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## **Experimental verification of functionality of fibre-reinforced** concrete submersible piers

J Buchlák<sup>1</sup>, J Matějka<sup>1</sup>, P Ryjáček<sup>1</sup>, P Bílý<sup>1</sup>, J Procházka<sup>1</sup>, J Pollert<sup>1</sup> and J Fabel<sup>2</sup>

<sup>1</sup>Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Praha 6, Czech Republic <sup>2</sup>C&COM Advertising, Veslařský ostrov 62, 147 00 Praha 4 – Podolí, Czech Republic

E-mail: petr.bily@fsv.cvut.cz

Abstract. Low capacity of river banks is a problem of many world cities. Extension can be realised in many ways. One of the ways is to use a system of floating piers. Usual types of piers are filled with floating material, which supports the pier for the whole lifetime. The system of piers described in this article is innovative, because it is supported by an air bag, which can be deflated and then the whole system sinks down to the bottom of the river. This can be helpful in case of danger of floods, because there will be no need to transport the piers to a secure dock. Piers are designed for easy modular connection in various groups. The main types of groups are linear and areal. This article briefly describes the design of fibre reinforced concrete pier and other support constructions which are necessary for the right function of the system. The design of the pier was verified by hydraulic experiments on models in scale 1:10 to real pier. The article contains the description and results of the experiments that have proven the system to be feasible.

### 1. Introduction

The river bank is a very frequently visited place in Prague. It is searched by tourists and citizens of the city because of its significance and surroundings. Lots of cultural and sport events are organized here. During these events there is not enough space on the river bank for people. The operator of Prague river banks is therefore looking for a way to increase its capacity. Logical improvement of the river bank would be its extension. Permanent river bank extension would be very expensive and difficult. Extension by floating piers could be a solution, but it is connected with another problem. The usual type of concrete pier is filled with floating material (for example polystyrene) and it floats all the time. In case of floods, all floating objects from the river must be moved to secured harbors to prevent any damage they would cause if carried away by the stream. The transport of objects to these harbors is technically demanding and the capacity of the harbors is limited. If the usual type of piers would be used for the extension, new secured harbors would have to be build, but there is a lack of both space and finance for this solution.

Because of these problems, the authors are trying to develop a new system of concrete piers with no need of transportation in case of floods. The key idea of that system is replacing the polystyrene with an air bag, which could be deflated if needed and the pier would sink down to the bottom of the river. A group of piers would be connected by a system of air pipes that would allow to inflate and deflate the whole group together using one blower. The submerged group would remain connected with the river bank by a pipe for inflating the air bags after the flood. The submerged pier would lie down on the

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bottom for the whole period of a flood. After the flood, the air bag would be re-inflated with air and the pier would float again.

Usual types of piers are made from three mostly used materials or their combination. These materials are wood, steel and concrete. Concrete piers are usually used for making big floating platforms. In our case, concrete was chosen also for the architectural reasons.

There are two existing types of submersible concrete piers (patents no. KR101550453 [1] and US4938629 [2]). In both these systems, the piers are submerged by flooding a cavity in a concrete shell. This is connected with many problems related to securing the leaktightness of the shell, pumping the water inside and outside the cavity, cleaning the cavity from dirt etc. These problems should be solved by using the system with air bags.

The following Figures 1, 2 and 3 show the main idea of the developed system of submersible piers and the visualization of piers on Prague river bank.



**Figure 1.** Floating concrete pier with inflated air bag.



**Figure 3.** Visualisation of linearly connected piers for cyclists on Prague river bank.





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Figure 2. Submerged concrete pier with deflated air bag.



**Figure 4.** Example of numerical analysis of deflections of a group of piers.

In the original architectural study, the system of piers was used to create a bicycle path. Further considerations have shown that the use of the piers for this purpose would not be ideal. There would be small gaps between two neighbouring piers, the depth of immersion of differently loaded piers would be different, leading to uneven surface of a group of piers unsuitable for cycling. Another problem is that the piers will be attractive for pedestrians and collisions with cyclists could occur. After a discussion with the operator of Prague river banks, the main purpose of the system was changed to a path that will be used only by pedestrians.

The system should be modular, so the owner will be able to connect the piers to different linear or areal units. The connection of piers needs to be designed for fast disconnection, so the whole system would be as variable as possible. Figures 5 and 6 show two examples of arrangement of piers.



**Figure 5.** Linear group of piers, used for example as a pathway.



**Figure 6.** Areal group of piers, used for example as a restaurant seating.

## 3. Materials

#### 3.1. Concrete shell

Fibre reinforced concrete (FRC) of C30/37 class was selected as the material for the piers (mixture composition is shown in Table 1). Polymer fibres will increase the resistance of the material to shrinkage, freeze-thaw cycles, abrasion and other environmental effects. The shell will be reinforced by steel wire mesh (10 mm bars per 150 mm in both directions). The bar reinforcement needs to be covered by a layer of concrete. The thickness of the cover layer (30 mm) defines the thickness of all pier components. Piers will be made as precast elements. This gives an advantage of precise production with better quality.

### 3.2. Air bag

After discussion with producer of air bags, PVC/Nitril with nylon insertion was chosen as the bag material. Thickness of the air bag is 2.5 mm. This should provide sufficient toughness and tightness of the air bag. In Figure 7, there is a similar air bag from the same producer.

Compound	Specification	Amount [kg/m <sup>3</sup> ]
cement	CEM I 42.5 R	400
water	-	180
w/c	0.45	-
fine aggregates	0/4 mm	950
coarse aggregates	4/8 mm	600
metakaolin	Mefisto L05	40
superplasticizer	Stachement	3
polymer fibres	Forta Ferro 54 mm	4.8

Table 1. FRC composition.



Figure 7. Example of an air bag of a similar type.

#### 4. Design of geometry and size of the pier

The design of the piers was optimized by numerical analysis (Figure 4) based on hydraulic laws and defined operational conditions of the piers. For the details, please refer to [3]. The maximum allowed tilt of the pier was defined as 4° and the minimum clear distance between the water surface and pier deck as 150 mm based on the information obtained from certifying authority.

The aim was to design the piers with maximum stability and loading capacity. These two conditions go against each other. The heavier is the pier, the more stable it is, but the lower is the loading capacity as the air bag has to support the self-weight of the pier. The size of the deck was designed to be 3.3 x 3.3 m; the height of the pier element was set to 0.95 m. The thickness of all components is 80 mm, which is defined by reinforcement diameters and cover layers (2x10 + 2x30 = 80 mm). The geometry is shown in Figures 8 and 9.



**Figure 8.** A section of the pier without the air bag showing the final dimensions.



**Figure 9.** Lower axonometry of the pier without the air bag.

A capacity test was carried out in order to find out how many people can theoretically fit in 3.3 x 3.3 m area, resulting in 51 people (approximately 4000 kg when 80 kg per person is considered, Figure 10). According to the calculations, the pier of the abovementioned geometry is able to carry 55 people when the load is evenly distributed over the whole area. However, the situations when a lower number of people is unevenly distributed is more critical. Therefore, the maximum allowed capacity of one pier element was set to 15 people (1200 kg, Figure 11). If this capacity is exceeded, the pier will not sink or overturn, but the tilt will increase and make the use of the pier uncomfortable.



**Figure 10.** Maximum theoretical load of the pier -51 people (4000 kg) on 3.3 x 3.3 m area.



**Figure 11.** Maximum allowable load of the pier – 15 people (1200 kg) on 3.3 x 3.3 m area.

#### 5. Connection system

The connection system must allow fast connection and disconnection of the piers. Steel hinged joints were designed and verified by loading tests (Figures 12, 13, 14). The joints consist of three parts: a case embedded in the concrete shell, a connection bar with cylindrical ends and a cap preventing the connection bar from vertical movements.

A mock-up of the connection and the surrounding part of the pier was created in 1:1 scale and tested in the laboratory to verify the bearing capacity. For the details, please refer to [3]. The tests have shown that the capacity of the joints is sufficient for the given purpose. The capacities reached during the tests were 3 - 4 times bigger than the maximum expected forces in the connections. The FRC mixture specified in Table 1 was used and bar reinforcement was placed in the mock-up in order to test also the concreting of the structure. No problems were detected.



Figure 12. ConnectionFigure 13. Load-bearing capacity test on 1:1system.mock-up.

Figure 14. A section of two connected piers.

#### 6. Design and production of models for hydraulic experiments

Hydraulic experiments are very important in design of floating structures. Firstly, not all situations can be properly simulated by numerical analysis. Secondly, the numerical models should always be verified by experiments.

The scale of hydraulic experiments was selected as 1:10. Pier model size was 330 x 330 x 95 mm with thickness of components 8 mm (Figure 16). This thickness was extremely low, so it was necessary to design a special concrete mixture (Table 2) and mould (Figure 15). The models needed to be created as precisely as possible, because every weight inaccuracy leads to unintended initial tilt of the pier.

Connection of piers was simulated by soft steel wires fastened in electrical chocolate block connectors embedded in concrete. The behavior of the connection was very similar to the real proposed connection system. The air bag was simulated by PVC foil glued to the bottom of the concrete model (Figure 17).

Compound	Specification	Amount [kg/m <sup>3</sup> ]
cement	CEM I 42.5 R	400
water	-	260
w/c	0.65	-
fine aggregates	0/4 mm	1600
metakaolin	Mefisto L05	80
superplasticizer	Sika 0.5	2

 Table 2. Material used for 1:10 models.



Figure 15. A mould prepared for concreting.



**Figure 16.** The model for hydraulic tests in scale 1:10 without the air bag.



**Figure 17.** The model with an "air bag" simulated by PVC foil.

## 7. Hydraulic experiments with models of piers

The hydraulic experiments that were performed can be divided in two groups. First group contains static hydraulic experiments. These experiments were carried out on calm water surface with no movements in order to verify and extend the numerically obtained values of tilt and draught of the piers. The models were loaded with different values of load in different loading patterns. The load from pedestrians was simulated by steel plates placed on the whole area or on one half of the pier. Around every tested group steel bars representing the railings were placed. All loads were in 1:1000 scale to be consistent with scaling of dimensions (1:10 in all three directions).

Dynamic hydraulic experiments were carried out on moving water surface. The surface was either waving, flowing or waving and flowing at the same time. Tilts and forces in anchorage cables and braces were measured. Detailed results can be found in [4].

## 7.1. Static hydraulic experiments

During static hydraulic experiments, 26 different loading states were tested. The differences between the states were:

- Arrangement of elements: lonely pier, pair of piers, linear group (5x1), areal group (3x3)
- Value of load on one element: 4000 g (max. theoretical) or 1200 g (max. allowable)
- Arrangement of load: load over the whole area, load on one half of the area
- Failure state failure of an air bag in one of the elements simulated

Some of the states were numerically analysed during the design of the pier before the hydraulic experiments. The experiments confirmed the results of numerical analyses.

The biggest tilt of 12.5° was observed on a lonely pier with 2000 g load placed on one half of the area (Figure 19). Even in this extreme case, the pier did not sink or overturn. When the piers were connected into linear or areal groups, the tilt decreased significantly (Figure 18). For example, in case of linear group loaded by maximum allowable load on one half of the area, the tilt was only 1.7°. As the piers are generally intended to be used in groups, the static tests proved that the design is functional.



**Figure 18.** Areal group of piers loaded by 4000 g on the middle pier of the group.



Figure 19. Lonely pier loaded by 2000 g on one half of the pier.

## 7.2. Dynamic hydraulic experiments

During dynamic hydraulic experiments (Figures 20 and 21), 27 different loading states were tested. The differences between states were:

- Arrangement of elements: lonely pier, pair of piers, linear group (3x1), areal group (3x2)
- Value of load on one element: 4000 g (max. theoretical) or 1200 g (max. allowable)
- Arrangement of load: load over the whole area, load on one half of the area
- Movement of water surface: just waves, just flow, flow and waves together



**Figure 20.** Dynamic hydraulic experiments with just waving water surface.



**Figure 21.** Dynamic hydraulic experiments with just flowing water surface.

The biggest variance of tilt was measured during experiments with just waving water surface. Height of the waves was set to 50 mm and length of the waves was 600 mm. This corresponds to the size of waves caused by the largest tugboats cruising on Vltava river. In loading state with lonely pier without any load, extreme tilt variance of  $20.4^{\circ}$  was measured. When piers were connected to linear group (3x1) with same conditions, the measured tilt variance decreased to  $11^{\circ}$ . After connecting to areal group (3x2), further decrease to just 4° was observed. These results proved that connecting the piers to bigger groups is very beneficial for the stability of the whole group. Another encouraging result was that the higher was the load of the pier, the more stable it was (i.e. the lower was the tilt variance).

Figure 22 shows static scheme during dynamic hydraulic experiments (Figure 23). Group of piers was anchored by elements preventing it from flowing away. Forces in these elements were measured by strain gauges.



**Figure 22.** Static scheme during dynamic hydraulic experiments.



Figure 23. Real dynamic hydraulic experiments.

The biggest forces in anchorage elements were measured in loading states where waving and flowing of the surface were combined. The speed of water flow corresponded to the initial phase of the flood when the piers would have been submerged under water (1.0 m/s in reality, i.e. 0.3 m/s in the test after scaling). The biggest measured force in tensioned cable was 46 N, the biggest force in compressed brace was 36.9 N. These forces couldn't be counted numerically, the experiments were the only way to obtain them. Anchorage elements will be designed according to these measurement.

## 8. Conclusions

The development, design and experiments have shown that the idea of submersible concrete piers is feasible. Hydraulic experiments have proven that the piers are in general sufficiently stable when used in groups. Dynamic hydraulic experiments have provided data for design of anchorage elements. Based on the results of the research, patent application for the system of submersible concrete piers was submitted to the Czech Patent Office.

Development of concrete piers will continue in 2019. After partial amendments of the design in accordance with the needs of the production company, two prototypes of the piers will be made in real scale. These prototypes should be tested in the river, with the focus on their stability and process of inflating and deflating the air bags. If the experiments confirm that the realization of the system is possible, it could be used on Prague river banks from the year 2020.

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