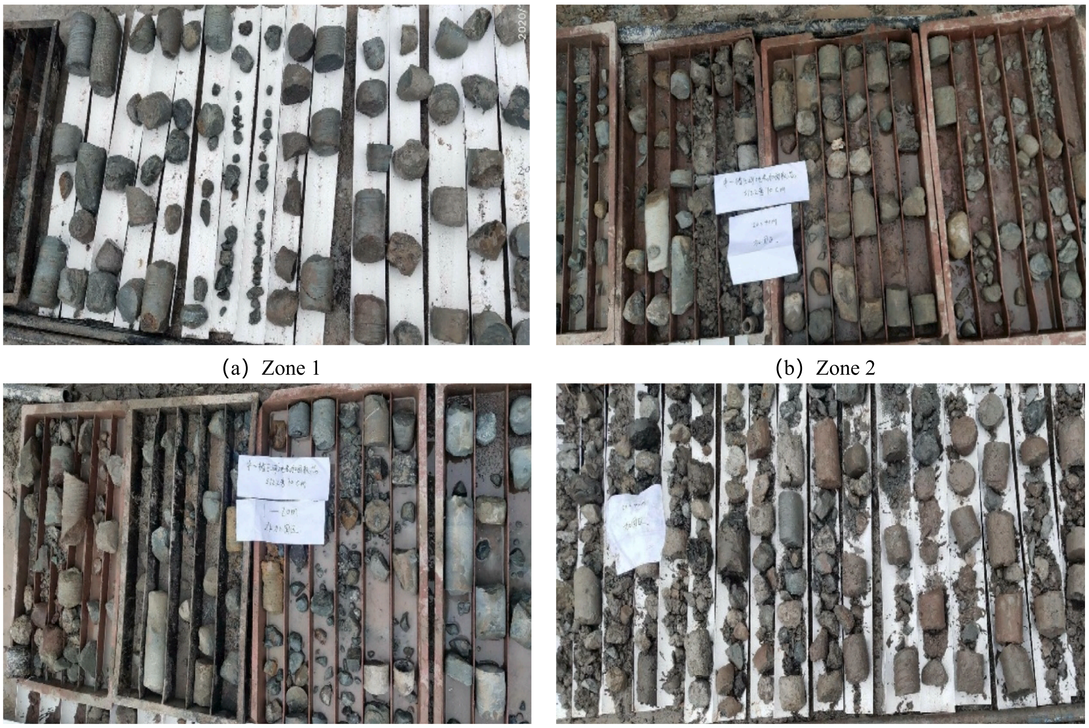


Fig. 9. On-Site monitoring of open-loop pressure at test locations.

Table 1
Illustrates the average values obtained from on-site test sections.

Grouting area	Open-loop pressure variance	Open-loop pressure standard deviation	Point load strength (KPa)	Uniaxial compressive strength (MPa)	Qualification rate (%)
Zone 1	0.0353	0.1878	186	3.32	84
Zone 2	0.0253	0.1590	197	3.78	89
Zone 3	0.0144	0.1202	216	4.36	93
Zone 4	0.0111	0.1054	227	4.69	96



(a) Zone 1 (b) Zone 2

(c) Zone 3 (d) Zone 4

Fig. 10. Core sampling diagram.

At each sampling point, three random core samples are selected for point load testing. The natural standard point load strength of the core samples is calculated according to the recommended method by the International Society for Rock Mechanics (ISRM) [21] and converted into uniaxial compressive strength. The average is taken as the representative value for the compressive strength of the core samples after grouting in each zone.

After 28 days from the completion of grouting, three samples are taken at each of the 48 core sampling points in the four test areas for unconfined compressive strength testing of the formation. The inspected samples are cut and ground to create 100 × 150 mm specimens, following the JTG/T233-2011 standard for cement-soil mix design. The unconfined compressive strength of the reinforced body should not be less than 1 MPa. The grouting acceptance rate is evaluated based on the unconfined compressive strength.

Due to poor grouting effectiveness in localized zones, although the overall grouting strength meets requirements, the acceptance rates for zones 1 and 2 are below 90 %, while zones 3 and 4 have inspection acceptance rates above 90 %. Consequently, according to the results, it is indicated that the optimized casing materials should ensure good uniformity and integrity of the formation after grouting. The mean values of on-site test sections are presented in Table 1.

4. Discussion

Given the intricacies of the casing material's opening process, several factors—such as aggregate quality percentage, material type, particle shape and size, casing thickness, and curing time—potentially affect the opening strength of the casing material, as illustrated in Fig. 11.

Based on preliminary experimental work, a comparative analysis was conducted using crushed stone and crushed ceramic materials [22,23]. The study revealed the potential utilization of various waste materials, such as crushed glass and broken ceramics, as aggregates[24]. Simultaneously, the reuse of such waste materials can significantly save energy costs, effectively reduce energy consumption, and contribute to minimizing adverse environmental impacts[25,26]. During the impact process, the influence of aggregates with different shapes and particle sizes is affected by the contact surface, resulting in significant variations in the force exerted on the casing material. This, in turn, has a certain impact on the open-loop mechanism of the casing material. Additionally, factors such as casing material thickness and curing time directly determine the strength of the plugging ring. Enhancing control over the plugging ring can improve the adaptability of the sleeve valve pipe under different geological conditions. Therefore, conducting a comprehensive study on the factors affecting the open-loop mechanism of the plugging ring is beneficial for promoting and guiding grouting projects under various geological conditions.

5. Conclusions

The introduction of sleeve valve pipe grouting casing materials into aggregates effectively reduces the challenge of long-distance infusion of high-viscosity grouting materials. It also enhances the probability of uniformly opening the grout plug, allowing aggregate

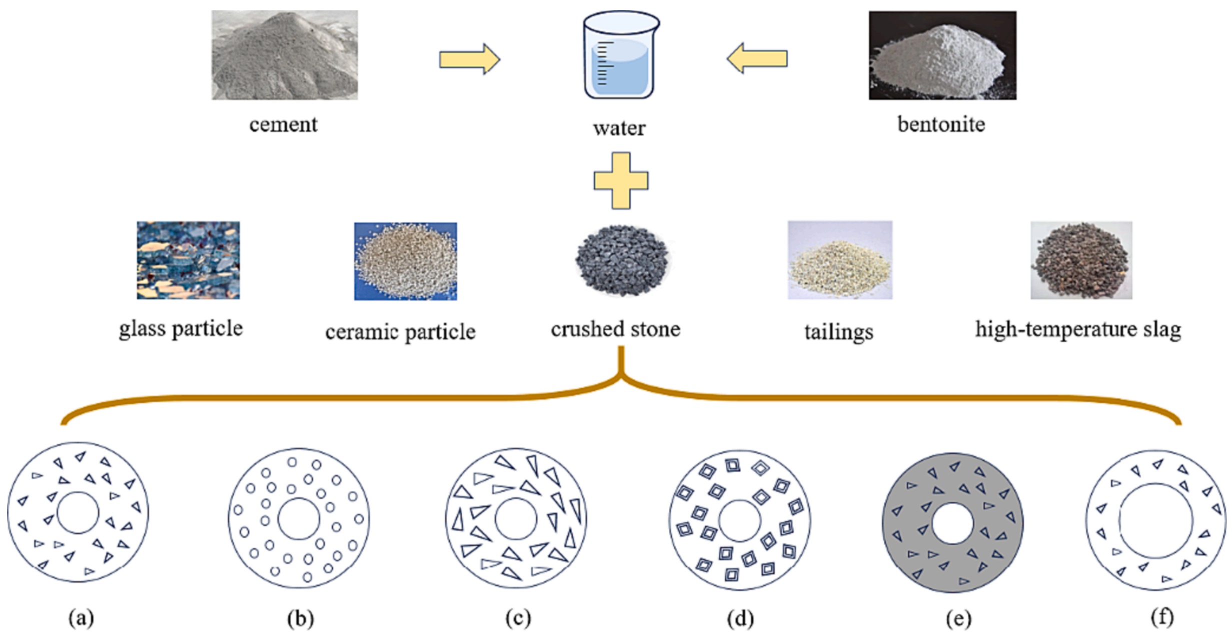


Fig. 11. Schematic diagram illustrating prospects and influential factors of environmentally-friendly aggregate application in closure ring material; (a) Percentage of aggregate mass, (b) Type of aggregate material, (c) Aggregate particle shape, (d) Aggregate particle size, (e) Thickness of closure ring, (f) Curing time of closure ring.

impacts to disperse into the formation, forming a cement slurry-crushed stone framework that further strengthens the formation. This concept provides theoretical support for improving the design and optimizing fluid systems. The reuse of waste materials as aggregates is crucial for achieving a cycle of environmental protection and economic development.

(1) A detailed analysis was conducted on the failure of opening the grout plug of deep-buried sleeve valve pipe grouting casing materials and the reasons for unidirectional slurry infiltration. The proposal to include crushed stones in casing material aims to reduce friction, enhance flowability, and decrease the probability of grout plug failure through a theoretical combination of splitting and impact composite effects of crushed stone aggregates.
(2) Indoor trials confirmed that the addition of aggregates does not significantly enhance casing strength, with an approximate daily strength increase of 2.6 % due to curing time. The hierarchy of casing strength impact is as follows: aggregate material type > curing time > aggregate quality percentage > aggregate particle size.
(3) Field trials demonstrated that the addition of medium and large-sized crushed stone aggregates stabilizes opening pressure. Moreover, the inclusion of aggregates promotes their impact on the grout plug. The application of crushed stone casing materials results in a more uniform grouting range compared to bentonite casing materials, showing an overall grouting effectiveness of over 90 % in on-site tests.

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CRediT authorship contribution statement

Tao Zhu: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Feng Huang:** Project administration, Funding acquisition. **Shuo Li:** Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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