Enhancing the Load-bearing Capacity of a Damaged Hydraulic Structure Rehabilitated by Underwater Concreting

Bach Phuong Ho Thi
Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam
hothibachphuong@iuh.edu.vn

Viet Duc Nguyen
Thuyloi University, 175 Tay Son, Dong Da, Hanoi, Vietnam
ducnv@tlu.edu.vn (corresponding author)

Quoc Vu Vuong
Thuyloi University, 175 Tay Son, Dong Da, Hanoi, Vietnam
vuongvlxd@tlu.edu.vn

Hoang Minh Dang
Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam
danghoangminh@iuh.edu.vn

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ABSTRACT

Due to the severe environment, damages often occur early on hydraulic structures, even in parts submerged in water. This paper presents a study on how the load-bearing capacity of the hydraulic structure is enhanced, once it has been rehabilitated by underwater concreting. A column has been considered as the hydraulic structure. The damaged part of the column was submerged in water, hence, it was repaired by the underwater concrete. For this, the tremie casting method was taken into account. The compression test results pointed out that the damaged column after rehabilitation had a similar load-bearing capacity to the undamaged column, while the not rehabilitated column had reduced load-bearing capacity by 20%. The failure mode of the damaged column after the rehabilitation presented longitudinal cracks along the body of the column, which is similar to that occurred in the undamaged column. Besides, there was no sign of delamination between the protective layer and the existing concrete of the damaged column, proving the feasibility of the selected casting method and concrete mixture for rehabilitation.

Keywords-hydraulic structure; rehabilitation; underwater concrete; antiwash high performance concrete; manufactured sand

I. INTRODUCTION

In both urban and rural areas, hydraulic structures are man-made systems that interact with surface runoff. These systems can be used to improve and regulate river and other water body flows, mitigate flooding, protect coastal areas, or help with stormwater drainage [1]. Any construction that is fully or partially submerged in water and interferes with the water's natural flow is known as a hydraulic structure [1, 2]. This type of structure, which is often constructed of reinforced concrete, can be erected in rivers, seas, or any other body of water, where it is necessary to alter the water's normal flow [3]. Hence, it is often affected by severe destructive agents including salts and other harmful components in water, apart from the fact that it needs to carry other mechanical and physical impacts [4]. Working in the aquatic environment combined with the climate change has led to shorten the life service of these structures [4-6]. After several years of operation, a series of defects including surface cracking, concrete erosion, reinforcement protective layer peeling off, can be found quite early on hydraulic structures [7, 8]. Such damage not only reduces the structure's ability to carry loads, but it also makes it more likely for hazardous chemicals, biological elements, and water to permeate the matrix and generate cavitation, which in turn causes damage [9, 10]. Therefore, it is necessary to enhance performance parameters such as load-bearing capacity, abrasion resistance of these structures, in order to prolong their service life instead of rebuilding them at high cost [11]. To repair the damage of a hydraulic structure submerged in water, it is regular to implement underwater concreting. So far, the tremie casting method seems to the most common one for the concerned purpose [12-14]. The basic idea behind this technique is that concrete is poured into a pipe or tube from above the surface, and the weight of concrete in the tube forces it into the previously placed mass of concrete. A hopper sits atop the tube, and the entire assembly is suspended from a staging or frame that is mounted to allow for vertical movement when a crane is used to hold it. Sections of the tube can be removed to make working easier as the pour rises.

In order to allow the water inside the tube to escape and to cause the first load of concrete to spread out horizontally into the shape of a mound, the tube's bottom should be on, or very close to, the mold bed at startup [15]. The tube's bottom should always be inside of previously poured concrete when pouring concrete continuously. The tremie must be moved up and down in order to control the flow of concrete in the tube, which is determined by gravity and friction with the tube wall. When pouring concrete, the tube must be kept from moving laterally. The poured concrete forms a circle and spreads out horizontally on the bed, with the top domed upward.

The aim of this paper is to present how the load-bearing capacity of the hydraulic structure is improved, once it is rehabilitated by underwater concreting. A damaged column structure is taken into consideration for the study. Antiwash/underwater high performance concrete is prepared and used for the rehabilitation of the damaged structure. The tremie casting method is implemented for the underwater concrete placement. Eventually, the load-bearing capacity of the columns with and without rehabilitation is analyzed thoroughly and their failure modes are also observed.

II. MATERIALS AND METHOD

A. *Constituent Materials*

In this study, Portland cement type I 42.5 R, which complies with European cement standard EN 197-1, was utilized. Silica Fume (SF), in addition to regular Portland cement, was regarded as a supplementary cementitious material. Detailed characteristics of cement and SF can be found in Tables I and II, respectively.

TABLE I. PHYSICAL AND MECHANICAL CHARACTERISTIC OF CEMENT

Parameter	Unit	Test result
Specific density	g/cm^3	3.1
Bulk density	g/cm^3	1.3
Blaine fineness	cm^2/g	3850
Consistency	%	29.0
Initial setting time	min	155
Final setting time	min	235
Soundness of cement	mm	1
3 days compressive strength	N/mm^2	28.3
28 days compressive strength	N/mm^2	46.5

This study suggested using manufactured sand to create an Antiwash High Performance Concrete (AHPC) mix that will be used to repair the structure using underwater concreting because natural sand is currently in short supply. Table III provides characteristics of the fine aggregate. Additionally, sieve analysis was done to determine the aggregate's grading; the outcomes are displayed in Table IV below.

TABLE II. PHYSICAL AND CHEMICAL CHARACTERISTIC OF SILICA FUME

Parameter	Unit	Test result
Specific density	g/cm^3	2.2
Bulk density	g/cm^3	0.94
Loss on ignition	%	4.3
Content of SiO_2	%	93.7
Content of Al_2O_3	%	0.92
Content of Fe_2O_3	%	0.52
Content of SO_3	%	0.63
Content of CaO	%	1.51

TABLE III. CHARACTERISTIC OF FINE AGGREGATE

Parameters	Manufactured sand
Specific density, g/cm^3	2.67
Bulk density, g/cm^3	1.55
Water absorption, %	1.95
Clay, silt and dust content,%	1.51
Fineness modulus	3.05

TABLE IV. GRADING OF FINE AGGREGATE BY SIEVE ANALYSIS

Sieve size	Manufactured sand
	Cumulative % retained
5	0.0
2.5	9.5
1.25	21.8
0.63	36.6
0.315	71.2
0.14	95.4
Pan	100

There are two kinds of chemical admixtures that are employed for the AHPC mix. The first is an anti-washout admixture, while the other is a third generation polycarboxylate superplasticizer, i.e. a high-range water reduction admixture. The former is a powdered underwater that, according to the supplier, is designed to improve the cohesiveness and integrity of concrete, allowing for notable decreases in binder washout in underwater concrete, particularly in terms of reducing segregation and bleed [16]. Finally, tap water was utilized to create the mix percentage.

B. *Mix Proportion*

The AHPC mix used in this investigation was prepared to achieve a strength class of 50 MPa at the age of 28 days. This strength class was selected because the concrete strength of the existing damaged structure was around 25 MPa. According to [5, 17], the protecting layer of concrete with a double strength is viable for rehabilitating the existing structure, in order to prevent from the debonding issue, which occurs in case the protecting layer stops adhering to a substrate material of the existing structure due to mainly a huge discrepancy of yielding stress between the materials. For proportioning the mix, the combined-type high performance self-compacting concrete mix design method was considered [18, 19], apart from the increase of powder content and superplasticizer usage in accordance with mix design guidelines of Professor Okamura [20, 21]. The dosage of the antiwash admixture was prescribed in compliance with the recommendation from the supplier. The detailed steps for mix design are described in [22]. Some trial-and-error was involved, and the final mix proportion of AHPC is presented in Table V.

TABLE V. MIX PROPORTION OF AHPC

Constituent materials in 1 m^3 (kg)					
Cement	**SF**	**Sand**	**Water**	**Antiwash admixture**	**Superplasticizer**
450	45	1605	185	2.5	8.5

To evaluate the performance of AHPC, several parameters were determined. At fresh state, flowability and loss of powder were registered. Details in how to record these parameters are explained in [23] and the illustration of flowability test are shown in Figure 1. At hardened state, compression and flexural strength of AHPC at 28 days were obtained, and the waterproof grade was acquired. Fresh and hardened properties of AHPC are presented in Table VI. It can be observed that AHPC is complied with the category prescribed in [24], which is suitable to be used in hydraulic structures.

TABLE VI. FRESH AND HARDENED PROPERTIES OF AHPC

Flowability	Loss of powder	Compression strength	Flexural strength	Waterproof grade
Cm	%	MPa	MPa	
20.0	8.3	50.5	3.05	12

Fig. 1. Flowability test of AHPC.

C. Column Rehabilitation and Test Procedure

Due to limitations of time and financial expenses, the hydraulic structure of column type was selected to prepare with the aim to present a preliminary structure concept. The column dimensions were 300 mm height and 150 mm diameter. The damaged column is shown in Figure 2(a). It can be seen that one end of the column has been slightly broken, hence it would affect its load-bearing capacity. Therefore, it is necessary to repair the defect. Besides, the defect is submerged in water, so the rehabilitation is conducted by underwater concreting.

The casting method is done by means of a tube of 400 mm length and 20 mm inner diameter, being connected to an inlet funnel with a maximum diameter of 58 mm. The tube is kept vertically and one end reaches the bed of the mold. After that, the AHPC is poured into the tube through the inlet funnel. Then, it will be slowly lifted up, and fresh AHPC will flow from the tube and fill the mold, while the water in the mold will gradually be pushed out, as it can be observed in Figure 2(b). The process finishes when AHPC overflows from the mold. At this time, the curing process begins. The entire mold is kept in a water tank for three days and then it is removed and the repaired column continues to be submerged in water until the testing date. The repaired column with the protecting layer of AHPC can be seen in Figure 2(c). The protecting layer has a thickness of 25 mm.

(a)

(b)

(c)

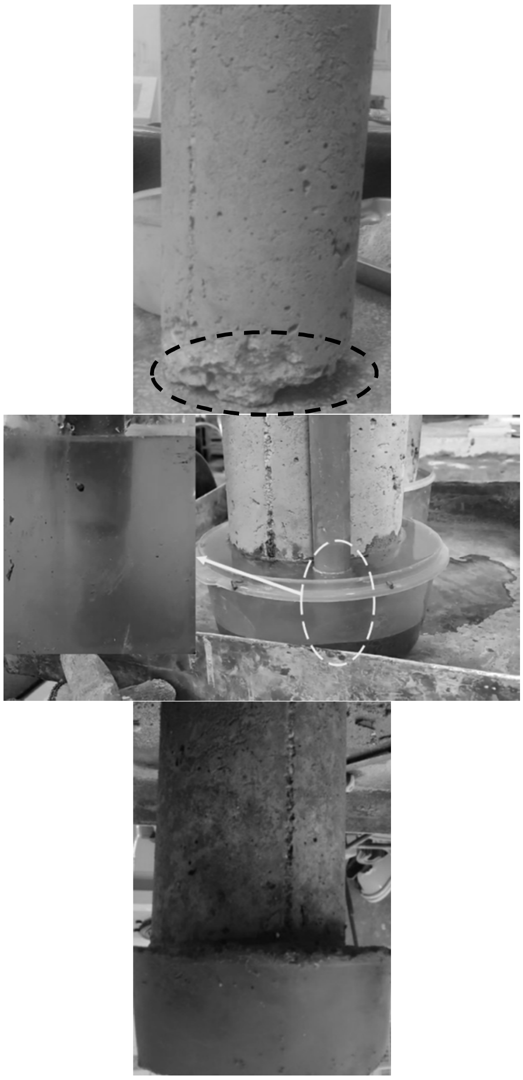

Fig. 2. Specimen preparation: (a) Damaged column, (b) underwater concreting with the tremie casting method, (c) column after rehabilitation with underwater concreting.

Once the repaired column reached the age of 28 days, it was subjected to compression test. The universal machine used for this test had a maximum load of 1000 kN, and its load rate was set at 10 kN /min. The test was conducted up until the point of failure to determine the column's maximum loading bearing capacity. Apart from the repaired column, a damaged and an undamaged column were also considered for compression test.

The test results could reveal how the damaged column perform, once it has been rehabilitated by AHPC with underwater concreting.

III. RESULTS AND DISCUSSION

A. Load-Bearing Capacity

The results of compression test on different columns are presented in Table VII. It can be seen that the undamaged column reaches the mean value of 506 kN with the equivalent stress being 28.6 MPa. This outcome is practical for the concrete strength class used for the production of the column. Looking into the magnitude yielded from the damaged column, the load-bearing capacity had a mean value of 419 kN, which is 20% reduced in comparison with the undamaged column. Meanwhile, the rehabilitated damaged column had a load-bearing capacity almost equal to that of the undamaged column. This indicates the significant role of AHPC in the rehabilitation of the damaged column, which enhances vitally load-bearing capacity.

TABLE VII. COMPRESSION TEST RESULTS

Column	Failure value	Mean value
	kN	kN
Undamaged	509	506
	495	
	514	
Damaged	412	419
	419	
	425	
Rehabilitated	504	501
	512	
	487	

B. Failure Mode

The failure mode of the damaged column after compression test is shown in Figure 3(a). It can be seen that the column failed due to the formation and propagation of oblique cracks along its body. Although compression force was applied to both ends of the column, due to damage at one end, the force cannot be completely transmitted from one end to the other, or other words, this is a case of eccentric compression. Therefore, the load-bearing capacity of this column decreases in comparison with the undamaged column, as explained above.

In the meantime, the repaired column behaved differently, and its failure mode can be seen in Figure 4(b). It can be observed immediately that longitudinal cracks have appeared on the body of the column. This type of failure is similar to the one occurred in case of the undamaged conventional concrete column [25]. However, a remarkable point is that this crack develops into the outer protecting layer of the AHPC, rather as delamination between the concrete of the existing column body and the newly AHPC of the external layer. This is even more striking when the concrete strength class of the existing column is only 25 MPa, while that of AHPC is about 50 MPa. This phenomenon also shows that despite being repaired and rehabilitated in an aquatic environment, the protective layer of AHPC still adheres firmly to the existing column body and remains inseparable from the damaged column body up to failure. Therefore, the load-bearing capacity of the damaged column after rehabilitation has increased significantly in comparison with the one without it.

(a)

(b)

Fig. 3. Failure modes: (a) Damaged column, (b) damaged column rehabilitated by AHPC with underwater concreting.

IV. CONCLUSION

This paper studied how the load-bearing capacity of the hydraulic structure enhances once it has been rehabilitated by underwater concreting. Compression test on the damaged column after rehabilitation by using underwater concreting has been carried out in order to analyze the outcomes of the undamaged column and the one without rehabilitation. The test results showed that the load-bearing capacity of the untreated damaged column was 20% less than that of the undamaged column. Meanwhile, the rehabilitated column had load-bearing capacity almost similar to that of the undamaged column.

Regarding the failure mode of the damaged column after the compression test, it possessed a big oblique crack due to the occurring eccentric compression. This phenomenon is caused by on the fact that the column has been damaged at the one end, therefore the force has not been distributed transversally from one end to the other. However, once the damaged column was rehabilitated by underwater concreting and the damaged area was covered by a protective layer, the failure mode presented a longitudinal crack along the body of the column, which is similar to that occurring in the undamaged column.

Besides, there was no sign of delamination between the protective layer and the existing concrete of the damaged column, indicating that the casting method and the concrete mixture were proper for underwater rehabilitation.

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REFERENCES

[1] A. Ahsan and M. Imteaz, "Introductory Chapter: Hydraulic Structures for Managing Water Resources Efficiently," in *Hydraulic Structures - Theory and Applications*, London, UK: IntechOpen, 2020, pp. 1–4.

[2] M. A. Tadda *et al.*, "Operation and Maintenance of Hydraulic Structures," in *Hydraulic Structures - Theory and Applications*, London, UK: IntechOpen, 2020.

[3] N. Allout, T.-H. Douara, S. Guettala, H. Charrak, and T. Boudina, "A Comparative Study of the Dam Stability at Various Stages using Numerical Modeling and in Situ Measurements: The Case Study of the Taksebt Dam, Tizi Ouzou, Algeria," *Engineering, Technology & Applied Science Research*, vol. 13, no. 2, pp. 10384–10388, Apr. 2023, https://doi.org/10.48084/etasr.5698.

[4] C. You and G. He, "Study on the Durability of Concrete under an Underwater Coupling Environment," *Geofluids*, vol. 2021, no. 1, 2021, Art. no. 1798000, https://doi.org/10.1155/2021/1798000.

[5] T. L. Ngo, "Study on the implement of fine-grain concrete with glass fiber for rehabilitation of marine structure at Giao Thuy-Nam Dinh," M.S. thesis, Thuyloi University, Hanoi, Vietnam, 2020.

[6] N. V. Duc, "Improving the Mechanical Performance of Shell Precast Concrete Blocks for Coastal Protection Structures of Hydraulic Works," *Engineering, Technology & Applied Science Research*, vol. 11, no. 1, pp. 6787–6791, Feb. 2021, https://doi.org/10.48084/etasr.4009.

[7] T. T. H. Nguyen, "Study on the improvement of reinforced concrete durability used for coast protection in Vietnam," Ph.D. dissertation, Thuyloi University, Vietnam, 2016.

[8] L. Sitek, P. Hlavacek, and L. Bodnarova, "Use of high-speed water flows for accelerated mechanical modelling of erosive wear of concrete surfaces," *MATEC Web of Conferences*, vol. 244, 2018, Art. no. 02007, https://doi.org/10.1051/matecconf/201824402007.

[9] L. Sitek *et al.*, "X-Ray CT Inspection of Subsurface Areas of Concretes Exposed to Fast Flowing Liquids," *New Trends in Production Engineering*, vol. 2, no. 1, pp. 450–459, 2019, https://doi.org/10.2478/ntpe-2019-0048.

[10] P. Hlavacek, L. Sitek, D. Klichova, and L. Bodnarova, "Effects of abrasives during accelerated simulation of mechanical corrosion of cement composites using abrasive water flow," *Acta Polytechnica CTU Proceedings*, vol. 22, pp. 31–37, Jul. 2019, https://doi.org/10.14311/APP.2019.22.0031.

[11] V. D. Nguyen, "Application of glass fibre-reinforced high strength selfcompacting mortar for rehabilitating marine structures," *Tap chi Khoa hoc Thuy loi va Moi truong*, vol. 72, pp. 10–17, 2020.

[12] G. Taylor, "Underwater concrete," in *Advanced Concrete Technology*, Oxford, UK: Butterworth-Heinemann, 2003.

[13] *TCN 59-2002: Hydraulic structures – concrete and reinforced concrete structures – Technical requirements. Appendix E – Instruction for underwater concreting*. Vietnam: Ministry of agriculture and rural development, 2002.

[14] F. H. Ahmad Zaidi *et al.*, "Geopolymer as underwater concreting material: A review," *Construction and Building Materials*, vol. 291, Jul. 2021, Art. no. 123276, https://doi.org/10.1016/j.conbuildmat.2021.123276.

[15] T. H. Nguyen, "Application of high performance fibre reinforced concrete for repairing hydraulic structure with underwater concrete," M.S. thesis, Hai Phong University, Vietnam, 2023.

[16] X. Song, H. Zheng, L. Xu, T. Xu, and Q. Li, "Comparative Study of the Performance of Underwater Concrete between Anionic and Nonionic Anti-Washout Admixtures," *Buildings*, vol. 14, no. 3, Mar. 2024, Art. no. 817, https://doi.org/10.3390/buildings14030817.

[17] V. D. Nguyen, *Study on antiwash concrete technology used for the rehabilitation of hydraulic structure by using underwater concrete*. Vietnam: Thuyloi University, 2022.

[18] *EFNARC / EFCA Guidelines for Viscosity Modifying Admixtures for Concrete Guidelines for VMA*. Farnham, UK: EFNARC, 2006.

[19] *Specification and Guidelines for Self-Compacting Concrete*. Farnham, UK: EFNARC, 2002.

[20] H. Okamura and M. Ouchi, "Self-Compacting Concrete," *Journal of Advanced Concrete Technology*, vol. 1, no. 1, pp. 5–15, 2003, https://doi.org/10.3151/jact.1.5.

[21] M. A. Memon, N. A. Memon, A. H. Memon, R. Bhanbhro, and M. H. Lashari, "Flow Assessment of Self-Compacted Concrete incorporating Fly Ash," *Engineering, Technology & Applied Science Research*, vol. 10, no. 2, pp. 5392–5395, Apr. 2020, https://doi.org/10.48084/etasr.3283.

[22] T. T. H. Nguyen, "Study on the use of different glass fiber contents for self-compacting mortar," *Tap chi Khoa hoc Thuy loi va Moi truong*, vol. 72, pp. 3–9, 2020.

[23] V. H. Nguyen, "Study on the use of mineral additives and fiber to produce high performance concrete for the coastal area of Nam Dinh Vu, Hai Phong province," M.S. thesis, Thuyloi University, Hanoi, Vietnam, 2018.

[24] *TCVN 9139:2012. Hydraulic Structures - Concrete and reinforced concrete Structures in coastal areas - Technical Specifications*. Hanoi, Vietnam: Ministry of Construction, 2012.

[25] A. M. Neville, *Properties of Concrete: Fourth and Final Edition*. New York, NY, USA: Wiley, 1996.