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BUILDING MATERIALS AND STRUCTURES

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SOCIETY FOR MATERIALS AND STRUCTURES TESTING OF SERBIA

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ON A MULTI-WAVE ELASTODYNAMICAL QUADRILATERAL INFINITE ELEMENT FOR SOIL STRUCTURE INTERACTION

O MULTIVALNOM ELASTODINAMIČKOM KVADRILATERALNOM BESKONAČNOM ELEMENTU ZA OBUHVATANJE INTERAKCIJE KONSTRUKCIJE I TLA

Konstantin S KAZAKOV

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1 INTRODUCTION

This section is devoted to review the historical background of infinite elements from the original works to the latest contribution. Exterior domain scattering problems appear naturally in many engineering fields such as electrodynamics, magnetic problems, fluid flow, thermal analyses and so on. Wave propagation in an elastic infinite media and scattering of waves on bodies in a fluid which extends infinitely are of particular interest. When numerical methods are used the main difficulty in such problems arises in unbounded domain that has to be discretizied. Many suggestions and ideas for the treatment of the exterior domain have been presented and discussed in a number of research papers over the period of three decades. The exterior (infinite) domain cannot be completely discretizied with standard finite elements, and a lot of efforts have been spent in the development of new infinite element techniques.

One possible approach is to just truncate the computational domain at some distance away and to impose „appropriate" boundary conditions. Such boundary is called "artificial" boundary. In this case so-called viscous, absorbing or transmitting boundary conditions can also be used. It is evident that the computational efficiency depends than on the localization of the "artificial" boundary and the type of the boundary conditions. In a lot of problems such techniques provide acceptable results. In Soil-Structure Interaction problems such techniques are known as *Substructural approach.*

Konstantin S. Kazakov, Associate Professor Dr.
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2 INFINITE ELEMENT METHOD WORKS

Infinite element method was introduced about three decades ago in the original work of Bettless. Then the method was developed and refined in many works. The first works were the works of Pissanetzky on the magnetostatics and Kim on the magnetic field problems. The original Bettless formulation is based on and derived for the Laplace problems. This formulation is very similar to the finite element formulation except for the element domain. In this formulation infinite element domain extends toward infinity in one direction and the corresponding shape functions being non polynomial but integrable over the element. Subsequently, Infinite elements are directly applicable in the Finite element method. Similar to the Finite element method, the order of the approximation and the choice of shape functions directly relate to the accuracy of an infinite element.

The mapped infinite elements were developed by Bettess and Zienkiewicz. These elements allow using polynomial shape functions and the used technique generates shape functions which are consistent with the form of the solution of the exterior domain. A mathematically precise variational formulation of infinite elements has only recently been discussed.

3 PRACTICAL CLASSIFICATION OF INFINITE ELEMENTS

From practical point of view infinite element can be classified into five classes:

- classical infinite elements,
- decay infinite elements,
- mapped infinite elements,
- elastodynamical infinite elements and
- Wave envelope infinite elements.

The origin of the idea and the development of every one of the above classes are difficult to be dated. The first class infinite elements are based on the original so called "classical" formulation of the infinite elements. Decay functions from different mathematical types are used in the decay infinite element formulation. The mapped infinite elements are developed by using mapping functions. These functions map the infinite domain of the element into a finite. By this approach the obtained infinite element is similar to the classical finite element. The latest researches of infinite elements are devoted to the development of the elestodynamical infinite elements and wave envelope infinite elements. The last two classes can be treated as a special combination of the mapped and decay infinite elements.

4 MULTI-WAVE ELASTODYNAMICAL QUADRILATERAL FOUR NODE INFINITE ELEMENT

The displacement field in the elastodynamical infinite element can be described in the standard form of the shape functions based on wave propagation functions [7] as:

$$\mathbf{u}(x,z,w)=\sum_{i=1}^{n}\sum_{q=1}^{m}N_{iq}(x,z,w)\mathbf{p}_{iq}(w)$$

or (1)

$$\mathbf{u}(x,z,w)=N_p(x,z,w)\mathbf{p}(w)$$

where $N_{iq}(x,z,w)$ are the standard shape displacement functions, $\mathbf{p}_{iq}(w)$ is the generalized coordinates associated with $N_{iq}(x,z,w)$, *n* is the number of nodes for the element and *m* is the number of wave functions included in the formulation of the infinite element. For horizontal wave propagation basic shape functions can be expressed as:

$$N_{iq}(x,z,w)=L_i(h)W_q(x,w) \tag{2}$$

where $W_q(x,w)$ are horizontal wave functions. By taking into account only the real parts of the wave functions, the equations of the wave propagation can be written as:

$$\mathrm{Re}W_q(x,w)=\cos\left(\frac{iw}{c_s}x\right)e^{-ax}$$

or (3)

$$\mathrm{Re}W_q(x,w)=\cos\left(\frac{iw}{c_p}x\right)e^{-ax}$$

where c_s, c_p are the velocities of the *S-waves* and *P-waves* respectively.

Expanding these functions in a Fourier-like series for all wave functions included in the formulation of the infinite element, the shape functions can be written as:

$$\mathrm{Re}W(x,t)=\frac{1}{m}\sum_{q=1}^{m}A_q\cos\left(\frac{ivq}{c_s}x\right)e^{-ax}$$

or

$$\mathrm{Re}W(x,t)=\frac{1}{m}\sum_{q=1}^{m}A_q\cos\left(\frac{ivq}{c_s}x\right)e^{-ax} \tag{4}$$

or

$$\mathrm{Re}W(x)=\frac{1}{m}\sum_{q=1}^{m}A_q\cos\left(\frac{ivq}{c_s}x\right)e^{-ax}$$

or

$$\mathrm{Re}W(x)=\frac{1}{m}\sum_{q=1}^{m}A_q\cos\left(\frac{ivq}{c_p}x\right)e^{-ax} \tag{4a}$$

where v is the lowest frequency and $w=vq$. The coefficients A_q can be written as:

$$A_q=\int_0^{T_x}\mathrm{Re}W(x,t)\cos\left(\frac{ivq}{c_s}x\right)dt \tag{5}$$

or in the form

$$A_q=\frac{1}{\Omega_e}\int_0^{\Omega_e}\mathrm{Re}W(x,t)\cos\left(\frac{ivq}{c_s}x\right)dt \tag{5a}$$

Using introduced in [11] hypotheses for the shape functions, equation (4) can be expressed as

$$\mathrm{Re}W(x,t)=\frac{1}{m}\sum_{q=1}^{m}\sum_{n=1}^{\infty}1\cos\left(\frac{ivq}{c_s}x\right)e^{-ax}$$

or

$$\mathrm{Re}W(x,t)=\frac{1}{m}\sum_{q=1}^{m}\sum_{n=1}^{\infty}1\cos\left(\frac{ivq}{c_p}x\right)e^{-ax} \tag{6}$$

and

$$\mathrm{Re}W(x)=\frac{1}{m}\sum_{q=1}^{m}\sum_{n=1}^{\infty}1\cos\left(\frac{ivq}{c_s}x\right)e^{-ax}$$

or

$$\mathrm{Re}W(x)=\frac{1}{m}\sum_{q=1}^{m}\sum_{n=1}^{\infty}1\cos\left(\frac{ivq}{c_p}x\right)e^{-ax} \tag{6a}$$

Then ***united shape function*** can be written as

$$N_i(x,z,t)=\sum_{q=1}^{m}N_{iq}(x,z,w)=L_i(h)\mathrm{Re}W(x,t) \tag{7}$$

or

$$N_i(x,z)=\sum_{q=1}^{m} N_{iq}(x,z,w)=L_i(h)\mathrm{Re}W(x) \quad (7a)$$

and

$$N_i(x,z,t)\mathbf{p}_i(t)=\sum_{q=1}^{m} N_{iq}(x,z,w)\mathbf{p}_{iq}(w)=$$

$$=L_i(h)\mathrm{Re}W(x,t)\mathbf{p}_i(t) \quad (8)$$

or

$$N_i(x,z)\mathbf{p}_i=\sum_{q=1}^{m} N_{iq}(x,z,w)\mathbf{p}_{iq}(w)=$$

$$=L_i(h)\mathrm{Re}W(x)\mathbf{p}_i \quad (8a)$$

and

Now equation (1) can be expressed as

$$\mathbf{u}(x,z,t)=\sum_{i=1}^{n} N_i(x,z,t)\mathbf{p}_i(t) \quad (9)$$

or

$$\mathbf{u}(x,z)=N_p(x,z)\mathbf{p} \quad (9a)$$

In equation (4.a), (6.a), (7.a), (8.a) and (9.a) time t is included indirectly.

The procedure described by the equations (4), (5) and (6) can be treated as superposing procedure based on a finite number of terms, where real components of the wave functions $\mathrm{Re}W_q(x,w)$ are preliminary shape functions or basis functions from mathematical point of view, and coefficients A_q are generalized coordinates with only one component, corresponding to the node *i* or weight coefficients from mathematical point of view.

It can be easily shown that in the case of only one wave function used in the computational model, only one frequency, the proposed ***multi-wave elastodynamical infinite element*** is reduced to ***single-wave elasto-dynamical infinite element***. It can be treated as a special case. In this case

$$N_i(x,z,t)=N_{iq}(x,z,w)=L_i(h)\mathrm{Re}W(x,w) \quad (10)$$

or

$$N_i(x,z)=N_{iq}(x,z)=L_i(h)\mathrm{Re}W(x) \quad (10a)$$

5 TWO DIMENSIONAL MAPPED INFINITE ELEMENT

Mapping functions and the Lagrangian isoparametric shape functions are given for a 2D axisymmetric four node quadrilateral mapping infinite element and for a 2D axisymmetric eight node quadrilateral mapping infinite element can be written as

5.1 2D axisymmetric four node quadrilateral mapping infinite element

5.1.1 Mapping functions

$$x=x_I\frac{(1-\eta)(-\xi)}{1-\xi}+x_J\frac{(1+\eta)(-\xi)}{1-\xi}+$$
$$+\frac{1}{2}x_K\frac{(1+\eta)(1+\xi)}{1-\xi}+\frac{1}{2}x_L\frac{(1-\eta)(1+\xi)}{1-\xi} \quad (11)$$

$$y=y_I\frac{(1-\eta)(-\xi)}{1-\xi}+y_J\frac{(1+\eta)(-\xi)}{1-\xi}+$$
$$+\frac{1}{2}y_K\frac{(1+\eta)(1+\xi)}{1-\xi}+\frac{1}{2}y_L\frac{(1-\eta)(1+\xi)}{1-\xi} \quad (12)$$

5.1.2 Lagrangian isoparametric shape functions

$$u=\frac{1}{4}u_I(1-h)(x^2-x)+\frac{1}{4}u_J(1+h)(x^2-x)+$$
$$+\frac{1}{4}u_K(1+h)(1-x^2)+\frac{1}{4}u_L(1-h)(!-x^2) \quad (13)$$

5.2 2D axisymmetric eight node quadrilateral mapping infinite element.

5.2.1 Mapping functions

$$x=x_I\frac{(1-\eta)(-1-\xi-\eta)}{1-\xi}+2x_J\frac{(1-\eta^2)}{1-\xi}+$$
$$+x_K\frac{(1+\eta)(-1-\xi+\eta)}{1-\xi}+\frac{1}{2}x_L\frac{(1+\eta)(1+\xi)}{1-\xi}+$$
$$+\frac{1}{2}x_M\frac{(1+\eta)(1+\xi)}{1-\xi} \quad (14)$$

$$y = y_I \frac{(1-\eta)(-1-\xi-\eta)}{1-\xi} + 2y_J \frac{(1-\eta^2)}{1-\xi} + y_K \frac{(1+\eta)(-1-\xi+\eta)}{1-\xi} + \frac{1}{2} y_L \frac{(1+\eta)(1+\xi)}{1-\xi} + \frac{1}{2} y_M \frac{(1+\eta)(1+\xi)}{1-\xi} \tag{15}$$

5.2.2 Lagrangian isoparametric shape functions

$$u = \frac{1}{4} u_I (1-\eta)(1-\xi)(-1-\eta-\xi) + \frac{1}{2} u_J (1-\eta^2)(1-\xi) + \frac{1}{4} u_K (1+\eta)(1-\xi)(-1+\eta-\xi) + \frac{1}{2} u_L (1+\eta)(1-\xi^2) + \frac{1}{2} u_M (1-\eta)(1-\xi^2) \tag{16}$$

5.3 Mass and stiffness matrices

The stiffness and mass matrices can be given in a standard of the Finite element method style as

$$[k_e] = \int_{\Omega_e} [\overline{B}]^T [D][\overline{B}] d\Omega_e$$

and

$$[m_e] = \left(\int_{\Omega_e} [\overline{N}]^T [\overline{N}] d\Omega_e \right) I \tag{17}$$

where $[N]$ are the shape functions and the $\{B_i\}$ vectors in the matrix $[B]$ are written as

$$\{\overline{B}_i\} = \begin{Bmatrix} \dfrac{\partial \overline{N}_i}{\partial x} \\ \dfrac{\partial \overline{N}_i}{\partial y} \end{Bmatrix} \quad \text{or} \quad \{\overline{B}_i\} = [J]^1 \begin{Bmatrix} \dfrac{\partial \overline{N}_i}{\partial h} \\ \dfrac{\partial \overline{N}_i}{\partial x} \end{Bmatrix} \tag{18}$$

where $[J]^1$ is the Jacobian matrix which defines the geometrical mapping and can be written as

$$[J]^1 = \sum_{i=1}^{4} \begin{Bmatrix} \dfrac{\partial N_i}{\partial h} x_i & \dfrac{\partial N_i}{\partial h} y_i \\ \dfrac{\partial N_i}{\partial x} x_i & \dfrac{\partial N_i}{\partial x} y_i \end{Bmatrix} \tag{19}$$

The domain differential $d\Omega_e$ must also be written in terms of the local coordinates as

$$d\Omega_e = dxdy = [J] dhdx \tag{20}$$

Subject to the evaluation of $\{B_i\}$ and $d\Omega_e$, which involves the mapping functions, the element stiffness and mass matrices may not be computed with standard Gaussian quadrature procedure. Note also that u and $\overline{N}$ are shape functions but N and M are mapping functions.

6 CONTINUITY THROUGH FINITE AND INFINITE ELEMENTS

The continuity through finite and infinite elements can be enforced in exactly the same way as between two finite elements because they have same degrees of freedom and approximation polynomial degrees. A sketch of the boundary between finite and infinite elements is given in *Fig.1*

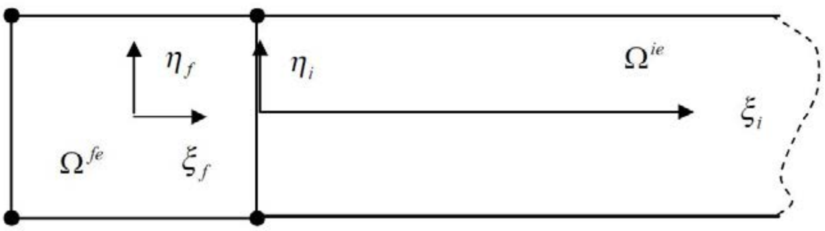

Fig.1 Sketch of the boundary between finite and infinite elements

7 $C^{(n)}$ RATE OF CONTINUITY

Here some basic requirements for $C^{(n)}$ continuity into the element domain and on the whole domain (the near and far field) are given.

$C^{(n)}$ continuity of a function $u_e(x,h)$ in a domain Ω_e is valid if

- The function $u_e(x,h)$ is of power $n+1$,
- The function $u_e(x,h)$ is n times differentiable and the surface $u_e^{(n)}(x,h)$ is smooth.
- $C^{(n)}$ continuity of a function $u(x,y)$ in a domain Ω is valid if
- The function $u(x,y)$ is of power $n+1$,
- The function $u(x,y)$ is n times differentiable and the surface $u^{(n)}(x,y)$ is smooth
- The function $u(x,y)$ is $n+1$ times differentiable on the nodes.
- Very often in SSI structural analysis it is enough to be ensured only C_1 continuity along *finite element / infinite element (FE/IE) line* or so-called *artificial boundary* in the form:

If line $h = const$ includes a node on the FE/IE line then

- The wave functions $W_q(x,w)$ and their first partial derivatives $\frac{\partial}{\partial x}W_q(x,w) \equiv W_q^x(x,w)$ have to be continuous and smooth on the line and also $W_q^x(x,w) = 0$ is needed on the nodes

If line $h = const$ does not include a node on the FE/IE line then

- The wave functions $W_q(x,w)$ and their first partial derivatives $\frac{\partial}{\partial x}W_q(x,w) \equiv W_q^x(x,w)$ have to be continuous and only the wave functions $W_q(x,w)$ have to be smooth. Also $W_q^x(x,w) = 0$ on the finite side of the infinite element is needed.

Requirement $W_q^x(x,w) = 0$ is needed on the every one point of the FE/IE line, then

$$\frac{\partial}{\partial x}N_{iq}(x,z,w) = L_i(h)\frac{\partial}{\partial x}W_q(x,w) \qquad (21)$$

When only the real parts of the wave functions are used

$$\frac{\partial}{\partial x}\mathrm{Re}W_q(x,w) = \frac{\partial}{\partial x}\left(\cos\left(\frac{iw}{c_s}x\right)e^{-ax}\right)$$

or

$$\frac{\partial}{\partial x}\mathrm{Re}W_q(x,w) = \frac{\partial}{\partial x}\left(\cos\left(\frac{iw}{c_p}x\right)e^{-ax}\right) \qquad (22)$$

Global FE/IE line is identical with local infinite element line $x = 0$, see *figure 1*. For $x = 0$

$$\frac{\partial}{\partial \xi}ReW_q(\xi,\omega) = \frac{\partial}{\partial \xi}\left(cos\left(\frac{i\omega}{c_s}\xi\right)e^{-\alpha\xi}\right) =$$

$$= -\alpha cos\left(\frac{i\omega}{c_s}\xi\right)e^{-\alpha\xi} - \frac{i\omega}{c_s}sin\left(\frac{i\omega}{c_s}\xi\right)e^{-\alpha\xi} =$$

$$\left(-\alpha cos\left(\frac{i\omega}{c_s}\xi\right) - \frac{i\omega}{c_s}sin\left(\frac{i\omega}{c_s}\xi\right)\right)e^{-\alpha\xi} = -\alpha$$

or

$$\frac{\partial}{\partial \xi}ReW_q(\xi,\omega) = \frac{\partial}{\partial \xi}\left(cos\left(\frac{i\omega}{c_p}\xi\right)e^{-\alpha\xi}\right) =$$

$$= -\alpha cos\left(\frac{i\omega}{c_p}\xi\right)e^{-\alpha\xi} - \frac{i\omega}{c_p}sin\left(\frac{i\omega}{c_p}\xi\right)e^{-\alpha\xi} =$$

$$\left(-\alpha cos\left(\frac{i\omega}{c_p}\xi\right) - \frac{i\omega}{c_p}sin\left(\frac{i\omega}{c_p}\xi\right)\right)e^{-\alpha\xi} = -\alpha \qquad (23)$$

When we assume $a \le d$ we practically ensure the requirement.

For the functions written as (4) and (4.a) the above requirement can be expressed as

$$\frac{\partial}{\partial x}\mathrm{Re}W(x,t) = \frac{1}{m}\sum_{q=1}^{m}A_q\frac{\partial}{\partial x}\cos\left(\frac{ivq}{c_s}x\right)e^{-ax} = -a$$

or

$$\frac{\partial}{\partial x}\mathrm{Re}W(x,t) = \frac{1}{m}\sum_{q=1}^{m}A_q\frac{\partial}{\partial x}\cos\left(\frac{ivq}{c_p}x\right)e^{-ax} = -a \qquad (24)$$

and

$$\frac{\partial}{\partial x}\mathrm{Re}W(x) = \frac{1}{m}\sum_{q=1}^{m}A_q\frac{\partial}{\partial x}\cos\left(\frac{ivq}{c_s}x\right)e^{-ax} = -a$$

or

$$\frac{\partial}{\partial x}\mathrm{Re}W(x) = \frac{1}{m}\sum_{q=1}^{m}A_q\frac{\partial}{\partial x}\cos\left(\frac{ivq}{c_p}x\right)e^{-ax} = -a \qquad (25)$$

8 CONCLUSION

This paper deals with the mapping functions and the Lagrangian isoparametric shape functions for a 2D axisymmetric four node quadrilateral mapping infinite element and for a 2D axisymmetric eight node quadrilateral mapping infinite element. In addition, the basic aspects of the C_1 and the C_n continuity along finite/infinite element line in two-dimensional substructure Soil-Structure Interaction problems are analyzed and discussed. In this class of models such a line marks artificial boundary between the near and the far field of the model. Finally, some important remarks about the C_1 and the C_n continuity are reviewed when the author proposed using wave functions in Soil-Structure Interaction models.

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ABSTRACT

ON A MULTI-WAVE ELASTODYNAMICAL QUADRILATERAL INFINITE ELEMENT FOR SOIL STRUCTURE INTERACTION

Konstantin S. KAZAKOV

In this paper, a multi-wave elastodynamical quadrilateral infinite element is proposed. This kind of element is appropriate for multi-wave soil-structure interaction problem. The formulation is based on the standard steps which are the same as in the Finite element method after mapping the infinite to finite domain of the element. It is shown that in the case of only one wave function used in the formulation, only one frequency, the proposed multi-wave elastodynamical infinite element is reduced as a special case to single-wave elastodynamical infinite element.

In addition, the mapping and the Lagrangian isoparametric shape functions for a 2D axisymmetric four node multi-wave elastodynamical quadrilateral infinite element and for a 2D axisymmetric eight node multi-wave elastodynamical quadrilateral infinite element are given. The basic aspects of the C_1 and the C_n continuity along the finite/infinite element (artificial boundary) line in two-dimensional substructure Soil-Structure Interaction problems are discussed. In this class of models such a line marks artificial boundary between the near and the far field of the model.

Key words: Wave propagation, Infinite Elements, Finite Element Method, Soil-Structure Interaction

REZIME

O MULTIVALNOM ELASTODINAMIČKOM KVADRILATERALNOM BESKONAČNOM ELEMENTU ZA OBUHVATANJE INTERAKCIJE KONSTRUKCIJE I TLA

Konstantin S. KAZAKOV

U ovom radu predložen je višetalasni elastodinamički četvorougaoni beskonačni element. Ova vrsta elementa je pogodna za proučavanje problema višetalasne interakcije konstrukcija-tlo. Formulacija se zasniva na standardnim koracima koji su isti kao u metodi konačnih elemenata (MKE) nakon mapiranja beskonačnog u konačni domen elementa. Pokazano je da se u slučaju samo jedne talasne funkcije (samo jedne frekvencije) koja se koristi u formulaciji, predloženi višetalasni elastodinamički beskonačni element svodi na poseban slučaj jednotalasnog elastodinamičkog beskonačnog elementa.

Pored toga, prikazani su preslikavanje i Lagranžove izoparametarske funkcije oblika za 2D osnosimetrični višetalasni elastodinamički četvorougaoni beskonačni element i za 2D osnosimetrični višetalasni elastodinamički četvorougaoni beskonačni element sa osam čvorova. Razmatraju se i osnovni aspekti C_1 i C_n, kontinuiteta duž pseudo-granične linije konačnog i beskonačnog elementa u dvodimenzionalnom problemu interakcije konstrukcija-tlo. U ovoj klasi modela takva linija označava veštačku granicu između bliskog i udaljenog polja modela.

Ključne reči: prostiranje talasa, beskonačni elementi, metoda konačnih elemenata, interakcija konstrukcije i tla

STRENGTHENING THE RAFT FOUNDATION OF AN EXISTING RC BUILDING BY APPLICATION OF JET-GROUTING METHOD

ПОЈАЧАЊЕ ТЕМЕЉНЕ ПЛОЧЕ ПОСТОЈЕЋЕ АРМИРАНОБЕТОНСКЕ ЗГРАДЕ ПРИМЕНОМ ЏЕТ-ГРОУТИНГ (МЛАЗНОГ ИЊЕКТИРАЊА) МЕТОДЕ

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1 INTRODUCTION

A case study of soil-foundation system strengthening is presented in the paper. The studied building's RC structure (columns and slabs for vertical loads and walls for seismic loads) has been designed in 2007 and planned to be realized in the seaside city of Burgas in Bulgaria. According to the original project the building consists of 14 levels as well as 5 underground levels. The execution process has started in 2008 and has been interrupted in 2010 as only the basement part of the building was constructed then. Due to investment intensions change it has been decided to construct the remaining superstructure and to extend it by 4 additional levels as well as to switch building's function from office to residential. In order to do so a strengthening project has been prepared. The project includes a number of measures regarding the superstructure (reparation, RC-jacketing, execution of new structural elements among others) as addition to the soil-foundation improvement.

Fig. 1. Existing condition and spatial view of the structure

The foundation of the existing part of the building consists of a raft. In order to reduce settlement due to the additional loads, [9], from the extension and for the sake of increasing the stiffness of the modulus of subgrade reaction in the numerical model it has been decided to execute jet-grouting as a hybrid soil improvement-structural strengthening measure – [18].

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The operating conditions (height of 2.80 m in the basement) have made this solution as an only option.

Jet-grouting soil improvement technique (described in [1], [7] and [8]) has gained popularity, [6], during the last few decades. Its application range is wide and some typical examples include foundations, retaining structures, water barriers, tunnels among others. The jet-grouting process is recognized as a cement soil stabilization. With the aid of high pressure (400 bar) cutting jets of water or cement suspension having a nozzle exit velocity ≥100 m/sec eventually air-shrouded the soil around the borehole is eroded. The eroded soil is rearranged and mixed with the cement suspension. The soilcement mix is partly flushed out to the top of the borehole through the annular space between the jet grouting rods and the borehole. Single fluid version (described in [4]) of the jet-grouting technique has been adopted for the particular project. In the single fluid system, the water-cement grout is injected into the ground through one or more nozzles. In this case, soil remoulding and subsequent cementation are both caused by the same fluid.

The adopted configuration of the 206 jet-grouting columns having a diameter of 80 cm is given on Figure 2. The execution process consists of seven major steps as follows: 1) drilling the existing raft; 2) forming the jet-grouting columns (length of 7 m and 5 m) through high-pressure injection of water-cement grout; 3) insertion of a steel pipes (• 114.3x8, length of 5 m and 2.5 m) for load transfer from the raft to jet-grouting column and for the sake of increasing its compressive bearing capacity; 4) grouting the space between the raft and the pipe; 5) insertion of reinforcement in the pipe – the upper part of the reinforcement sticks out of the raft so that it could be linked to the reinforcement of the foundation top jacketing; 6) grouting the inner volume of the pipe and execution of a 15 centimeter RC strengthening (top jacketing) of the existing raft.

2 SOIL CONDITIONS AND VERIFICATION OF JET-GROUTING COLUMN PROPERTIES

The soil conditions on site are shown on Table 1. The foundation raft is located at level +9.05 meaning that it layes on saturated Layer 3 (Pliocene clays).

Usually in practice, it is necessary to correlate the jet grouting effects (i.e., column diameter and properties) to the original soil properties (i.e., grain size, shear strength) and to the treatment procedures (i.e., treatment parameters). However, because all soils are inherently heterogeneous, the mechanical and geometrical characteristics of the columns are usually variable.

In the presented project a simple approach for verification of the jet-grouting columns' diameter has been adopted – [19]. Three test columns (TC-A1, TC-A2 and TC-A3) have been executed by three different treatment procedures. Thereafter, boreholes have been drilled in the center and perifery (at distance 40 cm from the center) of all three columns. In order to prove that a diameter of at least 80 cm is ensured, a continous sample is taken through the whole length of the borehole – [12] and [14]. The judgment is made on the basis whether treated medium is observed through the whole sample or not. In the particular case study test columns TC-A1 and TC-A2 showed unsatisfactory results. In contrast, test column TC-A3 demonstrated a treated zone with the desired dimensions (Fig 3.).

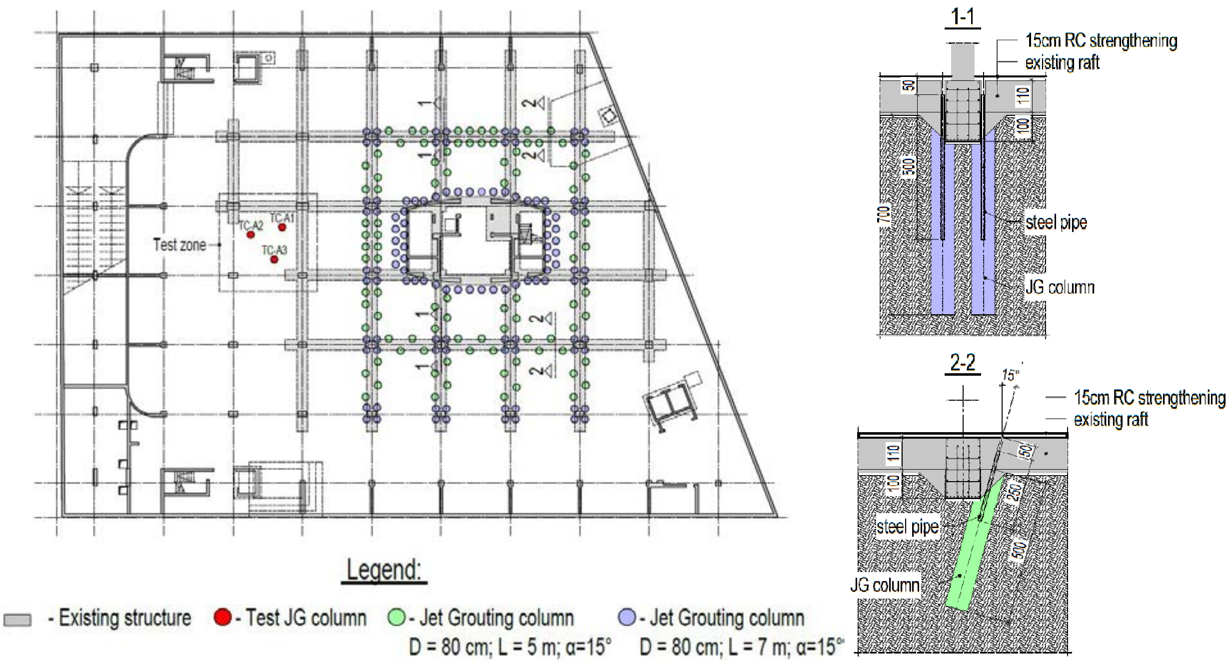


Fig. 2. Soil-foundation system strengthening approach

Table 1. Soil properties

Level [m]	Soil layer depth [m]	Soil layer height [m]	Layer number	Layer description	Characteristic values of soil parameters									
					Strength and deformability properties			Physical properties			Constitutive model parameters (HS Model)			N_{SPT}
26.60	0.00	0.80	1	Dark brown to light brown clay, Quaternary - *Q*	$E_{oed,100}$ =	4.75	MPa	$\gamma_{n,k}$ =	19.30	kN/m^3	E^{ref}_{50} =	11.88	MPa	20
					$E_{oed,200}$ =	5.55	MPa	$\gamma_{r,k}$ =	19.60	kN/m^3	E^{ref}_{oed} =	4.75	MPa	
					$E_{oed,300}$ =	9.10	MPa	$\gamma_{s,k}$ =	27.00	kN/m^3	E^{ref}_{ur} =	47.50	MPa	
					$E_{d,100}$ =	9.50	MPa	$\gamma_{d,k}$ =	15.20	kN/m^3	p_{ref} =	0.10	MPa	
					$E_{d,200}$ =	11.10	MPa	γ'_k =	9.30	kN/m^3	ν_{ur} =	0.20		
					$E_{d,300}$ =	18.20	MPa				• =	0.00	°	
					φ'_k =	5	°				m =	1.00		
					c'_k =	85	kPa				K^{NC}_0 =	0.58		
25.80	0.80	10.00	2	Light brown and yellow brown clay, sandy-silt with calcareous inclusions and gravel - Quaternary - *Q*	$E_{oed,100}$ =	3.20	MPa	$\gamma_{n,k}$ =	19.40	kN/m^3	E^{ref}_{50} =	8.00	MPa	27
					$E_{oed,200}$ =	5.15	MPa	$\gamma_{r,k}$ =	19.92	kN/m^3	E^{ref}_{oed} =	3.20	MPa	
					$E_{oed,300}$ =	11.50	MPa	$\gamma_{s,k}$ =	27.50	kN/m^3	E^{ref}_{ur} =	32.00	MPa	
					$E_{d,100}$ =	6.40	MPa	$\gamma_{d,k}$ =	15.60	kN/m^3	p_{ref} =	0.10	MPa	
					$E_{d,200}$ =	10.30	MPa	γ'_k =	9.40	kN/m^3	ν_{ur} =	0.20		
					$E_{d,300}$ =	23.00	MPa				• =	0.00	°	
					φ'_k =	23	°				m =	1.00		
					c'_k =	55	kPa				K^{NC}_0 =	0.58		
15.80	10.80	15.00	3	Pliocene clays – N_2	$E_{oed,100}$ =	2.94	MPa	$\gamma_{n,k}$ =	18.00	kN/m^3	E^{ref}_{50} =	5.88	MPa	35
					$E_{oed,200}$ =	4.39	MPa	$\gamma_{r,k}$ =	18.19	kN/m^3	E^{ref}_{oed} =	2.94	MPa	
					$E_{oed,300}$ =	9.89	MPa	$\gamma_{s,k}$ =	27.50	kN/m^3	E^{ref}_{ur} =	29.40	MPa	
					$E_{d,100}$ =	5.88	MPa	$\gamma_{d,k}$ =	12.90	kN/m^3	p_{ref} =	0.10	MPa	
					$E_{d,200}$ =	8.78	MPa	γ'_k =	8.00	kN/m^3	ν_{ur} =	0.20		
					$E_{d,300}$ =	19.78	MPa				• =	0.00	°	
					φ'_k =	17	°				m =	0.70		
					c'_k =	69.3	kPa				K^{NC}_0 =	0.71		

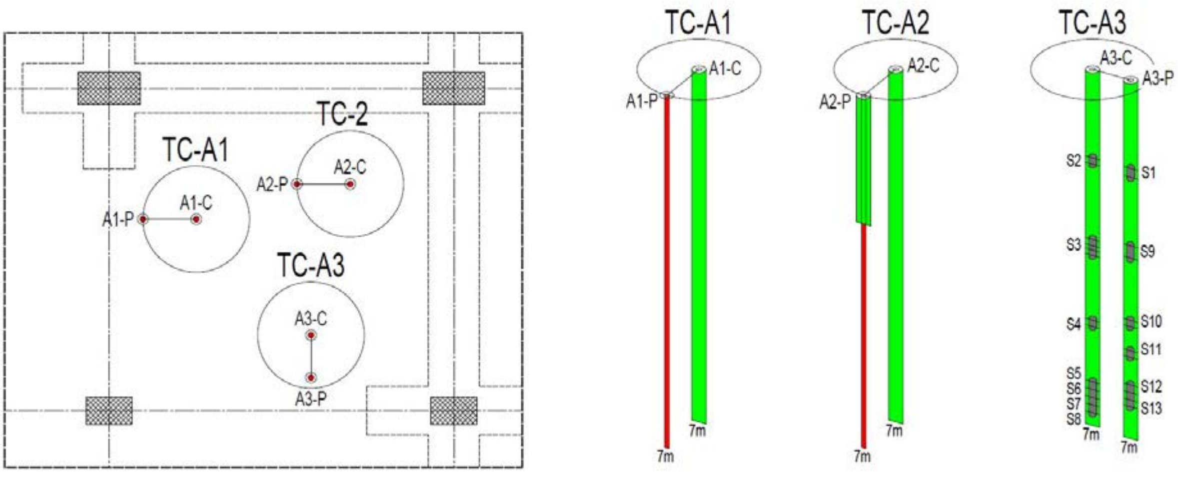
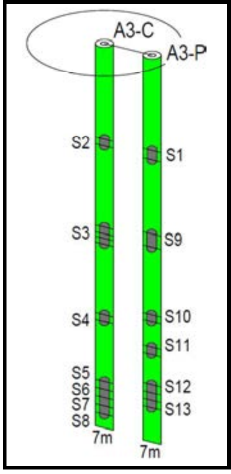


Fig. 3. Ensuring mechanical properties and column dimensions by means of test columns

Probes have been extracted from the only test column with satisfactory dimensions – in this case TC-A3. The mechanical properties (unconfined compressive strength, ultimate axial strain and deformation modulus) of the jet-grouting columns have been evaluated in the laboratory. Due to soil's heterogeneity results show values of wide range as it could be seen on Table 2. The compressive strength varies from 3.25 MPa to 8.10 MPa – [10]. A characteristic value of 4.50 MPa has been adopted as input value for the design.

Table 2. Test jet-grouting column TC-A3 properties obtained in the laboratory

Test column TC-A3	№	Depth	Unconfined compressive strength q_u	Ultimate axial strain $\varepsilon_{u,z}$	Deformation modulus E_o
-	-	[m]	[kPa]	[%]	[MPa]
	1	0.80 - 1.00 m	3272.2 ± 163.6	0.37 ± 0.04	885
	2	0.84 - 1.00 m	4992.2 ± 249.6	0.95 ± 0.09	525
	3	2.76 - 2.90 m	4576.9 ± 228.8	0.37 ± 0.04	508
	4	4.80 - 4.94 m	8092.5 ± 404.6	0.47 ± 0.05	1722
	5	6.00 - 6.23 m	7332.4 ± 366.6	0.49 ± 0.05	1496
	6	6.23 - 6.40 m	4664.6 ± 233.2	0.96 ± 0.10	486
	7	6.40 - 6.53 m	6038.4 ± 301.9	0.48 ± 0.05	1258
	8	6.53 - 6.71 m	6099.6 ± 305.0	0.62 ± 0.06	984
	9	2.60 - 2.88 m	4985.3 ± 249.3	0.76 ± 0.08	656
	10	4.50 - 4.63 m	6258.5 ± 312.9	0.94 ± 0.09	665
	11	5.20 - 5.36 m	5837.3 ± 293.7	0.73 ± 0.07	800
	12	5.60 - 5.76 m	6873.7 ± 343.7	0.86 ± 0.09	799
	13	5.86 - 6.00 m	5790.4 ± 289.5	0.77 ± 0.08	752

3 NUMERICAL ANALYSIS AND DESIGN

The „bed of springs“ model has been adopted as an approach for consideration of the soil-structure interaction effect in numerical analysis. Soil (as physically and mechanically described medium in Table 1) has been modelled as a continuum and represented by the Mohr-Coulomb constitutive model in SAP2000 software for the sake of evaluating the modulus of subgrade reaction. Stress which has been obtained through the analysis has been divided by the calculated settlement for the sake of determining the springs' stiffness (Fig. 4).

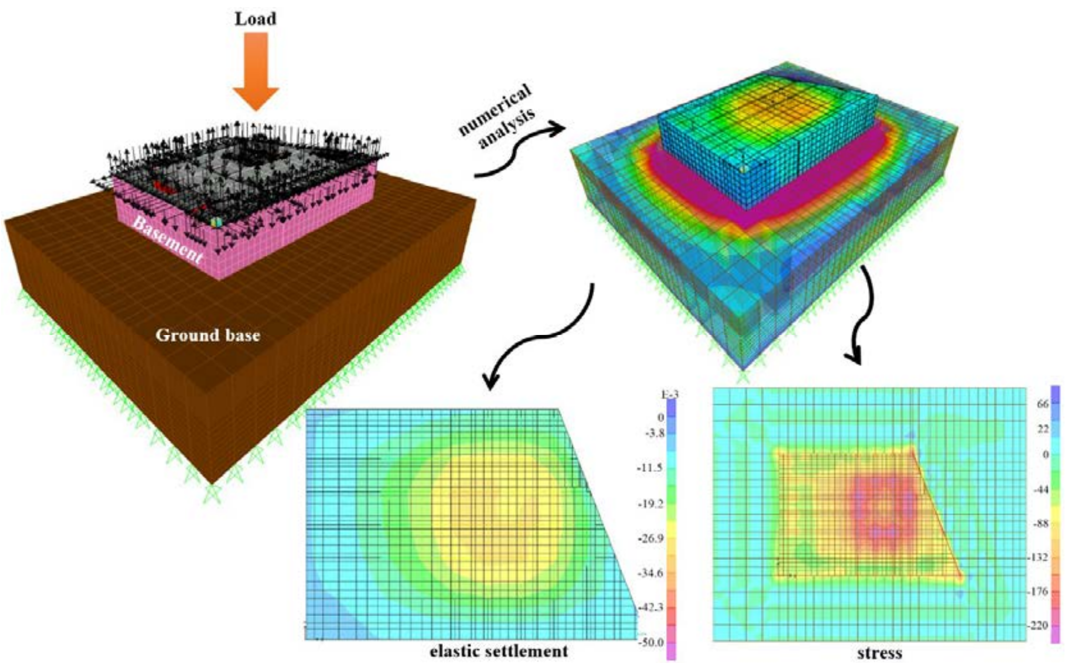


Fig. 4. Evaluation of modulus of vertical subgrade reaction through a numerical solution

The modulus of subgrade reaction of the jet-grouting treated area has been evaluated on the basis of a load-settlement relation which has been obtained through analytical procedures as well as a pile-test numerical FEM simulation as seen in [13] in the software PLAXIS 2D by using the Hardening-Soil (HS) constitutive model (explained in details in [17]) – Figure 5.

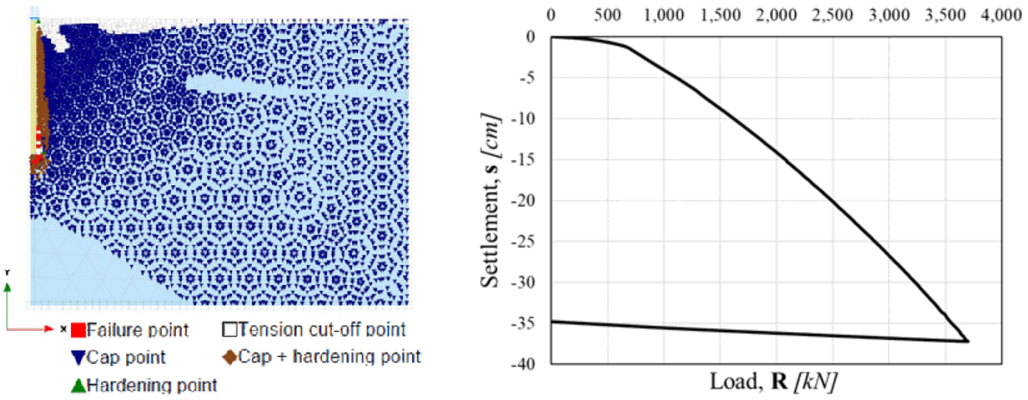


Fig. 5. Numerical FEM simulation of jet-grouting test in PLAXIS 2D

An overview of the adopted values for the modulus of subgrade reaction is given on Figure 6.

Furthermore, a 3D finite-element model which represents the superstructure in details has been developed in ETABS software. Elements from the program library have been adopted for the sake of representing the structural elements as the follows: frame elements for beams and columns, shell elements for walls, slabs and raft foundation. The soil has been modelled by area-spring elements. A comparison of the bending moments in the raft is made between a model with evenly distributed (same stiffness) springs (existing raft) and a model which considers the soil improvement (jet-grouting) by introducing zones with stiffer springs – Figure 7.

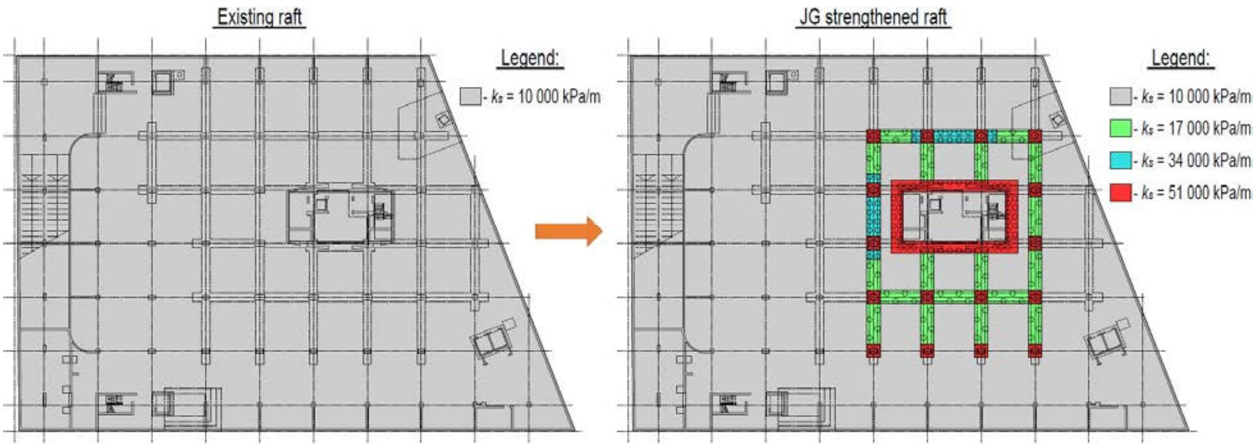


Fig. 6. Comparison of modulus of vertical subgrade reaction of the existing raft and the JG strengthened raft

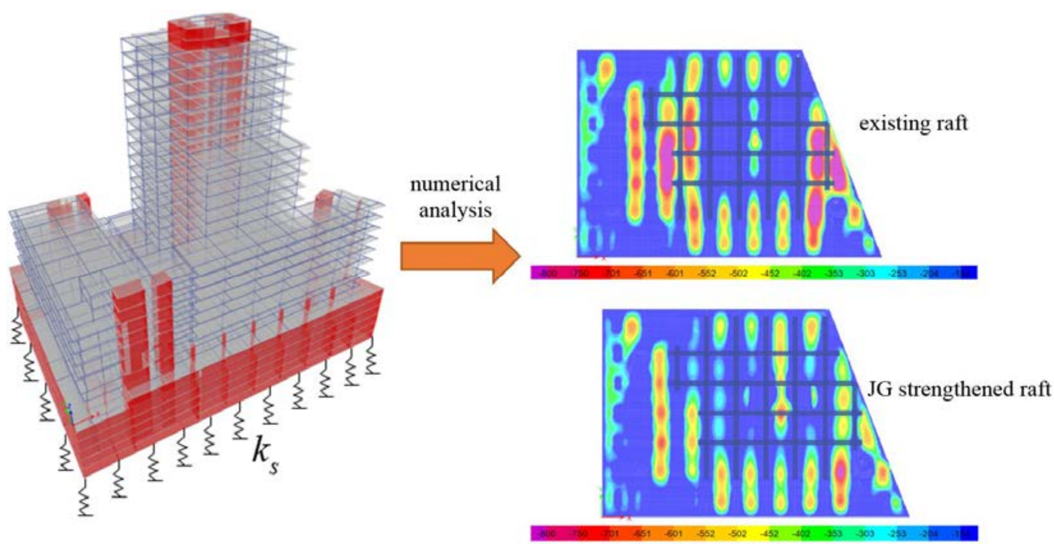


Fig. 7. 3D FEM model of the existing structure and bending moment in the raft (existing raft vs. JG strengthened raft)

A deterministic design approach (described in [5], [11], [15] and [20]) has been applied for the study. By means of such concept, which is typical in geotechnical engineering and suggested by Eurocode 7, uncertainties of the jet-grouting technique are considered by modifying actions on the structures, values of the material properties and overall bearing capacity by partial factors in order to obtain design values. For the material properties of jet-grouted elements, the characteristic values can be derived from the literature or, preferably, be taken from in-situ measurements.

Partial factors suggested by [2] and [5] are adopted in the presented study. A geometrical partial factor (g_D) of 1.15 has been chosen on the basis of available experimental information (limited) and column performance (isolated) hence design diameter (D_d) of 0.70 m has been set: D_k / g_D = 0.8 m / 1.15 = 0.7 m. A statistical analysis based on data from Table 2 has been adopted in order to set the characteristic value of unconfined compressive strength of the soil-grout column material ($q_{u,k}$) to 4 500 kPa. By application of material partial factor (g_M) of 1.5 design value of unconfined compressive strength ($q_{u,d}$) has been determined: $q_{u,d} = q_{u,k} / g_M$ = 4 500 kPa / 1.5 = 3 000 kPa.

Thereafter jet-grouting columns have been designed in a similar to piles matter. Naturally the treated zone has a remarkable bond with the surrounding soil due to the soil-mixing technique and consequently the geotechnical resistance (jet to soil failure), GEO Ultimate Limit State (ULS) according to Eurocode 7, is typically higher than the structural one (compressive strength of the column) – STR Ultimate Limit State (ULS) according to Eurocode 7.

Characteristic structural strength (bearing capacity) of the jet-grouting column, $R^{int}_{c,k}$, is calculated on the basis of design unconfined compressive strength and columns' diameter as follows: $R^{int}_{c,k} = q_{u,d} \times \pi \times (D_d / 2)^2$ = 3 000 kPa x π x (0.70 m / 2)^2 = 1 154 kN. Design structural strength (bearing capacity) of the jet-grouting column, $R^{int}_{c,d}$, has been evaluated by applying bearing capacity partial factor, g_R, of 2.2 as follows: $R^{int}_{c,d} = R^{int}_{c,k} / g_R$ = 1 154 kN / 2.2 = 525 kN. Overall structural bearing capacity (compressive strength – STR), has been increased by 699 kN by installing a Φ114.3x8 steel pipe (f_{yk} = 275 000 kPa) in the jet-grouting columns: $R_{c,d} = R^{int}_{c,d} + R^{int}_{c,d}$ = 525 kN + 699 kN = 1 224 kN.

End-bearing ($q_{b,k}$ = 2 000 kPa) and skin friction ($q_{s,k}$ = 175 kPa) have been evaluated on the basis of the available SPT results (Table 1) and soil type according to Figure 8 – [2].

According to [2] characteristic end-bearing resistance, $R_{b,k}$, is sanctioned depending on the method through which end-bearing, $q_{b,k}$, is obtained. In the presented study end-bearing, $q_{b,k}$, is evaluated on the basis of SPT results (Fig. 8) hence partial coefficient k_{SPT} of 0.1 is adopted. Thereafter the characteristic end-bearing resistance is related to the column cross-sectional area as follows: $R_{b,k} = k_{SPT} \times \pi \times (D_d / 2)^2 \times q_{b,k}$ = 0.1 x π x (0.70 m / 2)^2 x 2 000 kPa = 77 kN. Bearing capacity partial factor, g_b, of 2.0 is used in order to modify the characteristic end-bearing resistance, $R_{b,k}$, and hence to obtain the design: $R_{b,k} = R_{b,k} / g_b$ = 77 kN / 2.0 = 38.5 kN.

The characteristic skin friction resistance, $R_{s,k}$, is determined on the basis of jet to soil contact surface (area) and skin friction, $q_{s,k}$. Design skin friction resistance, $R_{s,d}$, is obtained by adopting a bearing capacity partial factor, g^{3m}_s, for the first 3 meters of the column and another one, g^{L-3m}_s, for the remaining part as follows: $R^{L=5m}_{s,d} = [2 \times \pi \times (D_d / 2) \times 3 \times q_{s,k}] / g^{3m}_s + [2 \times \pi \times (D_d / 2) \times (L - 3) \times q_{s,k}] / g^{L-3m}_s$ = [2 x π x (0.70 m / 2) x 3 m x 175 kPa] / 2.5 + [2 x π x (0.70 / 2) x (5 m – 3 m) x 175 kPa] / 2.0 = 846.5 kN for 5-meter long columns and $R^{L=7m}_{s,d} = [2 \times \pi \times (D_d / 2) \times 3 \times q_{s,k}] / g^{3m}_s + [2 \times \pi \times (D_d / 2) \times (L - 3) \times q_{s,k}] / g^{L-3m}_s$ = [2 x π x (0.70 m / 2) x 3 m x 175 kPa] / 2.5 + [2 x π x (0.70 / 2) x (7 m – 3 m) x 175 kPa] / 2.0 = 1 231.5 kN for 7-meter long columns.

Overall design geotechnical resistance (jet to soil failure – GEO), $R_{p,d}$, is a sum of design end-bearing resistance, $R_{b,d}$, and design skin friction resistance, $R_{s,d}$: $R^{L=5m}_{p,d} = R_{b,d} + R^{L=5m}_{s,d}$ = 38.5 kN + 846.5 kN = 885 kN for 5-meter long columns and $R^{L=7m}_{p,d} = R_{b,d} + R^{L=7m}_{s,d}$ = 38.5 kN + 1231.5 kN = 1270 kN for 7-meter long columns.

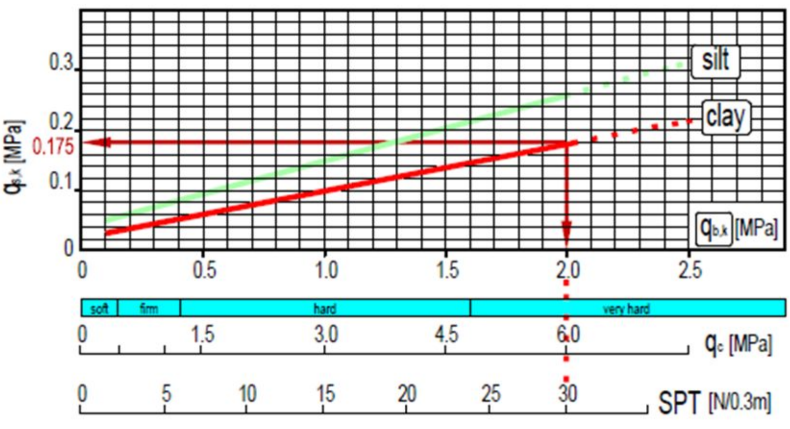


Fig. 8 Skin friction and end-bearing evaluation on the basis of soil type and SPT results – [2]

The smaller of the structural (STR) and geotechnical (GEO) bearing capacity is adopted as final design bearing capacity of the columns: $R^{L=5m}_{d}$ = min($R_{c,d}$; $R^{L=5m}_{s,d}$) = min(1 224 kN; 885 kN) = 885 kN for 5-meter long columns and $R^{L=5m}_{d}$ = min($R_{c,d}$; $R^{L=5m}_{s,d}$) = min(1 224 kN; 1 270 kN) = 1 224 kN for 7-meter long columns. In other words, geotechnical failure has turned out to be critical for the shorter (5-meter) jet-grouting bodies whereas structural failure would be critical for the longer (7-meter) ones. Design forces from the analysis are evaluated as 820 kN and 1 200 kN for the 5-meter and 7-meter columns, respectively, which means that they are smaller than their design bearing capacity.

Eurocode 7 suggests that two out of three partial factor groups (actions group, material group and bearing capacity group) which have values higher than 1.0 ought to be combined and respectively applied depending on the adopted Design Approach (either DA1, DA2 or DA3). However, as seen in the above-described procedure, due to uncertainties in the hybrid soil-structure strengthening behaviour and according to provisions given in [2] and [5] partial factors larger than 1.0 for all three groups have been accepted in the presented study.

4 PROBLEMS AND SOLVATIONS

All foundation strengthening measures have been executed in limited operation space of 2.80 m – Figure 9. The extracted material during injection and soil-mixing (reflux) has been sucked out through a pump located on the ground surface. In order to avoid filling the existing foundation with reflux, caps have been plugged in the circular raft openings right after forming each consecutive column.

The execution process has been strictly monitored. The total injected grout volume has been tracked for each column in parallel with the Injection Pressure, Rotation and Flow, [16], by means of an Injection Diagram, [3], which has been obtained directly from the jet-grouting machine (MDT – Mc 80 B has been employed for the study) software. Volume of injection grout is expected to be similar for all jet-grouting bodies. If some deviation is observed then measures ought to be taken and the Designer is informed. The monitored parameters (Injection Pressure, Rotation and Flow) should be kept constant during the whole depth of treatment. Anomaly in the diagrams would mean that the soil has not been treated evenly and in such case variation in the jet-grouting column diameter might be expected. A typical Injection Diagram for Column No. 152 is shown on Figure 10.

During the execution of the jet-grouting columns a defect has been detected in about 90 of them. Although the injection procedure has been performed all the way to the top of the raft, settlement of the columns of about 70 cm below the bottom edge of the foundation has been observed the reason for which remains unknown. In order to solve the problem the following technology has been applied: 1) the affected zone between the raft and the jet has been flushed by water under pressure through a tube in order to liquefy the grout reflux in it; 2) expandable grout MAPEI Expanjet (up to 20% volume expansion and compressive strength of 10 MPa) has been injected at 5 bar pressure. In order to ensure a closed system all neighbouring openings (except for one for reflux excess) have been sealed with a packer. In the end 50 m^3 of grout has been injected additionally. The adopted approach is presented on Figure 11.

Fig. 9. Execution of the hybrid soil improvement-structural retrofitting approach by applying the jet-grouting technique

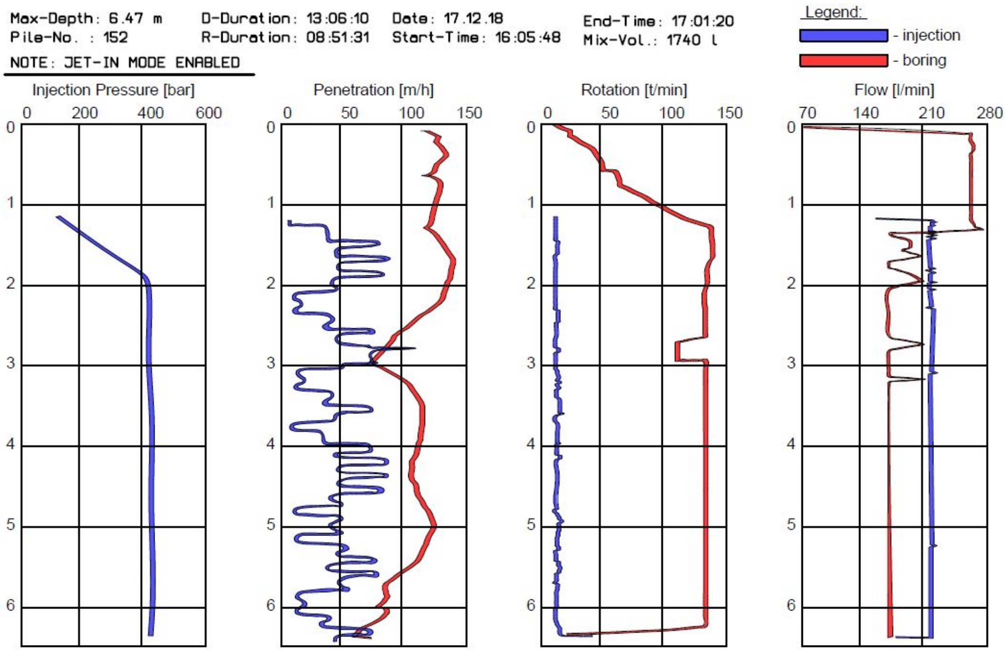


Fig. 10. Example Injection Diagram obtained directly from the "jet-grouting" machine (MDT – Mc 80 B) for Column No. 152

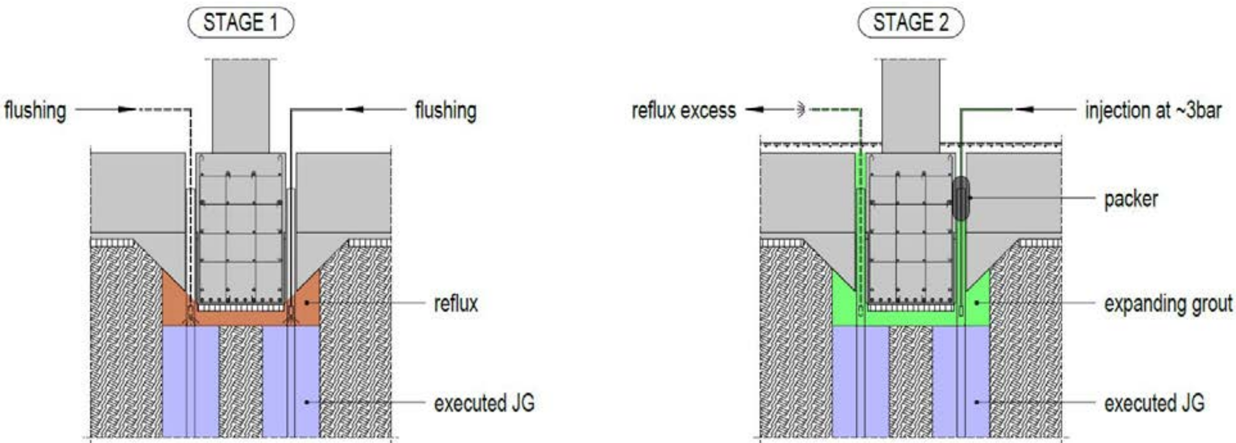


Fig. 11. Filling the void between the jet-grouting columns and the existing raft at two stages

5 CONCLUSIONS

The adopted hybrid soil improvement-structural retrofitting approach by applying the jet-grouting technique has ensured an adequate performance of the structure during and after its extension. The strengthening measure has stiffened the soil-foundation zone below the high-rise part of the building which has influenced the redistribution of the bending moments in a favourable way as well as it has reduced the expected settlement significantly. Although some defects have been detected the reparation measures have guaranteed the undisturbed exploitation of the structure.

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SUMMARY

STRENGTHENING THE RAFT FOUNDATION OF AN EXISTING RC BUILDING BY APPLICATION OF JET-GROUTING METHOD

Nikolay MILEV
Anton SARIEV

This paper presents the application of the jet-grouting method as a structural and ground improvement technique for strengthening the soil-raft foundation system of an existing reinforced concrete building. The structural system of the originally designed super-structure consists of columns for bearing the vertical loads and shear walls for ensuring the adequate seismic response. The building has been executed up until level zero by 2010. However, during construction, the investment intensions have been changed and the owner has decided to extend the structure by additional floors which in turn has caused the need of redesign of the building above the ground level and strengthening of its underground part. The aim of the study is to demonstrate the adopted design approach for strengthening the soil-raft foundation system *and applied* methodology for proving the predicted jet-grouting properties (diameter, length, compressive strength and elasticity modulus) as well as to outline the difficulties which have occurred during execution and the solutions of some important problems.

Key words: jet-grouting, single fluid system, raft foundation, soil improvement, foundation strengthening

APSTRAKT

POJAČANJE TEMELJNE PLOČE POSTOJEĆE ARMIRANOBETONSKE ZGRADE PRIMENOM DŽET-GROUTING (MLAZNOG INJEKTIRANJA) METODE

Nikolaj MILEV
Anton SARIEV

U ovom radu prikazana je primena metoda džet-grouting (mlaznog injektiranja) kao tehnike za pojačanje konstrukcije i poboljšanja tla, tj. za pojačanje sistema temelja ispod postojeće armirano-betonske zgrade. Konstrukcijski sistem prvobitno projektovane nadgradnje sastoji se od stubova za prenošenje vertikalnih opterećenja i smičućih zidova kako bi se osigurao adekvatan seizmički odgovor konstrukcije. Zgrada je izvedena do nivoa nula do 2010. godine. Međutim, tokom gradnje, investicijski kapaciteti i zahtevi su promenjeni i vlasnik se odlučio da proširi tu konstrukciju dodatnim spratovima što je zauzvrat izazvalo potrebu redizajna (pre-projektovanja) zgrade iznad nivoa zemlje i pojačanje njegovog podzemnog dela. Cilj studije je pokazati usvojeni Projektantski pristup za pojačavanje sistema temelja na ravnoj ploči i primenjenu metodologiju za dokazivanje predviđenih svojstava džet-groutinga (prečnik, dužina, čvrstoća na pritisak i modul elastičnosti) kao i da se opišu poteškoće do kojih je došlo tokom rešavanja nekih važnih problema.

Ključne reči: mlazno injektiranje (džet grouting), sistem sa jednom tečnošću, temeljna ploča, poboljšanje tla, pojačanje temelja

IZGRADNJA DRUMSKOG MOSTA PREKO REKE SAVE KOD OSTRUŽNICE

CONSTRUCTION OF ROAD BRIDGE OVER THE SAVA RIVER NEAR OSTRUŽNICA

Bojan BIZETIĆ
Igor ĐURĐEVIĆ
Goran TOMAŠEVIĆ

STRUČNI RAD
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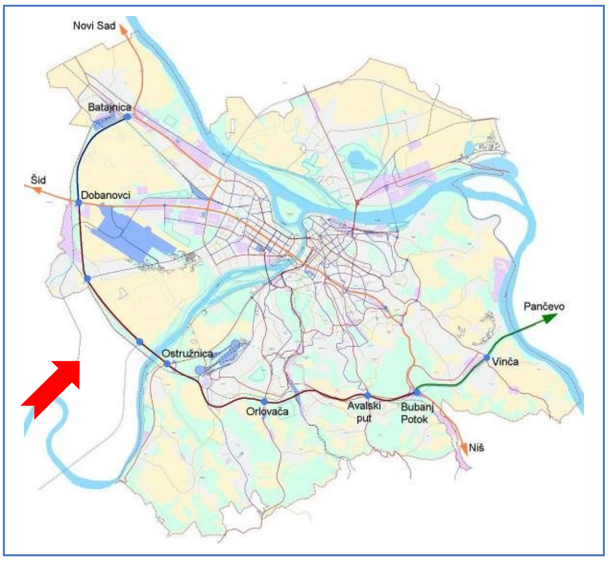
1 UVOD

Postojeći drumski most preko reke Save kod Ostružnice lociran je u blizini Beograda, u Republici Srbiji. Izgrađen je u okviru prve faze jugozapadne obilaznice oko Beograda. Povećanje saobraćaja, posebno tranzitnog, rezultiralo je potrebom povećanja kapaciteta obilaznice oko Beograda, kako bi se rasteretilo saobraćajno opterećenje autoputa koji prolazi kroz centar grada.

1 INTRODUCTION

Present road bridge over the Sava river near Ostružnica is located near Belgrade, in the Republic of Serbia. It is constructed within the first phase of the south-western bypass around Belgrade. The increase of traffic, especially transit, resulted in the necessity of increasing the capacities of the bypass around Belgrade, to relieve the traffic load on the highway that runs through the city centre.



Slika 1. Lokacija mosta preko reke Save kod Ostružnice
Fig. 1. Location of the bridge over the Sava river near Ostružnica

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Izgradnja obilaznice započeta je 1991. godine, a prva faza je obuhvatala poluprofil (desnu traku) autoputa od Dobanovaca do Bubanj Potoka, predviđenu da se koristi za dvosmerni saobraćaj do završetka druge faze. Zbog poznatih okolnosti (sankcije međunarodne zajednice, hiperinflancija, ratna dejstva, NATO bombardovanje itd.) izgradnja prve faze je više puta prekidana, tako da je prva faza na delu od Dobanovaca do Resnika (sektori 1-5) završena u maju 2012. Trenutno su završene obe faze na delu od Dobanovaca do Ostružnice (sektori 1 i 2), radovi na drugoj fazi mosta preko reke Save kod Ostružnice (sektor 3) u završnoj su fazi, a planirano je da preostali radovi na obilaznici (sektori 4, 5 i 6) budu završeni do kraja 2021. godine.

Izgradnja postojećeg mosta preko reke Save (za desnu traku) započela je 1991. godine i trajala je, zbog navedenih okolnosti, sve do 1999. godine. Neposredno pre puštanja u saobraćaj, 28. aprila 1999. most je delimično srušen tokom NATO bombardovanja, da bi do 2004. godine bio potpuno obnovljen i pušten u saobraćaj. Novi most za drugu fazu obilaznice odnosno levu traku autoputa u konstruktivnom smislu potpuno je identičan postojećem, pošto su prvom fazom izgradnje bili obuhvaćeni zajednički rečni stubovi za obe mostovske konstrukcije. Izgradnja ove konstrukcije započeta je u julu 2016. godine.

Construction of the bypass around Belgrade began in 1991, and the first phase included a semi-profile (right lane) of the highway from Dobanovci to Bubanj Potok, intended to be used for two-way traffic until the completion of the second phase. Due to known circumstances (international community sanctions, hyperinflation, warfare, NATO bombing, etc.), construction of the first phase was repeatedly interrupted, so that the first phase on the section from Dobanovci to Resnik (Sectors 1-5) was completed in May 2012. Currently, both phases are completed on the section from Dobanovci to Ostružnica (Sections 1 and 2), the works on the second phase of the bridge over the Sava River near Ostružnica (Sector 3) are in the final phase, and it is planned that the remaining works on the bypass (Sections 4, 5 and 6) will be completed by the end of 2021.

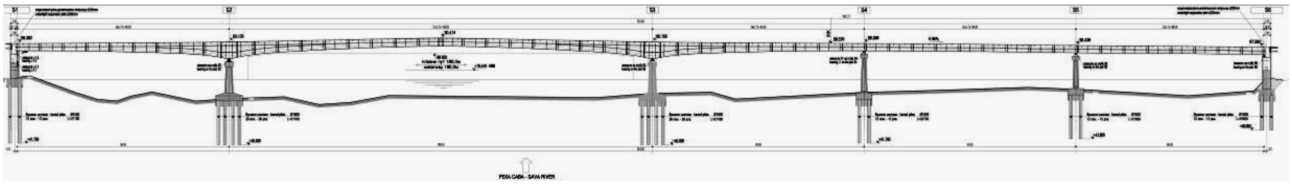
The construction of the existing (right lane) bridge had begun in 1991 and lasted until 1999 due to the above circumstances. Shortly before its opening for traffic, on April 28th, 1999, the bridge was partially demolished during the NATO bombing, and by 2004 it had been completely rebuilt and put into service. The left lane bridge, whose construction is in progress, is constructively identical to the existing one, since the first phase of construction included river piers for both bridge structures. Construction of this structure began in July 2016.

2 KRATAK OPIS MOSTOVSKE KONSTRUKCIJE

Ukupna dužina mosta je 1.963 m i sastoji se od četiri dela: prednapregnute betonske prilazne konstrukcije na levoj obali (L = 592,30 m) i desnoj obali reke (L = 699,13 m), armirano-betonske konstrukcije preko autoputa Beograd-Obrenovac (L = 85,30 m) i čelične konstrukcije preko reke Save (L = 586,00 m). Čelična konstrukcija preko reke Save je kontinualni čelični sandučasti nosač, s pet raspona, promenljive visine, od 3,8 m do 7,9 m i najdužim rasponom od 198 m. Ukupna težina čelične konstrukcije je 4250 tona.

2 BRIEF DESCRIPTION OF BRIDGE STRUCTURE

Total length of the bridge is 1.963 m and it comprises 4 sections: prestressed concrete approach structures on the left riverside (L=592,30 m) and right riverside (L=699,13 m), reinforced concrete structure over Belgrade-Obrenovac highway (L= 85,30 m) and steel structure over the Sava river (L=586,00 m). Steel structure over the Sava River is 5-span continuous steel girder, with box cross section of variable height, from 3,8 m to 7,9 m and with the longest span of 198 m. The total weight of the steel structure is 4250 tons.



Slika 2. Dispozicija čelične konstrukcije mosta
Fig. 2. Layout of the steel structure over the river

3 TEHNOLOGIJA MONTAŽE ČELIČNE KONSTRUKCIJE

Projektovanom tehnologijom montaže bio je predviđen konzolni način izgradnje uz korišćenje plovne dizalice i privremenih oslonaca - čeličnih šipova pobijenih u korito reke. Zbog toga je konstrukcija podeljena na 56 montažnih polja, dužine 7,5-11,0 m i teških 60-85 tona. Nakon pregleda rečnog korita magnetometrima visoke rezolucije, otkriveno je postojanje velikog broja nepoznatih čeličnih objekata koji bi po gabaritima mogli biti neeksplodirana ubojna sredstva (NUS). Zbog toga se projektovana tehnologija montaže pokazala visoko-

4 METHODOLOGY OF STEEL STRUCTURE INSTALLATION

The designed installation methodology envisaged a cantilevered construction using a floating crane and temporary supports - steel piles driven into the river bed. Therefore, the construction is divided into 56 mounting sections, 7.5 - 11.0 m long and weighing 60-85 tons. After the high-resolution magnetic survey of the riverbed, it was discovered that there were a large number of unknown steel objects that could have been unexploded ordnance (UXO). Therefore, the designed installation methodology turned out to be high risky since the rizičnom pošto bi moguća NUS mogla biti aktivirana tokom pobijanja čeličnih šipova u rečno korito.

Kako bi se izbeglo postavljanje privremenih oslonaca u rečnom koritu, razmatrane su različite alternative uz uslov da se već izvedeni delovi konstrukcije iskoriste u najvećoj mogućoj meri. Kao optimalna u datim uslovima, usvojena je nova metodologija koja uključuje: (I) podužno prevlačenje sekcije mosta S4-S6 ukupne dužine 187 m uz korišćenje pomoćnog plutajućeg oslonca, (II) konzolnu montažu delova konstrukcije iznad rečnih stubova S1, S2, S3 i S4 i (III) podizanje tri sekcije konstrukcije L=77(68) m.

possible UXO could be activated during the driving of steel piles into the river bed.

In order to avoid the placement of temporary supports in the riverbed, various alternatives were considered, subject to condition that the already executed parts of the structure are used as far as possible. After considering possible alternatives, new methodology that includes (I) incremental launching over floating pier of the bridge (section previously preassembled on the riverside L=187 m) and (II) lifting of 3 structure sections (L=77 m, G=550 tons) pre-assembled in the shipyard 10 km far from the bridge location, launched into river and transported to the site were selected as optimal in current conditions.

(I) Podužno prevlačenje

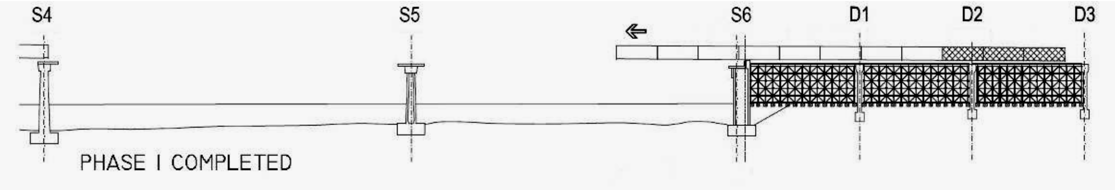
Segment mostovske konstrukcije između stubova S4 i S6 (L=187 m) ugrađen je podužnim prevlačenjem, pošto je presek konstantne visine. Ovaj segment mosta predmontira se na radnoj platformi smeštenoj na obali, a zatim se hidrauličnim presama podužno prevlači na projektovanu poziciju. Ova operacija je podeljena u četiri faze:

– Faza I: podužno prevlačenje 45 m dugačkog segmenta bez pomoćnog oslonca;

(I) Incremental launching

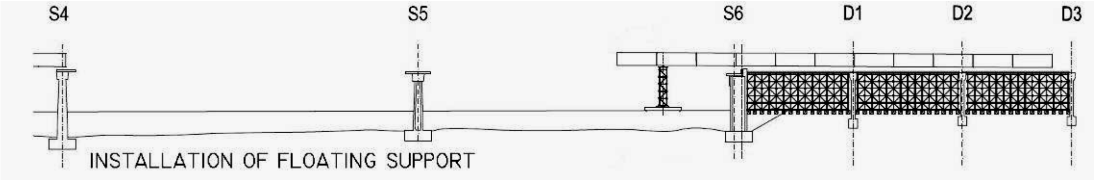
Bridge section between piers S4 and S6 (L=187 m) was installed by incremental launching since the cross-section is of constant height. This section of the bridge is preassembled on the launching platform located on the riverside and then pushed over the river by hydraulic jacks until reaching final position. This operation is divided in four phases:

– Phase I: launching of 45 m long segment as cantilever, without floating support;



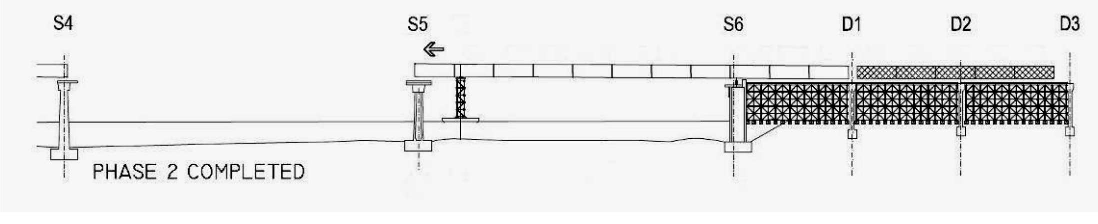
– Međufaza I/II: postavljanje pomoćnog oslonca kako bi se omogućio nastavak podužnog prevlačenja;

– Intermediate phase I/II: installation of floating support, to enable continuation of launching;



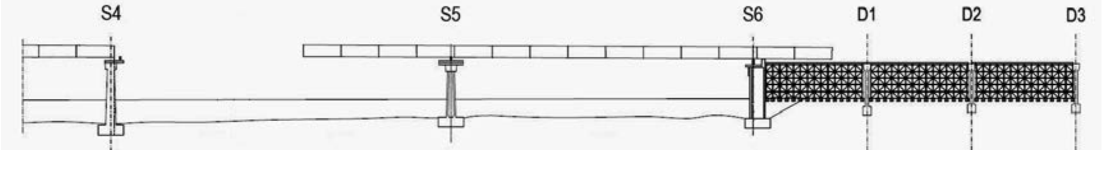
– Faza II: podužno prevlačenje 44 m dugačkog segmenta oslonjenog na pomoćni oslonac, do stuba S5;

– Phase II: launching of 43 m long segment supported by floating pier, until reaching pier S5;



– Faza III: podužno prevlačenje 44 m dugačkog segmenta bez pomoćnog oslonca;

– Phase III: launching of 44 m long segment as cantilever, without floating support;

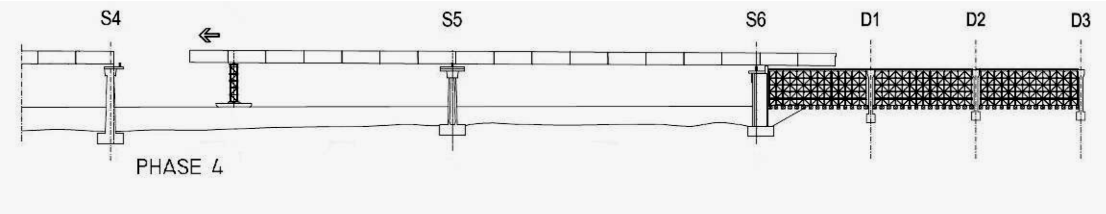


– Međufaza III/IV: postavljanje pomoćnog oslonca kako bi se omogućio nastavak podužnog prevlačenja;

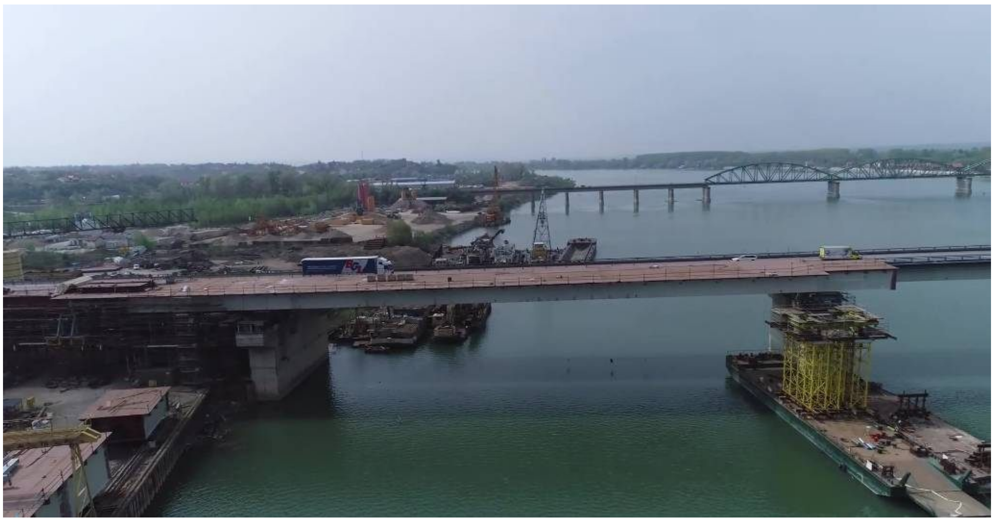
– Faza IV: podužno prevlačenje 55 m dugačkog segmenta oslonjenog na pomoćni oslonac, do stuba S4

– Intermediate phase III/IV: installation of floating support, to enable continuation of launching;

– Phase IV: launching of 55 m long segment supported by floating pier, until reaching pier S4



Slika 3. Prva faza podužnog prevlačenja segmenta S4–S6
Fig. 3. First phase of incremental launching of segment S4 - S6



Slika 4. Druga faza podužnog prevlačenja segmenta S4–S6
Fig. 4. Second phase of incremental launching of segment S4 - S6

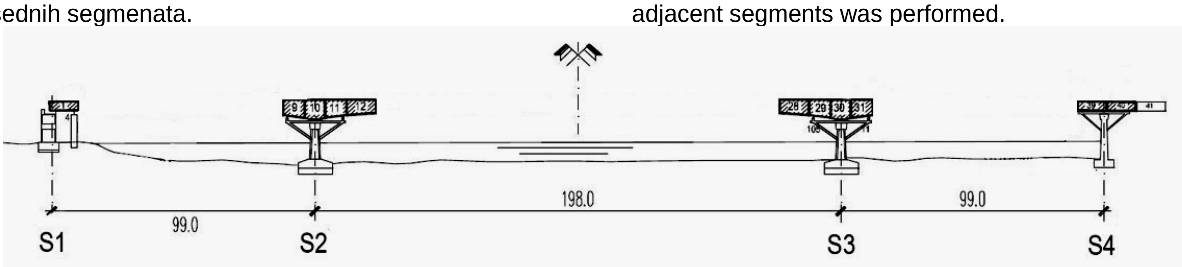
Slika 5. Segment S4 - S6 nakon završetka podužnog prevlačenja
Fig. 5. Segment S4 - S6 after completed incremental launching

(II) Konzolna montaža delova konstrukcije iznad stubova S1, S2, S3 i S4

Da bi se omogućilo podizanje segmenata konstrukcije koji su predmontirani u brodogradilištu i transportovani na gradilište rekom, potrebno je formirati osnovu sa koje će se raditi podizanje. Zbog toga je izvršena slobodna konzolna montaža najpre baznih (oslonačkih) segmenata iznad stubova S1, S2, S3 i S4, a nakon toga i susednih segmenata.

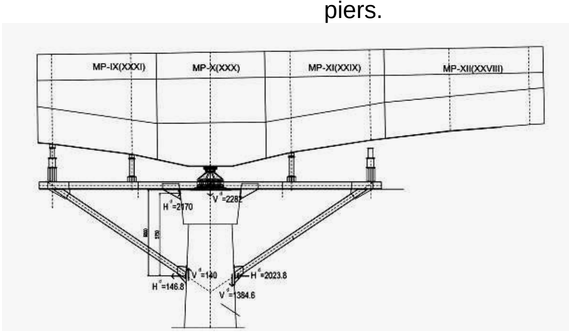
(II) Cantilever assembly of structure segments over river piers S1, S2, S3 and S4

In order to allow the lifting of segments of structure that are pre-assembled in the shipyard and transported to the site by the river, it was necessary to form the basis from which the lifting is to be carried out. Therefore, free cantilever assembly of the base (support) segments above the piers S1, S2, S3 and S4, and subsequently of adjacent segments was performed.

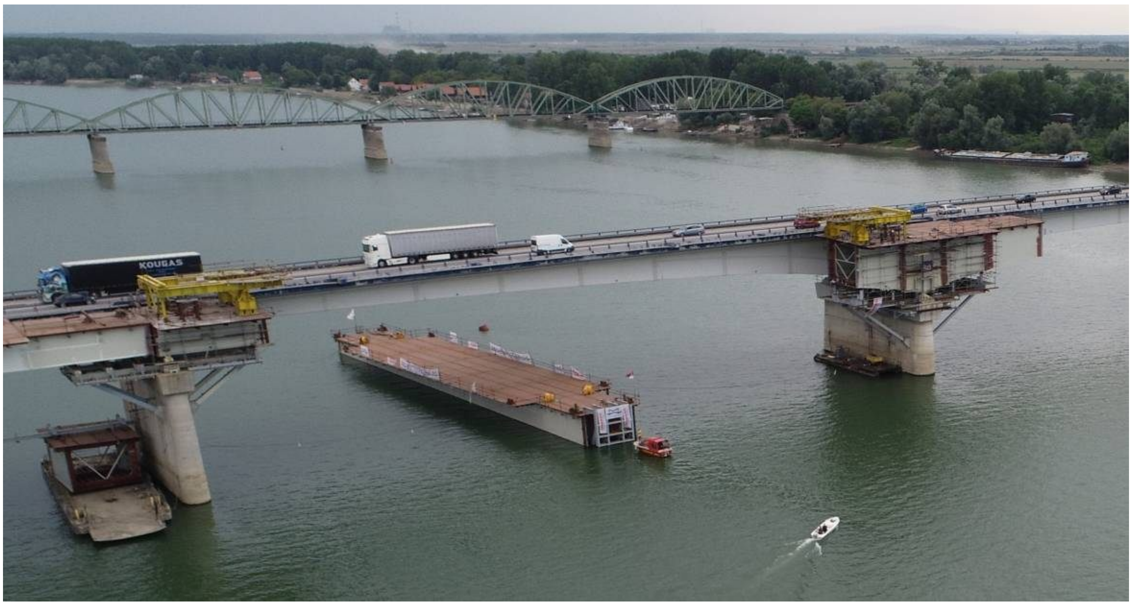


Kako bi se obezbedila stabilnost elemenata čelične konstrukcije mosta u ovoj fazi montaže, bilo je neophodno konstruisati i montirati pomoćni alate - privremene oslonce iznad stubova S2, S3 i S4. Pored obezbeđenja stabilnosti, ovi privremeni oslonci preuzimaju deo uticaja u fazi dizanja i prenose ih na stubove.

In order to ensure the stability of the steel structure elements at this stage of assembly, it was necessary to construct and install auxiliary tools - temporary supports above the piers S2, S3 and S4. In addition to providing stability, these temporary supports take over some of the impacts during the lift phase and transfer them to the piers.



Slika 6. Dispozicija pomoćnog oslonca na stubu S2
Fig. 6. Layout of temporary support on pier S2



Slika 7. Stubovi S4 i S4 s montiranim pomoćnim osloncima, delovima čelične konstrukcije mosta i „Derik” kranovima
Fig. 7. Piers S4 and S3 with installed temporary supports, steel structure segments and “Derrick” cranes

(III) Podizanje tri sekcije čelične konstrukcije

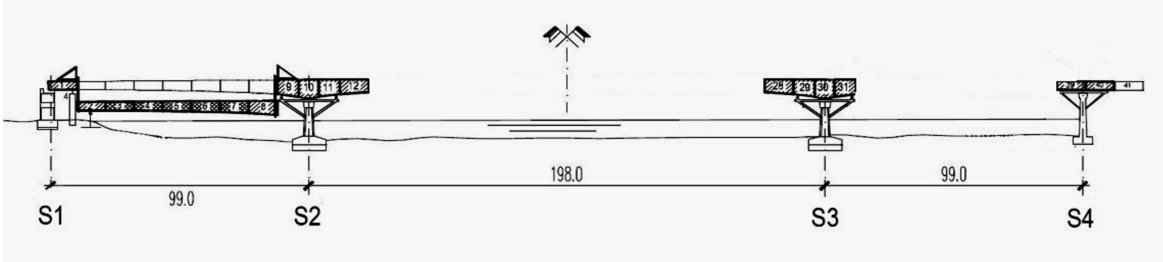
Ostatak čelične konstrukcije montiran je podizanjem tri sekcije (L = 77/68 m, G = 550/450 tona) prethodno montirane u brodogradilištu 10 km od lokacije mosta. Pre porinuća u reku, ugrađeni su dodatni elementi koji obezbeđuju vodonepropusnost i plovnost svake sekcije. Prevoz do mesta ugradnje obavljen je rečnim tegljačima, a podizanje je urađeno „Derik” kranovima uz korišćenje četiri hidraulične prese kapaciteta 200 t.

– Faza I: podizanje sekcije MP2-MP8, L=77 m, G~550 t

(III) Lifting of 3 structure sections

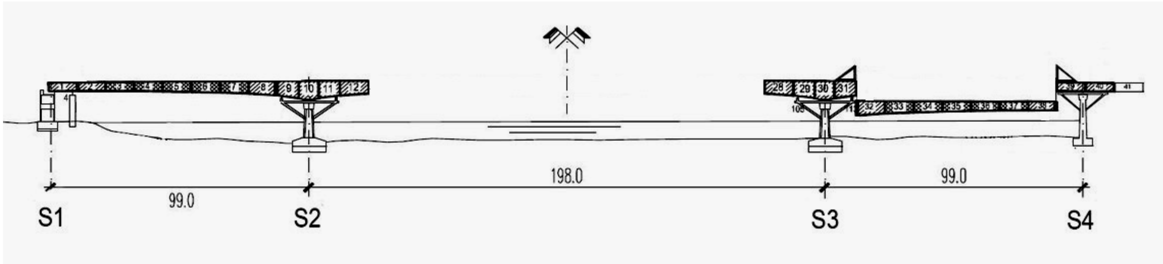
The rest of the steel structure was installed by lifting of 3 structure sections (L=77/68 m, G=550/450 tons) previously assembled in the shipyard 10 km far from the bridge location. Additional elements for providing water tightness and navigability were installed before launching the segments into the river. Transport to the site was performed by tugboats and lifting was done by “Derrick” cranes and 4 hydraulic jacks, each capacity of 200 t.

– Phase I: lifting of section MP2-MP8, L=77 m, G~550 t



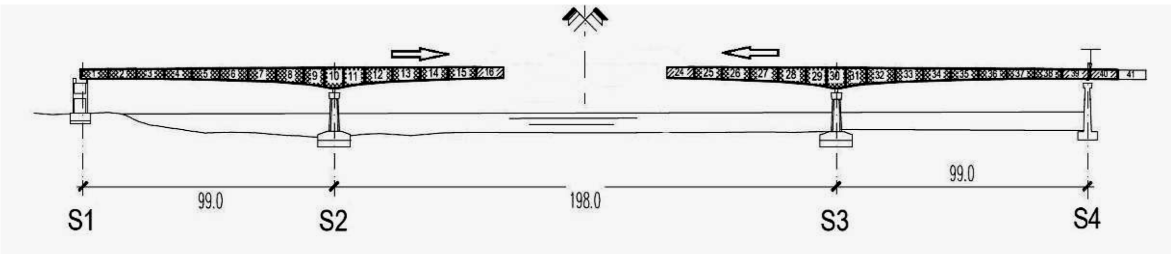
– Faza II: podizanje sekcije MP32–MP38, L=77 m, G~550 t

– Phase II: lifting of section MP32-MP38, L=77 m, G~550 t



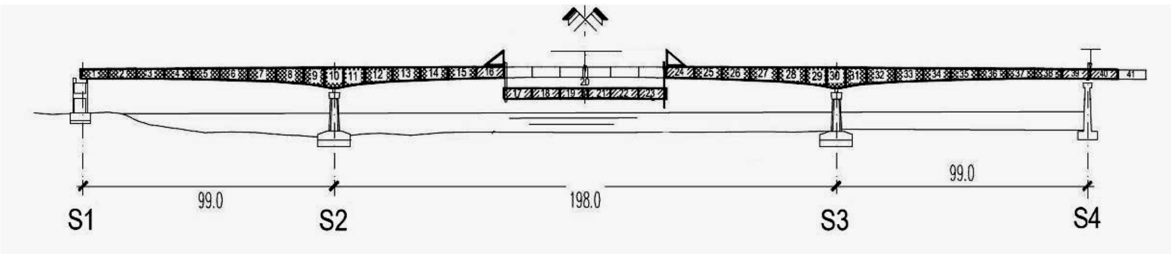
– Faza III: konzolna montaža elemenata MP13–MP16 i MP24–MP27 plovnom dizalicom

– Phase III: cantilever installation of segments MP13-MP16 and MP24-MP27 by floating crane



– Faza IV: podizanje sekcije MP17–MP23, L=68 m, G~450 t

– Phase IV: lifting of section MP17-MP23, L=68 m, G~450 t



Slika 8. Predmontaža sekcija konstrukcije mosta u brodogradilištu
Fig. 8. Pre-assembly of steel structure sections in the shipyard

Slika 9. Rečni transport sekcija konstrukcije mosta
Fig. 9. River transport of structure sections

Slika 10. Podizanje segmenta S1–S2
Fig. 10. Lifting of segment S1 - S2

4 PODACI O PROJEKTU, INVESTITORU, PROJEKTANTU, IZVOĐAČU I STRUČNOM NADZORU

Pored izgradnje mostovskih konstrukcija, projekat obuhvata i deo saobraćajnice - leve trake autoputa dužine 955 m kao i sve prateće radove (sakupljanje i prečišćavanje atmosferskih voda, javnu rasvetu, saobraćajnu opremu i signalizaciju, uređenje putnog pojasa). Investitor radova je Javno preduzeće „Putevi Srbije”, a radovi se finansiraju iz kredita Evropske investicione banke. Projektnu dokumentaciju je izradio „Institut za puteve” iz Beograda, a deo projektne dokumentacije koji se odnosi na mostove izradilo je preduzeće „Mostprojekt AD” iz Beograda. Izvođač radova je konzorcijum „Strabag AG – Ed. Zublin AG – Dywidag Bau GmbH – Strabag d.o.o.” Podizvođač radova na izradi elemenata i montaži čelične mostovske konstrukcije je preduzeće „Mostogradnja AD” iz Beograda koje je ranije izgradilo i postojeći most za desnu traku obilaznice. Stručni nadzor nad izvođenjem radova poveren je konzorcijumu koji čine UTIBER Kozuti Beruhazo Kft. - Project Biro UTIBER d.o.o. - Institut IMS AD.

4 INFORMATION ABOUT PROJECT, EMPLOYER, DESIGNER, CONTRACTOR AND SUPERVISION

In addition to the construction of bridge structures, the scope of project also includes a road section - the left lane of the highway 955m long, as well as all supporting works (collection and purification of atmospheric waters, public lighting, traffic signs and road furniture, road reserve landscaping etc.) The employer is Public Enterprise "Roads of Serbia", and the works are funded by a loan from the European Investment Bank. The design documentation was prepared by the Belgrade “Highway Institute” and the part of the design related to bridges was made by the company “Mostprojekt AD” from Belgrade. The contractor is a consortium consisting of Strabag AG - Ed. Zublin AG - Dywidag Bau GmbH - PZP Zajecar A.D. (Strabag d.o.o.). The subcontractor for the production and installation of the steel bridge structure is company “Mostogradnja AD” from Belgrade, which also in the past built the existing right-line bridge. Supervision of the works was entrusted to the consortium comprising UTIBER Kozuti Beruhazo Kft. - Project Bureau UTIBER d.o.o. - Institute IMS AD.

REZIME

IZGRADNJA DRUMSKOG MOSTA PREKO REKE SAVE KOD OSTRUŽNICE

Bojan BIZETIĆ
Igor DJURDJEVIĆ
Goran TOMAŠEVIĆ

Drumski most preko reke Save kod Ostružnice, ukupne dužine 1.963 m, sastoji se od armirano-betonskih prilaznih konstrukcija na levoj i desnoj obali reke, dok je srednja konstrukcija preko reke Save kontinualni čelični sandučasti nosač, s pet raspona, ukupne dužine od 586 m. Montaža čelične konstrukcije prvobitno je planirana konzolnom ugradnjom 56 sekcija-montažnih polja, korišćenjem plovne dizalice i privremenih oslonaca - čeličnih šipova pobijenih u korito reke. Nakon pregleda rečnog korita magnetometrima visoke rezolucije, ova se metodologija pokazala visoko-rizičnom zbog mogućeg postojanja neeksplodiranih ubojnih sredstava (NUS), preostalih nakon NATO bombardovanja, koja bi mogla biti aktivirana tokom pobijanja čeličnih šipova u korito reke. Da bi se izbeglo postavljanje privremenih oslonaca u rečnom koritu, projektovana metodologija montaže čelične konstrukcije morala je biti izmenjena. Nakon razmatranja mogućih alternativa uz uslov očuvanja već izvedenih radova, kao optimalna u datim uslovima, usvojena je nova metodologija koja uključuje: (I) podužno prevlačenje sekcije mosta S4-S6 ukupne dužine 187 m uz korišćenje pomoćnog plutajućeg oslonca, (II) konzolnu montažu delova konstrukcije iznad rečnih stubova S1, S2, S3 i S4 i (III) podizanje tri sekcije konstrukcije L=77(68) m.

Ključne reči: Ključne reči: drumski most, Ostružnica, armirano-betonske prilazne konstrukcije, kontinualni čelični sandučasti nosači, konzolna gradnja, prevlačenje/potiskivanje čelične konstrukcije.

ABSTRACT

CONSTRUCTION OF ROAD BRIDGE OVER THE SAVA RIVER NEAR OSTRUŽNICA

Bojan BIZETIĆ
Igor DJURDJEVIĆ
Goran TOMAŠEVIĆ

Road bridge over the Sava river near Ostružnica, with a total length of 1.963 m, consists of reinforced concrete approach structures on the left and right riverside, while the middle structure over the Sava River is 5-span continuous steel box girder, with a total length of 586 m. Construction of steel structure was originally planned by cantilever installation of 56 sections, using a floating crane and temporary supports - steel piles placed in the river bed. After the high-resolution magnetic survey of the riverbed, this methodology has proved to be highly risky due to the possible existence of unexploded ordnance (UXO) left after NATO bombing, that could be activated during the piling into the riverbed. To avoid installation of temporary supports in the riverbed, the original methodology for the assembly of the steel structure had to be revised. After considering possible alternatives and to preserve already executed works, new methodology that includes (I) incremental launching over floating support of the bridge section S4-S6 with a total length of 187 m, (II) cantilever assembly of structure segments over river piers S1, S2, S3 and S4 and (III) lifting of 3 structure sections L=77(68) m, was selected as optimal under the given conditions.

Key words: Key words: road bridge, Ostruznica, reinforced concrete approaching structures, continuous steel box main girders, cantilever bridge construction, launching of steel structure.

ZAVISNOST SILA ZATEZANJA MEMBRANSKIH KONSTRUKCIJA OD RAZLIČITIH PARAMETARA POD DEJSTVOM KONCENTRISANE SILE

TENSILE MEMBRANE STRUCTURE FORCES DEPENDENCE ON DIFFERENT PARAMETERS UNDER POINT LOAD ACTION

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ORIGINALNI NAUČNI RAD
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1 UVOD

Zategnute membranske konstrukcije trenutno su tema mnogih istraživanja. Iako njihovo projektovanje još uvek nije standardizovano na nivou Evrope, publikovane su *Smernice za projektovanje* [5] i *Nacrt evropskog pravilnika* [17]. Postoji mnogo povoljnih karakteristika membranskih konstrukcija, pre svega, njihova mala sopstvena težina, njihove atraktivne forme i veliki rasponi. Uz to, poznata su i njihova nepovoljna svojstva. Zbog svojih termičkih karakteristika, one se češće koriste za natkrivanje nego za zatvaranje prostora. Upravo ova tema trenutno je aktuelna u istraživanjima [4,8,10]. Ipak, postoji i puno aspekata membranskih konstrukcija koji još uvek nisu dovoljno istraženi. Efekti dejstva koncentrisanih sila za sada nisu potpuno razjašnjeni. Ovaj rad prikazuje istraživanje koje se bavi ispitivanjem uticaja koncentrisanih sila na sile zatezanja u membrani. Koncentrisane sile u proračunu najčešće predstavljaju dejstvo ljudi koji stoje na membrani, što se obično dešava pri održavanju membrane. Sile zatezanja su ključne u proračunu membranskih konstrukcija. Na osnovu maksimalnih sila zatezanja, određuje se odgovarajući membranski materijal za svaku konstrukciju. Zbog

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1 INTRODUCTION

Tensile membrane structures are subject of many ongoing researches. On the European level, they are still not codified; however, the *Design Guide* [5] and *Prospect for European Guidance for the Structural Design* [17] are published. There are many advantageous properties of tensile membrane structures, most notably their low self-weight, attractive forms, and large spans. Additionally, some of their negative aspects are also known. Thermal properties of tensile membrane structures are the main reason why they are preferably used to cover open spaces instead of enclosing them. This is one of the most interesting research areas in the field of tensile membrane structures [4,8,10]. However, there are also some aspects of tensile membranes which are still insufficiently explored. The effects of point load actions on tensile membrane structures are currently incompletely clarified. This paper presents research that deals with the impact of point load actions on changes of membrane forces. Point load actions are mostly induced by persons standing on the membrane. This usually happens during the maintenance of the structure. On the

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strukture membranskog materijala, sile zatezanja definišu se u dva pravca – glavnom i pomoćnom, tako da prate pravce vlakana tkanog membranskog materijala.

Ne postoji veliki broj istraživanja koja se bave dejstvom koncentrisanih sila na membranske konstrukcije, niti njihovim silama zatezanja. Ipak, Hantington tvrdi da dejstvo koncetrisanih sila treba uzeti u obzir pri proračunu membranskih konstruckija [9]. Poznato je da koncentrisane sile izazivaju velike ugibe i promene sila zatezanja kod membrana [12]. Jedno istraživanje bavi se ugibima gumene membrane pod dejstvom koncentrisane sile [15]. Valdez, Migel i Onate predlažu metodologiju analize i testiraju je na ravnoj membrani opterećenoj koncentrisanom silom [20]. Ugibi membrane pod dejstvom koncentrisane sile, u zavisnosti od nekoliko parametara, takođe su istraživani [13,14]. Bridžens, Gosling i Birčal ispitivali su karakteristike membranskog materijala i prikazivali naprezanja membrane u glavnom i pomoćnom pravcu, pri biaksijalnom testiranju [2,3]. Gosling i Bridžens predložili su novi pristup prikazivanju ponašanja materijala [6]. Bridžens i Birčal prikazali su rezultujuće sile zatezanja membrane pod dejstvom opterećenja od snega i vetra [1]. Gosling i koautori dali su podatke za sile zatezanja pod istim opterećenjem u sklopu svog istraživanja [7].

Ovaj rad prikazuje istraživanje zavisnosti sila zatezanja od različitih parametara. Nadograđuje već objavljeni rad [11] dodavanjem još jednog parametra. Promenjivi parametri jesu visina modela, intenzitet sila prednaprezanja i orijentacija membranskog materijala. Cilj istraživanja jeste da načini korak ka boljem razumevanju efekata dejstva koncentrisanih sila na membranske konstrukcije i ka otkrivanju njihovih tipova koji su osetljiviji na ovo dejstvo. Uz to, istraživanje teži davanju odgovora na pitanje koliko je značajno dejstvo koncentrisanih sila na membranske konstrukcije. Istraživanje će biti sprovedeno tako što će biti upoređivane maksimalne sile zatezanja pod dejstvom koncentrisane sile i još jednog uobičajenog opterećenja, pri različitim vrednostima analiziranih parametara. Vetar i sneg često deluju na membranske konstrukcije. Seizmička dejstva kod njih nisu značajna zbog male težine konstrukcije, međutim, ukoliko konstrukcija sadrži i neke teške delove, treba sprovesti seizmičku analizu [5,21]. Stoga, zbog dinamičke prirode dejstva vetra, opterećenje od snega – kao najmanje kompleksno – izabrano je za poređenje s dejstvom koncentrisane sile.

other hand, membrane forces are fundamental during the structural analysis of tensile structures. Based on the values of maximum tensile force, the appropriate membrane material is selected for each analyzed structure. Due to the membrane material structure, membrane forces are analyzed in two directions, warp and weft, following the yarns of the woven fabric.

There are few researches investigating point load actions on tensile membrane structures or the membrane forces of tensile membranes. However, Huntington states that point loads should be taken into account in the structural analysis of tensile membrane structures [9]. It is known that point load actions cause large deflections and changes in tensile membrane forces [12]. There is a research exploring the deflections of a rubber membrane under point load [15]. Valdes, Miguel and Onate test the proposed analysis methodology on flat membrane under point load [20]. Deflections of membrane structures under point load depending on several parameters are also investigated [13,14]. Bridgens, Gosling and Birchall investigate membrane material behaviour and show warp and weft stresses under biaxial testing [2,3]. Gosling and Bridgens proposed a new approach for fabric stress-strain behaviour representation [6]. Bridgens and Birchall present results for membrane forces under snow and wind loading [1]. Gosling et al. also provide data for membrane forces under the same loads as a part of their research [7].

This paper presents research done on the dependence of membrane forces on different parameters. It builds on the previously published paper [11] by adding one more variable parameter into consideration. Variable parameters are the height of the model, the intensity of prestressing forces, and the orientation of the membrane material. The goal of the research is to make a step towards better understanding the effects of point load actions and finding out which types of tensile membrane structures are more susceptible to point load actions. Additionally, this research aims to investigate the importance of the point load actions for tensile membrane structures. It will be done by comparing maximal membrane forces under point and another common load at different sets of variable parameters. Wind and snow loads act commonly on tensile membrane structures. Seismic loads are insignificant because of the lightweight nature of membranes; however, if the structure incorporates some heavy parts, a seismic analysis should be conducted [5,21]. Therefore, due to the dynamic nature of wind actions, snow load was selected for comparison with point load action as the least complex.

2 METODOLOGIJA

Istraživanje predstavljeno u ovom radu izvedeno je na modelima membranskih konstrukcija formiranih u softveru Sofistik [16]. Korišćeni softver već je upotrebljavan u naučnim istraživanjima, na primer, u doktorskim disertacijama [13,18,19]. Određeni parametri modela nisu menjani, dok su drugi varirani kako bi se ispitao njihov uticaj na intenzitete sila zatezanja.

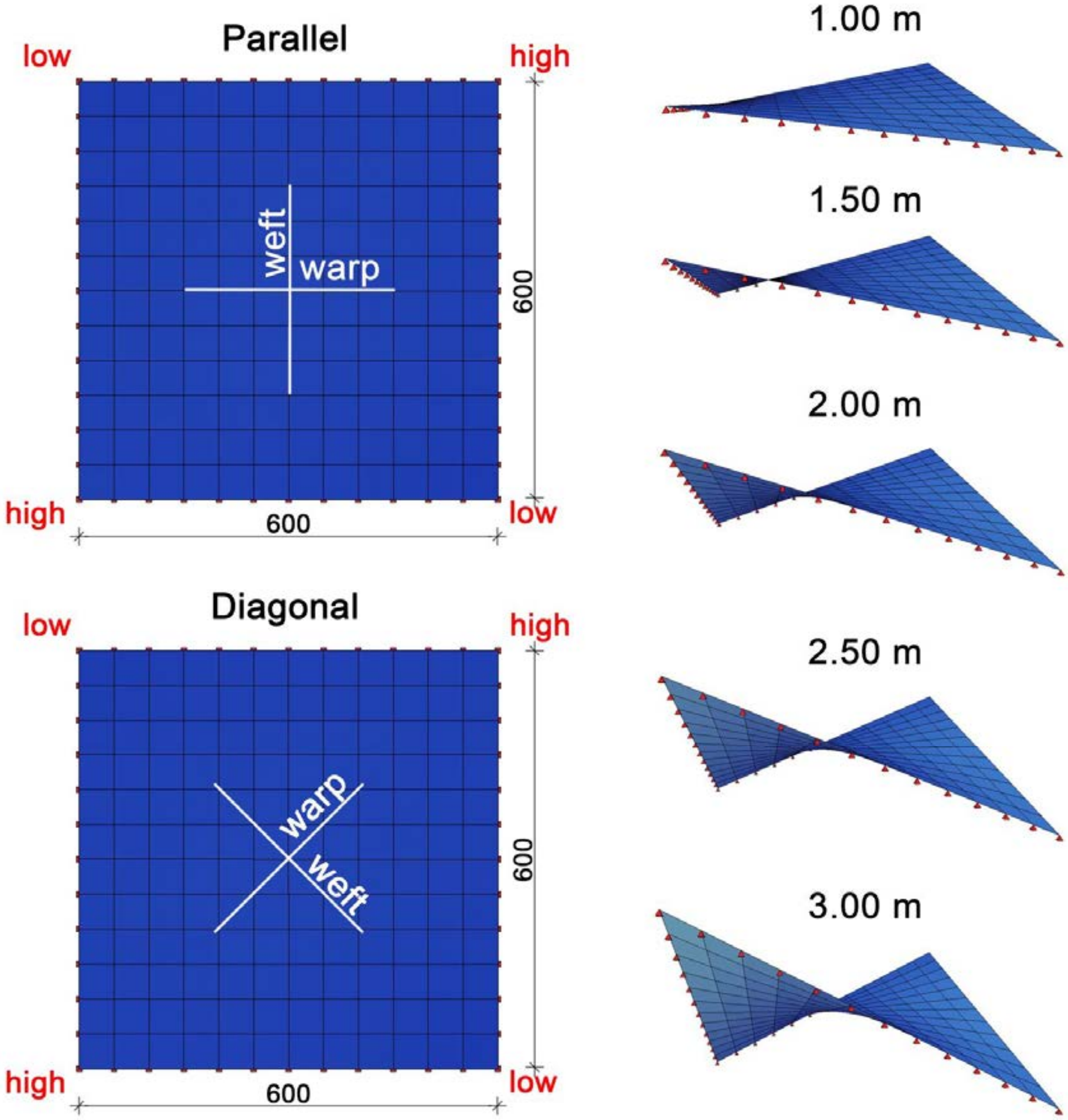
Svi modeli imaju kvadratnu osnovu, sa stranicom dužine 6 m. Modeli su sedlastog oblika, sa po dva viša i po dva niža oslonca. Ivični oslonci su pravi i nepomerljivi. Karakteristike membranskog materijala

2 METHODOLOGY

Research for this paper is conducted on models of tensile membrane structures which are formed in software Sofistik [16]. This software was already used in scientific researches, for example, in the doctoral thesis [13,18,19]. Some model parameters are fixed for all models, while others are varied in order to investigate their influence on membrane force intensities.

All models have a square base with a 6 m side. The models are saddle-shaped with two high and two low supports. Edges are straight and fixed. Membrane material properties are also unvaried. Elastic modulus is nisu varirane. Moduo elastičnosti je 600 kN/m, moduo smicanja – 25 kN/m, a Poasonov koeficijent je 0,3. Debljina membrane je 1 mm. Membrana je podeljena na 144 konačna elementa, dimenzija približno 0,5x0,5 m. Ista opterećenja deluju na sve modele. Koncentrisana sila intenziteta 1 kN deluje u centru membrane vertikalno naniže. Opterećenje od snega deluje intenzitetom 0,6 kN/m^2 vertikalno naniže preko cele membrane, slično kao i u prethodnim istraživanjima [1,7].

600 kN/m, the shear modulus is 25 kN/m, and the Poisson coefficient is 0.3. The thickness of the membrane is 1 mm. The membrane is divided into 144 finite elements, approximately 0.5x0.5 m. The same loads are applied to all models. Point load with 1 kN intensity, the vertical downward direction is applied in the centre of the membrane. Snow load of 0.6 kN/m^2 with a vertical downward direction is applied across the whole membrane, as in previous researches [1,7].



Slika 1. Promena orijentacije membranskog materijala i visine modela korišćene u istraživanju
Figure 1. Variation of material orientation and model height used in research

Tri parametra konstrukcije su varirana. To su orijentacija membranskog materijala, visina modela i intenzitet sila prednaprezanja membrane. Orijentacija materijala određuje se prilikom projektovanja. Ona utiče na izgled i konstruktivne karakteristike membrane. Dve vrste orijentacije se najčešće primenjuju – paralelna i dijagonalna. Kod paralelne orijentacije vlakna membrane paralelna su sa ivicama membrane, a kod dijagonalne vlakna su paralelna s dijagonalama osnove. Obe ove orijentacije analizirane su u istraživanju. Promena visine

Three parameters of the structure are varied. They are the orientation of the membrane material, height of the model, and intensity of prestress forces. The orientation of the membrane material, or patterning direction, is defined during the design process. It affects the visual appearance and the structural behaviour of the membrane. Two orientations are most commonly used, parallel and diagonal. In parallel patterning yarns of the membrane material are in the same direction as the edges, while in diagonal patterning yarns are in the modela iste osnove utiče na promenu zakrivljenosti. Što je veća visina modela, to je veća i zakrivljenost. S obzirom na osnovu analiziranih modela dimenzija 6x6 m, za visinu modela, kao najrealističnije, izabrane su vrednosti između 1 m i 3 m. Ispitivane su sledeće vrednosti: 0,5, 1,0 1,5, 2,0, 2,5 i 3 m. Prednaprezanje membrane služi da pomogne u odupiranju spoljašnjem opterećenju. Ono se definiše vrednošću intenziteta u glavnom i pomoćnom pravcu, ali su u ovom istraživanju oni uzimani kao jednaki. Vrednosti od 1 do 5 kN/m koriste se najčešće i kao takve su uzete za granične vrednosti u ovom istraživanju. Ispitivane vrednosti intenziteta prednaprezanja su 1, 2, 3, 4 i 5 kN/m. Slika 1 prikazuje promene orijentacije membrane i visine ispitivanih modela. Promene intenziteta prednaprezanja nisu vidljive, te nisu mogle biti prikazane na slici.

Analizirane su dve vrste orijentacije membranskog materijala, pet visina modela i pet različitih intenziteta prednaprezanja membrane. Ovo ukupno daje 50 različitih modela koji će biti ispitivani. Svaki model će biti izložen dejstvu opterećenja, a rezultati maksimalnih sila zatezanja biće praćeni. Analiza je izvršena po teoriji trećeg reda. Softver Sofistik koristi modifikovanu metodu gustine sile za proračun membranskih konstrukcija.

3 REZULTATI I DISKUSIJA

Prikazano istraživanje podeljeno je u tri dela. U prvom delu, analiziran je raspored intenziteta sila zatezanja. Promene intenziteta sila su praćene i opisane. Drugi deo posvećen je analizi parametara koji utiču na promene intenziteta sila zatezanja. Rezultati ovog dela mogu da se koriste za smanjenje maksimalnih sila zatezanja pod dejstvom koncentrisane sile. U trećem delu istraživanja, ispitivan je značaj dejstva koncentrisanih sila na membranske konstrukcije. Upoređene su rezultujuće maksimalne sile zatezanja pod dejstvom koncentrisane sile i opterećenja od snega.

3.1 Raspored sila zatezanja

Nakon izvršenog proračuna svih modela, usledila je analiza rezultata. Primećeni su određeni obrasci ponašanja kada je u pitanju raspored intenziteta sila zatezanja u membrani. Jedan karakterističan primer prikazan je na slici 2. Na toj slici prikazani su rezultati za model koji ima visinu 2 m, intenzitet prednaprezanja 3 kN/m i paralelnu orijentaciju materijala. Slika prikazuje vrednosti intenziteta sila zatezanja u glavnom i pomoćnom pravcu, i od dejstva koncentrisane sile i od dejstva snega. Kao što je i bilo očekivano, maksimalna sila zatezanja, pod dejstvom koncentrisane sile, zabeležena je na mestu dejstva opterećenja, odnosno u centru membrane. U glavnom pravcu područje sila zatezanja s višim intenzitetom proteže se duž vlakana glavnog pravca prema ivicama membrane. Najveći deo membrane trpi samo male promene u intenzitetima sila zatezanja. Na manjem delu membrane dolazi do smanjenja intenziteta sila zatezanja. Slično se događa i

same direction as the diagonals of the base. Both of these orientations are analyzed in this research. Changing the height of the models with the same base directly affects the curvature of the model. The higher the model, the greater the curvature is. For the 6x6 m base, in this research, the height of the models is varied from 1 to 3 m. These values are selected as the most realistic for the given base dimension. The analyzed values of the model height are 1.0, 1.5, 2.0, 2.5, and 3.0 m. Prestressing the membrane will help it resist external loads more efficiently. The intensity of the prestress is defined separately in warp and weft direction, but in this research, these values are taken to be the same. The range of prestressing values from 1 to 5 kN/m covers the most frequently used prestress intensities. Therefore, in this research, values of 1, 2, 3, 4, and 5 kN/m are selected for analysis. Figure 1 shows the variations of membrane orientation and model height. The change of prestressing intensity is not shown since it does not affect the appearance of the membrane.

There are two variations in material orientation, five different values for the height of the models, and five different values for the prestress intensities. This makes a total of 50 different models that will be analyzed. Each of the models will be loaded, and resulting maximal membrane forces will be monitored. The third-order theory is used in the analysis. Software Sofistik uses a modified force density method for the calculation of membrane structures.

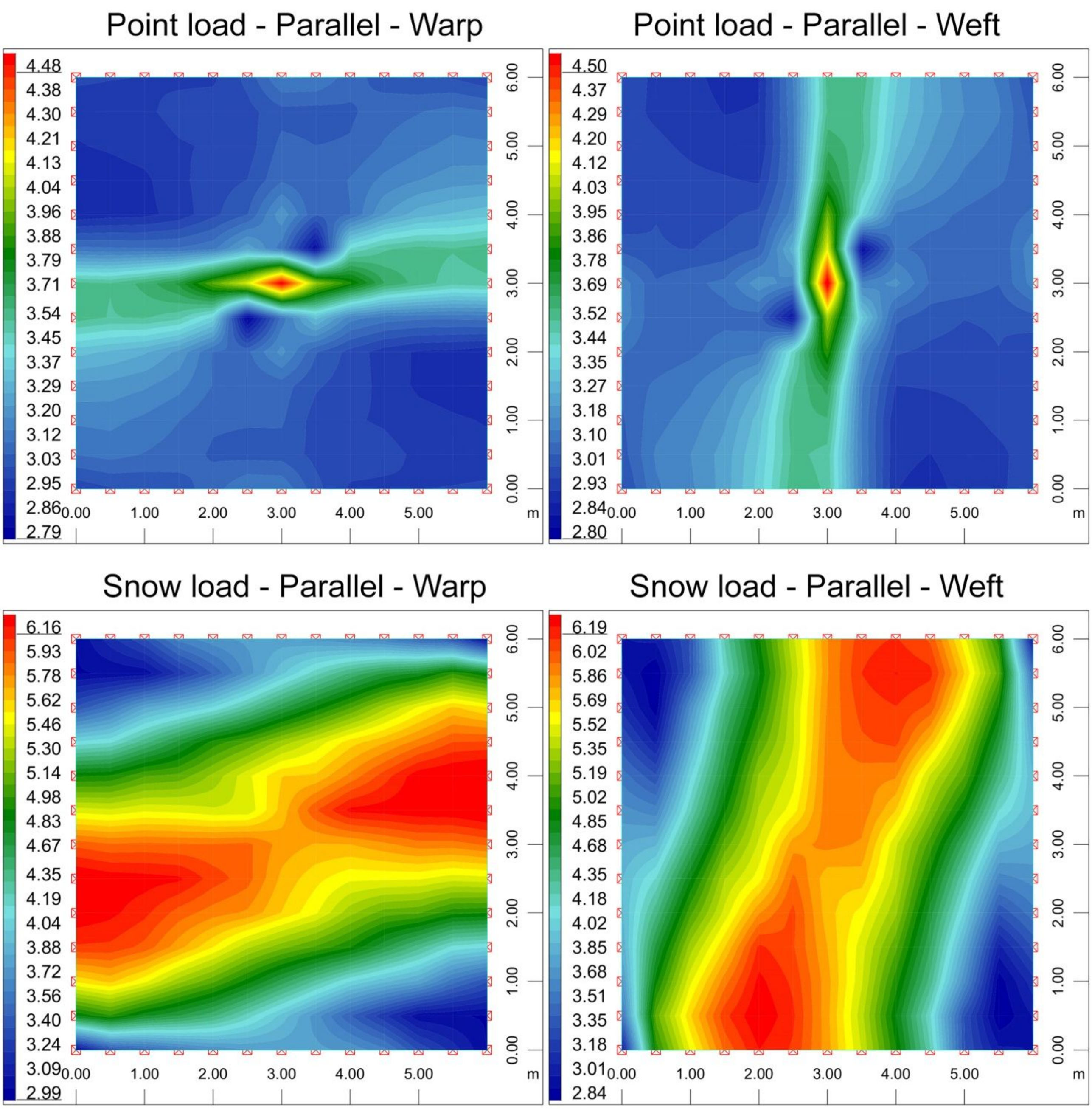
3 RESULTS AND DISCUSSION

The research is divided into three parts. In the first part layout of the membrane forces under point load is investigated. Changes of membrane forces are monitored and described. The second part of the research analyzes the parameters that influence changes of membrane forces. The obtained results can be used for reducing maximal membrane forces under point load. The third part of the research investigates the importance of point load actions to tensile membrane structures. Resulting maximal membrane forces from point load action will be compared to the results under snow load.

3.1 Force intensities layout

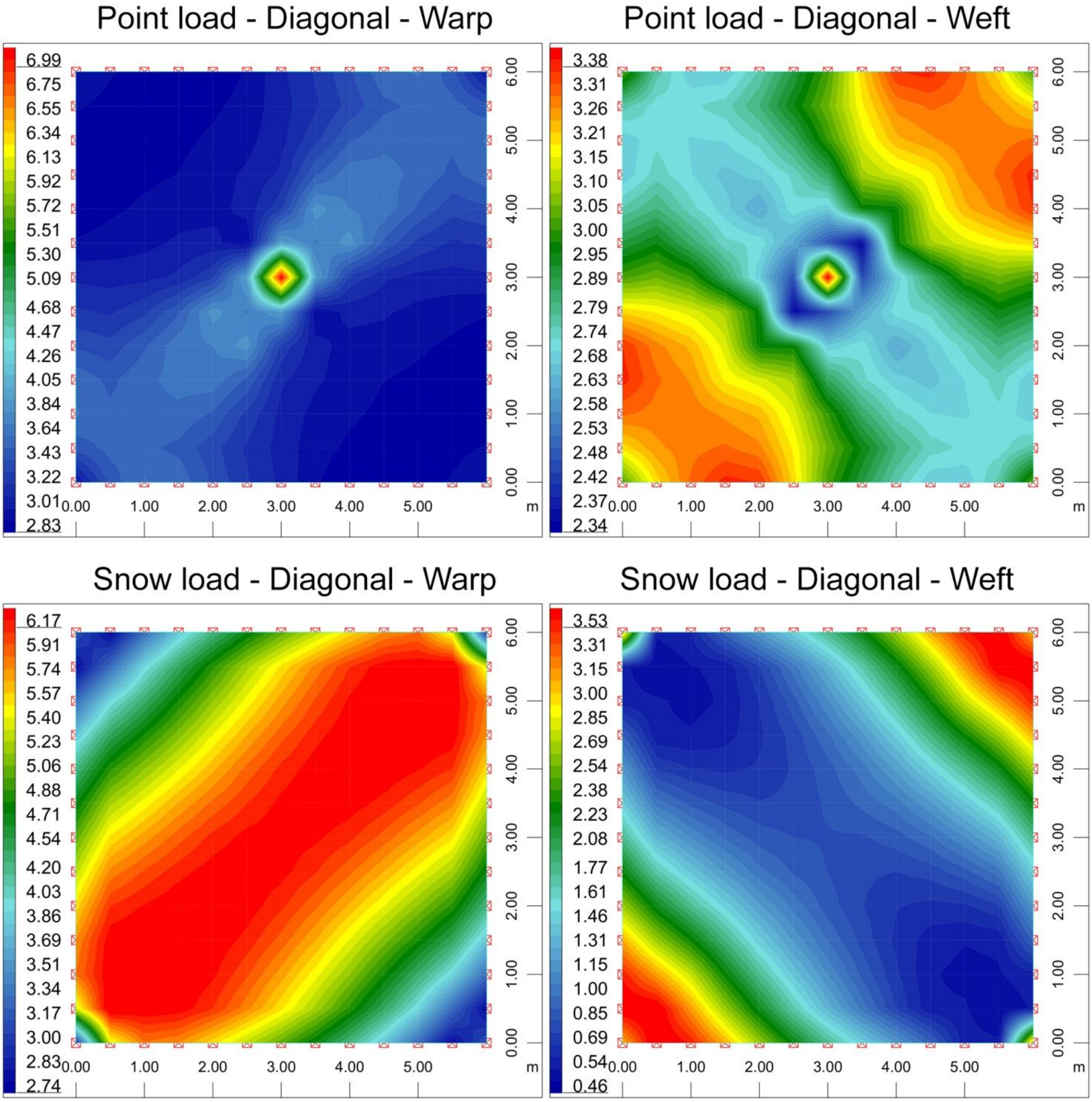
After the calculation has been carried out on all models, the results were analyzed. Specific patterns of behaviour are noted regarding the layout of membrane force intensities. One typical example is shown in Figure 2. In this figure, the results from a model with the 2 m height, prestress intensity of 3 kN/m, and parallel membrane orientation are presented. The figure presents membrane forces in both warp and weft direction, from point load and snow load. As expected, maximal membrane forces under point load in both directions occur in the position of the point load, i.e. in the centre of the membrane. Area of higher membrane forces in warp extends along the direction of warp yarns towards the edge supports. The largest part of the membrane suffers only small changes in membrane force. A smaller part of the membrane will experience a reduction of membrane forces. A similar situation is in u pomoćnom pravcu, gde oblast s većim intenzitetom sila prati vlakna pomoćnog pravca, počevši od centra membrane. Zapravo, rasporedi intenziteta sila zatezanja u glavnom i u pomoćnom pravcu ogledalski su preslikani sa osom simetrije koja prolazi kroz dva niža ili dva viša oslonca. Nasuprot ugibima, koji su pod dejstvom snega najveći u centru membrane, sile zatezanja su najviše blizu ivičnih oslonaca. Najniže sile zatezanja zabeležene su u nižim osloncima. Rasporedi intenziteta sila pod dejstvom snega u glavnom i pomoćnom pravcu takođe su simetrični po dijagonalama.

the weft direction, where higher membrane forces follow the direction of weft yarns, starting from the centre. Actually, the layout of forces in weft and the layout in warp direction are mirrored along the axis defined by either two low points or two high points. In contrast to deflections where maximal deflections are recorded in the centre, the snow load produces maximal membrane forces close to the edge supports. Minimal forces occur at low points. The layout of membrane forces under snow load in warp and weft are also mirrored along diagonals.



Slika 2. Sile zatezanja analiziranog modela s paralelnom orijentacijom materijala pod dejstvom koncentrisane sile i opterećenja od snega – u glavnom i u pomoćnom pravcu

Figure 2. Membrane forces of the analyzed model with parallel patterning under point and snow load in warp and weft directions



Slika 3. Sile zatezanja analiziranog modela s dijagonalnom orijentacijom materijala pod dejstvom koncentrisane sile i opterećenja od snega – u glavnom i u pomoćnom pravcu

Figure 3. Membrane forces of the analyzed model with diagonal patterning under point and snow load in warp and weft directions

Slika 3 prikazuje rezultate za model s visinom od 2 m, intenzitetom prednaprezanja 3 kN/m i dijagonalnom orijentacijom materijala. Jedina razlika u poređenju s modelom prikazanim na slici 2 jeste u orijentaciji materijala. Ipak, rezultati kod ovih modela uočljivo su drugačiji, i u pogledu intenziteta sila zatezanja i prema njihovom rasporedu. U odeljku 3.2 biće detaljnije razmatrani intenziteti sila, dok se ovaj deo bavi samo njihovim rasporedom. Pri dejstvu koncentrisane sile, maksimalne sile

Figure 3 shows the results from the model with 2 m height, prestress intensity of 3 kN/m, and diagonal patterning. The only difference compared to the model in Figure 2 is in membrane material orientation. However, the results differ significantly, both in the intensity of membrane forces and in their layout. Chapter 3.2 will discuss the maximal intensity of membrane forces in more detail, while here, only the layout of forces will be discussed. Under point load, maximal membrane forces zatezanja u glavnom pravcu zabeležene su na mestu dejstva opterećenja, odnosno u centru membrane. Visoki intenziteti sila zatezanja koncentrisani su oko ove tačke. Međutim, u pomoćnom pravcu, maksimalne sile primećene su ili u centru membrane ili kod ivica membrane blizu viših oslonaca. Kod viših intenziteta prednaprezanja i viših modela, maksimalne sila zatezanja u pomoćnom pravcu nisu se nalazile u centru membrane. Ovo se objašnjava većom sposobnošću membrane da se odupre dejstvu koncentrisane sile u centralnom delu bilo zbog veće zakrivljenosti, zbog povećanog intenziteta prednaprezanja ili zbog kombinacije ovih faktora. Niži intenziteti sila zatezanja nalaze se blizu nižih oslonaca, a u nekim slučajevima u centru membrane. Raspored sila zatezanja u pomoćnom pravcu skoro se potpuno razlikuje u odnosu na model s paralelnom orijentacijom materijala. U glavnom pravcu, oblast membrane s višim silama zatezanja pruža se duž glavnih vlakana prema višim osloncima. Veći deo membrane ima male promene intenziteta sile zatezanja. Raspored intenziteta sila zatezanja sličan je modelu s paralelnom orijentacijom materijala, budući da područje visokih intenziteta sile zatezanja prati glavna vlakna, s tim što su vlakna drugačije orijentisana. Pod dejstvom opterećenja od snega, u glavnom pravcu, najveće sile zatezanja nalaze se u centralnom delu membrane i ka višim osloncima. Treba napomenuti i to da su ponovo visoki intenziteti sila zatezanja raspoređeni duž vlakana pravca koji se razmatra. Najniže sile zatezanja postoje kod nižih oslonaca. Raspored intenziteta je u pomoćnom pravcu obrnut. Oblast s nižim intenzitetom sila zatezanja proteže se od centralnog dela membrane k nižim osloncima. Maksimalne sile zatezanja nalaze se blizu viših oslonaca.

3.2 Promena intenziteta sila zatezanja

U ovom odeljku prikazani su rezultati za svih 50 modela opterećenih koncentrisanom silom. Najpre su prikazani rezultati za modele s paralelnom orijentacijom membranskog materijala. Intenzitet prednaprezanja i visina modela varirani su prema usvojenoj metodologiji. Maksimalne sile zatezanja ovih modela prikazane su na slici 4. Grafici na slici prikazuju rezultate za glavni i pomoćni pravac zasebno. Na sličan način, na slici 5 prikazani su i rezultati modela s dijagonalnom orijentacijom materijala.

Prvi zaključak u vezi s rezultatima predstavljenim na slici 4 jeste da su maksimalne sile zatezanja pod dejstvom koncentrisane sile iste i u glavnom i u pomoćnom pravcu. Ovakvo ponašanje objašnjava se dvostrukom simetrijom membrane. U slučaju paralelne orijentacije materijala, vlakna glavnog i pomoćnog pravca iste su dužine i jednako su opterećena, te su sile zatezanja iste. Sledeći zaključak jeste da je uticaj dva analizirana parametra na sile zatezanja potpuno različit. Može se primetiti da visina modela praktično ne utiče na vrednost maksimalnih sila zatezanja. Ovo je veoma zanimljivo, jer se smatra da je povećanje visine modela, odnosno povećanje zakrivljenosti modela, način da se smanje negativni uticaji spoljašnjeg opterećenja. Međutim, u slučaju paralelne orijentacije materijala, vlakna nisu zakrivljena iako je model zakrivljen, budući da se forma modela može generisati s dva seta pravih linija. Stoga, povećanje visine modela ne utiče na

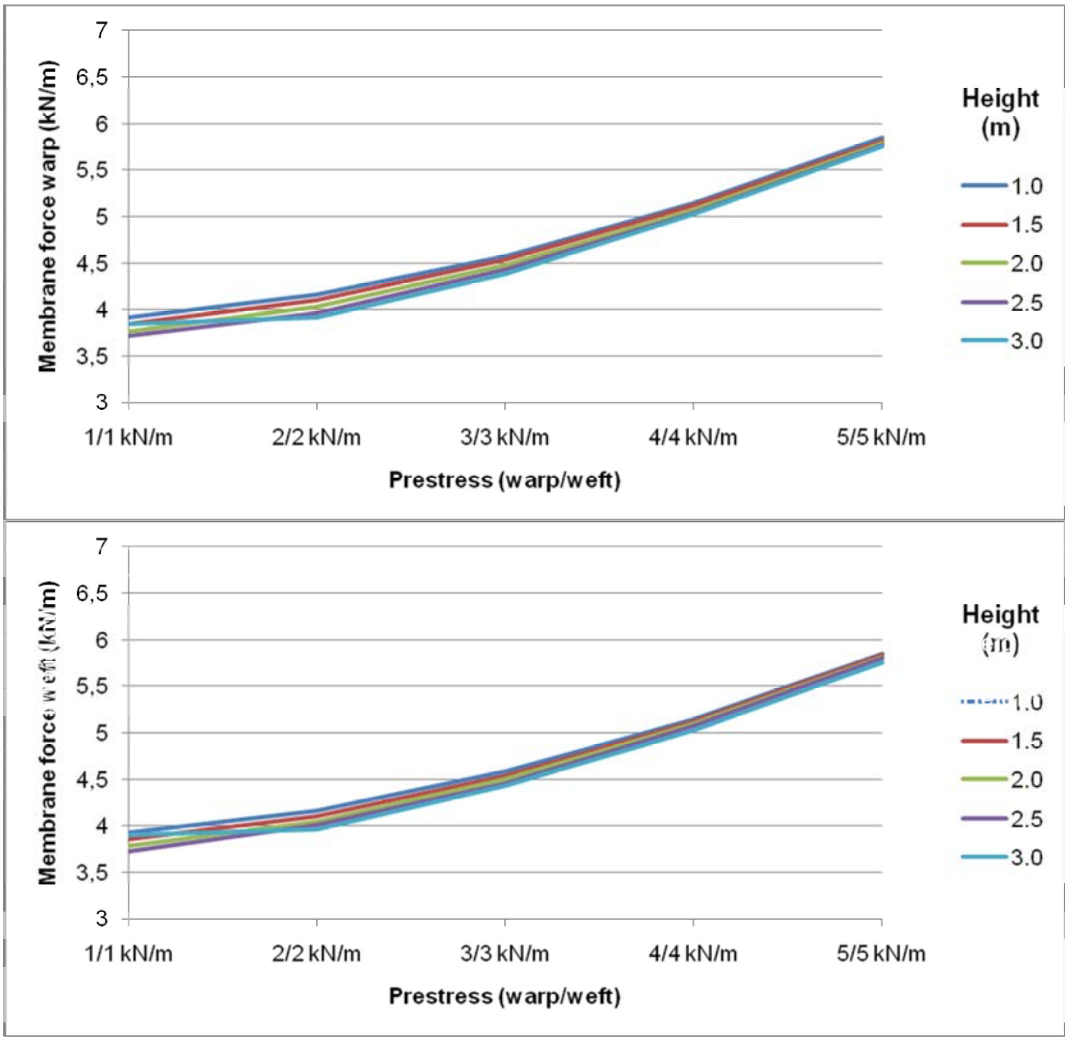
in warp occur at the position of point load, in the centre of the membrane. High intensities are concentrated around this point. However, in weft direction maximal forces occur either in the centre of the membrane or at the edge supports close to high points. At higher prestress intensities and larger height of the models, maximal forces in weft are unlikely to occur at the centre. This is explained by the increased capacity of the membrane under the position of point load to resist loading either by increased curvature, increased prestress forces, or both. Lower membrane forces exist in the areas close to the low supports and, in some cases, in the centre of the membrane. The layout of forces in the weft direction is almost completely different compared to the model with parallel orientation. In warp direction, the area of higher forces spreads along the direction of warp yarns towards the high supports. Most of the membrane has small changes in membrane forces. This layout is similar to the one on the model with parallel orientation since the areas of high membrane forces are aligned with the warp yarns, only the yarns are differently oriented. Under snow load in the warp direction, high membrane forces are located in the central part of the membrane and towards the high supports. It can be noted that, once again, the arrangement of high forces follows the direction of the analyzed yarns. Lowest membrane forces are present at low supports. In weft direction, the layout is quite the opposite. The area of low membrane forces stretches in the central part of the membrane and towards the low supports. Maximal membrane forces are present close to high supports.

3.2 Change of force intensities

This chapter shows the results for all 50 analyzed models under point load action. First, the results for models with parallel membrane material orientation are presented. The intensity of the prestress and the height of the models were varied in the selected range. Maximal membrane forces of these models are shown in Figure 4. The graphs in this figure show the results for warp and weft direction separately. In the same manner, the results of models with diagonal patterning are given in Figure 5.

The first conclusion about the results presented in Figure 4 is that the maximal membrane forces under point load in warp and weft directions are the same. This behaviour is explained by double symmetry of the membrane. In the case of parallel membrane material orientation, the yarns of warp and weft have the same length and are evenly loaded, thus the resulting membrane forces are the same. The next conclusion is that the impact of the two analyzed parameters on maximal membrane forces is much different. It can be noticed that the height of the models practically does not affect the value of the maximal membrane force. This is very interesting since increasing the height of the model, i.e. increasing the curvature of the models, is often used as a method for reducing the negative effects of external loads. However, in the case of parallel patterning, yarns lack curvature, although the model is double curved since the form of the model can be generated with sets zakrivljenost vlakana, te ostaju prava, ako zanemarimo nabore nastale tkanjem vlakana. S druge strane, povećanje intenziteta prednaprezanja dovodi do povećanja maksimalnih sila zatezanja. Ova veza je nelinearna. Promena maksimalnih sila zatezanja u slučaju svih modela pod dejstvom koncentrisane sile najveća je pri intenzitetu prednaprezanja od 1 kN/m, a opada s povećanjem intenziteta prednaprezanja. Minimalne sile zatezanja pod dejstvom koncentrisane sile nisu istraživane u ovom radu.

of straight lines. Therefore, the increase of models' height does not affect the curvature of the yarns and they remain straight if we disregard crimp. On the other hand, the increase of the prestress intensity will lead to an increase in maximal membrane forces. This relation is nonlinear. The change of maximal membrane force for all model heights, under point load, is the largest at models with the prestress intensity of 1 kN/m and this change decreases as the prestress intensity increases. Minimal forces under point load are not investigated in this research.



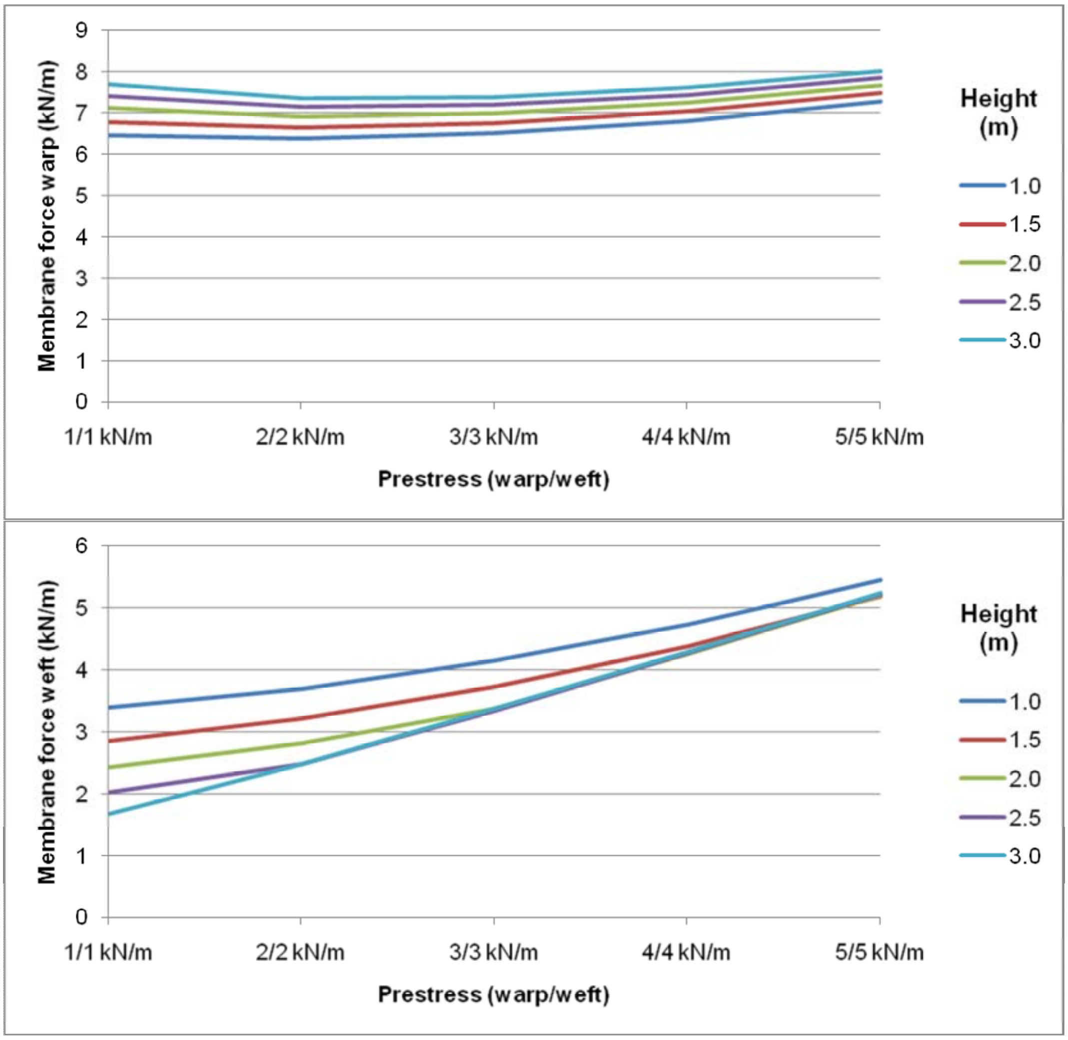
Slika 4. Maksimalne sile zatezanja modela s paralelnom orijentacijom materijala pri različitim vrednostima intenziteta prednaprezanja i visine modela – u glavnom (gore) i u pomoćnom pravcu (dole)

Figure 4. Maximal membrane forces of models with parallel patterning under different prestress intensity and model height, in warp (above) and weft (below)

Rezultati prikazani na slici 5 prikazuju različito ponašanje membrana s dijagonalnom orijentacijom materijala, u odnosu na one s paralelnom orijentacijom. Pre svega, rezultati u glavnom i u pomoćnom pravcu nisu isti. Razlog za to jeste suprotna zakrivljenost vlakana glavnog i pomoćnog pravca kod dijagonalne orijentacije materijala. Zbog toga, opterećenja koja deluju vertikalno naniže nemaju isti uticaj na njih. U glavnom pravcu, oba analizirana parametra značajna su

The results presented in Figure 5 show different behaviour of membranes with diagonal orientation, compared to parallel orientation. The results in warp and weft direction are different. The reason for this lies in the fact that warp and weft yarns have opposite curvature in models with diagonal patterning. Therefore, vertical downward loads do not have the same impact on them. In the warp direction, both of the analyzed parameters influence the maximal membrane forces. Increase of za vrednost maksimalnih sila zatezanja. Povećanje visine modela rezultira povećanjem maksimalne sile zatezanja. Povećanje intenziteta prednaprezanja ima kompleksnije dejstvo. Prilikom povećanja intenziteta prednaprezanja, sile zatezanja najpre opadaju, a zatim rastu. Ovakvo ponašanje detaljno je objašnjeno u prethodnom istraživanju [11]. Sila zatezanja pod dejstvom opterećenja jednaka je zbiru sile prednaprezanja i promene vrednosti sile izazvane dejstvom opterećenja. Na analiziranim modelima, promena vrednosti intenziteta sile smanjuje se s povećanjem intenziteta sile prednaprezanja, dajući sumu prikazanu na slici 5. U pomoćnom pravcu, intenzitet prednaprezanja ima veći uticaj na sile zatezanja u poređenju s visinom modela. Povećanje intenziteta prednaprezanja rezultuje povećanjem maksimalnih sila zatezanja. Visina modela ima značajniji uticaj na maksimalne sile zatezanja u pomoćnom pravcu kada su u pitanju modeli s nižim intenzitetom prednaprezanja, a taj uticaj opada s povećanjem prednaprezanja.

model height results in an increase in the maximal membrane force. The increase in the intensity of prestressing has a more complex impact. When increasing the intensity of prestressing membrane forces start declining at first, but afterward, it starts to increase. This phenomenon is explained in detail in previous research [11]. Membrane force under load equals prestressing force plus the change of membrane force due to loading. On the analyzed models, the change of membrane forces decreases as the prestress forces increase, giving the sum as presented in Figure 5. In the weft direction, the intensity of prestressing has a greater impact on membrane forces than the height of the model. The increase of prestressing intensity results in an increase in maximal membrane forces. The height of the model has a more significant influence on the maximal membrane forces in weft for models with lower prestress intensity, and it decreases as the prestress increases.



Slika 5. Maksimalne sile zatezanja modela s dijagonalnom orijentacijom materijala pri različitim vrednostima intenziteta prednaprezanja i visine modela – u glavnom (gore) i u pomoćnom pravcu (dole)

Figure 5. Maximal membrane forces of models with diagonal patterning under different prestress intensity and model height, in warp (above) and weft (below)

Intenziteti maksimalnih sila zatezanja upoređivani su kod modela s paralelnom i dijagonalnom orijentacijom materijala. Modeli s paralelnom orijentacijom imaju maksimalne sile zatezanja u glavnom pravcu od 3,72 do 5,85 kN/m. Maksimalne sile zatezanja kod modela s dijagonalnom orijentacijom materijala jesu od 6,38 do 8,01 kN/m. Ovo znači da modeli s dijagonalnom orijentacijom materijala imaju veće maksimalne sile zatezanja u glavnom pravcu. U pomoćnom pravcu, sile zatezanja kod modela s paralelnom orijentacijom materijala iste su kao i u glavnom pravcu, a kod modela s dijagonalnom orijentacijom imaju vrednosti od 1,67 do 5,46 kN/m. Treba istaći i to da svi modeli s dijagonalnom orijentacijom materijala imaju manje maksimalne sile zatezanja u pomoćnom pravcu nego modeli s paralelnom orijentacijom materijala.

3.3 Poređenje sila zatezanja pod dejstvom koncentrisane sile i opterećenja od snega

Raspored intenziteta i promena vrednosti intenziteta sila zatezanja analizirani su u prethodna dva poglavlja. Međutim, značaj vrednosti intenziteta sila zatezanja pod dejstvom koncentrisane sile nije razmatran. Ovaj deo istraživanja posvećen je istraživanju značaja dejstva koncentrisanih sila na membranske konstrukcije. Kako bi se ovaj značaj ispitao, rezultati dejstva koncentrisane sile upoređeni su s rezultatima dejstva opterećenja od snega. Intenzitet koncentrisane sile od 1 kN, koji predstavlja dejstvo jednog čoveka, te tipično opterećenje snegom od 0.6 kN/m^2, uzeti su za poređenje. Ovi intenziteti opterećenja predstavljaju uobičajene vrednosti i zbog toga su izabrani za komparaciju. Slika 6 prikazuje rezultate poređenja opterećenja od snega i koncentrisane sile za modele s paralelnom orijentacijom. Maksimalne sile zatezanja pri dejstvu koncentrisane sile oduzete su od odgovarajućih sila zatezanja pri dejstvu opterećenja od snega. Praktično, negativni rezultati ukazuju na to da su sile zatezanja veće pri dejstvu koncentrisane sile nego pri dejstvu snega. Među modelima s paralelnom orijentacijom materijala nema takvih slučajeva. U najvećem broju slučajeva, sile zatezanja znatno su veće pri dejstvu opterećenja od snega. Razlika u intenzitetu sila zatezanja pri opterećenju od snega i koncentrisane sile opada s povećanjem visine modela, a najmanja je za model s najmanjom silom prednaprezanja.

Slika 7 prikazuje rezultate za modele s dijagonalnom orijentacijom membranskog materijala na isti način kao i slika 6. Rezultati prikazani na slici 7 pokazuju da su razlike zavisne – i od visine i od intenziteta prednaprezanja. U glavnom pravcu, vrednost razlike smanjuje se s povećanjem visine modela. Osim toga, vrednost razlike se smanjuje i sa smanjenjem intenziteta prednaprezanja. U pomoćnom pravcu, razlike se takođe smanjuju sa smanjenjem vrednosti prednaprezanja. Povećanje visine modela ne dovodi do jednoznačne promene razlika.

Treba napomenuti i to da među modelima s dijagonalnom orijentacijom ima puno negativnih vrednosti. U glavnom pravcu od analiziranih 25 modela postoji 16, a u pomoćnom pravcu od 25 modela postoji 11 kod kojih koncentrisana sila dovodi do većih sila zatezanja nego opterećenje od snega. Ukupno, postoji devet modela kod kojih koncentrisana sila proizvodi veće

Maximal membrane force intensities among models with parallel and diagonal patterning were also compared. Models with parallel patterning have maximal force intensities in warp direction from 3.72 to 5.85 kN/m. Maximal membrane forces of models with diagonal patterning are from 6.38 to 8.01 kN/m. This means that models with diagonal patterning have larger maximal membrane forces in the warp direction. In weft direction, membrane forces of models with parallel patterning are the same as in warp, and membrane forces of models with diagonal patterning range from 1.67 to 5.46 kN/m. It should be noted that all models with diagonal patterning have smaller membrane forces in weft direction compared to models with parallel patterning.

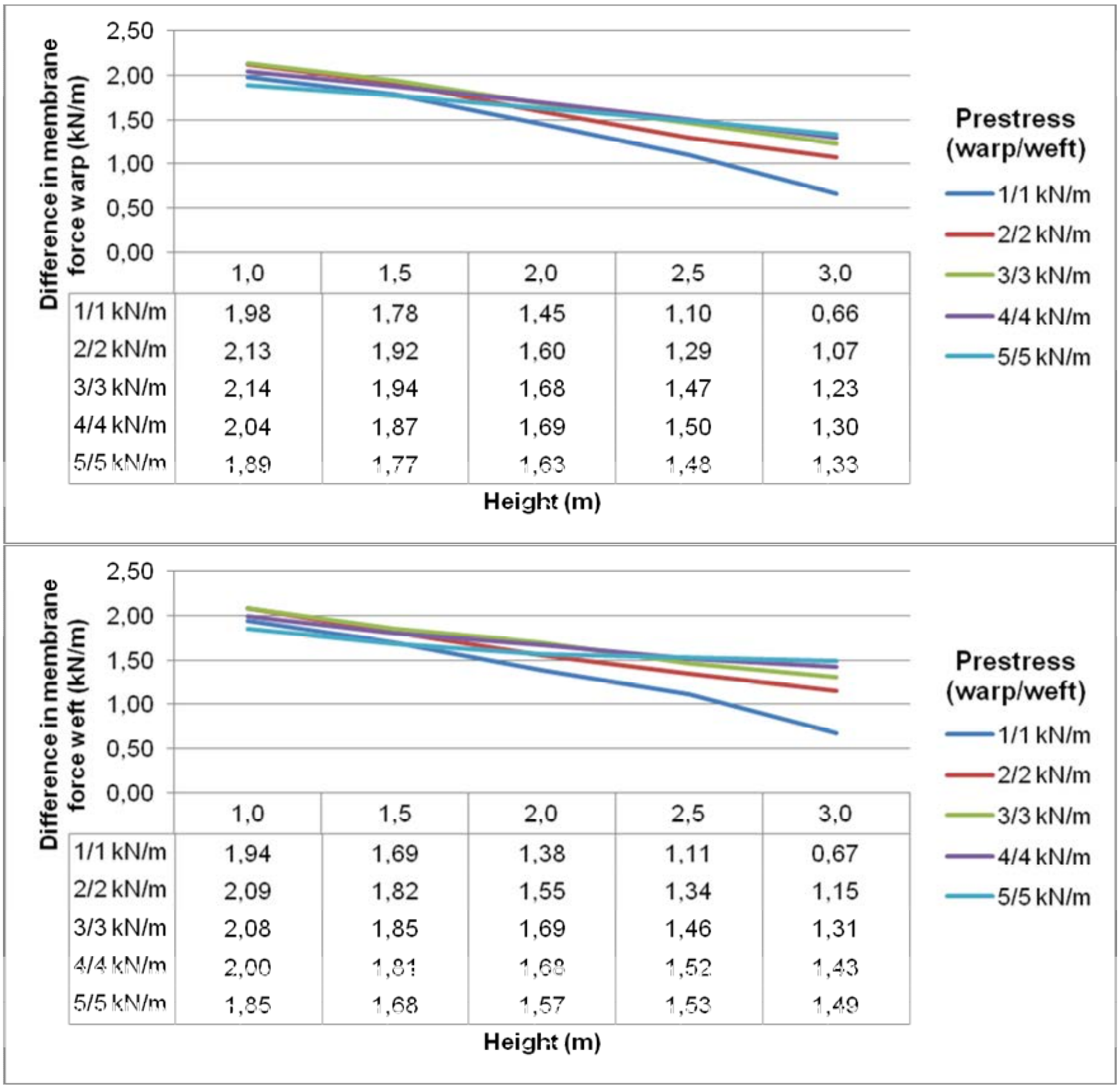
3.3 Comparison of force intensities under point and snow load

The layout of force intensities and change of force intensities were analyzed in two previous chapters. However, the importance of values of membrane forces under point load was not discussed. This part of the research is dedicated to exploring the significance of point load actions to membrane forces of tensile membrane structures. In order to check the importance of point load effects, they were compared to the effects of snow load. The intensity of 1 kN for point load, representing one man, and the typical intensity of 0.6 kN/m^2 for snow load were selected for analysis. These load intensities simulate common loads acting on membrane structures and thus provide comparable results. Figure 6 presents the results of the comparison of snow load and point load effects to membrane forces for models with parallel patterning. Maximal membrane forces under point load were deducted from corresponding membrane forces under snow load. Practically, negative results would show that membrane forces are larger under point load than under snow load. Among models with parallel membrane material orientation, there are no such cases. In most cases, membrane forces are significantly larger under snow load. The difference in membrane forces under snow and point load decreases with the increase of height of the model and is the smallest for the model with the lowest prestress value.

Figure 7 presents the results for the models with the diagonal orientation of membrane material in the same way as Figure 6. Results in Figure 7 show that differences are dependent on both the height of the model and the prestress intensity. In warp direction value of differences decreases as the height of the models increases. In addition, it decreases with the decrease of the prestress intensity. In the weft direction value of differences also decreases when the prestress intensity is lowered. However, the increase of model height will not lead to an unambiguous change of differences.

It can be noted that among models with diagonal orientation, there are many cases with negative values. In warp there are 16 models out of 25 and in weft 11 out of 25 models in which point load produces larger membrane forces than the snow load. Overall, there are 9 models in which point load produces larger membrane sile zatezanja i u glavnom i u pomoćnom pravcu, u poređenju sa opterećenjem od snega. Najveća razlika između sila zatezanja izazvanih koncentrisanom silom i opterećenjem od snega zabeležena je u glavnom pravcu kod modela sa intenzitetom prednaprezanja 1 kN/m i s visinom od 3 m. Ova razlika iznosi 3,47 kN/m u korist koncentrisane sile. Ovaj rezultat je značajan jer dokazuje relevantnost dejstva koncentrisanih sila na membranske konstrukcije.

forces in both warp and weft directions compared to snow load. The largest difference between point and snow load is recorded in warp direction in model with 1 kN/m prestress value and 3 m height. This difference has a value of 3.47 kN/m and is in favour of point load. This finding is very important and proves the significance of point load actions to tensile membrane structures.

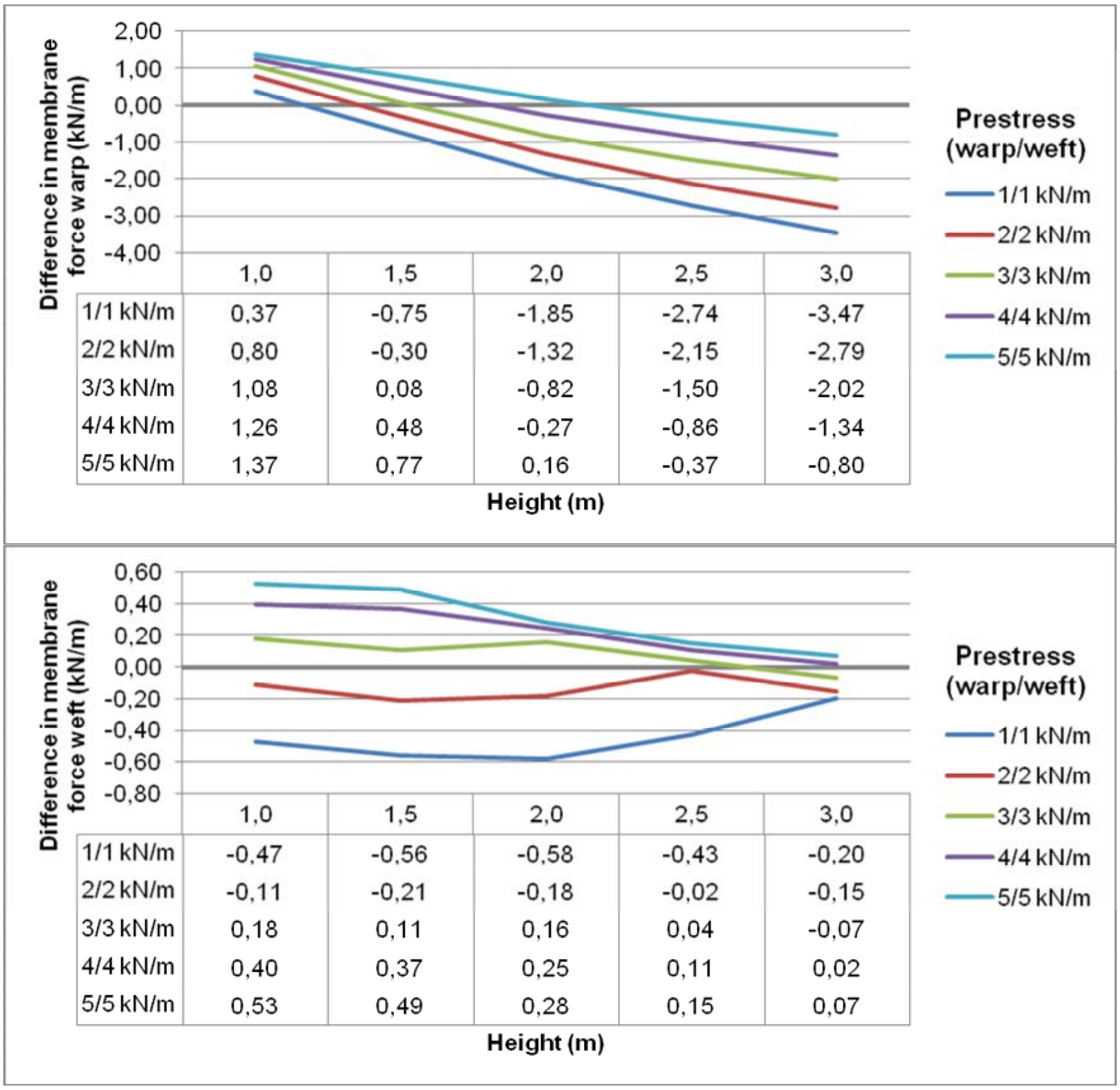


	1,0	1,5	2,0	2,5	3,0
1/1 kN/m	1,98	1,78	1,45	1,10	0,66
2/2 kN/m	2,13	1,92	1,60	1,29	1,07
3/3 kN/m	2,14	1,94	1,68	1,47	1,23
4/4 kN/m	2,04	1,87	1,69	1,50	1,30
5/5 kN/m	1,89	1,77	1,63	1,48	1,33

	1,0	1,5	2,0	2,5	3,0
1/1 kN/m	1,94	1,69	1,38	1,11	0,67
2/2 kN/m	2,09	1,82	1,55	1,34	1,15
3/3 kN/m	2,08	1,85	1,69	1,46	1,31
4/4 kN/m	2,00	1,81	1,68	1,52	1,43
5/5 kN/m	1,85	1,68	1,57	1,53	1,49

Slika 6. Razlika maksimalnih sila zatezanja kod modela s paralelnom orijentacijom materijala između opterećenja snegom i koncentrisanom silom – u glavnom (gore) i u pomoćnom pravcu (dole)

Figure 6. Difference of maximal membrane forces of models with parallel patterning between snow load and point load, in warp (above) and weft (below)



	1,0	1,5	2,0	2,5	3,0
1/1 kN/m	0,37	-0,75	-1,85	-2,74	-3,47
2/2 kN/m	0,80	-0,30	-1,32	-2,15	-2,79
3/3 kN/m	1,08	0,08	-0,82	-1,50	-2,02
4/4 kN/m	1,26	0,48	-0,27	-0,86	-1,34
5/5 kN/m	1,37	0,77	0,16	-0,37	-0,80

	1,0	1,5	2,0	2,5	3,0
1/1 kN/m	-0,47	-0,56	-0,58	-0,43	-0,20
2/2 kN/m	-0,11	-0,21	-0,18	-0,02	-0,15
3/3 kN/m	0,18	0,11	0,16	0,04	-0,07
4/4 kN/m	0,40	0,37	0,25	0,11	0,02
5/5 kN/m	0,53	0,49	0,28	0,15	0,07

Slika 7. Razlika maksimalnih sila zatezanja kod modela s dijagonalnom orijentacijom materijala između opterećenja snegom i koncentrisanom silom – u glavnom (gore) i u pomoćnom pravcu (dole)

Figure 7. Difference of maximal membrane forces of models with diagonal patterning between snow load and point load, in warp (above) and weft (below)

4 ZAKLJUČAK

U ovom istraživanju, ispitivani su različiti modeli membranskih konstrukcija, opterećeni koncentrisanom silom od 1 kN u centru membrane kako bi se odredili efekti ovog dejstva na sile zatezanja. Nijedan drugi parametar modela nije menjan, izuzev orijentacije membranskog materijala, intenziteta prednaprezanja membrane i visine modela. Promenama navedenih parametara formirano je 50 različitih modela. Svi modeli su opterećeni koncentrisanom silom, a takođe i opterećenjem od snega intenziteta 0.6 kN/m^2, radi poređenja.

U prvom delu istraživanja, analiziran je raspored intenziteta sila zatezanja pod dejstvom koncentrisane sile. Zaključeno je da maksimalne sile zatezanja nastaju na mestu dejstva koncentrisane sile, izuzev u nekim slučajevima u pomoćnom pravcu kod modela s dijagonalnom orijentacijom membranskog materijala.

4 CONCLUSION

In this research, different models of tensile membrane structures were tested for the effects of 1 kN point load acting in the centre of the membrane on membrane forces. All model parameters except the orientation of the membrane material, the intensity of the prestressing force and the model height were kept constant. By changing these parameters, 50 models were created. All models were loaded with the same point load and also 0.6 kN/m^2 snow load that is used for comparison.

In the first part of the research, the general layout of the membrane forces under point load is analyzed. It was concluded that maximal membrane forces occur at the position of point load action, except in some cases in weft direction among models with diagonal patterning. Models with parallel material orientation have mirrored layouts of warp and weft membrane forces. Yarns that

Modeli s paralelnom orijentacijom materijala imaju ogledalski preslikan raspored sila zatezanja u glavnom i pomoćnom pravcu. Vlakna direktno opterećena koncentrisanom silom imaju povećane intenzitete sila zatezanja, od pozicija dejstva sile ka osloncima. Veliki deo membrane trpi samo male promene intenziteta sila zatezanja. Modeli s dijagonalnom orijentacijom imaju različite rasporede sila zatezanja u glavnom i pomoćnom pravcu zbog suprotne zakrivljenosti vlakana glavnog i pomoćnog pravca membrane.

Drugi deo istraživanja posvećen je istraživanju uticaja variranih parametara na maksimalne sile zatezanja u membrani. Rezultati su pokazali da promena visine modela ne utiče na maksimalne sile zatezanja ukoliko je orijentacija materijala paralelna. Povećanje intenziteta prednaprezanja izaziva povećanje maksimalnih sila zatezanja kod modela s paralelnom orijentacijom. Modeli s dijagonalnom orijentacijom imaju relativno male promene maksimalnih sila zatezanja u glavnom pravcu, kada se menjaju visina modela i intenzitet prednaprezanja. Povećanje visine modela dovodi do povećanja maksimalne sile zatezanja u glavnom pravcu. U pomoćnom pravcu, povećanje intenziteta prednaprezanja rezultovaće znatnim povećanjem maksimalnih sila zatezanja. Visina modela ima značajniji uticaj na maksimalne sile zatezanja pri nižim vrednostima intenziteta prednaprezanja.

U poslednjem delu istraživanja, maksimalne sile zatezanja pod dejstvom koncentrisane sile upoređene su s maksimalnim silama zatezanja pod dejstvom opterećenja od snega. Ovo je sprovedeno kako bi se ocenio značaj promena maksimalnih sila zatezanja pri dejstvu koncentrisane sile. Modeli istih karakteristika, izuzev orijentacije materijala, imaće veće maksimalne sile zatezanja u glavnom i manje u pomoćnom pravcu kod dijagonalne orijentacije materijala pri dejstvu koncentrisane sile. Međutim, kada se uporede sa silama zatezanja izazvanim dejstvom opterećenja od snega, svi modeli s paralelnom orijentacijom materijala imaju manje maksimalne sile zatezanja pri dejstvu koncentrisane sile. Među modelima s dijagonalnom orijentacijom materijala, devet modela ima veće sile zatezanja i u glavnom i u pomoćnom pravcu, u poređenju s dejstvom opterećenja od snega. To pokazuje da – pod određenim vrednostima parametara – koncentrisana sila može da izaziva značajnije promene nego dejstvo snega.

Istraživanje prikazano u ovom radu bavi se temom koja do sada nije bila detaljno razmatrana. Zbog toga, izloženi zaključci trebalo bi da posluže da se dalje istraži ponašanje membranskih konstrukcija pri dejstvu koncentrisane sile. Nalaze ovog istraživanja trebalo bi potvrditi eksperimentalnim testiranjima na realnim membranskim konstrukcijama. Dalja istraživanja biće usmerena ka ispitivanju membranskih konstrukcija s fleksibilnim ivicama. U sledećoj fazi istraživanja efekata dejstva koncentrisanih sila na membranske konstrukcije biće istraživane minimalne sile zatezanja i potencijalni nestanak zatezanja u membrani.

are directly affected by point load have increased force intensities starting from the point load position towards the supports. A large part of the membrane will suffer small changes of membrane forces. Models with diagonal patterning have different layout of forces in warp and weft due to opposite curvature of warp and weft yarns.

The second part of the presented research aimed at investigating the influence of varied parameters on maximal membrane forces. The results showed that the change of model height does not affect maximal membrane forces if the orientation of material is parallel. The increase of prestressing intensity causes the increase of maximal membrane forces at models with parallel patterning. Models with diagonal patterning in warp direction have relatively small changes of maximal membrane forces when the height of the model and prestress intensity are varied. The increase of model height leads to an increase of maximal membrane forces in the warp. In weft direction increase of prestressing intensity will result in a significant increase of maximal membrane forces. The height of the model has a larger influence at lower prestress intensities.

In the last part of the research, maximal membrane forces under point load are compared to maximal membrane forces under typical snow load. This was motivated by the need to evaluate the significance of changes in maximal membrane forces under point load. Models with the same properties, except the orientation of the material, will have larger maximal forces in the warp and lower maximal forces in weft in case of diagonal patterning under point load. However, when compared to membrane forces under snow load, all models with parallel patterning have lower membrane forces caused by point load. Among models with diagonal patterning, nine models have larger membrane forces in both warp and weft compared to snow load. This shows that under certain sets of parameters, point loads can have a more significant impact on membrane forces than snow load.

The research presented in this paper deals with the topic that was not previously investigated in detail. Therefore, the presented findings should be used to further analyze the behaviour of tensile membrane structures under point load actions. Conclusions obtained during this research should be verified by experimental testing on real tensile membrane structures. Further research will be directed towards the tensile membrane structures with flexible edges. The next phases of the research regarding the effects of point loads on tensile membrane structures will investigate minimal membrane forces and the possible loss of tension in the membrane.

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REZIME

ZAVISNOST SILA ZATEZANJA MEMBRANSKIH KONSTRUKCIJA OD RAZLIČITIH PARAMETARA POD DEJSTVOM KONCENTRISANE SILE

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Koncentrisane sile mogu da izazivaju znatne ugibe zategnutih membranskih konstrukcija. Istraživanje predstavljeno u ovom radu bavi se efektima dejstva koncentrisane sile na sile zatezanja membranskih konstrukcija. Kako bi se ovi efekti ispitali, varirana su tri parametra konstrukcije, a praćene su sile zatezanja izazvane dejstvom koncetrisane sile. Varirani parametri jesu visina modela, intenzitet sila prednaprezanja i orijentacija membranskog materijala. Istraživanje je sprovedeno na modelima formiranim u specijalizovanom softveru. Kako bi se ocenio značaj efekata dejstva koncentrisane sile, rezultujuće sile zatezanja upoređene su sa silama zatezanja pod dejstvom opterećenja od snega. Rezultati istraživanja pokazuju raspored intenziteta sila zatezanja u membrani pod dejstvom koncentrisane sile i zavisnost maksimalnih sila zatezanja od ispitivanih parametara. Pri određenim kombinacijama ispitivanih parametara, koncentrisana sila izaziva vrlo značajne sile zatezanja.

Ključne reči: zategnute membranske konstrukcije, sile zatezanja, dejstvo koncentrisanih sila, opterećenje od snega, orijentacija materijala, intenzitet sila prednaprezanja, visina modela

ABSTRACT

TENSILE MEMBRANE STRUCTURE FORCES DEPENDENCE ON DIFFERENT PARAMETERS UNDER POINT LOAD ACTION

Vuk MILOSEVIC
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Point load actions may have a significant impact on deflections of tensile membrane structures. Research presented in this paper is aimed at exploring the effects of point load actions on membrane forces of tensile membrane structures. Therefore, three different parameters of the structure were varied, and the membrane forces resulting from point loads were monitored. Variable parameters are the height of the model, the intensity of prestressing forces, and the orientation of the membrane material. The research was done on models in specialized software. In order to evaluate the significance of point load effects, membrane forces were compared to those under snow load. The results of the research show the layout of membrane forces under point load and dependence of maximal membrane forces on the varied parameters. Specific sets of analyzed parameters lead to significant values of maximal membrane forces under point load action.

Key words: tensile membrane structures, membrane forces, point load actions, snow load, patterning direction, prestress intensity, model height

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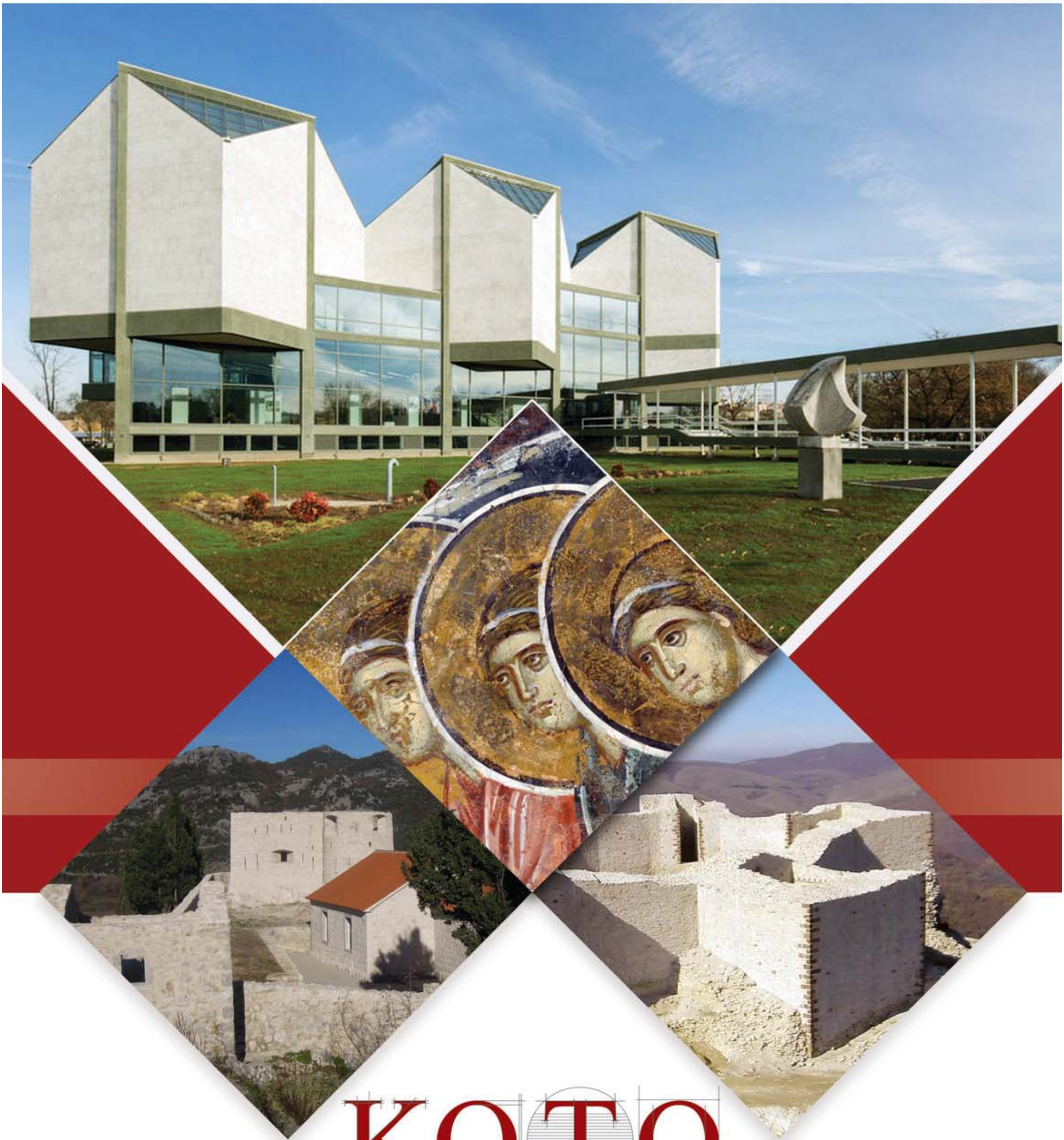

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Kadrovsku strukturu Instituta IMS čine doktori nauka, diplomirani inženjeri sa licencama Inženjerske komore Srbije i stručni tehnički kadar. Inženjeri Instituta IMS aktivno učestvuju na naučno-stručnim skupovima u zemlji i inostranstvu.

Institut IMS kontinuirano unapređuje kvalitet poslovanja na svim nivoima, kako u okviru terenskih i laboratorijskih ispitivanja, tako i na izradi projektno-tehničke dokumentacije s ciljem uspešne realizacije postavljenih zadataka.

Izvođenje istražnih radova sa pontona za novi most Beška,2007.god.

Geotehnička istraživanja i ispitivanja – in situ

Od terenskih istražnih radova izdvajamo izvođenje istražnih bušotina (IB), standardnih penetracionih opita (SPT), statičkih penetracionih opita (CPT i CPTU), opita dilatometarskom sondom (DMT i SDMT), ispitivanja vodopropustljivosti tla različitim terenskim metodama (VDP), ugradnja pijezometara i dr.
Terenske metode ispitivanja šipova zauzimaju značajno mesto u našoj delatnosti, a na tržištu se izdvajamo kao lideri u toj oblasti u proteklој deceniji.

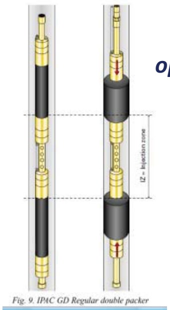

DLT-dinamičko ispitivanje šipova

Ispitivanje šipova

SLT metoda (Static load test) ispitivanje nosivosti šipova statičkim opterećenjem;
DLT metoda (Dynamic load test) ispitivanje nosivosti šipova dinamičkim opterećenjem;
PDA metoda (Pile driving analysis) omogućava praćenje i optimizaciju procesa pobijanja prefabrikovanih betonskih i čeličnih šipova u tlo;
PIT (SIT) metoda (Pile(Sonic) integrity testing) koristi se za ispitivanje integriteta izvedenih šipova (dužine, prekida, suženja ili proširenja).


CPT/CPTU opiti


Aktivno klizište



oprema za ispitivanje vodopropusnosti stena pod pritiskom do 10 bar-a metodom LIŽONA

Laboratorija za puteve i geotehniku

Laboratorija za puteve i geotehniku akreditovana je kod Akreditacionog tela Srbije – ATS prema SRPS ISO/IEC 17025:2006. U njoj se vrše ispitivanja tla (identifikaciono–klasifikaciona ispitivanja, fizičko–mehanička modelska ispitivanja), kamenog agregata i brašna, bitumena i bitumenskih emulzija, asfaltnih mešavina. U okviru laboratorijskih ispitivanja na terenu vrši se kontrola kvaliteta ugrađenog materijala i izvedenih radova (prethodna, tekuća, kontrolna ispitivanja i izvođenja opita in situ).

Projektovanje puteva i sanacija klizišta

U okviru projektovanja značajno mesto u radu zauzimaju geotehnička istraživanja terena i projekti sanacije klizišta - nestabilnih kosina useka i nasipa puteva i prirodno nestabilnih padina . Značajna su i projekovanja svih vrsta fundiranja specijalnih geotehničkih konstrukcija. Ističe se i iskustvo u oblasti putarstva, na projektovanju novih, rehabilitacija i rekonstrukcija postojećih puteva svih rangova sa pratećim objektima i dimenzionisanjem kolovoznih konstrukcija.

Nadzor

Naši inženjeri imaju veliko iskustvo u kontroli i proveri kvaliteta izvođenja svih vrsta radova, kontroli građevinske dokumentacije i praćenju radova u skladu sa njom, kao i rešavanju novonastalih situacija tokom izvođenja radova.

BUILDING TRUST

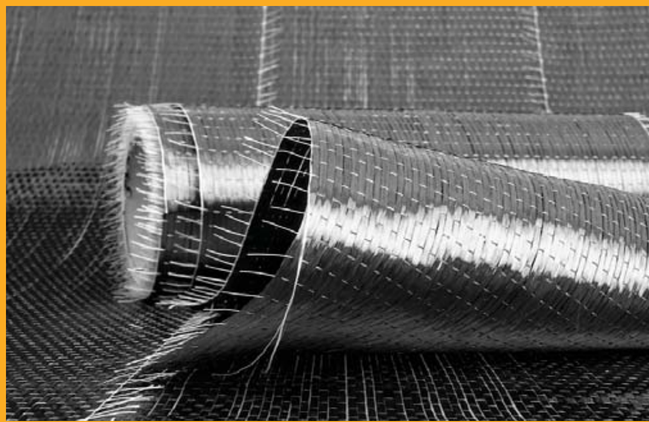
NAPREDNA SIKA REŠENJA U OBLASTI STRUKTURALNIH OJAČANJA

Kompanija Sika pruža trajnu dodatnu vrednost vlasnicima građevinskih objekata, njihovim konsultantima i izvođačima, kao i tehničku podršku tokom svih faza projekta, od ispitivanja uslova i razvoja inicijalnog koncepta ojačanja pa sve do uspešnog završetka i primopredaje projekta

SIKA – VAŠ PARTNER NA GRADILIŠTU

- Globalni lider na tržištu građevine i građevinske hemije
- Najbolja tehnička ekspertiza i praksa za sanaciju betona i strukturalna ojačanja
- Odlična reputacija kod vodećih izvođača i ugovarača posla

SIKA VREDNOSTI I INOVACIJE U GRAĐEVINI



- Integrisani proizvodi i sistemi visokih performansi koji mogu da povećaju i poboljšaju kapacitet, efikasnost, trajnost i estetiku zgrada i drugih objekata – u korist naših klijenata i boljeg održivog razvoja
- Sika mreža obučenih i iskusnih građevinskih stručnjaka

JEDINSTVENA SIKA REŠENJA U ZAHTEVNIM USLOVIMA

- Rešenja za gotovo sve uslove apliciranja
- Kontrolisano vreme rada, vreme sazrevanja i očvršćavanja za različite vremenske uslove
- Posebna rešenja završnih ojačanja za korišćenje kod betona slabije jačine i drugih podloga

POTVRĐENI SIKA SISTEMI I TEHNIKE APLICIRANJA

- Preko 40 godina iskustva u strukturalnim ojačanjima, sistemima i tehnikama
- Proizvodi i sistemi sa brojnim testovima i procenama kako internim tako i eksternim
- Najviši međunarodni standardi proizvodnje i kontrole kvaliteta

PUT INŽENJERING

Put inženjering d.o.o punih 25 godina radi kao specijalizovano preduzeće za izgradnju infrastrukture u niskogradnji i visokogradnji, kao i proizvodnjom kamenog agregata i betona. Preduzeće se bavi i transportom, uslugama građevinske mehanizacije i specijalne opreme.

Za spravljanje betona koristimo drobljeni krečnjački agregat sa našeg kamenoloma, deklarisanih frakcija, kontrolisane vlažnosti. Kompletan proces proizvodnje i kontrole kvaliteta vršimo prema važećim standardima.

Kao generalni izvođač radova, vršimo koordinaciju svih učesnika na projektu, planiranje, praćenje i nabavku materijala, kontrolu kvaliteta izvedenih radova, poštujući zadate vremenske rokove i finansijski okvir investitora.

Obradu armature vršimo brzo, stručno i kvalitetno, sa kompjuterskom preciznošću i dimenzijama po projektu.

Osnovi princip našeg poslovanja zasniva se na individualnom pristupu svakom klijentu i pronalaženje najoptimalnijeg rešenja za njegove transportne i logističke potrebe.

Koristeći inovativne tehnike i kvalitetan građevinski materijal iz sopstvenih resursa, spremni smo da odgovorimo na mnoge zahteve naših klijenata iz oblasti niskogradnje.

Naša kompanija u oblasti visokogradnje primenjuje sistem prefabrikovnih betonskih elemenata koji u odnosu na klasičnu gradnju ima brojne prednosti.

Usluge građevinskom mehanizacijom vršimo tehnički ispravnim mašinama, sa potrebnim sertifikatima kako za rukovaoce građevinskim mašinama tako i za same mašine.

Osnovna prednost prefabrikovane konstrukcije jeste brzina kojom konstrukcija može biti projektovana, proizvedena, transportovana i namontirana.

Prednapregnute šuplje ploče su konstruktivni elementi visokog kvaliteta, proizvedeni u fabrički kontrolisanim uslovima.

Raspolažemo opremom i mašinama za sve zemljane radove, kipere i dampere za rad u teškim terenskim uslovima, automiksere i pumpe za beton, autodizalice, podizne platforme.

Izvodimo hidrograđevinske radove u izgradnji kanalizacionih mreža za odvođenje atmosferskih, otpadnih i upotrebljenih voda, izvođenjem hidrograđevinskih radova u okviru regulacije rečnih tokova, kao i izvođenjem hidrotehničkih objekata.

Izrađujemo betonske "New Jersey profile" koji se u svetu koriste za preusmeravanje saobraćaja i zaštitu pešaka u toku izgradnje puta, kao i Betonblock sistem betonskih blokova.

Sakupljanje i privremeno skladištenje otpada vršimo našim specijalizovanim vozilima i deponujemo na našu lokaciju sa odgovarajućom dozvolom. Kapacitet mašine je 250 t/h građevinskog neopasnog otpada.

Površinski kop udaljen je 35 km od Niša. Savremene drobilice, postrojenje za separaciju i sejalica efikasno usitnjavaju i razdvajaju kamene agregate po veličinama. Tehnički kapacitet trenutne primarne drobilice je 300 t/h.

Uslugu transporta vršimo automikserima, kapaciteta bubnja od 7 m³ do 10 m³ betonske mase. Za ugradnju betona posedujemo auto-pumpu za beton, radnog učinka 150 m³/h, sa dužinom strele od 36 m.

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