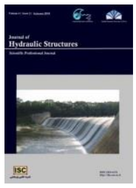
Journal of Hydraulic Structures
J. Hydraul. Struct., 2022; 8(3):72-87
DOI: 10.22055/jhs.2023.40491.1212



High Deformable Anchorage System in Slabs-on-Grade in Hydraulic Structures

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Abstract

Severe local differential displacements and the resulting high stresses in the slabs-on-grade in hydraulic structures are often caused by the displacement of bottom layers with cracks and joints or the presence of swollen soils. In addition to the above factors, the uplift due to hydrostatic and hydrodynamic pressure due to water flow under the slabs can also cause differential displacements. In this research, a ductile anchorage system with high deformable concrete element is introduced and using the designed setup, its effectiveness in comparison with conventional elastic anchorage system in the slabs under a wide uniform uplift load has been studied. High deformable concrete elements have the same strength as ordinary concrete but their compressive strain can reach 60%. These types of concrete elements are in the form of precast elements, which have many applications in structures. At first, to obtain a proper high deformable concrete element, several tests were carried out on various samples and compositions, and the behavior of the high deformable elements was studied and achieved. Experimental and numerical results show that the rate of energy absorption in deformable anchorage systems is 4 times that of conventional elastic anchors, and the use of ductile supports can prevent cracking of slabs in hydraulic structures.

Keywords: Concrete Slab, Ductile Anchorage System, High Deformable Concrete, Hydraulic Structures, Uplift Pressure.

Received: 22 April 2022; Accepted: 30 November 2022

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1. Introduction

The structures interacting with surface runoff, namely hydraulic structures, are designed for two critical technical challenges: conveyance of water, and dissipation of kinetic energy, which in all cases, these structures are very sensitive to vertical and horizontal displacements due to environmental or flow-induced conditions. Crack initiation and propagation in these structures, particularly in spillways and stilling basins, mostly relatively thin concrete slabs, cause permanent damage. As shown in Figure 1, some recent incidents due to this phenomenon are failure of the service and emergency spillways of Orville dam (the tallest dam in the United States) in February 2017, and also Bukan dam (the largest dam in the northwest of Iran) suffered damage in April 2019. Therefore, to reduce the damages and, consequently, structural failure determining the most appropriate supporting system for damping local displacements and consequently initiation and propagation in hydraulic structures slabs is one of the significant challenges for civil engineers.

(a) (b)

Figure 1. Differential displacement in chute slab causing uplift in spillways leading to failure: (a) Spillway of Bukan Dam (Iran), April 2019, Constructed from 1967 to 1971; (b) Spillway of Orville dam (United States), February 2017, Constructed from 1961 to 1968 (California Department of Water Resources).

The most significant causes of cracks and damages in overflow slabs are relatively large local deformations, which are mainly due to displacement in the foundation due to leaching of the loose layer between the rocks and their slipping on each other, the presence of swollen soils, lack of proper drainage and the phenomenon of melting and freezing (González Betancourt [1]). Figure 2 shows the schematic view of the uplift of the reclamation spillway slabs and the creation of differential displacement due to stagnation pressures (USBR/USACE Best Practices Chap. VI-1, [2, 3]).

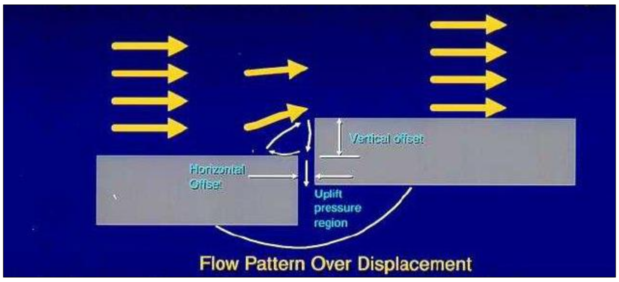


Figure 2. Schematic view of the uplift of the reclamation spillway slabs and the creation of differential displacement due to stagnation pressures (USBR/USACE Best Practices Chap. VI-1, [2, 3]).

Flow-driven uplift forces in hydraulic structures historically have been a common topic of interest for safe and reliable design. It has studied investigations that address unknowns related to uplift pressures and resulting flows into cracks and joints caused by high-velocity chute-supported flows. Bollaert [4] has documented the generation of significant uplift pressures in both lined and unlined basins with open joints by detailing the generation of large dynamic pressures, especially when air entrainment is present, and their effect on scouring in unlined rock basins subject to jet impingement. In a related study, Melo et al. [5] discussed the influence of joint location and geometry in concrete-lined plunge pools subjected to jet impact. Various researchers have also contributed to understanding the physical processes affecting uplift and rock scouring (Hepler and Johnson [6]; Trojanowski [7]; Chen [8]).

There are several methods to prevent slabs from damages, including increasing the thickness of the slab, using center beams at regular intervals, using piles under the slabs, or combining them, which are usually costly. Fiorotto and Salandin [9] found that the applicability of the equivalent thickness criterion based on the balance of the forces acting on the slabs in static condition is unsafe for anchored slabs, because this criterion yields an inadequate area for the anchor steel. The results lead to a recommendation to double the area of anchor steel as computed by the equivalent thickness criterion for the design of slabs in stilling basins. Another common method used in the stabilization of these structures is to sew the slab to the rigid bed by anchors, which in addition to bearing the uplift pressure, should also limit the movements caused by landslides or swelling of the swollen soil.

Common features in today’s designs that were often omitted in legacy concrete spillways and may affect the overall safety of the design include flexible waterstops, transverse cutoffs, filtered foundation drains, anchor bars, reinforcement continuous across joints, and double-mat reinforcement (U.S. Department of the Interior, Bureau of Reclamation, 2014). Figure 3 indicates the common defensive design details used in modern spillway designs. An evaluation of the design details used for a particular spillway during the data review portion of a comprehensive evaluation can help to identify potential vulnerabilities, which may increase the likelihood that a potential failure mode could initiate. Many of the concrete spillways in operation today, like the aforementioned structures, were designed and constructed more than 50 years ago. The knowledge of the loads and vulnerabilities associated with the operation of concrete spillways has increased significantly within the period. As a result, many of the common design features and details previously used have been revised to resist the loads better and reduce the likelihood that a probable failure mode can fully develop.

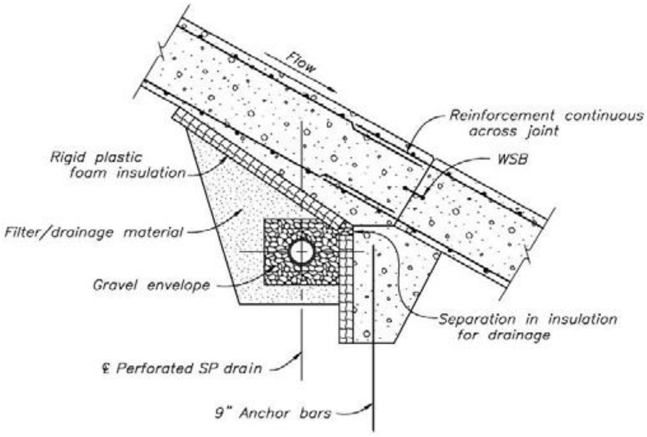


Figure 3. Common precautionary measures to prevent the concrete slab uplift (USBR/USACE Best Practices Chap. VI-[1 - 3]).

Conventional anchorage systems (rigid systems) do not allow movement in the vertical direction of the slabs, which will also cause damages and cracks in the joints. If a support system can be proposed, which, in addition to sewing the slab to the rigid floor, also allows for minimal displacement, then destructive local displacements can be transformed into uniform and general displacement. The use of ductile elements between the slab and the anchor (creating a soft support system) to reduce local deformation and concentration of stresses at the slab anchorage points seems appropriate.

Over the past two decades, a series of yielding elements have been developed and improved, for instance, the FFU element (Kurokawa et al. [10]), Meypo, DeCo-grout, Complex (Mezger et al. [11]), and Telescope yielding element (Verient et al. [12]). Highly deformable concrete (HDC or Hidcon) element is usually made of a high-strength concrete matrix with porous additives (Radoncic et al. [13]). If the Hidcon element is adopted as the yielding element, some other additives are also often used, in order to increase the compressive strength and deformability of this element (Wu et al. [14]). Kovari was able to achieve high ductility concrete behavior by using compounds of cement, water, Hollow Glass, superplasticizer, and steel fibers. He is the first one in the production of high ductility concrete (HDC) elements (Kovari [15]).

These kinds of ductile elements can be used as prefabricated components as fuses and connection joints in tunnel lining in squeezing zones, bridge and building construction and etc. In fact, these elements damp applied loads and displacement (Thut et al. [17]; Kovari [15, 16]; Singh et al. [18]; Opolony et al. [19]; Alilou et al. [20]; Zheng et al. [21]). Deng investigated the seismic performance of RC columns strengthened with high ductile fiber reinforced concrete (HDC). The experimental results from lateral cyclic loading tests on the specimens show that the failure mode of the columns could be changed from brittle to ductile under the confinement effect of the HDC jackets (Deng et al. [22]).

Flexural behavior of reinforced concrete beams strengthened by highly ductile fiber reinforced concrete and reactive powder concrete (RPC) in the tension and compressive zones is studied. The experimental results showed that the flexural capacity of specimens strengthened by an HDC layer in the tension zone was notably increased and that the specimens strengthened by an RPC layer in the compressive zone exhibit much higher ductility than the control concrete beams (Deng *et al*. [23, 24]).

New type of textile-reinforced high ductile concrete composite (TRHDC) for use in the confinement of masonry columns has been made. In this research, by doing experimental and analytical studies, it was found that TRHDC confinement can improve both the load-carrying capacity and the deformability of masonry columns relative to the unconfined condition. Besides, the analytical values are in agreement with test results but should need further experimental investigations in the future to verify the reliability of expressions rather than those used in this study (Li *et al*. [25]). Deng has presented the results of an experimental investigation on the compressive behavior of clay brick masonry columns confined with HDC. Also, analytical models were adopted to predict the compressive strength of HDC systems. The calculation model gives a better approximation to predict the compressive strength of confined masonry columns (Deng *et al*. [26-31]).

Nonlinear behavior of ductile reinforced concrete (RC) shear walls having different parameters has been investigated. In this analytically research, the effects of the analyzed parameters on the nonlinear behavior of the RC shear walls were evaluated in terms of curvature ductility, moment capacity, peak displacement, the angular displacement and displacement ductility values (Foroughi *et al*. [32]). Yuan investigated the synergy effect in tensile properties of no-slump high-strength high-ductility concrete (NSHSDC) based on polyethylene (PE) and steel fibers (SF). In their study the compressive, flexural, and tensile strength of NSHSDC with three different *W/B* ratios reinforced by different values of PE fiber were evaluated (Yuan *et al*. [33]).

The purpose of this study is to present a new method to improve the performance of the slabs-on-grade against the uplift pressure and prevent high local displacements. In this scheme, using the high deformable concrete (HDC) elements in ductile anchorage system is proposed to absorb the energy to prevent differential displacements in hydraulic structure slabs. In fact, by using the plasticity potential of HDC elements, the slab can be protected against cracking and failure.

2. Materials and Mixing Design

2.1. HDC material and proportions

The selected mix design was prepared to use in precast HDC elements, which have very high energy absorption. The proportions of concrete components of HDC element are presented in Table 1. This study deals with aspects of energy absorption and stress-strain behavior of HDC elements. Stress-strain behaviors of samples are taken as the main part of the research. Achieving suitable concrete mix design for HDC elements has been followed by their performance investigations and applicability in structural elements. For this purpose, some cylinder specimens were used to investigate the effect of using HDC elements on the stress-strain behaviors of slabs. Test site is Sahand University of technology structure laboratory in this study.

Table 1. Selected mixture proportions of fiber mortar with confined tube (PC) (selected mixing design).

Cement	Micro-silica	Quartz powder	Quartz sand	Lime powder	Water	Super plasticizer	Hollow glass	PP fibers
kg/m^3	*kg/m*^{3}	*kg/m*^{3}	*kg/m*^{3}	*kg/m*^{3}	*liter*	*kg/m*^{3}	*kg/m*^{3}	*kg/m*^{3}
200	42	430	1182	47	142	7	11	7

2.2. Material properties

The specification and material properties of the confining tube of HDC elements are provided in Table 2. In addition, the pictures of confining tubes are shown in Figure 4. In Table 3, the chemical and physical properties of cement and micro-silica used in concrete of HDC elements have been provided.

Table 2. Specification and mechanical properties of confining tubes.

Confining tube	Size	Nominal stress*	Compression yield strength (MPa)	Tensile strength (MPa)	Impact strength*	Number of specimens
PVC	100 by 100 mm	4 bar	60	42.1	15	3
Polypropylene	100 by 100 mm	6 bar	N/A	27.6-28.3	1.1	3
		8 bar				3
		10 bar				3
		12 bar				3

(a) **(b)**

Figure 4. Confining tubes of HDC elements: (a) PVC; (b) polyethylene tubes with different nominal stresses.

Table 3. Chemical and physical properties of cement and micro-silica.

Material	Portland cement-type II	Micro-silica
Sio_2 (%)	20.7	94-96
Cao (%)	65.0	0.2-0.7
Al_2O_3 (%)	5.2	0.4-0.9
Fe_2O_3 (%)	4.6	0.8-2
Other (%)	4.5	2-4
Density (g/cm^3)	3.12	0.57-0.64
Blaine (cm^2/g)	3200	20000

2.3. The numerical model

The numerical model of the circular conventional reinforced concrete slab and the anchorage system was created similar to the laboratory setup. The model was meshed with hexagonal-brick elements. The dimensions and geometry of the slab and the anchorage system precisely follow the laboratory setup. The post-cracking behavior of slab concrete, both compressive and tensile, and the determination of the input data for the concrete damage plasticity constitutive (CDP) constitutive model was obtained based on experimental results, which were also compared to the Kent–Park equations (Kent and Park. [36]). Other material parameters, including dilation angle, eccentricity, the ratio of biaxial to uniaxial compression, Kc, and viscosity parameter, were introduced in the CDP model based on ABAQUS documentation (Soranakom and Mobasher [37]).

2.4. Mortar preparatio

For each type of the proposed cementitious mix designs, firstly, dry ingredients (i.e., sand, quartz sand, quartz powder, cement, and micro-silica) were put into the mixer for about 2 minutes. Then the mixture of water and plasticizer was added and stirred for about 5 minutes. Finally, fibers were added, and additional mixing was applied for about 2 minutes. The samples were demolded for 24-h and stored in a curing box at about 22°c with 100% relative humidity.

2.5. Compression test of HDC elements

The UTM standard loading machine, manufactured by Zweick Roel, Germany, was used to draw the load-displacement curves. It should be noted that this device has very high accuracy compared to the conventional compression device used to obtain the compressive strength of concrete samples. Figure 5 illustrates a UTM device with high accuracy. The loading rate is defined as the amount of stress increase at a time unit. In addition to the ratio of water to cement, the weight ratio of cement to aggregate, and aggregate grading, surface texture, other factors affect the strength of concrete samples, which include sample size, rate of loading speed. The loading rate of the concrete test sample affects the strength shown by the specimen. As the rate of stress gets higher, the concrete exhibits more resistance. According to Standard ASTM C39/C39M–01, the maximum permitted loading speed for loading force ranges from 0.15 to 0.3 MPa/s, and the maximum permitted loading speed for loading displacement is (1 mm/min) or (0.016 mm/s). It should be noted that the purpose of this section is to compare the modulus of deformability. The test method with the UTM device has been used with the displacement control method, which has a loading speed of 0.01 mm/s on test pieces.

Figure 5. UTM loading machine.

3. Compression Test Results of HDC Elements

The deformability capacity of HDC element under compressive load has been shown in Figure 6. As shown in this Figure, the confining tubes due to the polyethylene's intrinsic deformability exhibits remarkable plastic deformation. This subject was recognized to provide excellent energy absorption.

Figure 6. Deformability capacity of HDC element under compressive pressure.

As shown in the diagram of Figure 7, the stress-strain behavior of all the samples is the same. It means that elastic, plastic, and strain hardening behavior have been caused in all HDC elements. This property is related to the presence of polyethylene sheath, which has this type of behavior. The area below the strain-stress diagram indicates energy absorption. The energy absorption of HDC elements with different confining tubes has been provided in Table 4.

HDC elements present a high initial stiffness within a small strain range, followed by an almost unchanged resistance over a great strain range after reaching their yielding stress. The strain of the HDC elements can reach to amount to 60%, and its resistance exhibited a high increase in the later deformation stage. As can be seen, another advantage of the HDC element should be highlighted in that there usually does not exist a sudden brittle failure.

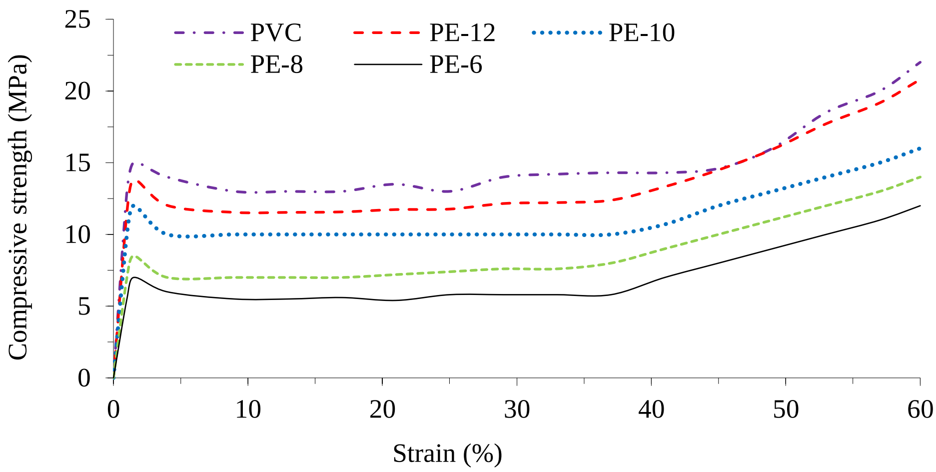


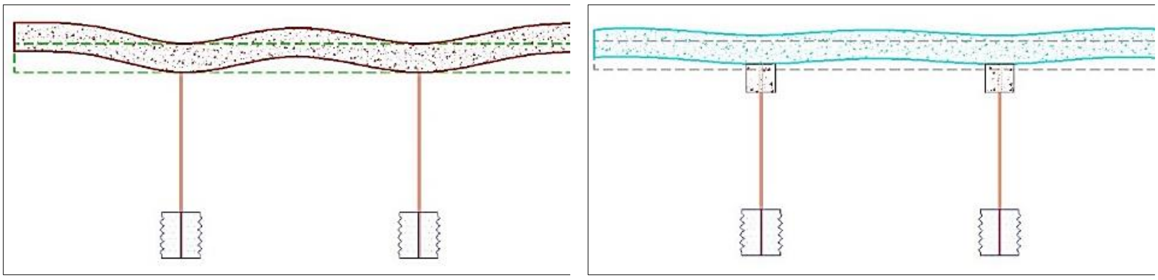
Figure 7. Stress-strain behavior of HDC elements with various confining tubes.

Table 4. Energy absorption of different HDC elements.

HDC element type	Energy absorption (KJ)
PE-6	324
PE-8	406
PE-10	521
PE-12	624
PVC	691

4. Deformable Anchorage System Setup

Using the high deformable concrete (HDC) elements in anchorage system instead of conventional (elastic) system is proposed to absorb the energy to prevent differential displacements in hydraulic structure slabs; the details are presented in Figure 8, which shows the ductile anchorage system concept and conventional rigid system. In fact, by using the plasticity potential of HDC elements, the slab can be protected against cracking and failure.

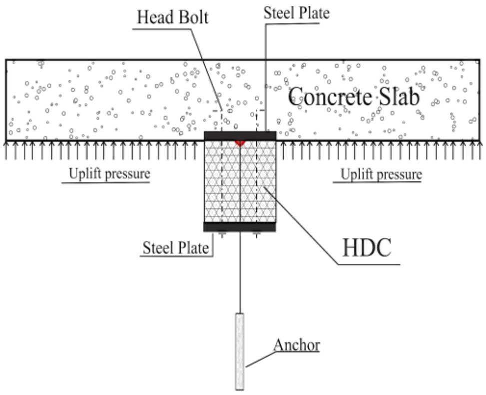


(a) (b)

Figure 8. Anchorage system to reduce differential displacements in hydraulic structure slabs: (a) conventional anchorage system; (b) deformable anchorage system with high deformable concrete (HDC) elements.

One of the advantages of deformable anchorage system is that the high deformable elements act as a fuse, and instead of cracking and destruction in the slab body, the HDC elements will be damaged, and these elements can be replaced, so the cost of repairing the damage will be much lower. In other words, these elements transform differential displacement to uniform displacement and cause more minor stresses inside the slab. This method can be used to rehabilitate existing hydraulic structures that have been designed and constructed with former standards. In the conventional anchorage system, only the elastic capacity of the materials is used, while in the proposed anchorage system, in addition to the elastic capacity, the plastic capacity of the deformable elements can also be used to absorb energy.

Hence, this research aims to experimentally produce high deformable concrete (HDC) elements with proper stress-strain behavior due to the slab concrete compressive strength. A schematic view of the soft supporting system concept using HDC elements in slabs-on-grade in hydraulic structures is shown in Figure 9 in detail.



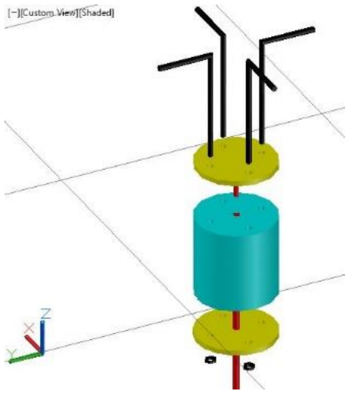


Figure 9. Schematic view of the soft supporting system concept using HDC elements in slabs-on-grade in hydraulic structures.

The concrete slab used in this experiment is a circular slab with a diameter of 1 meter and a thickness of 10 cm with the strength of 30 MPa. The reinforcement mesh used is symmetrical single layer rebar with a diameter of 8mm (ϕ8) and distances of 20 cm. A schematic view of the reinforcement rebar is given in Figure 10. The slab test set-up was designed and constructed in the Sahand University of Technology laboratory to measure the displacements and applied loads (see Figure 11), which the details are represented in Figure 12.

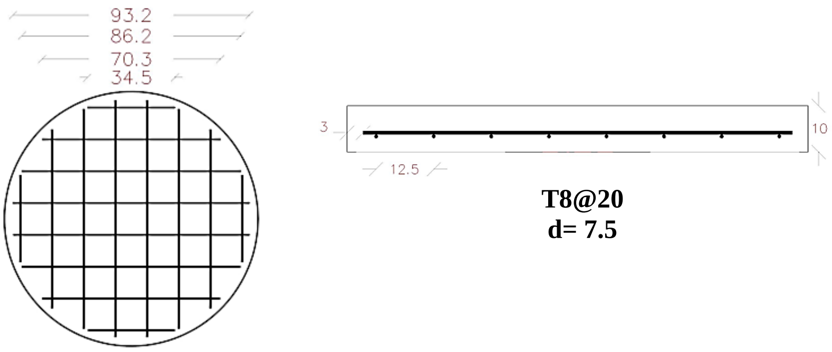


Figure 10. Specifications of concrete slab reinforcement.

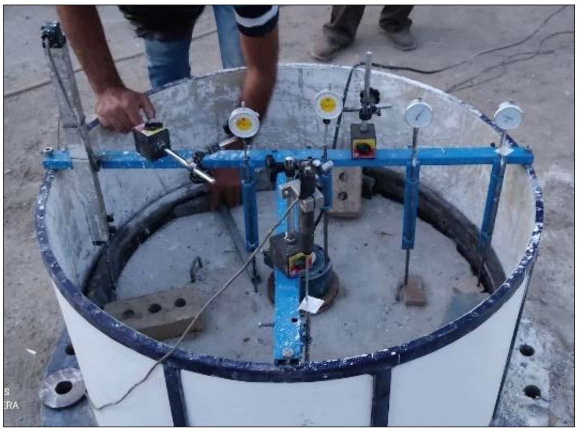


Figure 11. The concrete slab test setup.

1	**Steel nut**
2	**Steel washer**
3	**Load Cell**
4	**Steel plate**
5	**High deformable element (HDC)**
6	**Reinforced concrete slab**
7	**Anchor rod**
8	**Saturating tube**
9	**steel rigid floor**
10	**quicklime chamber**
11	**GRP enclosure ring**
12	**Digital displacement monitor**
13	**Relocation puzzler**
14	**Submersible drainage sump pump**

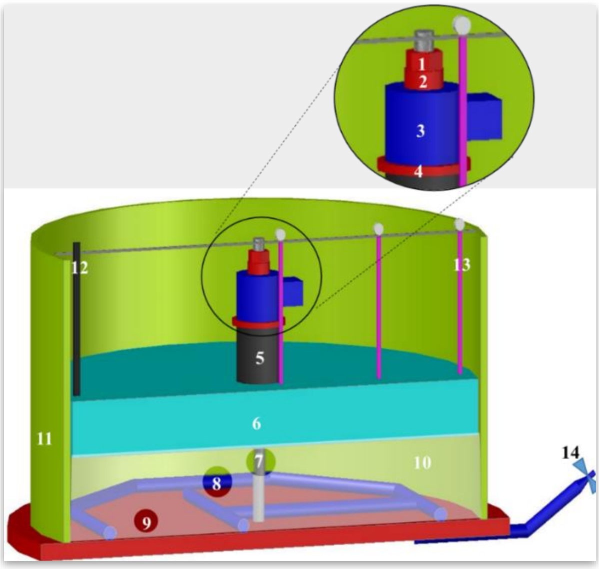


Figure 12. A 3D schematic of the proposed slab test set-up and its details.

Quicklime is filled under the slab, which reacts by adding water and increasing its volume, causing a uniform uplift force applying the slab. The displacement of the quicklime samples at different overheads has been calculated concerning time using ASTM D4546-14 standard [34, 35]. Figure 13 shows the displacement-time diagram in the quicklime sample with an overhead of 1.25 kg/cm^2, according to the set-up conditions and the designed slab capacity. Due to the gradual increase in the volume of quicklime in contact with water, the loading is uniform and similar to static uplift. The loading mechanism is designed to increase the pressure gradually and uniformly in all areas under the slab.

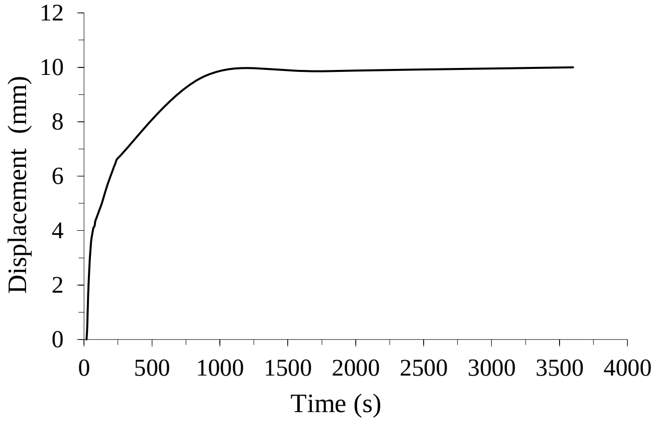


Figure 13. Diagram of swelling rate of quicklime with an overhead of 1.25 kg/cm^2.

5. Results and Discussion

Increasing the ductility of the slabs increases the energy absorption of the samples as well as the tolerance of the ductility capacity. Slabs that are exposed to heterogeneous displacements are extremely vulnerable. In this study, the behavior of slabs under uplift loads has been investigated with high deformable anchors with elastoplastic behavior. In order to investigate these cases, in the laboratory, two slabs with the same mechanical characteristics were loaded, one slab was stabilized according to the conventional method, and the other slab was stabilized using a high deformable anchorage system. The experimental and numerical results of the slabs with and without the HDC elements in their anchorage systems are presented in Figure 14. The results of these experiments, which include displacement and load, were recorded using LVDT and load cell, respectively. Based on the Figure 14, the area under the curve in the load-displacement diagram shows the amount of energy absorption. As it is clear from the diagram, the amount of energy absorption increases greatly due to the presence of a malleable element in the anchorage system. This issue will reduce the amount of cracks in the slabs of hydraulic structures that are sensitive to cracks.

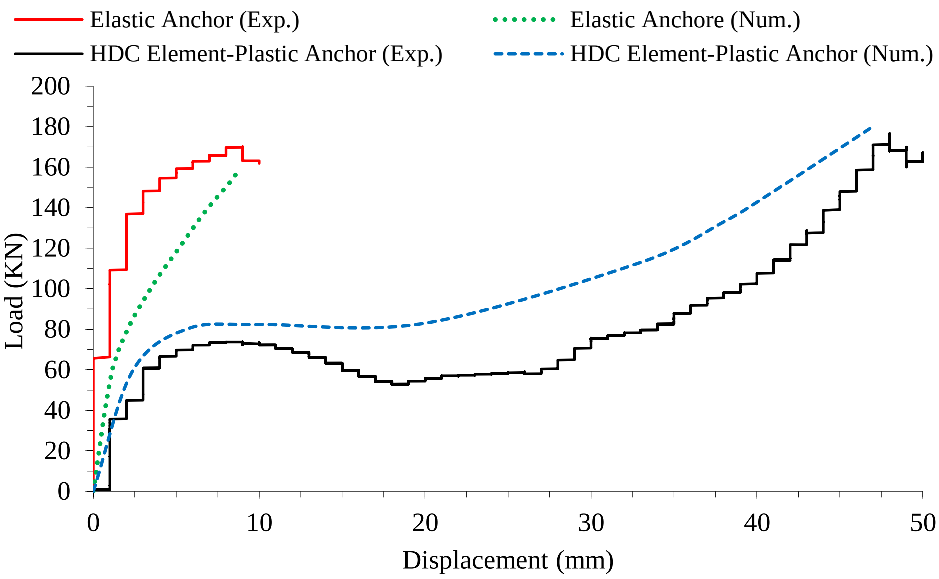


Figure 14. Load-displacement diagram of the slabs with elastic and HDC anchorage system.

Based on the obtained laboratory and numerical results (presented in Figure13), the amount of energy absorption in the deformable anchorage system is about 4 times higher than the conventional system. The deformable system also has the hardening behavior at the end of its, which this feature can be considered as a limiting factor of deformation that is observed in displacements above 30 mm. Figure 15 shows the surface of the circular concrete slabs tested at the same application uplift load in both modes using the conventional (elastic) and deformable (plastic) anchorage systems.

Figure 15. Concrete Slab under the uniform loading: (a) with rigid anchorage system; (b) with deformable anchorage system.

As seen in Figure 15, the slab undergoes a radial crack next to the conventional rigid anchor. This is while the cracks are reduced in the slab with the malleable element and instead of the crack in the slab, the element acts as a fuse and the cracks occur in the old shaped element.

6. Conclusion

The main purpose of this research is to construct a high deformable anchorage system in order to use it as a fuse or energy absorbing element in slabs in hydraulic structures that are uplifted under various factors. In this regard, laboratory studies have been conducted in two different phases. In the first stage, five high deformable concrete (HDC) elements were constructed and loaded to increase the ductility and increase the energy absorption capacity. According to the definition of HDC elements, unlike ordinary concrete, which has a brittle behavior, these elements have ductile behavior, including elastic, plastic, and strain hardening behavior, which is related to the presence of polyethylene sheath.

In the next stage of the study, a laboratory set-up has been designed and built to test the concrete slab and the anchorage support system. In this section, both the conventional rigid anchorage system and the proposed ductile anchorage system were tested, and the following results were obtained: In case of using high deformable anchorage system, the energy absorption of the slab greatly increases (more than 4 times) compared to the conventional anchorage system.

- The use of ductile anchorage support system prevents the propagation of cracks and damages in the slabs and progressive collapse in such hydraulic structures which are subjected to cyclic loading.
- HDC anchorage system convert differential displacement to uniform displacement which will be result in overall structural stability.
- Ductile anchorage support system improves structural performance when exposed to unconventional loads and on the other hand the aspects of passive defense, especially unknown factors upgrade.
- Depending on the environmental conditions and the deformation of the ground, a suitable model for using HDC anchorage system can be provided by designer.

As a general conclusion, it can say that these ductile elements damp applied loads and displacements, and due to the elastoplastic behavior of the high deformable anchorage system and their lower compressive strength compared to the concrete slab, these elements act as fuses, and first, these ductile elements are damaged. A significant advantage is that these ductile elements are prefabricated to replace and repair damaged anchors after failure. As a result, HDC anchorage can be used in squeezing and swelling zones to decrease stress in structural elements.

The experimental program was conducted on available materials such as PVC and polypropylene tubes. Further studies are underway to test epoxies and other materials with nonlinear properties for intended applications. More analytical studies will be directed to investigate the failure mechanisms of high deformable elements, including confining tubes and concrete core.

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