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Rationale for New Pontoon-Cable Bridge Structure Parameters for Providing Uninterrupted Transportation

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Abstract

A novel type of pontoon bridge was proposed, characterized by fully submerged pontoons, creating excessive buoyant forces, and overdeck cable intended for keeping them from surfacing. Various scheme configurations were calculated using FEM to determine structure's behaviour and substantiate its parameters. Result show increased rigidity, when compared to traditional floating bridges, which translates into improved passenger comfort and overall usability.

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1. Introduction

The implementation of uninterrupted, modern, and safe transport has become a necessity for most passenger and freight services. To meet these requirements, it is imperative to implement new design principles that will enable the creation of efficient and safe transport structures. One of the principles that can be applied when creating new bridge designs is tensegrity. It was introduced into engineering theory by Richard Buckminster Fuller (Micheletti and Podio-Guidugli, 2022). This is a very simple principle conceptually, but its practical implementation requires a system of requirements (Ovchynnykov and Tiutkin, 2024):

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- structural components are in a state of pure compression or pure tension;
- compressed elements are not in direct contact;
- pre-stressing of the tendons ensures constant force direction and structural integrity;
- the structure is sufficiently rigid to maintain the constant sign of forces in its members under loading;
- the structure is in a state of self-equilibrium and does not require external constraints for stability.

Thus, the theoretical principle in its original form can currently be applied only partially. Despite its partial application, the tensegrity principle has been successfully implemented in numerous engineering fields, including bridge design (Gomez-Jauregui et al., 2023; Gilewski et al., 2015; Wang et al., 2024). However, even with the possibility of adjusting the tensegrity principle, its application in bridge construction is still limited to pedestrian bridges (Rhode-Barbarigos at al., 2010; Tej et al., 2014).

The evolution of bridge design means that many structures do not fit neatly into the categories of simple, continuous, truss etc. Suspension bridges with long spans, tensegrity bridges, pontoon bridges should be considered mechanisms that require a paradigm shift in their overall calculation (Wang et al., 2024; Zheng et al., 2017).

The fusion of ancient pontoon (floating) bridge designs with modern tensegrity principles holds great potential for innovative engineering solutions (Ovchynnykov and Tiutkin, 2024; Zhang et al., 2017; Raftoyiannis et al., 2014; Chen et al., 2020). They are used both as temporary crossings during military actions, natural disasters or when rapid structure restoration is needed and as permanent structures where it’s technologically or economically feasible. With their significant advantages, such as mobility, construction speed, material efficiency and possibility of reusing in different locations, also come drawbacks, including (Wang et al., 2024; Zhang et al., 2017):

- navigation obstruction;
- significant wind, waves and current influence;
- following the water level;
- notable displacements under both static and dynamic loads, leading to diminished passenger comfort (Zhang and Li, 2021) etc.

To counter some of these problems, the main solutions are anchoring the pontoons or using extremely large and heavy reinforced concrete structures for long bridges, as well as increasing the girder rigidity or mooring pontoons in different ways (Hagiwara and Fujishiro, 2024; Luo et al., 2024; Habibi et al., 2023; Bjerkås, 2013).

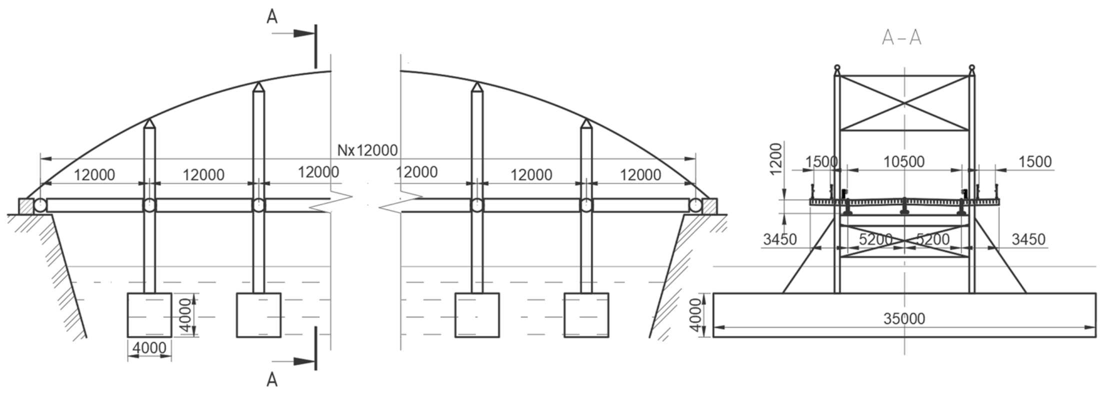

Fig. 1. Frontal and side views of proposed bridge with dimensions (mm) set for calculation.

To address the disadvantages that come with floating on the water surface and big displacements, the structure of pontoon-cable bridge was proposed (Ovchynnykov and Tiutkin, 2024). The structure is based on the notion of using fully submerged pontoons, that provide fixed buoyant force, greater than maximum amount of permanent and temporary loads on it (Ovchynnykov and Kuzminskyi, 2020). To stop them from surfacing, instead of more standard solutions, above-deck cable in tension is proposed, that takes the shape of quadratic curve to bear emergent loads (Fig. 1). Forces between pontoons and the cable are transferred by the bars-pylons, that also serve as supports for the bridge deck. The girder and deck form simple beams, i.e. divided on each pylon and supported with hinges. With this type of support the deck will not interfere with pure pontoon-cable work, but will ensure pylon's stability along the longitudinal axis, providing structural stability. Thus, the general idea of a bridge resembles an inverted suspension or underdeck bridge.

The aim of this research is to substantiate the parameters of a novel pontoon-cable bridge design, representing a significant advancement in the evolution of traditional floating bridge concepts.

2. Methods

To obtain an answer to set tasks, a series of numerical calculations has been performed using finite element method for planar problem using LIRA-CAD R16 software. The model consists of simple beams with fixed span length of 12 m between the pontoons, that are assembled into general structure of 4 to 14 hinged spans for calculation. Span structure has a provisional cross-section roughly determined based on the span length and anticipated loading from temporary highway traffic. The width of the bridge is set as 10.5 m of roadway and two footpath of 1.5 m each. For current calculations the girder cross-section is a steel I-beam with height of 1.2 m that was obtained by reducing the section given on fig. 1 for simple planar problem. Pylons-struts are placed as span supports and cable supports. They are appointed a steel box cross-section of high rigidity and aren't considered in any detail for current problem. A cable element is placed along the tops of supports and anchored on the span end-points (Fig. 2). These end-points prohibiting any axial movement is the only boundary condition for the bridge, as the vertical stability is derived from pontoons. The control scheme uses only spans and pontoon supports, as for traditional floating pontoons, to obtain reference values.

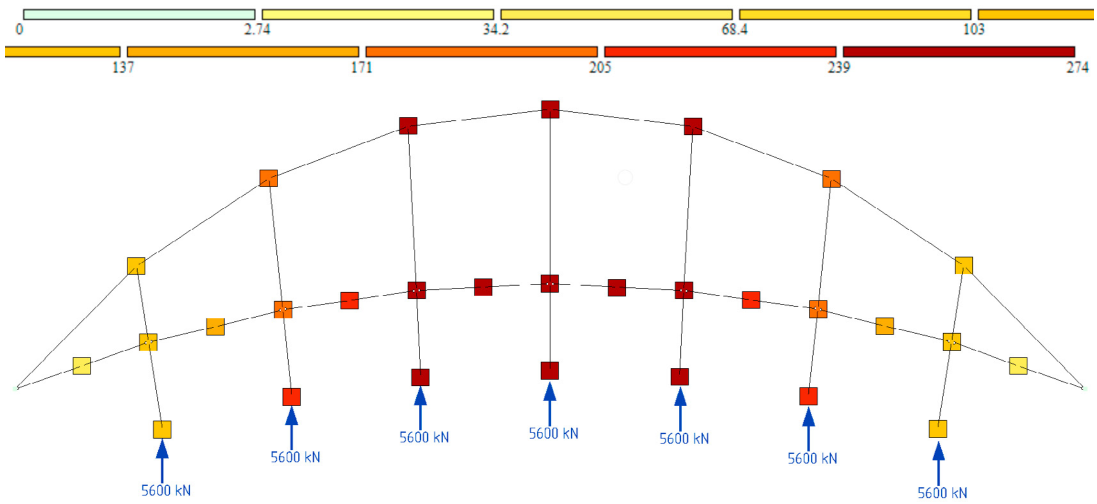

Fig. 2. Computational model with initial loading and displacements after applying permanent loads

Pontoons in the control scheme are represented by spring elements with a stiffness coefficient of AxB kN/m, where A and B are the dimensions of the pontoon base and water unit weight is set as 1 (thus simply calculating a problem for box sinking under the load). In cable model pontoons are modelled only as a constant upwards force, that equals buoyancy force of the pontoon (no actual pontoon elements are present). Pontoons themselves are taken as 4x4x35 m boxes for the calculation simplification (as cylindrical shape would obviously be better for submerged ones). And the cable was selected iteratively for each span so as to ensure adequate displacements after initial loading from buoyant forces. As an increment value, a rigidity of 180 mm wire rope was taken with added multiplier (4 times for 96 m, 8 – for 144 m etc.) Cable shape is described with eq. 1 with the initial rise of the cable (*f*) set as 1/6 of the span length (*L*).

$$y = \frac{4 \cdot f \cdot x}{L^2} \cdot (L - x) \quad (1)$$

where x – coordinate from leftmost point, y – cable rise above deck level at point x, f – max cable rise, L – span length.

3. Results

Static load calculations were performed for various points along the general span: specifically, at each point above the pontoons and at the midpoint between each pair of. Singular forces of 100 kN (for general picture) and 1000 kN (close to maximum anticipate load) were considered. Absolute displacements were yielded by the calculation, but as they are not as informative for the case with prestresses due to buoyant forces, relative displacements due to temporary loads were calculated, as well as displacement differences, i.e. the difference between maximum displacement under the load and maximum counter-displacement observed at the free part of the span.

Control scheme for every span length yielded expected fixed results consistent with simple calculation of floating pontoon. Force of 100 kN resulted in 71 mm of additional sinking and 1000 kN – to 715 mm, with all the uninfluenced pontoons resting at initial displacement after applying permanent loads. And if the force is located between the pontoons, the displacements of two influenced ones are 36 mm and 357 mm respectively.

In the cable scheme (Fig. 2) the displacements are dependent on the total span length. Notably, the sinking of the loaded pontoon also causes a rise in some other ones. Moreover, the observed displacement differences between these pontoons demonstrate a nearly linear relationship across the load range, with a tenfold increase in displacement between the 100 kN and 1000 kN loads. An example of displacements plots for different force positions is presented on fig. 3.

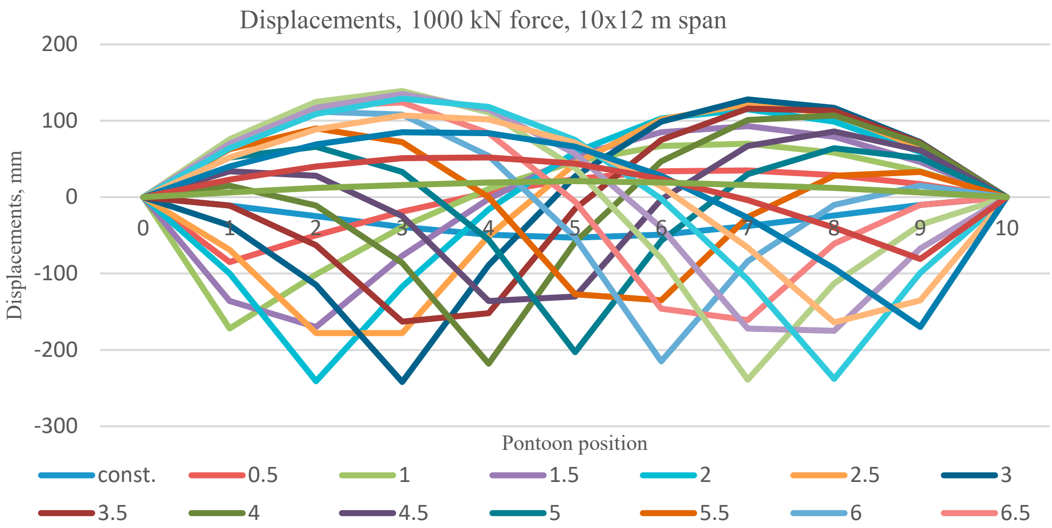

Fig. 3. Pontoon displacements depending on the 1000 kN force position.

Although displacements per se are almost three times smaller, than those of control scheme (242 mm and 715 mm), the rising pontoons create displacement differential less than half of those on control scheme (378 mm and 715 mm). However, local force movements, such as shifting the load from the middle of the span to a pontoon, result in significantly less change in cable scheme (Fig. 3). In the control scheme such displacement changes from 715 mm to

357 mm, resulting in 358 mm difference, and for 10-span cable scheme it's 242 mm to 178 mm, resulting in 94 mm difference.

Analysis of displacements also shows, that both displacements and displacement differences do not increase significantly with the total span length increase. This negligible increase, coupled with the smooth deformed curve suggests improved passenger comfort for longer spans (Fig. 4).

Overall, with obvious improvements over conventional floating bridges, pontoon-cable structure still somewhat lacks rigidity, as could be expected, as suspension bridges, which share a main bearing element, also exhibit inherent flexibility and similar, although inverted, general behaviour. Therefore, it may be feasible to adapt standard techniques used to increase the rigidity of suspension bridges for application in proposed bridge designs. To illustrate the concept, a simple two-cable (or additional strand) scheme was used in the analysis (Fig. 5). These measures nearly halve both maximum sinking and displacement differences, significantly stabilizing the position. However, the length of the deformed curve also shortens, resulting in a virtually unchanged incline.

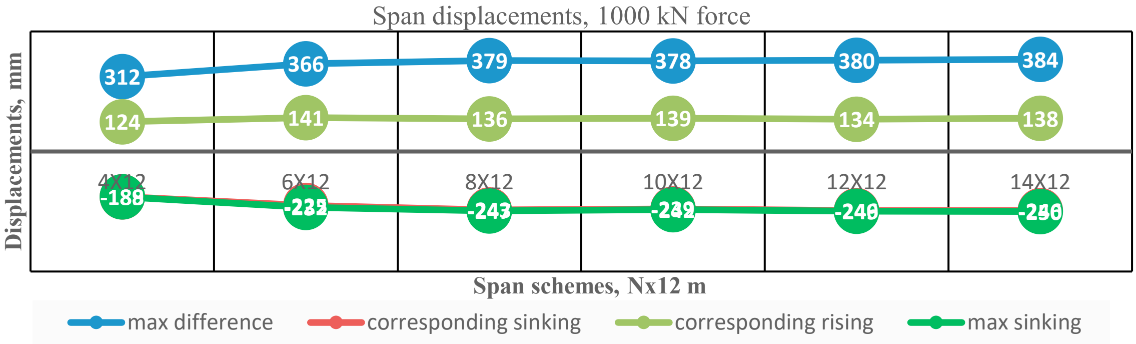

Fig. 4. Maximum displacements for calculated span configurations

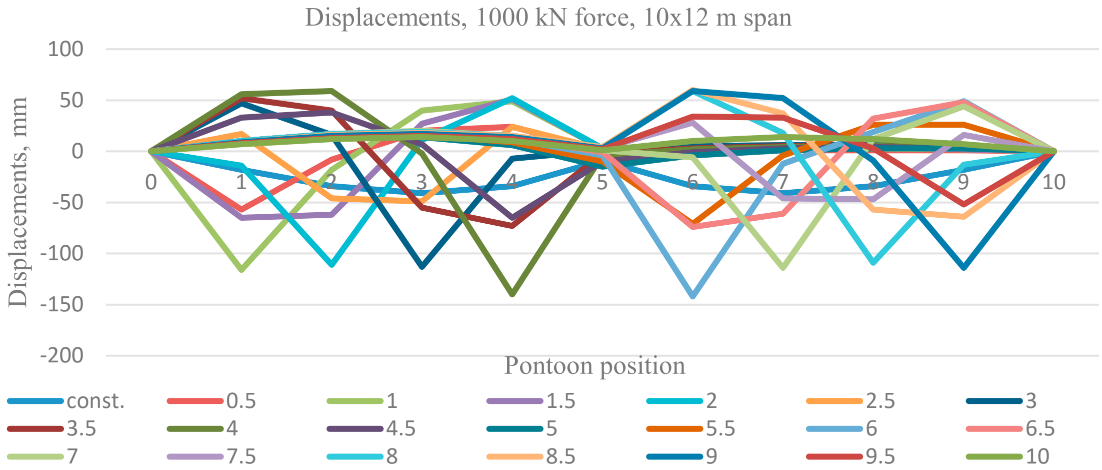

Fig. 5. Pontoon displacements depending on the 1000 kN force position for 2-cable scheme.

A significant drawback for such structures will be the rise of the cable and strut length to support it and transmit loads. With set 1/6 of length as a rise value, it reaches 20 m for 120 m span (10x12 m), and 28 m for 168 m (14x12 m), which may be challenging to design cost-effectively from engineering point of view. But for suspension bridges lower values of cable sag are considered optimal. So, for a 120 m span (10x12 m configuration) calculations were conducted for cable rises of 1/10 and 1/12 of length, i.e. 12 and 10 m respectively, to estimate the cable rise influence on bridge's behaviour. Calculations results are shown in table 1. Dead weight displacements are relative to the initial position, while rising/sinking displacements are relative to the stabilized position after the application of dead weight. For rise of 1/12 additional calculation was performed with cable stiffness increased by one-third.

Table 1. Span behaviour for various cable rise

	Rise of L/6	Rise of L/10	Rise of L/12	Rise of L/12*
Initial displacements (buoyancy), mm	330	772	1078	811
Dead weigh rel. displacement, mm	-53	-96	-118	-95
Max rel. displacement difference, 1000 kN	378	235	195	197
Corresponding rel. sinking, mm	-239	-159	-137	-135
Corresponding rel. rising, mm	139	76	58	62
Max rel. sinking, mm	-242	-161	-139	-138

Result analysis shows, that lowering the cable rise increases both initial displacements and dead weight displacements, but lowers both maximum sinking and displacement differences noticeably. Additionally, increasing cable stiffness leads to lower initial displacements, but doesn't affect behaviour under temporary loads.

4. Conclusions

The proposed pontoon-cable new bridge structure, described in this study, represents an advancement over traditional floating bridge designs. This approach significantly improves the overall behaviour of the bridge, particularly its stiffness in the vertical plane, which translates into improved passenger comfort and overall usability. Calculations conducted for various scheme configurations have demonstrated that the full scope of applications for this bridge type remains to be determined. At the same time, it was proven that for spans up to 170 meters, both rigidity and possible comfort of movement improve significantly.

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