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A New Method for Constructing the Protection and Seepage Control Layer for CSGR Dam and Its Application

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Abstract: Effective seepage control is crucial for maintaining the structural integrity of Cemented Sand, Gravel and Rock (CSGR) dams. Traditional methods using conventional concrete (CVC) or grout-enriched roller-compacted concrete (GERCC) are costly and disruptive. This paper presents a novel technique for constructing the protection and seepage control layer in Cemented Sand, Gravel and Rock (CSGR) dams. The method involves grouting and vibrating the loosened Cemented Sand, Gravel and Rock (CSGR) material to create vibrated grout-enriched Cemented Sand, Gravel and Rock, which performs similarly to concrete. A new surface water stop structure has also been developed for the structural joints. Laboratory tests revealed that Cemented Sand, Gravel and Rock (CSGR) with a vibrating–compacted (VC) value of 2–6 s and a compressive strength of 4 MPa meets design requirements for medium and low dams when the slurry addition rate is 8–12%. The T-shaped surface water stop demonstrated a bonding strength of over 1.8 MPa, withstanding a water pressure of 1.6 MPa. This method, integrated with dam body construction, reduces material costs by about 50% and eliminates construction interference. Specialized equipment for this technique has been developed, with a capacity of 12 m^2/h. Implemented in the Minjiang Navigation and Hydropower Qianwei Project and Shaping I Hydropower Station, it has shown significant economic, environmental and safety benefits, promoting sustainable dam construction.

Keywords: cemented sand, gravel and rock dam; protection and seepage control layer; vibrated grout-enriched cemented sand, gravel and rock; T-shaped surface water stop; grouting and vibrating equipment

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1. Introduction

The Cemented Material Dam (CMD), is a new type of dam featuring characteristics lying between those of embankment dams and concrete dams. Jinsheng Jia of China introduced the concept of the CMD in 2009 and subsequently published a paper on the topic in 2012 [1]. In response, the International Committee on Large Dams (ICOLD) formed a technical committee dedicated to CMD in 2013. The following year, Chinese technical guidelines for CMD, prepared by Liu et al. were published [2]. It is categorized into Cemented soil dam, HCC (including Hardfill dam, Cemented Sand and Gravel (CSG) dam, Cemented Sand, Gravel and Rock (CSGR) dam) and Cemented rockfill dam [3]. The CSGR dam has been developed drawing upon the design principles of both the Hardfill dam and the CSG dam. In comparison to these predecessors, it relaxes the requirements for aggregate size further, eases control over fine particle content and composition, and proposes new methods for quality control in supporting construction [4,5]. The anti-seepage system of the CSGR dam primarily depends on the upstream protection provided by the protection and seepage control layer, although there is currently no durability requirement for the internal dam's anti-seepage capabilities. The material strength and aggregate gradation needed for the internal dam are low, allowing for a wider selection of aggregate with relaxed screening and washing requirements. This enables the use of riverbed sand and gravel directly in construction, reducing costs and promoting environmental friendliness. The protection and seepage control layer typically follows the construction methods of Hardfill and CSG dams, commonly utilizing conventional concrete (CVC) or grout-enriched roller-compacted concrete (GERCC) [6–8]. During the construction phase, materials such as CSGR, CVC, and GERCC are typically employed and built simultaneously. However, the construction of this structure entails complexity and potential interferences. This complexity arises due to notable differences between CSGR and CVC or GERCC in expansion coefficient, elastic modulus, and hydration heat parameters. Consequently, ensuring quality control during construction is often a cause for concern [9–11]. Hence, a novel approach is suggested: incorporating vibrated grout-enriched CSGR in constructing the protection and seepage control layer of the CSGR dam. This innovation promises to enhance construction efficiency significantly while simultaneously reducing project costs.

The grouting and vibrating technology of the roller-compacted concrete (RCC) dam projects involves adding an appropriate amount of cement slurry (generally between 4% and 8% of the total volume of GERCC) to the newly mixed dry-hard roller-compacted concrete mixture, then using an immersible vibrator to compact and form an anti-seepage material with similar flow characteristics to CVC [12]. This material replaces the commonly used CVC as the impervious barrier on the upstream surface of the dam. This method not only reduces the production and transportation costs but also solves the problem of effective transition and combination of different materials between RCC and CVC, enhancing continuity and integrity [13]. Therefore, in theory, it is feasible to use this technology as a protective layer for CSGR dams. Compared to concrete, CSGR material has a more complex gradation and uses less cementitious material. The amount of slurry grout directly affects the construction work of the vibrated grout-enriched CSGR, as well as the properties and durability after hardening. Therefore, experimental research is necessary.

The typical arrangement for the split water stop in the protection and seepage control layer of Hardfill and CSG dams usually involves buried water stops [14–16]. The surface water stop for concrete face rockfill dams was also pioneered by Jinsheng Jia [17]. This innovation has seen extensive adoption in concrete face rockfill dams exceeding 200 m in height [18,19]. It typically consists of a rubber rod, plastic filler, and anchoring rubber plate. This design addresses the drawbacks of buried water stops, yet its structure is intricate and its cost is elevated [20]. The subsequent advancement in coated surface water stops optimized the anchorage cover plate by incorporating a polyurea coating film [21]. This innovation eliminated the need for an anchorage system, simplifying construction processes. However, the heightened efficiency came at the expense of increased costs [22]. Consequently, there is a need to develop a new type of surface water stop that balances safety, cost-effectiveness, and ease of construction for CSGR dams.

The construction of CSGR dams differs significantly from that of RCC dams. This contrast is particularly evident in medium and low dams, where narrow construction sites and faster filling speeds are common requirements. The grouting and vibrating equipment designed for RCC dams [23–25] cannot be directly applied to CSGR dams because, unlike RCC, CSGR dam materials exhibit variation depending on the available material type for excavation in the reservoir area or nearby locations, and typically lack a fixed gradation. The maximum particle size is 150 mm for dams and up to 300 mm for cofferdam construction; hence, there is high fluctuation in mud and water content during mixing. Consequently, there is a need to develop grouting and vibrating equipment tailored to the characteristics of CSGR materials and the specific requirements of construction site conditions.

In this paper, a novel concept is introduced, suggesting the utilization of vibrated grout-enriched CSGR materials as the protection and seepage control layer for CSGR dams. The proposed configuration method is tailored to the vibrated grout-enriched CSGR. Additionally, a new type of T-shaped surface water stop is devised, along with the determination of supporting construction parameters. Furthermore, efficient grouting and vibrating mechanical equipment suitable for narrow warehouse surfaces is developed. The feasibility of the proposed idea is validated through its application in the Tangba Protection Dam of the Qianwei Navigation and Hydropower Hub Project on the Minjiang River and Shaping I Hydropower Station on the Dadu River.

2. A New Idea for the Construction of the Protection and Seepage Control Layer for the CSGR Dam

The construction of the protection and seepage control layer for the CSGR dam must fulfill the objectives of anti-seepage effectiveness and durability and strength, while also addressing challenges such as minimizing construction interference between CVC, RCC, and CSGR components within the dam body, as well as overcoming difficulties related to accessibility for rolling machinery near the boundary areas. Combined with the construction experience from Tangba Protection Dam and Shaping I Hydropower Station, a novel approach has been devised: employing vibrated grout-enriched CSGR as the protection and seepage control layer for the CSGR dam, as illustrated in Figure 1. This method also introduces a redesigned water stop structure. Additionally, to address challenges encountered in constructing CSGR dams on non-rock foundations, it is proposed to relocate the cutoff wall to the upstream side of the dam. The key features of this innovative concept include:

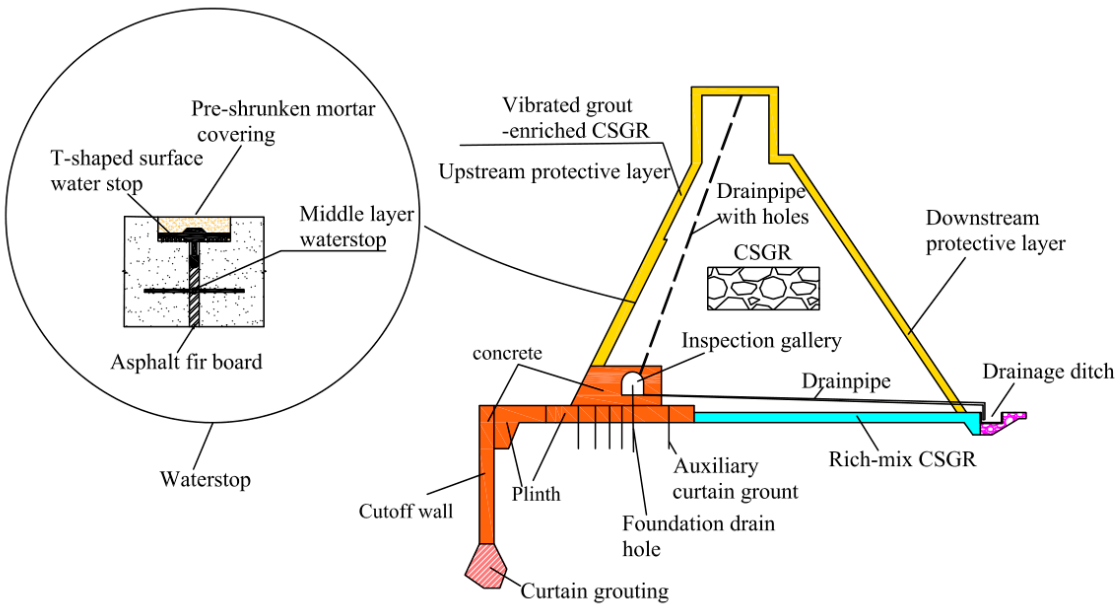


Figure 1. New cross-section of CSGR dam.

(1) The anti-seepage and drainage zoning design of the CSGR dam.

The protection and seepage control layer of the CSGR dam includes the upstream, downstream and top areas. Its function is considered according to the concrete face rockfill dam, which undertakes the anti-seepage under the action of high-pressure water. The dam body is designed according to the bearing body, which mainly meets the requirements of stability against sliding and compressive strength. Drainage is set between the protection and seepage control layer and the bearing body, and it is discharged in time when water leakage occurs, which can further relax the restrictions on the dam material. When the CSGR dam is constructed on the sandy pebble foundation and the dam height is low, the drainage can be canceled because the sandy pebble foundation itself has drainage capacity.

(2) The vibrated grout-enriched CSGR is used as the material of protection and seepage control layer.

Combined with the sand, gravel and rock of the Tangba protection dam riverbed, according to the design requirements of the protection and seepage control layer, a suitable admixture was selected to develop a vibrated grout-enriched CSGR with a 90-day compressive strength greater than 15 MPa, an impermeability grade of W8 and a frost resistance grade of F100 (Fn, F represents the frost resistance grade of concrete and n represents the frost resistance grade value. Fn indicates that the specimen is damaged after n freeze–thaw cycles of concrete, where n = 100) Combined with the sand, gravel and rock of the Shaping I Hydropower Station riverbed, a suitable admixture was selected based on a series of laboratory trial compatibility tests to develop a vibrated grout-enriched CSGR that can meet the compressive strength of more than 20 MPa, the impermeability grade of W12 (Wp, W represents the impermeability grade, p represents the concrete impermeability grade value. Wp indicates that the test sample can withstand hydrostatic pressure of P/10 MPa without any water seepage, where p = 12), and the frost resistance grade of F225, as shown in Table 1. The properties of the vibrated grout-enriched CSGR material can reach the indexes of CVC and RCC materials, and it is safe and reliable as the protection and seepage control layer material of the dam body. Because it is CSGR, the construction technology is consistent with the bearing body of the dam body, so the construction equipment and construction technology have been further simplified, avoiding the interference caused by the simultaneous construction of conventional concrete as the protection and seepage control layer and CSGR as the dam body material. It is proposed to add a slurry rate of 8–12% in the fresh CSGR materials, so that its workability can be changed from dry and rolling CSGR to slump and vibratable CSGR, whose compactness can be further improved by full vibration.

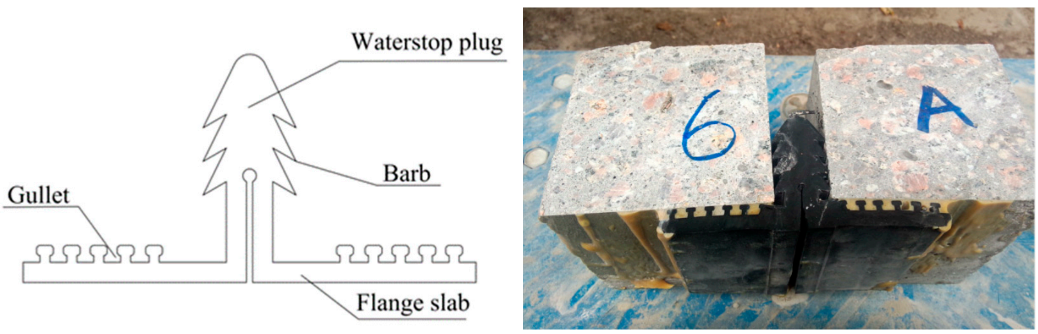
Table 1. Mixing ratio of vibrated grout-enriched CSGR.

Project	Design Index	Quantity for 1 m^3 Slurry (kg)				Slurry Rate (%)	Quantity for 1 m^3 Vibrated Grout-Enriched CSGR (kg)				Slump (cm)	90 d Compressive Strength	Impermeability Grade	Frost Resistance Grade
		Water	Cement	Water Reducing Admixture	Air Entraining Admixture		Water	Cement	Fly Ash	Aggregate				
*A**	C_{90}15W6F50	540	1270	12.7	0.127	8	153.6	138.6	36.8	2200.3	6.0	22.5	W8	F100
*B**	C_{90}20W6F50	540	1270	1.0	0.127	7	126.7	135.4	46.5	2264.5	8.5	24.2	W12	F225

*A** refers to Tangba Protection Dam; *B** refers to Shaping I Hydropower Station.

(3) For the Tangba protection dam, the structural form of separating the cut-off wall from the dam body is proposed, which avoids the mutual interference between the cut-off wall construction and the dam construction, and facilitates the repair and reinforcement when problems occur during the period of operation.

(4) A new T-shaped surface water stop structure (Figure 2) is proposed, which has a simple structure, convenient construction and can adapt to large deformation [26].



(**a**) (**b**)

Figure 2. New T-shaped surface water stop structure: (**a**) schematic diagram; (**b**) object picture.

3. Experimental Study on Vibrated Grout-Enriched CSGR Material of Tangba Protection Dam

The new idea has been fully applied to the Tangba Protection Dam of Qianwei Navigation and Hydropower Hub Project on the Minjiang River. For this reason, the Tangba Protection Dam is taken as an example for a detailed introduction.

3.1. Project Background

The Qianwei Navigation and Hydropower Hub Project is located in the lower reaches of the Minjiang River in Sichuan Province, China. It is the third step of shipping and hydropower planning in the lower reaches of the Minjiang River (Leshan–Yibin). The project grade is second-class and the project scale is large (2) type [27]. Its primary development objective is to prioritize navigation while integrating power generation, water supply, and irrigation to foster local economic and social advancement. The hub's normal water level stands at 335 m, with a total reservoir capacity of 228 million cubic meters. Positioned approximately 2 km upstream of the hub's right bank, the protection dam or dike spans around 2.76 km in length, reaching a maximum height of 15 m. Engineered to withstand a 20-year flood standard, the project is designated as Grade 4. The construction of the protection dam necessitates placement atop a 13-m-thick layer of sand and gravel cover. Originally, a solution involving a geotextile membrane core wall and rockfill dam was proposed. However, concerns regarding potential leakage failure and overtopping risks prompted the proposal of an alternative solution: the CSGR dam depicted in Figure 3. This design features a trapezoidal cross-section with a symmetrical profile, boasting a slope ratio of 1:0.5 on the upstream face and 1:0.7 on the downstream face. The primary body of the dam is constructed from Cemented Sand, Gravel and Rock, boasting a design strength of $C_{180}4$ (that is 180-day compressive strength of 4 MPa). As a protective measure against seepage, cemented and compacted gravel material is employed on the upstream side, adhering to the design specifications of $C_{90}15W6F50$ (that is, a 90-day compressive strength (C) of 15 MPa, and impermeability and frost resistance grades of W6 and F50, respectively). To ensure watertightness, T-shaped surface water stops are deployed for joint sealing along the dam body and between the plinth and the cutoff wall. Also, due to the low height of the dam and its foundation consisting of sand and gravel, it possesses a drainage capacity. Consequently, the drainage setting between the protective anti-seepage layer and the main body of the dam is canceled.

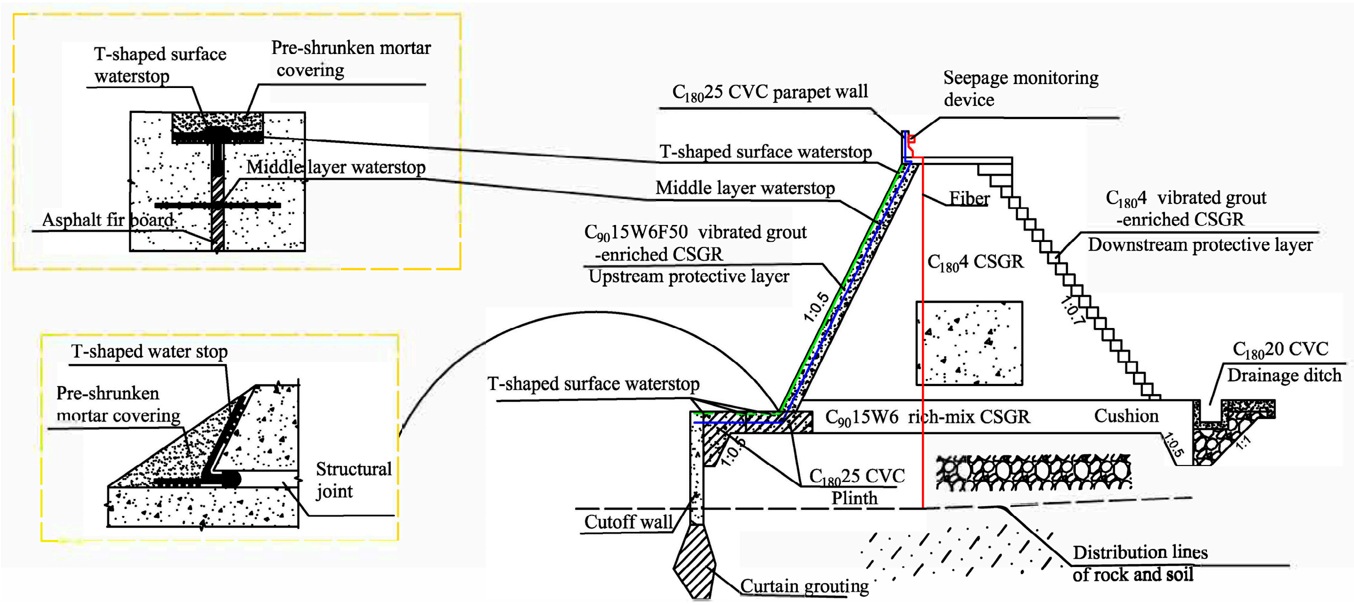


Figure 3. The cross-section of Tangba protection dam.

3.2. Raw Materials

3.2.1. Cement

The cement is P.O 42.5 ordinary Portland cement produced by Sichuan Qianwei Baoma Cement Co., Ltd. (Leshan, China), and its physical and chemical composition is shown in Table 2.

Table 2. Chemical and physical parameters of the cement.

Chemical			Physical									
SO_3 (%)	MgO (%)	Cl^- (%)	Density (g/cm^3)	Fineness (%)	Specific Surface Area (cm^2/g)	Standard Consistency (%)	Setting Time (min)		Compressive Strength (MPa)		Flexural Strength (MPa)	
							Initial	Final	3 d	28 d	3 d	28 d
2.87	2.5	0.015	3.16	6.6	3610	27.2	140	190	30.6	49.5	5.7	7.8

3.2.2. Fly Ash

The fly ash is grade II ash provided by Leshan Runsen Waste Recycling Co., Ltd. (Leshan, China), and its physical and chemical characteristics are shown in Table 3. According to Table 3, the fineness is achieved by screening fly ash through a 45 µm square hole sieve, and the fineness of the fly ash samples is expressed by the mass percentage of the sieve residue on the sieve. The water demand ratio is the ratio of the water demand of CSGR materials prepared with fly ash compared to specimens without fly ash (control). These are supported by ASTM C618 [28]. With strength activity index, the compressive strength of the test mortar and the control mortar is measured after 28 days, and the activity of the test mortar was determined by the ratio of the compressive strength of the two [29].

Table 3. Chemical and physical parameters of the fly ash.

Chemical		Physical				
SO_3 (%)	f-CaO (%)	Density (g/cm^3)	Fineness (%)	Water Demand Ratio (%)	Moisture Content (%)	Strength Activity Index (%)
2.42	2.6	2.47	20.0	98	0.5	70.6

3.2.3. Admixture

The GK-4A water-reducing admixture and GYQ air-entraining admixture were provided by Shijiazhuang Mayor An Yucai Building Materials Co., Ltd. (Shijiazhuang, China), and the performance test was carried out using the cement in Table 2. According to Table 4, the results indicated that the admixture and cement exhibited good compatibility. Also in Table 4, the difference in setting time refers to the difference between the setting time of the CSGR with admixture and those without admixture [30]. The ratio of compressive strength refers to the ratio between the compressive strengths of samples with admixture to those without admixture at different ages [31].

Table 4. Chemical and physical parameters of the admixtures.

Product	Chemical				Physical							
	pH	Cl^-	Na_2SO_4 (%)	Alkali (%)	Density (g/cm^3)	Bleeding Rate Ratio (%)	Water Reduction (%)	Difference in Setting Time (min)		Ratio of Compressive Strength (%)		
								Initial	Final	3 d	7 d	28 d
GK-4A	7.0–8.0	0.02	10	1.5	0.6	43.0	25.4	110	90	180	160	155
GYQ	7.0–8.0	0.03	13	1.3	0.8	25	6.2	90	115	100	98	94

3.2.4. Natural Aggregate

The riverbed sand, gravel and rock aggregate near the upstream of the Qianwei Navigation and Hydropower Hub Project was selected for the test. A total of 22 groups of particle screening tests were conducted based on gradations ranging from 150~80 mm, 80~40 mm, 40~20 mm, 20~5 mm, and below 5 mm. The gradation envelope of the gravel aggregate is depicted in Figure 4 (*S*1 to *S*22 represent the gradation of the material, *M*1, *M*2, and *M*3 represent the finest, average and coarsest gradation, respectively). Among these gradations, the proportion of extra-large stones (80~150 mm) ranges from 16% to 32%, averaging 22.3%. The proportion of boulders or large stones (40~80 mm) ranges from 23% to 33%, with an average of 28.9%. Medium stones (20~40 mm) constitute 17% to 19%, averaging 18.9%. Small stones (5~20 mm) represent 7% to 14%, with an average of 11.1%. The proportion of sand (less than 5 mm) varies from 10% to 29%, averaging 18.8%. The coarsest gradation's sand ratio within the envelope line is 10.3%, while the finest gradation's sand ratio is 28.1%. The average fineness modulus of the sand is 1.44, indicating it is super fine sand, with an average mud content of 2.3%.

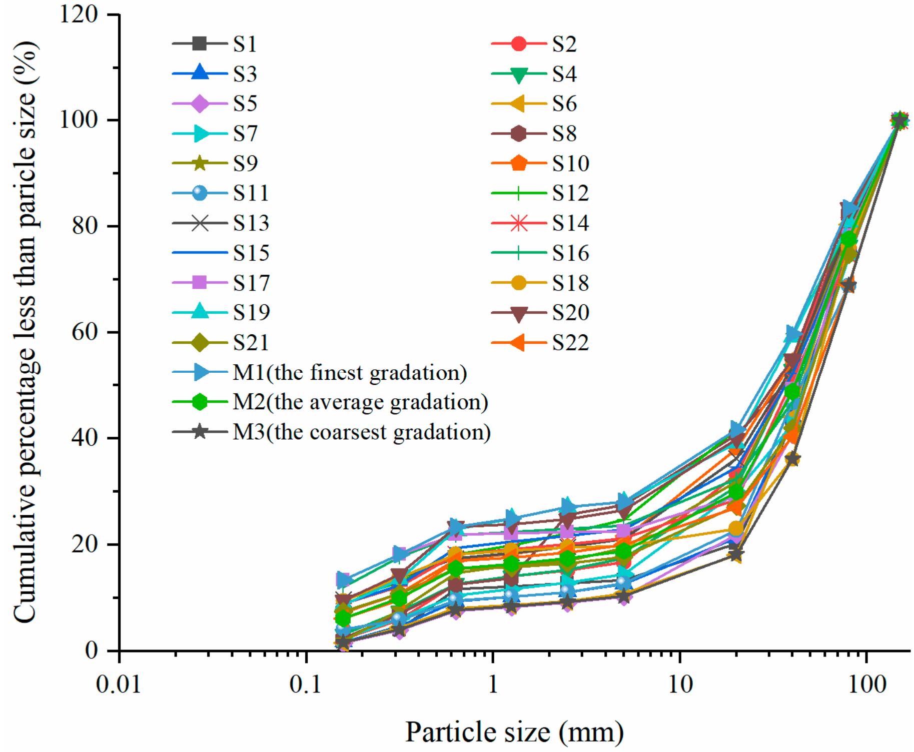


Figure 4. Particle size distribution curve of aggregate (Cumulative Sieve Residue).

3.3. The Mix Proportion of CSGR

According to the principle of 'double gradation and double strength' proposed by Jia Jinsheng, the mixing material is prepared and controlled [2]. In this process, the maximum particle size of coarse aggregate is set at 150 mm, with a cementitious material content of 80 kg/m^3. The vibrating–compacted (VC) value at the mixer's exit is regulated between 2 to 8 s without any admixture. The specific details are outlined in Table 5, where the schemes A1 and A2 represent *M*1 aggregate (the finest gradation, sand ratio is 28.1%, extra-large stones: large stones: medium stones: small stones = 27.5: 35.6: 23.3: 13.6) and *M*2 aggregate (the average gradation, sand ratio is 18.8%, extra-large stones: large stones: medium stones: small stones = 22.9: 33.0: 25.2: 18.9), respectively, for producing CSGR materials with the lowest strength, denoted as $C_{180}4$.

Table 5. Mix proportion of CSGR.

Scheme	Sand Ratio (%)	W/Cm Ratio	VC Value(s)	Quantity for 1 m^3 CSGR (kg)					Compressive Strength (MPa)		
				Water	Cement	Fly Ash	Coarse Aggregate	Fine Aggregate	28 d	90 d	180 d
*A*1	28.1	1.43	3.5	114	40	40	1649.39	644.61	2.7	5.5	6.5
*A*2	18.8	1.06	6.0	85	40	40	1942.30	449.70	6.0	11.2	12.4

3.4. The Vibrated Grout-Enriched CSGR

3.4.1. Slurry

The slurry material must exhibit excellent rheological properties and be capable of rapid diffusion within the laid CSGR, ensuring that the grouted and mixture attain the required degree of compaction to meet the design specifications for the anti-seepage protective layer. Typically, a higher water–cement ratio in the slurry enhances its rheological performance, but this necessitates a greater volume of slurry to achieve the desired design criteria. Therefore, a method was adopted by Feng et al. [32] to optimize the slurry mix ratio by minimizing the water–binder ratio, considering both slurry diffusion within the uniform mixture and its spread across the vibrating surface. The recommended slurry mix ratios are presented in Table 6. The rheology of the slurry is regulated through Marsh fluidity, maintained within the range of 6 to 12 s. Additionally, the specific gravity of the slurry, measured using a specific gravity meter, serves as a control index for the water–cement ratio during mixing.

Table 6. Mix proportion of slurry.

No.	1 m^3 Slurry Material Dosage (kg^3)				Marsh Fluidity (s)	Density (kg/L)
	Water	Cement	Water Reducing Admixture	Air Entraining Agent		
*A*580	540	1270	12.9	1.29	11	1.884

3.4.2. Determination of the Amount of Grouting

Utilizing the slurry compositions listed in Table 6 as the grouting material and incorporating the *A*1 and *A*2 CSGR mixtures from Table 4, six distinct slurry addition rates were established: 5%, 6%, 8%, 10%, 12%, and 14%, respectively. The prepared vibrated grout–enriched CSGR is marked as *GA*1 and *GA*2. Following the guidelines outlined in "Test code for hydraulic concrete" (SL/T 352-2020) [33], the 'indoor mixing and forming method of GERCC', was executed using a vibrating table. Various volumes of the specified slurry, as detailed in Table 6, were added to the machine-mixed CSGR. After undergoing three rounds of manual mixing, specimens were formed. Wet sieving ensured particles larger than 40 mm were not retained, and subsequent tests were conducted to measure the slump and air content of the resulting specimens.

The test results are depicted in Figure 5. Figure 5a indicates that the slump of the mixture post slurry addition ranges between 10 and 60 mm, while the indoor air content falls within the 4% to 5.8% range, signifying improved workability of the mixture. In Figure 5b, it is evident that the compressive strength of vibrated grout-enriched CSGR escalates with increasing slurry rate. At an 8% slurry rate, with a total cement content of 176 kg/m^3, the 90-day compressive strength exceeds 15 MPa, meeting design specifications (where *GA*1 surpasses a design strength of 15 MPa at an 80% strength guarantee rate, and *GA*2 exceeds a preparation strength of 17.9 MPa). Concurrently, the impermeability grade reaches W8 and the frost resistance grade reaches F100, as illustrated in Figure 5c,d, satisfying the requirements for impervious layer materials for dams with heights below 30 m (with a minimum allowable impermeability grade of W4). However, at a 12% slurry addition rate, the resulting vibrated grout-enriched CSGR contains a total cementitious material of 223 kg/m^3, achieving a 90-day compressive strength surpassing 20 MPa, with an impermeability grade of W11 and a frost resistance grade of F125. This meets the design criteria for impervious layer materials for dams, with heights ranging from 30 to less than 70 m (with a minimum allowable impermeability grade of W6). Notably, a 14% slurry addition rate increases the cementitious material content to 247 kg/m^3, significantly impacting economic feasibility and raising the risk of cracking, hence not recommended.

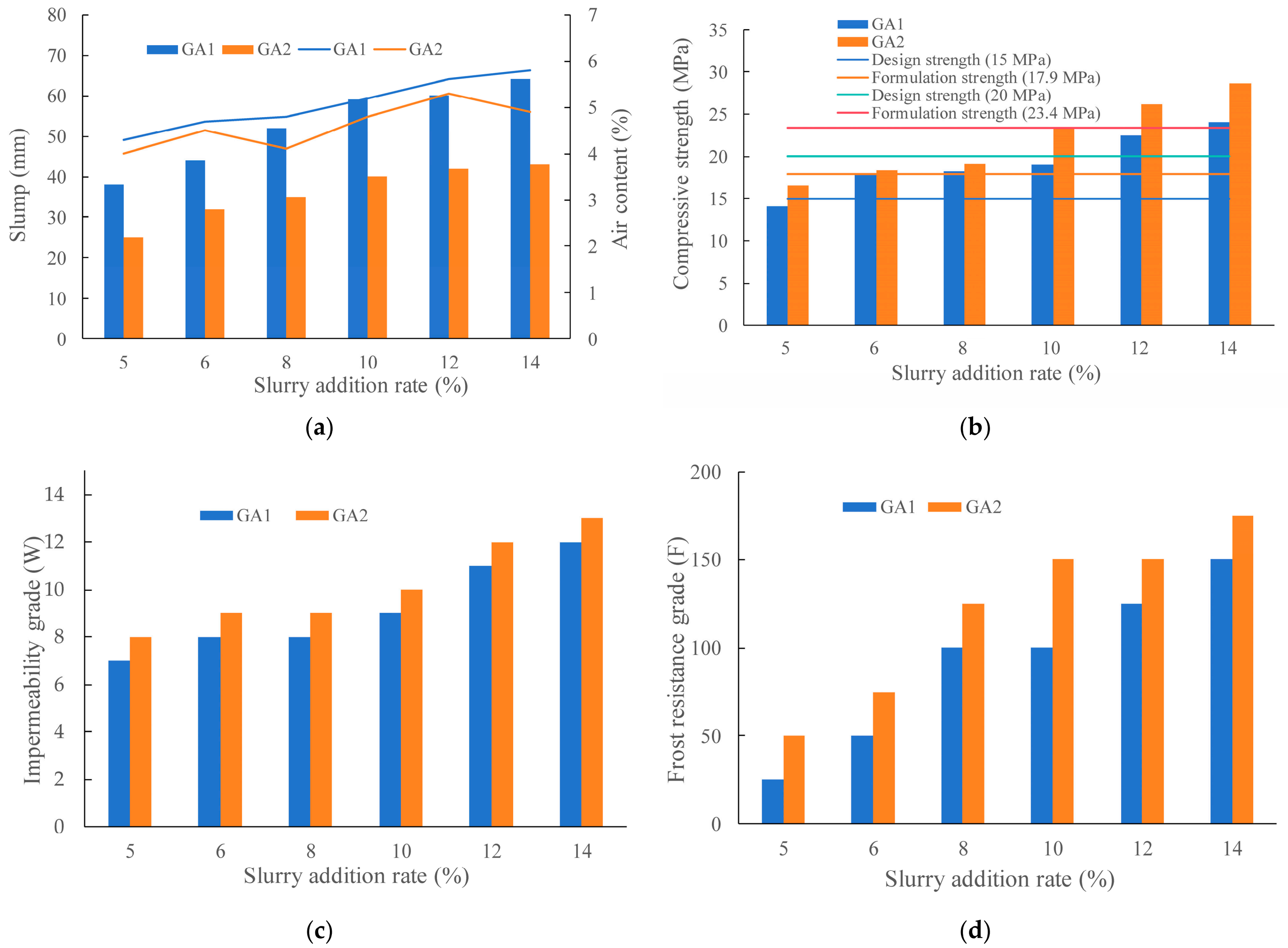


Figure 5. Test results of different slurry addition rates: (**a**) slump and air content; (**b**) 90-day compressive strength; (**c**) 90-day impermeability grade; (**d**) 90-day frost resistance grade.

4. Test of T-Shaped Surface Water Stop

4.1. Bond Strength Test

The pull-out test, according to "Test methods for building waterproofing coatings" (GB/T 16777-2008) [34], was utilized to examine the bonding efficacy of a T-shaped surface water stop and a protective anti-seepage layer surface.

4.1.1. Test Conditions

Concrete prism specimens measuring 400 mm × 100 mm × 100 mm were prepared for surface treatment using structural adhesive under various conditions, including air drying, surface brushing, and application of an interfacial agent after 24 h of drying and soaking. The pull-out test was conducted after 180 days under outdoor natural conditions (refer to Figure 6). Eight distinct working conditions were established for the test, each comprising three specimens and undergoing 12 pull-out tests, as outlined in Table 7. Notably, the interfacial agent used is a substance aimed at enhancing the bonding performance between the structural adhesive and wet concrete.

(a) (b)

Figure 6. Pull-out test of structural adhesive: (**a**) Pull-out test; (**b**) Typical case after failure.

Table 7. Pull-out test results under different working conditions.

No.	Specimen Situation	Brushed Surface	Applied Surface Coating Agent	Average Drawing Strength (MPa)	Destructed Sites
1	*A* [1]	✓	✓	2.32	Specimen body
2	*B* [2]	✓	×	3.87	Specimen body
3	*B*	✓	✓	3.91	Specimen body
4	*A*	×	✓	2.34	50% of the specimen body, 50% of the interface between the agent and the specimen
5	*A*	×	×	1.82	Between the interface agent and the specimen
6	*B*	×	✓	2.78	Between the interface agent and the specimen
7	*A*	✓	×	1.83	Specimen body
8	*B*	×	×	3.11	Between the interface agent and the specimen

[1] *A* is soaked in water for 24 h, and the surface is dried; [2] *B* is a dry specimen; ✓ means specified condition satisfied; × means specified condition not satisfied.

4.1.2. Test Results

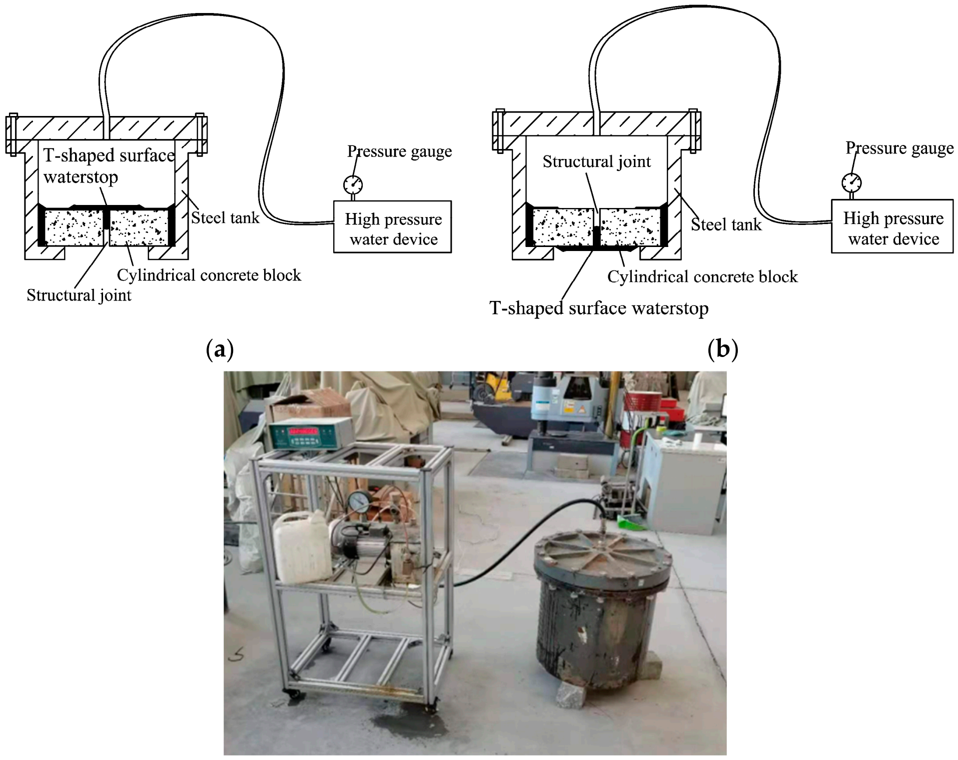
The results are presented in Table 7. Across various conditions, the bonding strength of the structural adhesive exceeds 1.8 MPa. Applying an interfacial agent to the surface of wet specimens enhances the bonding strength to some degree, though it remains lower than that achieved under dry conditions. The presence of contaminants like surface debris on the concrete surface diminishes bonding strength with the structural adhesive, compromising the effectiveness of water sealing. The pull-out failure strength of the T-shaped water stop measures approximately 0.6 MPa, with failures typically occurring at the interface between the water stop and the structural adhesive. Hence, before the T-shaped water stop installation, it is crucial to brush or clean surface contaminants like debris and ensure dryness before applying the structural adhesive, followed by proper sealing post-installation.

4.2. Water Resistance Test

To the surface of precast concrete specimens with cracks, T-shaped surface water stops were adhered, and hydraulic pressure tests, according to "Hydrophilic expansion waterproofing sealant " (JG/T 312-2011) [35], were conducted on both the upstream and downstream sides to study the water pressure resistance of the water stops.

4.2.1. Test Scheme

The experiment was conducted in a test tank, with an inner diameter of 47.5 cm and a height of 50 cm, capable of withstanding internal pressures of over 2 MPa. The T-shaped surface water stop was installed in the penetrating seams of concrete specimens measuring 45 cm in diameter and 25 cm in height. The concrete specimens were placed into the test tank, and the surrounding seams were filled and sealed with sealant. The experimental setup is depicted in Figure 7. After the structural adhesive had fully cured, the tank was filled with water, and hydraulic pressure was applied using automatic pressure loading equipment to maintain a stable pressure throughout the test period.



(c)

Figure 7. Water pressure test of T-shaped surface water stop: (**a**) Upstream water pressure test (**b**) Downstream water pressure test (**c**) Test device.

During the upstream water pressure test, the pressure was incrementally increased by 0.2 MPa each time, while during the downstream water pressure test, it was incremented by 0.1 MPa. Each pressure level was maintained for 2 h to stabilize. The water pressure was continuously increased until failure and leakage occurred in the water stop, or until reaching the pressure limit of 2 MPa, at which point the test was stopped. The maximum water pressure reached during the test was recorded. Three sets of tests were conducted, and the average value was calculated as the maximum load-bearing water pressure of the T-shaped water stop.

4.2.2. Test Results

The results of the water pressure resistance test are shown in Table 8. The test indicates that the T-shaped surface water stop exhibits a minimum resistance to an upstream water pressure of 1.6 MPa, providing excellent water sealing effectiveness for structural joints in medium and low CSGR dams with a dam height H < 70 m. The minimum resistance to downstream water pressure is 0.4 MPa. For safety considerations, a buried water stop design is also required after the installation of the T-shaped surface water stop.

Table 8. Results of the water pressure resistance test for the T-shaped surface water stop.

Test Classification	Failure Water Pressure/MPa		
	First Group	Second Group	Third Group
Upstream water pressure	1.6	2.0	2.0
Downstream water pressure	0.4	0.5	0.4

5. Research and Development of Special Grouting and Vibrating Equipment for CSGR

To address the practicality of specialized equipment, the developed equipment needs to possess features such as flexibility in movement, rapid grouting and vibrating from multiple directions and angles, as well as simultaneous grouting and vibrating capabilities. The grouting and vibrating capacity of a single device should reach 12 m^2/h. Therefore, a piece of specialized equipment, as shown in Figure 8, has been designed and developed. This equipment includes a control system, grouting and vibrating system, rail-type vibrating head, laser ranging system, etc. Construction can be divided into five stages, as shown in Figure 9. The first to the second stage requires 5 s (rapid insertion); the second to the third stage lasts for 40 s, including 20 s of grouting and 15 s of vibrating; the third to the fourth stage lasts for 19 s (slow extraction of vibrating); the fourth to the fifth stage takes 5 s. For typical CSGR levees with a paving area of 50 m long, 70 cm wide, and 70 cm thick, construction can be completed within 2 h using this equipment, significantly improving construction efficiency.

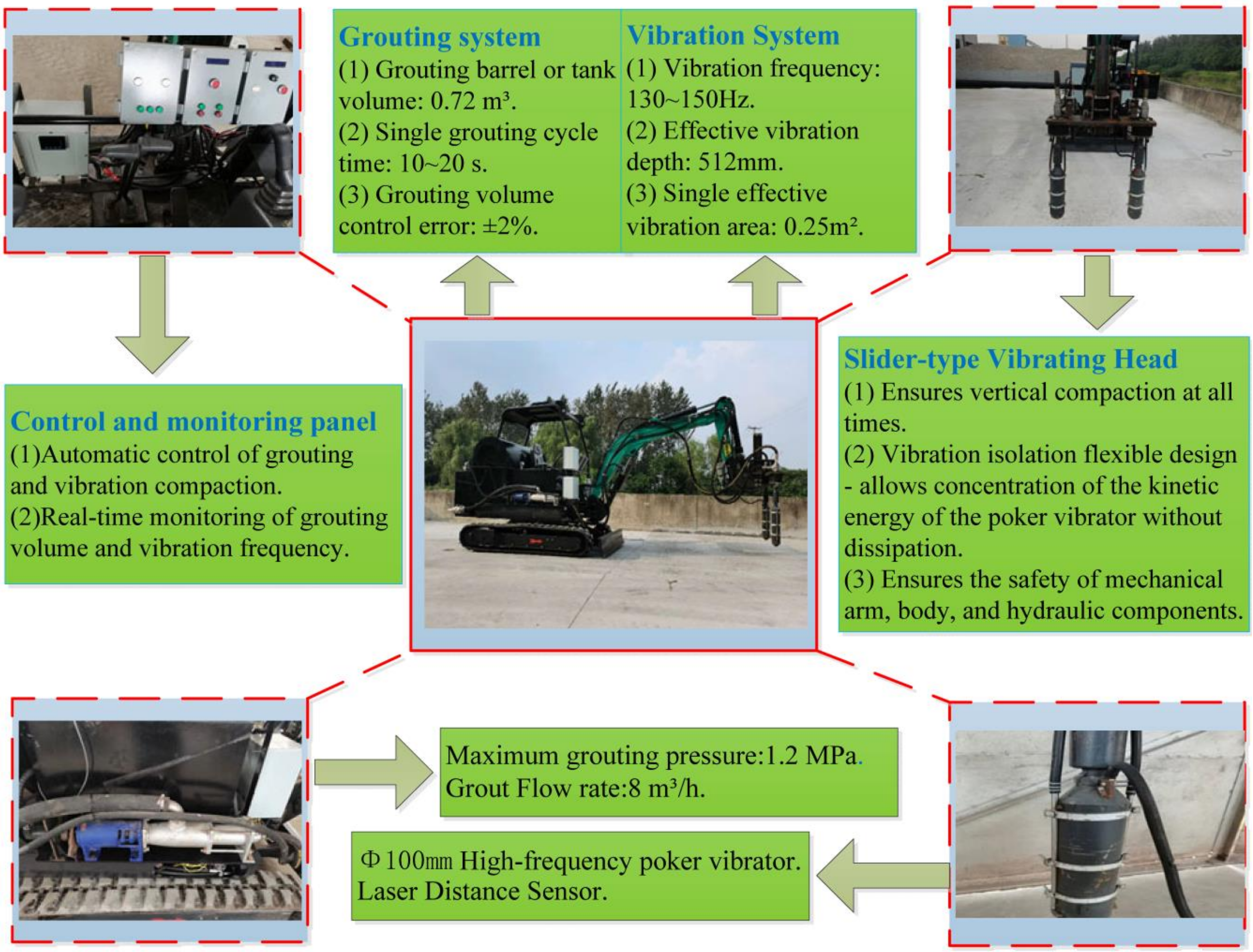


Figure 8. The grouting and vibrating equipment of CSGR.

The equipment is built upon a micro crawler hydraulic excavator platform, with the entire body occupying a footprint of 2.3 m in length and 1.35 m in width. Leveraging its mobility, rotation capability, hydraulic system, and work apparatus, it can maneuver flexibly on the dam surface without disrupting the compacting process of the dam body. The grouting and vibrating system composition and working principle of the equipment are shown in Figure 10. The equipment boasts a total engine power of 35 KW, which powers actions such as grouting, vibrating, and movement during construction. Grouting can be achieved through either automated quantified grouting or interactive human–machine control for uniform grout distribution. A stable hydraulic drive is employed, controlled by a microcontroller that actuates electromagnetic directional valves to enable the forward rotation of hydraulic motors, propelling the screw pump to discharge grout. A rotary encoder monitors the pump's rotation speed, regulating the grout output accordingly. To prevent slurry sedimentation and pipe blockage, a microcontroller governs a three-way actuator for slurry circulation, facilitating both injection and backflow. Additionally, a low-speed stirring device is installed within the slurry tank to maintain slurry consistency. Vibrating is executed using a dual-head high-frequency vibrator with an adjustable vibration frequency, driven by an engine-powered belt drive system for frequency control. Moreover, grouting pipes are directly welded and integrated on both sides of the poker vibrator. During operation, the vibrator is inserted vertically into the loosened CSGR, enabling simultaneous vibrating and grouting. Laser distance measurement is utilized during the vibrating to maintain a safe distance between the template and the vibrating rod, thereby preventing damage to the template. After each grouting and vibrating work, the whole slurry pipeline should be cleaned in time by pumping clear water to avoid slurry precipitation and pipe blockage, and the pulley group with vibrating head should be deeply cleaned and lubricated. Regularly inspect and maintain the lubrication system, filtration system, hydraulic system and electrical system of the entire equipment, replace worn parts in a timely manner, ensure that all safety functions are functional, and maintain detailed maintenance activity logs.

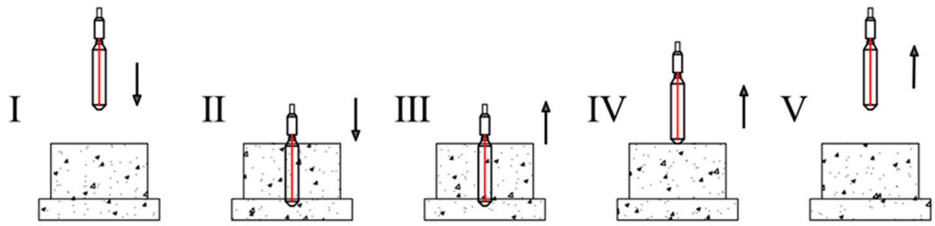


Figure 9. Working state of grouting and vibrating equipment (I is the ready stage, II is the insertion stage, III is the grouting and vibrating stage, IV is the redraw stage and V is back to the ready stage for the repetitions of the cycle).

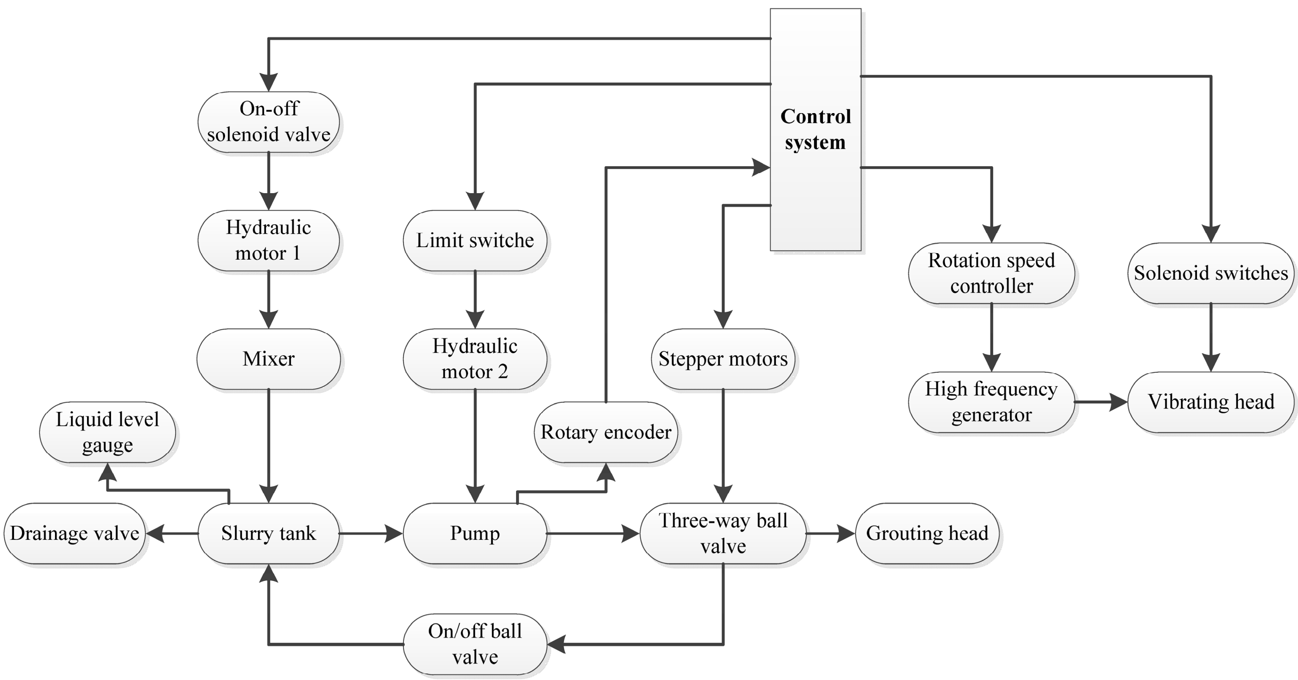


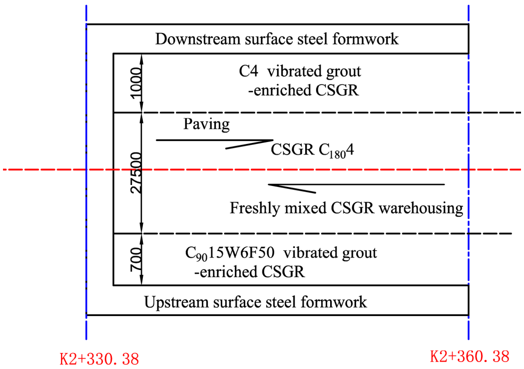
Figure 10. Design system composition and working principle of the equipment.

6. On-Site Constructions of the Vibrated Grout-Enriched CSGR

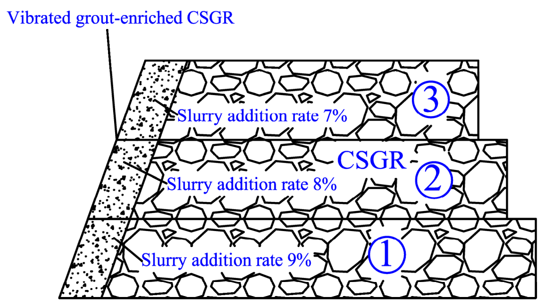
6.1. On-Site Test

The dam aggregate consists of the natural sand, gravel and rock material excavated from the riverbed. During construction, it is not subjected to screening or washing, and particles larger than 150 mm are removed. To ensure safe construction practices, digital mixing and intelligent control techniques can be employed [6]. Previous indoor testing has demonstrated that when the slurry addition rate is 8%, the vibrating–compacted slurry CSGR material meets the design requirements of C_{90}15W6F50. However, in actual construction, the characteristics and construction nuances of CSGR materials often result in deviations from indoor test results. Hence, field testing is conducted to determine the optimal slurry addition rate.

The field rolling test section is situated along the dam axis, spanning from pile number K2 + 330.38 to K2 + 425.38 within the dam body. Upon the completion of the test, this section is directly integrated into the CSGR dam for permanent structures. The specific area for the vibrated grout-enriched CSGR test is delineated in Figure 11a, focusing on the dam between pile numbers K2 + 330.38 and K2 + 360.38. The test procedure employs full-section flat paving, with a paving layer thickness of approximately 50 cm.



(**a**)



(**b**)

Figure 11. The layout of the field test of vibrated grout-enriched CSGR: (**a**) test area (**b**) slurry adding test scheme.

For the vibrated grout-enriched CSGR test area, which constitutes the upstream protective layer, the width measures 70 cm. The special grouting and vibrating equipment operates according to the configuration depicted in Figure 9. From bottom to top, the slurry rates are set at 9%, 8%, and 7%, as illustrated in Figure 11b.

The test results are presented in Table 9, indicating that the on-site strength of CSGR meets the design specifications for Cemented Material Dam (CMD) engineering. Table 10 displays the test results for CSGR with added slurry and vibration. It is observed from Table 10 that the slurry mix ratio prepared indoors aligns with the engineering requirements for vibrated grout-enriched CSGR. When determining the amount of slurry for construction cost considerations, a preference should be given to an 8% grouting ratio. However, if quality assurance is prioritized, a 9% slurry addition rate is recommended. At this rate, the total cementitious material quantity is 187 kg/m^3, with a total water demand ranging from 126 kg/m^3 to 152 kg/m^3.

Table 9. Test results of CSGR mixture.

Layer Number	VC Value/s	Compressive Strength /MPa	
		Minimum Value	Mean Value
①	10.3	5.6	7.6
②	8.7	4.2	7.1
③	6.0	4.5	8.3

Table 10. Test results of different slurry addition rate.

Slurry Addition Rate (%)	Surface Quality	Compressive Strength (MPa)		Impermeability Grade	Freeze Resistance Grade
		Minimum Value	Mean Value		
7%	surface less slurry	12.2	15.8	W8	F50
8%	the surface can be slurried, the slurry is suitable	14.4	17.4	W9	F50
9%	the surface can be slurried, the slurry is rich	15.2	19.8	W11	F75

6.2. Application

The Tangba Protection dam has a total length of 2.7 km, with a crest elevation of 336.10 m and the filling volume of CSGR material reached 373,000 m^3. The vibrated grout-enriched CSGR with a slurry rate of 9% was used in the protection and seepage control layer on both the upstream and downstream areas. Through sequential rolling and layer-by-layer construction, the total amount of vibrated grout-enriched CSGR used is 20,867 m^3. Figure 12 illustrates the completed Tangba Protection Dam. The quality test results in the construction process are presented in Table 11. The protective layer of the dam meets the design requirements of C_{90}15W6F50. The T-shaped surface water stop totals 10,163 m. Its installation and fixation were straightforward, ensuring fast construction speed, easy replacement and repair in subsequent stages (Figure 13).

Figure 12. The completion of Tangba CSGR dam.

Table 11. Quality test results of vibrated grout-enriched CSGR.

Types of CSGR		Vibrated Grout-Enriched CSGR C_{90}15W6F50
Design index	Impermeability grade	W6
	Compressive strength guarantee rate/%	80
	Compressive strength/MPa	15
	Frost resistance grade	F50
Measured value	Impermeability grade	>W6
	Compressive strength guarantee rate/%	88
	Minimum strength/MPa	11.8
	Average strength/MPa	18.6
	The standard deviation of compressive strength	3.8
	The qualified rate of frost resistance at design age/%	100

(a) (b) (c)

Figure 13. The installation of the T-shaped surface water stop: (**a**) transverse joint water stop (**b**) water stop between protection layer and toe slab (**c**) mortar cover protection.

From 15 to 16 May 2020, the first phase of water storage was completed, with the water level rising from 326 m to 330 m. Subsequently, from 15 to 16 September 2021, the second phase of water storage concluded, resulting in the water level increasing from 330 m to 335 m (see Figure 14). The water storage operations have been ongoing for nearly four years. Notably, optical fiber leakage measuring devices installed after the transverse joint have detected no leakage points, indicating the commendable comprehensive anti-seepage performance of the dam body. It is worth highlighting that during the impoundment period, the levee endured the '8 18' catastrophic flood in 2020. Despite the large-scale disaster in Leshan and Qianwei, it effectively withstood the excessive flood, ensuring the safety of life and property for over 11,000 residents and more than ten major enterprises in Tangba Township. The safety and reliability of the dam have met the anticipated standards.

Figure 14. The impoundment of the flood control levee to an elevation of 335 m.

7. Discussion

The costs of utilizing conventional concrete (CVC), grout-enriched roller-compacted concrete (GERCC), and vibrated grout-enriched CSGR, solely in terms of factory material costs (reference unit price: P.O 42.5 grade ordinary Portland cement 450 yuan/t, fly ash 120 yuan/t, high-efficiency water reducing agent 8000 yuan/t, air-entraining agent 13,000 yuan/t.), excluding expenses like transportation and mixing, are compared in Table 12. From this comparison, it becomes evident that CVC and GERCC are the most expensive options, whereas vibrated grout-enriched CSGR stands out for its significantly lower cost attributed to the use of on-site gravel materials. The cubic meter cost of vibrated grout-enriched CSGR is less than 50% of CVC, and vibrated grout-enriched CSGR and its construction benefits from the streamlined process of rolling out the CSGR dam body, which reduces interference and enhances promotional advantages.

Table 12. Cost comparison of different protection and seepage control layers.

Material	The Amount of Cementitious (kg/m^3)		Cost per Cubic Meter (Yuan)	Construction Technology	Remarks
	Cement	Fly Ash			
CVC	140	60	310	Vibration, needs grading of aggregate and has interference with CSGR rolling construction.	The average aggregate is 90 yuan per ton
GERCC	151	36	293	Grouting and vibrating, needs grading of aggregate and has interference with CSGR rolling construction	The average aggregate is 90 yuan per ton
Vibrated grout-enriched CSGR	151	36	142	Grouting and vibrating, needs grading of aggregate and has less interference (high seamless transition) with CSGR rolling construction.	The average aggregate is 20 yuan per ton

The vibrated grout-enriched CSGR is produced by grouting and vibrating directly onto the pre-paved CSGR material. In contrast to CVC, it plays a pivotal role in coordinating transition deformations at the interface between the impermeable layer and the main dam. This not only bolsters the continuity and integrity of the dam structure but also mitigates the local damage and stripping caused by abrupt shifts in material characteristics. Moreover, vibrated grout-enriched CSGR minimizes the variety of materials required at batching plants, thereby boosting production efficiency and decreasing construction interference. As a result, it emerges as an optimal choice for future CSGR dam protection and seepage control layers. However, ongoing research is essential to comprehensively understand its long-term material performance and engineering applications. The successful deployment of vibrated grout-enriched CSGR at the Tangba Protection Dam serves as a promising case study for similar projects.

This study delves into the influence of slurry quantity on properties of vibrated grout-enriched CSGR material and construction efficacy, refining conventional joint sealing methods and investigating water sealing effectiveness. Nonetheless, challenges remain in utilizing this technology in 100-m-high dams, prompting the consideration of external flexible geomembrane installation for taller structures. Variations in geographical applicability underscore the need for further research into more frost-resistant types of cemented sand, gravel and rock. These considerations highlight avenues for future advancements in CSGR technology to enhance dam construction practices.

8. Conclusions

This paper introduces a newly developed and successfully applied method for utilizing vibrated grout-enriched CSGR as the protective and seepage control layer in CSGR dams, in conjunction with a T-shaped water stop structure. Additionally, specialized construction equipment for slurry addition and CSGR vibration has been developed. The main conclusions are as follows:

(1) Using the cement slurry with a water–cement ratio of 0.42, under the grouting rates of 8% and 12%, the $C_{180}4$ dry-hard cemented sand, gravel and rock with a VC value of 2~8 s can be changed into the vibro-cemented sand, gravel and rock with a slump of 10–60 mm grade $C_{90}15W8F100$ and $C_{90}20W11F125$, respectively.

(2) A strong bonding effect exists between the new T-shaped surface water stop and the protective layer, with a bonding strength exceeding 1.8 MPa. The water stop surface

exhibits an anti-water pressure ability greater than 1.6 MPa, effectively sealing joints in CSGR dams.

(3) Specially developed CSGR grouting and vibrating equipment can be adapted for use in the construction of the upstream and downstream impermeable protective layers of CSGR under conditions characterized by limited surface area and large particle size.

(4) When the height of the dam is low, Cemented Sand, Gravel and Rock dams can be constructed on non-rock foundations. To ensure project safety, a design approach is employed that separates the cutoff wall from the dam body, and utilizes a T-shaped surface water stop design to prevent mutual interference.

The novel technique has demonstrated significant economic, environmental, and safety advantages in the Minjiang Navigation and Hydropower Qianwei Project and the Shaping I Hydropower Station on the Dadu River. The developed technique will offer immense sustainability when adopted in subsequent projects: Firstly, it will reduce construction costs by replacing traditional concrete with a vibrated grout-enriched CSGR mixture, utilizing locally available materials and reducing cement usage through fly ash substitution. Secondly, it will optimize construction processes by simplifying the construction of the protection and impermeable layer, thereby reducing time and disruptions. Thirdly, it will provide environmental benefits by minimizing the carbon footprint, thus promoting eco-friendly practices. Lastly, safety shall be enhanced through specialized equipment automation and the use of the developed T-shaped surface water stop, ensuring greater stability of dam structures.

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Abbreviations

The following abbreviations are used in this manuscript:

CSGR	Cemented Sand, Gravel and Rock
CVC	Conventional concrete
GERCC	Grout-Enriched Roller-compacted concrete
VC	Vibrating–compacted
CMD	Cemented Material Dam
CSG	Cemented Sand and Gravel
(ICOLD)	International Committee on Large Dams
CMD	Cemented Material Dam
HCC	Hardfill, Cemented Sand and Gravel (CSG), Cemented Sand, Gravel and Rock (CSGR)
RCC	Roller-compacted concrete

References

1. Jia, J.; Zheng, G.; Ma, F. Studies on cemented material dam and its application in China. In Proceedings of the 6th International Symposium on Roller Compacted Concrete (RCC) Dams, Zaragoza, Spain, 23–25 October 2012.
2. *Chinese Standards SL678-2014*; Technical Guideline for Cemented Granular Material Dams SL678. China Water & Power Press: Beijing, China, 2014. (In Chinese)

3. Jia, J.; Lino, M.; Jin, F.; Zheng, C. The Cemented Material Dam: A New, Environmentally Friendly Type of Dam. *Engineering* **2016**, *2*, 490–497. [CrossRef]
4. Londe, P.; Lino, M. The faced symmetrical hardfill dam: A new concept for RCC. *Int. Water Power Dams Constr.* **1992**, *44*, 19–24.
5. Sakamoto, T.; Yoshida, H.; Yasuda, N.; Maeda, K.; Takei, A. The design and construction of trapezoidal CSG dams in Japan. *Hydropower Dams* **2017**, *24*, 68–75.
6. Jia, J.; Ding, L.; Wu, Y.; Zhao, C.; Zhao, L. Research and application of cemented sand and gravel technology based on soft rock. *Appl. Sci.* **2023**, *13*, 4626. [CrossRef]
7. Sina, K.; Farshbaf, A. A new solution for water-tightening of the cemented sand-gravel (CSG) hardfill dams. *Innov. Infrastruct. Solut.* **2023**, *8*, 173.
8. Chen, J.; Liu, P.; Xu, Q.; Li, J. Seismic analysis of hardfill dams considering spatial variability of material parameters. *Eng. Struct.* **2020**, *211*, 110439. [CrossRef]
9. Ding, Z.; Xue, J.; Zhu, X.; Wang, J. Optimization of CSG dam profile based on response surface methodology. *Case Stud. Constr. Mater.* **2022**, *17*, e01430. [CrossRef]
10. Guo, L.; Zhang, J.; Guo, L.; Wang, J.; Shen, W. Research on Profile Design Criteria of 100 m CSG Dams. *Case Stud. Constr. Mater.* **2022**, *16*, e01137. [CrossRef]
11. Cai, X.; Zhang, Y.; Guo, X.; Zhang, X.; Li, F.; Zhang, T. Review on research progress of cemented sand and gravel dam. *Sci Eng Compos Mater.* **2022**, *29*, 438–451. [CrossRef]
12. *Chinese Standards DL/T 5788-2019*; Construction Specification for Hydraulic Grout Enriched Vibrated Concrete DL/T 5788. China Electric Power Press: Beijing, China, 2019. (In Chinese)
13. Musselman, E.; Flynn, R.; Zimmer, G.; Young, J. Field Trial for Air Entrained Grout Enriched Roller Compacted Concrete. In Proceedings of the 2nd International Seminar on Dam Protection against Overtopping, Fort Collins, CO, USA, 7–9 September 2016.
14. Amir, A.; Ali, N.; Mohsen, G.; Seyed, H. Seismic evaluation of cemented material dams—A case study of Tobetsu Dam in Japan. *Earthq. Struct.* **2016**, *10*, 717–733.
15. Kim, S.; Choi, W.; Kim, Y.; Shin, J.; Kim, B. Investigation of Compressive Strength Characteristics of Hardfill Material and Seismic Stability of Hardfill Dams. *Appl. Sci.* **2023**, *13*, 2492. [CrossRef]
16. Guillemot, T.; Lino, M. Design and Construction Advantages of Hardfill Symmetric Dam—Case Study: Safsaf Dam in Eastern Algeria. In Proceedings of the 6th International Symposium on Roller Compacted Concrete (RCC) Dams, Zaragoza, Spain, 23–25 October 2012.
17. Xu, Y.; Hao, J. Development and prospect of slab joint waterstop technology of CFRDs. *J. China Inst. Water Resour. Hydropower Res.* **2018**, *16*, 457–465. (In Chinese)
18. Cho, B.H.; Nam, B.H.; Seo, S.; Kim, J.; An, J.; Youn, H. Waterproofing performance of waterstop with adhesive bonding used at joints of underground concrete structures. *Constr Build Mater.* **2019**, *221*, 491–500. [CrossRef]
19. Ma, H.; Chi, F. Technical Progress on Researches for the Safety of High Concrete-Faced Rockfill Dams. *Engineering* **2016**, *2*, 332–339. [CrossRef]
20. Sun, Z.; Li, J.; Fei, X. Flexible water stop structure with flat cover on the surface of concrete face joint in cold area. *Water Power* **2019**, *45*, 50–53. (In Chinese)
21. Zeinizadeh, A.; Mirzabozorg, H.; Noorzad, A.; Amirpour, A. Hydrodynamic pressures in contraction joints including waterstops on seismic response of high arch dams. *Structures* **2018**, *14*, 1–14. [CrossRef]
22. Wu, Y.; Jia, J.; Wang, Y.; Zheng, C.; Zhao, L.; Jia, B. Investigation on Hydraulic Fracturing and Flexible Anti-Hydrofracturing Solution for Xiaowan Arch Dam. *Appl. Sci.* **2023**, *13*, 9302. [CrossRef]
23. Wang, C.; Luo, W.; Xu, B. The Control System Design of Concrete Mixing Station based on PLC. In Proceedings of the 2020 IEEE International Conference on Information Technology, Big Data and Artificial Intelligence (ICIBA), Chongqing, China, 6–8 November 2020; pp. 1498–1501.
24. Nagy, P.B.; Pistrol, J.; Kopf, F.; Adam, D. Integrated compaction control based on the motion behavior of a deep vibrator. *Transp. Geotech.* **2021**, *28*, 100539. [CrossRef]
25. Wan, D.; Guan, T.; Yang, S. Intelligent monitoring of concrete vibration quality under the integrated perception of space-air-ground. *J. Chin. Ceram. Soc.* **2023**, *51*, 1219–1227. (In Chinese)
26. Wang, Y.; Jia, J.; Zheng, C.; Jia, Y.; Liu, Z. A Water Stop Structure and Its Construction Method. CN 105019404A, 29 June 2015. (In Chinese).
27. Chen, Z.; Feng, J.; Li, R.; Wang, Y.; Peng, F.; Li, K. Field observation and numerical modelling of supersaturated dissolved gas at river confluence. *Ecol. Model.* **2022**, *471*, 110017. [CrossRef]
28. *ASTM C 618-03*; Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International: West Conshohocken, PA, USA, 2023.
29. *ASTM C109*; Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). ASTM International: West Conshohocken, PA, USA, 2023.
30. *ASTM C403/C403M*; Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance. ASTM International: West Conshohocken, PA, USA, 2016.
31. *ASTM C39/C39M*; Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International: West Conshohocken, PA, USA, 2021.

32. Feng, W.; Jia, J.; Ma, F. Study on durability of dam materials and new-type protective materials for cemented sand and gravel dam. *Shuili Xuebao* **2013**, *44*, 500–504. (In Chinese)
33. *Chinese Standards SL/T 352-2020*; Test Code for Hydraulic Concrete SL/T 352. China Water & Power Press: Beijing, China, 2020. (In Chinese)
34. *Chinese Standards GB/T 16777-2008*; Test Methods for Building Waterproofing Coatings GB/T 16777. Standards Press of China: Beijing, China, 2008. (In Chinese)
35. *Chinese Standards JG/T 312-2011*; Hydrophilic Expansion Waterproofing Sealant JG/T 312. Standards Press of China: Beijing, China, 2011. (In Chinese)