Reliability and Robustness Evaluation of a Remotely Operated Siphon System for Flood Mitigation during Hurricanes

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ABSTRACT

Flood is one of the most disastrous natural calamities which results in loss of human lives coupled with significant economic and infrastructural losses. Climate change and anthropogenic activities result in increased flood frequency and magnitude. This paper discusses an exclusive way of flood mitigation by utilizing and integrating structural and nonstructural approaches. Effective usage of storage systems (wetlands, detention ponds, and reservoirs) by operating in a coordinated manner plays a vital role for the same objective. For this purpose, a low-cost, green, and smart system have been designed by integrating hardware and software components. A framework has been developed to control siphon, gates, pumps, water level sensors, and air-vents, and perform a remote operation using a 3G/4G cellular connection. A prototype has been designed and tested multiple times in the field. To check the reliability and robustness of the system, structural analysis has been performed using a finite element software by applying suitable wind load. This load includes hurricane-force winds as the primary purpose of this system is to mitigate floods due to extreme rainfall and storm surge caused by hurricanes. The structural response of the siphon system against these high-intensity winds is also analyzed, laying the groundwork for future wind structure interaction analysis.

INTRODUCTION

Hurricanes are almost always associated with heavy rainfall. Recent Hurricanes such as Irma, Matthew, Florence, Harvey, and Michael have proven this point. In addition, due to climate change, temperature becomes warmer, resulting in more evaporation and, thus, heavy rainfalls, which may result in flooding (Bariweni et al. 2012). Because of an increase in temperature glaciers are melting due to which sea level is rising. Flood has lots of devastating effects such as human life losses, economic damages, destruction of crops, waterborne diseases, etc. Many studies have been conducted to study the rain ingress into the structures during these extreme wind forces accompanied by rainfall (Vutukuru et al. 2019, Gan Chowdhury et al. 2018).

The conventional way to control flooding is to use structural approaches such as building dams, reservoirs, and other storage units. Because of urbanization and development, especially in the metro areas, there is no or little scope to utilize structural approaches. Therefore, non-structural approaches such as wetlands, ponds, etc. are employed to mitigate flooding. It is seen often that structural and non-structural approaches are not operated in a coordinated manner, hence reducing their effectiveness. Thus, this paper proposes a non-structural approach which is green and smart and can be integrated with structural approaches to mitigate flooding. The proposed system consists of software and hardware components, which are explained in the coming section.

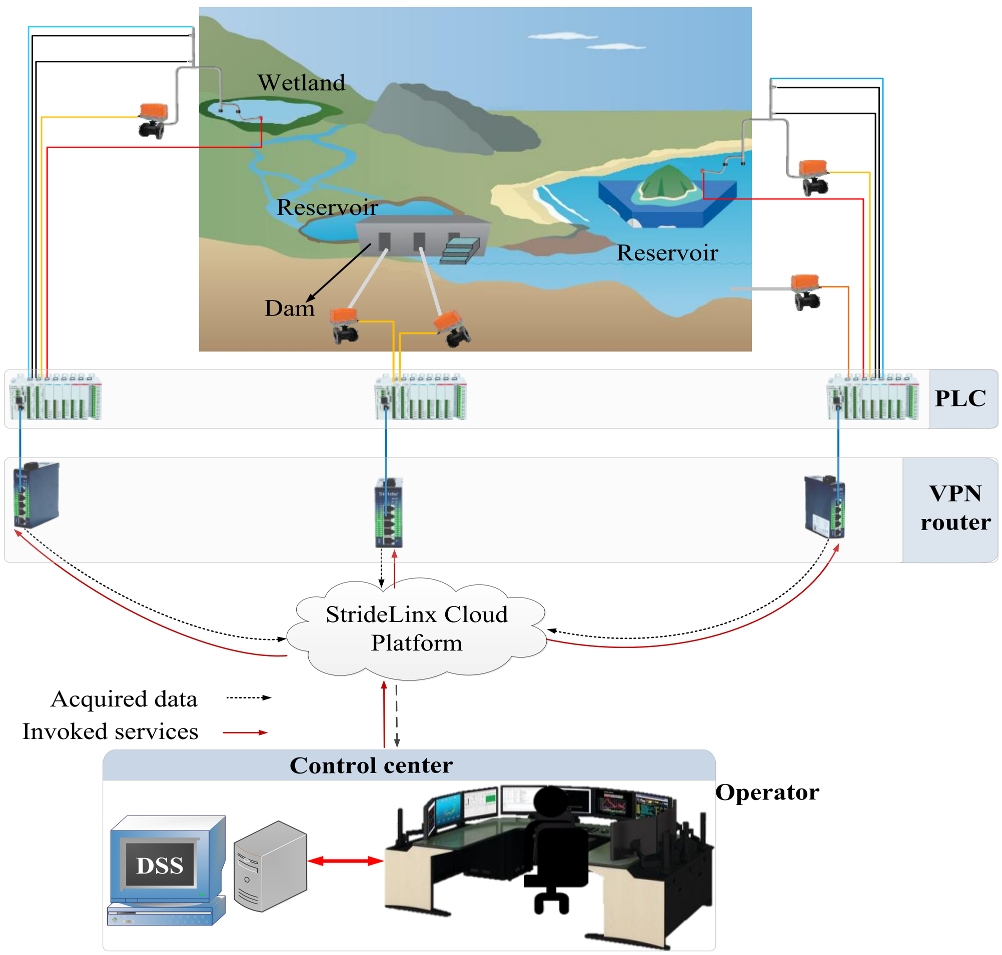

Fig. 1. Overview of the proposed architecture to release water

This study aimed to explore the reliability and robustness of the proposed hardware architecture by exposing it to the extreme hurricane-force winds. The analysis was be done by using finite element software. The objective of this study is to find the weak link in the proposed structure. New solutions will then be proposed and implemented if possible, to enhance the reliability and robustness of the proposed system.

THE ARCHITECTURE OF THE PROPOSED SYSTEM

An overview of the proposed architecture is illustrated in Fig. 1. As shown in Fig. 1, the hardware is employed in the fields which will collect data and transfer it to the Programmable

Logic Control (PLC). The PLC will forward that data to the control center with the help Virtual Private Network (VPN) router. All the data will be stored in the cloud and will be accessed by the control center. Based on the input data collected from the field, the program will run its algorithm and communicate back the results obtained to the hardware deployed in the field using the VPN router and the PLC.

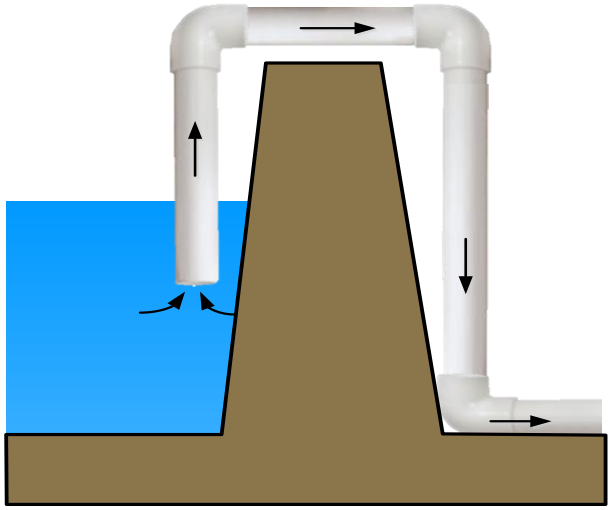

Fig. 2. Schematic of a conventional siphon

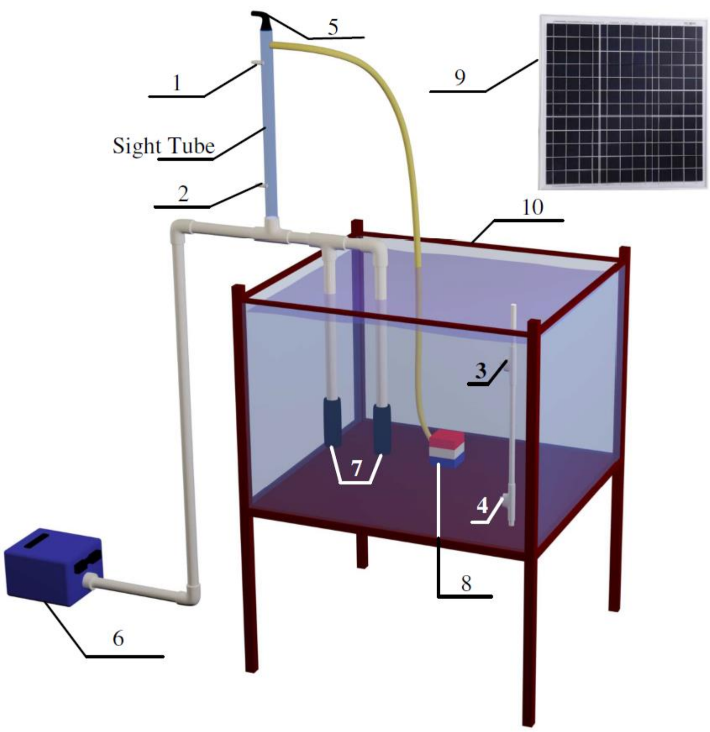

Fig. 3. Schematic of the hardware of the siphon system: (1-4) level switches; (5) air vent; (6) actuated valve; (7) check valves; (8) bilge pump; (9) solar panel; and (10) wetland (Qin et al. 2019)

A siphon is an inverted tube, as shown in Fig. 2 that transfers the water from a higher elevation to lower using gravitational force (Potter and Barnes 2002). Bubble formation inside the siphon takes place when the vapor pressure drops below the fluid vapor pressure, which stops the flow (Garrett 1991) as well as limits the maximum height of crest in siphon (Hughes 2010). The maximum siphon height with water is about 34 feet at standard atmospheric pressure (Calvert 2000). However, for practical purposes, it is designed below 34 feet to accumulate other head losses (Garrett 1991).

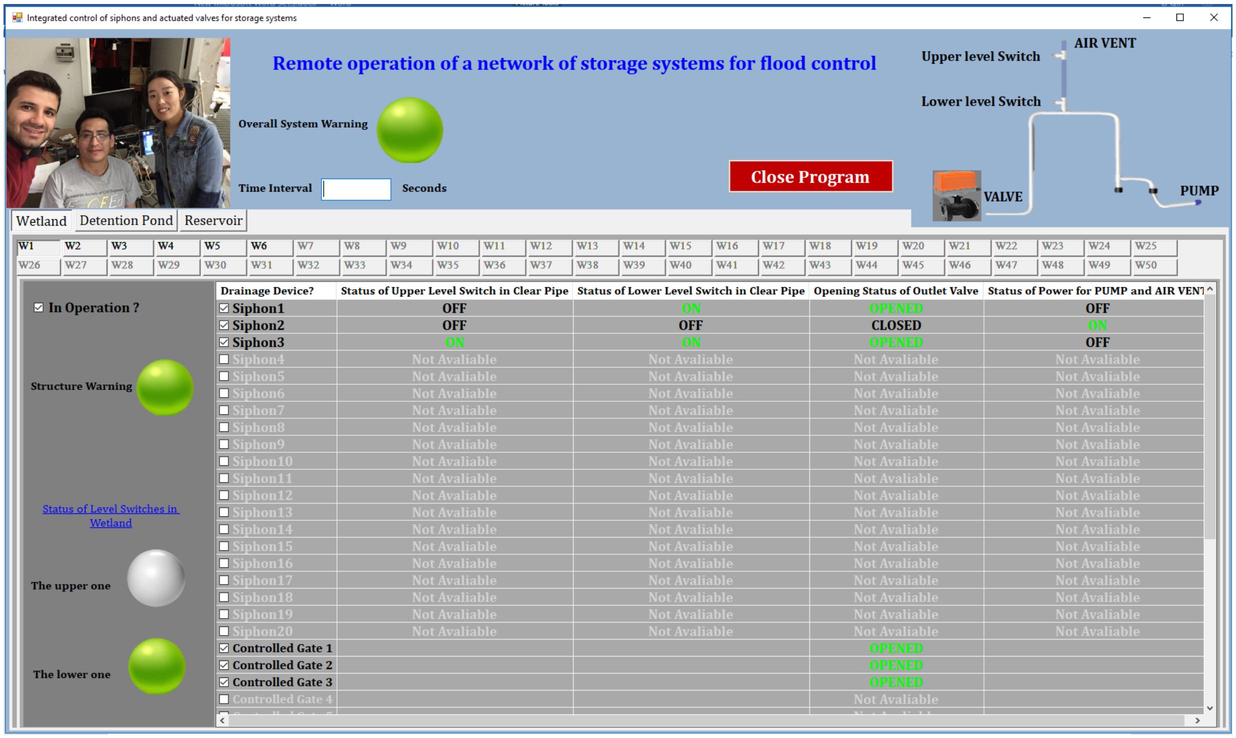

Fig. 4. Software interface for remote operation of storage systems (Leon and Verma 2019)

Fig. 3 illustrates the schematic of the hardware of the siphon system. It consists of level switches installed in the wetland and in the siphon pipe, air vent to release pressure when bilge pump primes the siphon system, actuated valve to release the water from the storage units, check valve to prevent the backflow of water from the siphon pipe, and solar panel to provide clean and green energy to all the devices as demonstrated in the Fig. 3.

SOFTWARE FOR CONTROLLING AN ARRAY OF ACTUATED GATES AND OTHER DEVICES

The interface, as illustrated in Fig. 4, is developed using the C# programming language. The schematic of the siphon with all its components is illustrated in the top right corner of the interface. The interface is designed for various storage units such as wetland, detention ponds, and reservoirs. As shown in Fig. 4, within the wetland tab, the total number of wetlands is shown. Inside each wetland, a total number of siphons installed is shown. The status of the level switches, on and off, depends upon the water level. Similarly, when the pump and the actuated valve is open, it shows ON and OPENED respectively. The overall warning can be checked by examining the structure warning for each of the storage units from the left side of the interface. If it is green in color, all the components are working fine. If it turns red, some of the components are not working properly.

INTEGRATION OF HARDWARE AND SOFTWARE COMPONENTS

The overall schematic of hardware and software components and their communication is illustrated in Fig. 5. As seen from Fig. 5, the software component collects data and updates it accordingly, which reflects in the interface. The collected data are stored in the cloud database. The data is provided by the VPN routers, which gets the data from the devices in the field via PLC. The algorithm in the control center process input data and accordingly communicates back to hardware devices in the field.

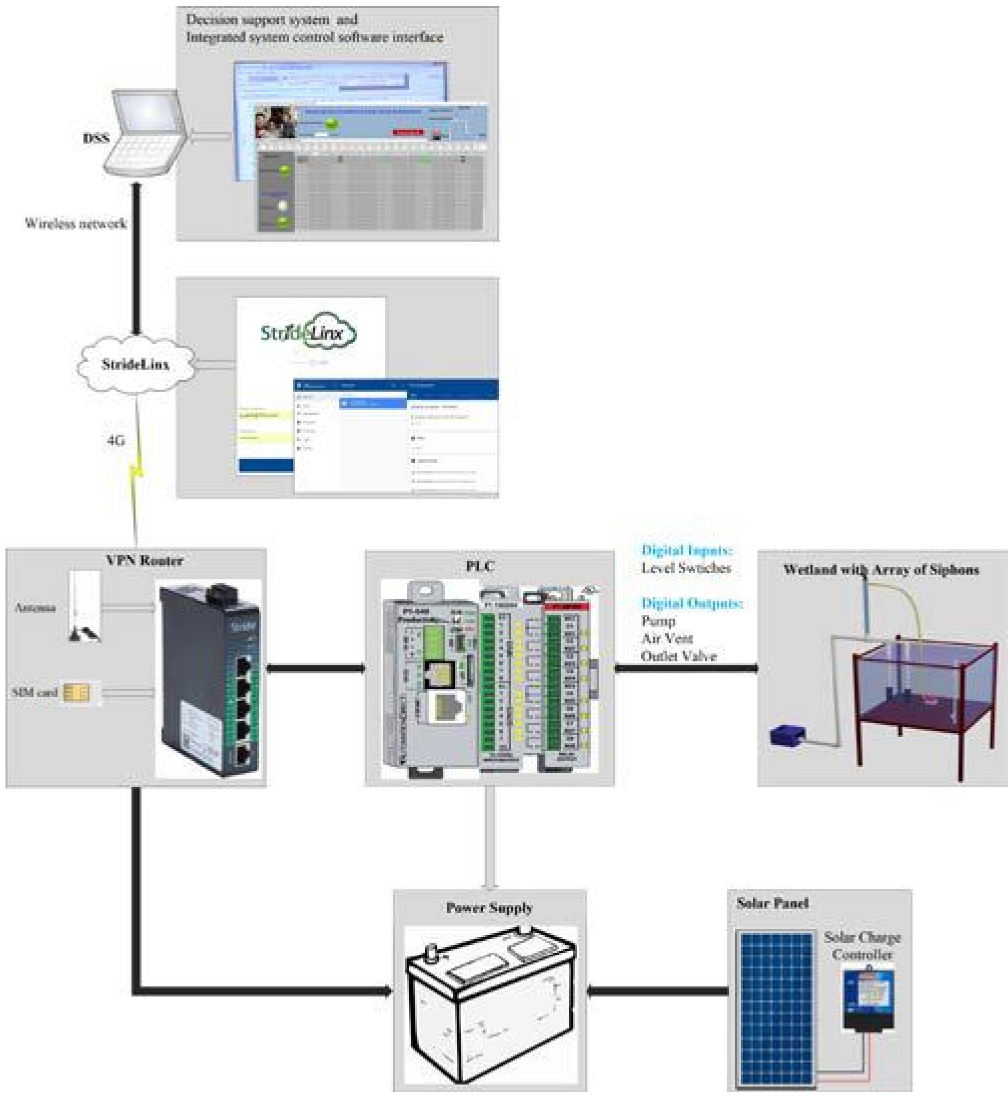

Fig. 5. Schematic of the integration of the control software, communication, and the siphon hardware (Leon and Verma 2019)

PROTOTYPE TEST

The prototype test has been performed using 6-inch diameter siphons, as illustrated in Fig. 6. A video of the operation of the 6-in diameter siphon can be seen at https://youtu.be/Zw_2hCd0G9o. The total estimated cost of the siphon system is around $2,500.

RELIABILITY AND ROBUSTNESS TESTS

Operational reliability is defined as the reliability noticed during the actual observation (Yang and Xiw 2000). Herein, the operational reliability is enhanced by using redundant devices. For instance, instead of a single pump, two pumps will be utilized. If one pump becomes un-operational, the second pump will ensure proper operation, and the system will not halt. Meanwhile, a broken pump can be repaired.

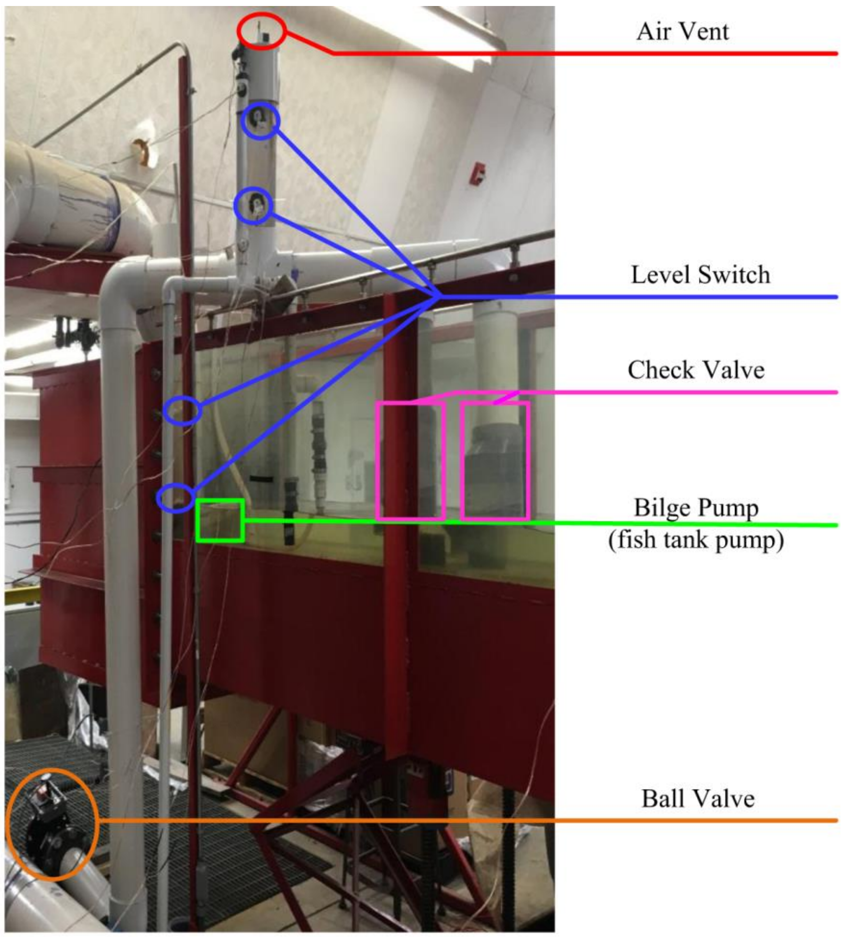

Fig. 6. The 6" diameter siphons tested in the lab (Qin et al. 2019)

To increase the robustness, the whole setup is then exposed to Hurricane Force Winds of category 5 to test the reliability and robustness of the system and simulated using Finite Element software to get initial values of base shear forces and bending moments.

In this section, the structural reliability and performance criteria of the integrated remotely operated siphon system is explained by applying wind pressure on the sloped pipe. Since the primary purpose of developing this system is to withstand floods during hurricanes, hurricane-force winds were applied to evaluate the structural performance of the system. For this purpose, as a preliminary approach, SAP2000 software was used to model and apply wind loads on the system. Wind loads were applied as per ASCE 7-16 standards considering the area of impact to be Miami. The Schedule-40 pipe was employed with a diameter of 6 ft., the length of about 25 ft., with a thickness of 0.04 ft or an outer diameter of 6.08 ft. The radial mesh size was assumed to be 0.24 (a ratio of 1:100 is maintained for results to be converging). Fig. 8 shows the model of the sloped pipe with meshing used in this study.

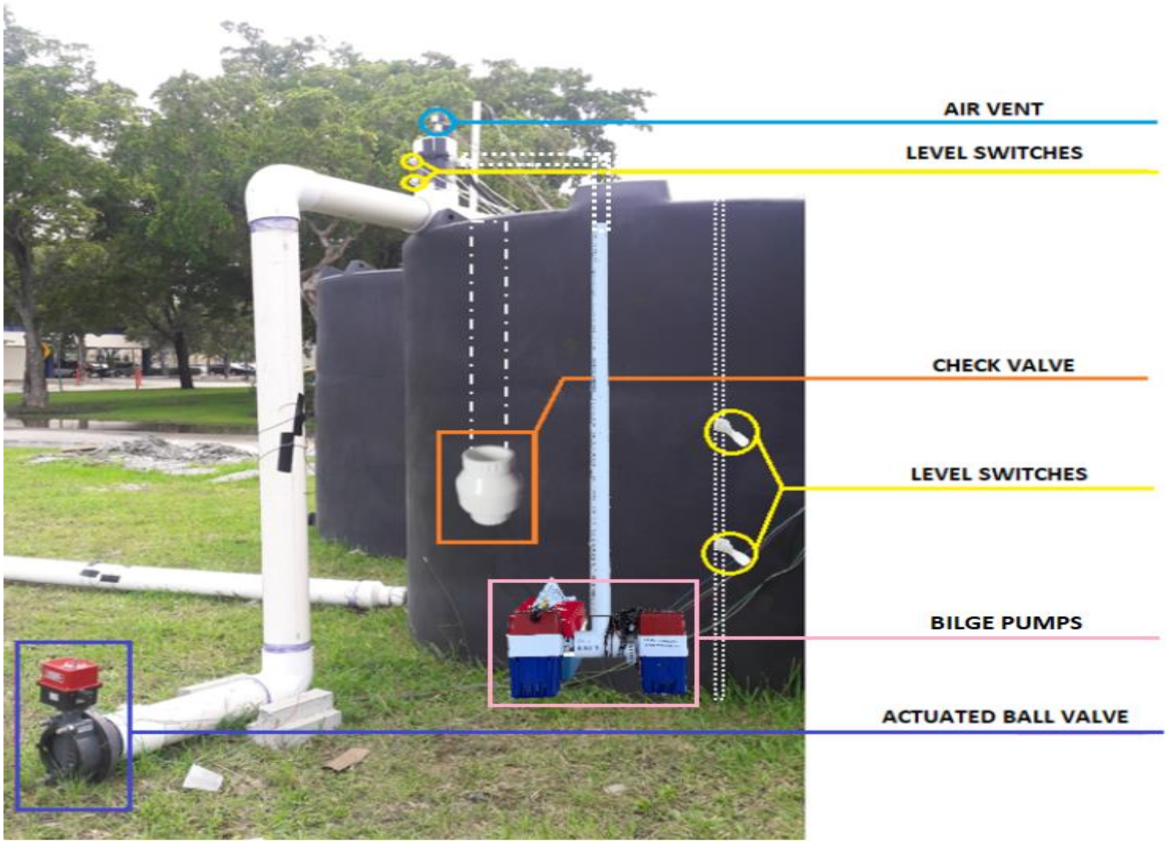

Fig. 7. The operational reliability of pumps

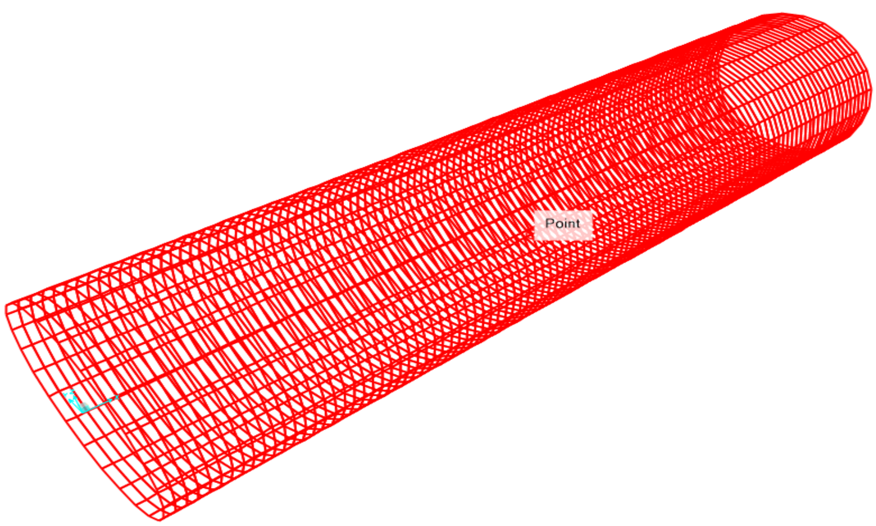

Fig. 8. 3-D view of circular pipe showing mesh elements

The supports were assumed to be pin supports to find out the corresponding reactions. These reactions would later help in finding the amount of support that would be needed to withstand the hurricane-force winds in the field. Fig. 9 shows the added pin supports and their locations.

The analysis was then performed using ASCE 7-16 by applying wind pressure corresponding to a velocity of 157 mph (70m/s) corresponding to a category-5 hurricane in the Saffir-Simpson Scale and then the results were analyzed. The results of interest in this study would include maximum support reaction. The maximum support reaction was found to be 120 kips, and hence the concrete platform on which the system rests should be able to withstand this force. The authors understand the limitation of SAP for not being able to simulate Wind Structure Interaction and hence are in the process of experimentally validating the Numerical results obtained from ANSYS Fluent with experimental results from a wind tunnel, for eg., Wall of Wind.

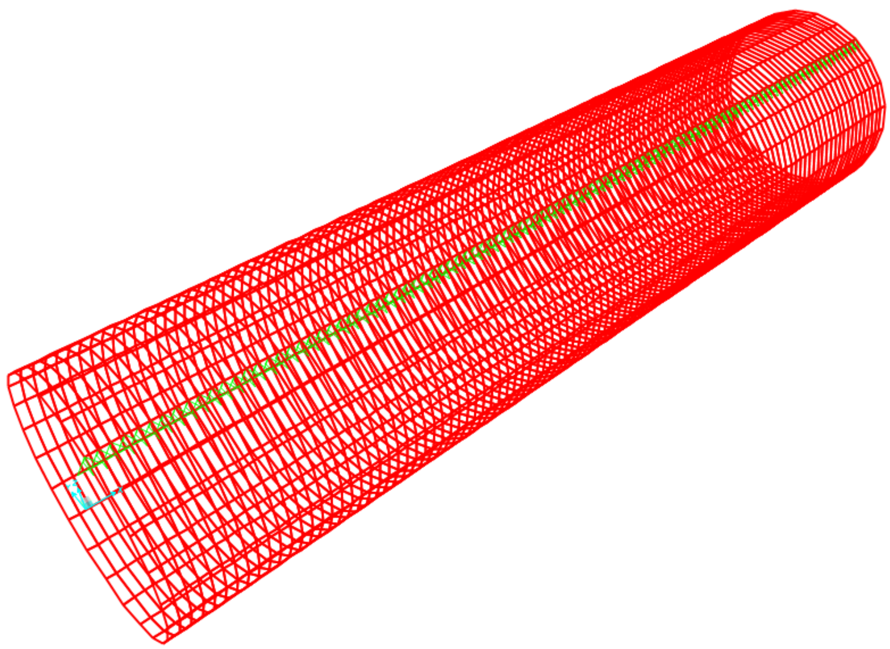

Fig. 9. Pin support locations on the model

CONCLUSION

This paper presents an architectural framework for remote operation by combining hardware and software components. The proposed nonstructural approach can be integrated with structural approaches to mitigate flooding. The proposed system includes modular units with an integrated framework to control hardware employed in the field that uses a 3G/4G cellular network for communication. The operational reliability of the system is increased by adding redundant devices that ensure proper operation of the system in case of failure of some devices. The robustness of the system was checked by using Finite Element Software, SAP2000, to apply hurricane-force winds as an initial structural check. These results gave an idea about the resisting structural forces and moments and hence modified the structural aspects of the siphon system. This Finite element study also laid a framework for future wind tunnel/Numerical study for Wind Structure Interaction.

ACKNOWLEDGMENTS

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