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BUILDING MATERIALS AND STRUCTURES

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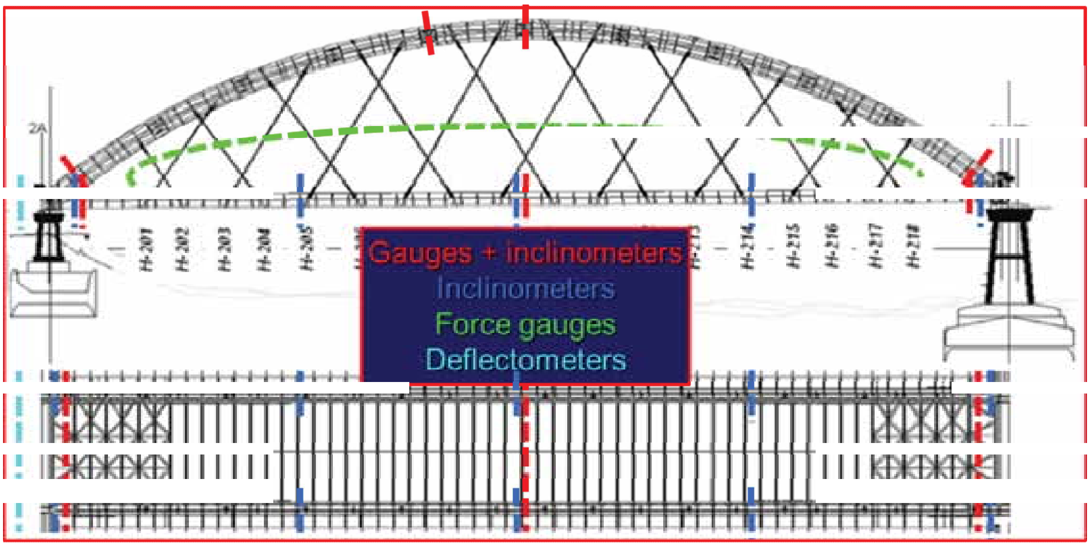
JOURNAL FOR RESEARCH OF MATERIALS AND STRUCTURES



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RAZVOJ BESKONAČNIH ELEMENATA ZA SIMULACIJU NEOGRANIČENOG MEDIJA

DEVELOPMENT OF INFINITE ELEMENTS FOR SIMULATION OF UNBOUNDED MEDIA

Kemal EDIP
Vlatko SHESHOV
Julijana BOJADJIEVA
Aydin DEMIR
Hakan OZTURK

ORIGINALNI NAUČNI RAD
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1 INTRODUCTION

In simulation of physical problems, the area of interest for analysis is usually very small when compared to the dimensions of the surrounding medium such as in underground openings, tunnelling, mining operations etc. It is important to differentiate these problems by considering the boundaries remote from the area of interest, thus, extending the medium to infinity. In finite element (FE) analysis of this kind of problems extending of mesh and applying fixed boundaries is disadvantageous since numerous finite elements should be included.

In order to overcome this problem, infinite elements were proposed by Bettes [1] in the literature. In the work of Beer [2] the infinite elements were used to analyze problems in an underground excavation in pre-stressed infinite medium. Curnier [3] in his work uses infinite element to model unbounded domain economically by using less number of elements and different descent shape functions. In the work of Bettess and Jacqueline [4] the static infinite element is derived extending to infinity in one direction.

On the other hand, the transient wave propagation in elastic media takes place in many fields such as soil dynamics analysis, earthquake engineering, geotechnical engineering etc. The improved simulation is the one that gives a seismic response of the soil model identical to that obtained in the case of the prototype, i.e., the semi-infinite soil layer 1D response under vertically propagating shear waves[5]. Numerical simulation experiences of wave propagation show that simulation of surrounding boundaries is the point which should be considered with special care. In particular, due to these boundaries problems in soil dynamics are more difficult than the problems in structural dynamics because of the radiating waves at the boundaries. The wave propagation problems are solved using the finite element method although the numerical simulation takes place only in the finite element domain. Efficient modelling of infinite media is important since unbounded spatial domain presents a challenge for numerical modelling for simulation of infinite domains.

In the work of Bettess and Zienkiewicz [6] the appropriate boundary conditions are presented for solving the wave problem at the boundaries. In the work of Medina and Penzien[7] an axisymmetric infinite element is developed to solve elastic wave propagation problems in unbounded domain in which the elements are capable of transmitting Rayleigh, shear and compression waves in frequency domain. This type of formulation uses Gauss-Laguerre quadrature scheme for computing the infinite elements numerically. In the work of Medina and Taylor [8]several improvements have been done to the infinite elements. Namely, the approximation accuracy of the infinite elements is obtained by a) selecting realistic shape functions containing approximately the form of the expected

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solution and b) increasing the number of element nodes in the infinite direction. In the work of Chuhan and Chongbin[9] with the consideration of the behaviour of wave amplitude attenuation and phase delay the formulation of a frequency-dependent compatible infinite elements have been derived.

On the other hand, the transmitting boundaries have been simulated by many other authors Lysmer and Kuhlmeyer[10], White et. al. [11], Kausel[12] and Cundall et al. [13] who have presented various promising techniques. Toward this end, absorbing infinite elements have been developed by combination of static infinite elements with absorbing layers. In the work of Haggblad [14] a six node infinite element is developed adding the absorbing layer. Similarly, in the work of Edip [15], static infinite elements with 1/n decay function has been combined with absorbing boundaries. The main advantage in using these type of infinite elements lays in the simplification of usage of conventional Gauss-Legendre abscissae and weights. Further usage of absorbing infinite elements can be found in the works of other authors [16-19].

In this work the infinite elements have been developed considering both static and dynamic conditions. Next, the development and verification of the infinite elements is given.

2 DEVELOPMENT OF STATIC AND ABSORBING INFINITE ELEMENTS

Mapping the infinite domain to finite element seems the most logical solution to develop infinite elements using nodes at special points even in infinity. The figure 1 illustrates the mapping functions logic.

The element field variables are approximated in such a way that standard interpolation functions are used to obtain a decay function with 1/*r* rate for the field variables, where r stands for the distance from the 'pole' of the element to a point in the infinite domain.

In defining the positioning of the pole(s) in infinite elements, special attention should be given to the geometry and the field variable expansion. Moreover, the uniqueness of the mapping and the continuity of the solution between elements with common sides has to be considered by choosing the shape functions according to the number of nodes. The main advantage of the mapped infinite elements is the usage of the conventional Gauss-Legendre abscissa and weights. The main benefit of the proposed infinite elements is in the number of nodes which allow coupling with four or eight nodded finite elements. Element matrices are constructed by using the procedures as described in Bathe[20]. By adding together the parts from each element constituent, the governing incremental equations for equilibrium in dynamic analysis are obtained.

The formulation of infinite elements follows the same procedure as for the finite elements. The mapping functions are added to present the mapping of the domain. The infinite element is obtained as a six and eight node element as shown in Figure 2.

The element displacement in *u* and *v* direction is interpolated with the usual shape functions *N1*, *N2*,*N4* and *N5:*

$$\begin{aligned} u &= [N_1 \quad N_2 \quad 0 \quad N_4 \quad N_5 \quad 0]\mathbf{u} \\ v &= [N_1 \quad N_2 \quad 0 \quad N_4 \quad N_5 \quad 0]\mathbf{v} \end{aligned} \tag{1}$$

The vectors **u** and **v** of expression (1) are nodal point displacements in global coordinates.

$$\begin{aligned} N_1 &= -(1-s)r(1-r)/4 \\ N_2 &= (1/2)(1-r^2)(1-s) \\ N_4 &= -(1+s)r(1-r)/4 \\ N_5 &= (1/2)(1-r^2)(1+s) \end{aligned} \tag{2}$$

For coordinate interpolation in *r-s* coordinate system a one-dimensional mapping is applied.

$$\begin{aligned} r &= [M_1 \quad M_2 \quad 0 \quad M_4 \quad M_5 \quad 0]\mathbf{r} \\ s &= [M_1 \quad M_2 \quad 0 \quad M_4 \quad M_5 \quad 0]\mathbf{s} \end{aligned} \tag{3}$$

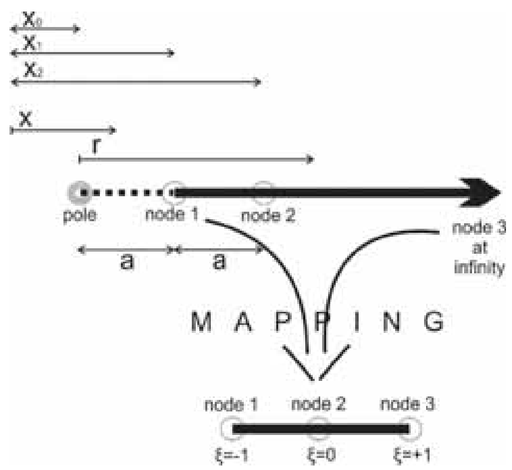

Fig. 1 Representation of the domain in infinite element

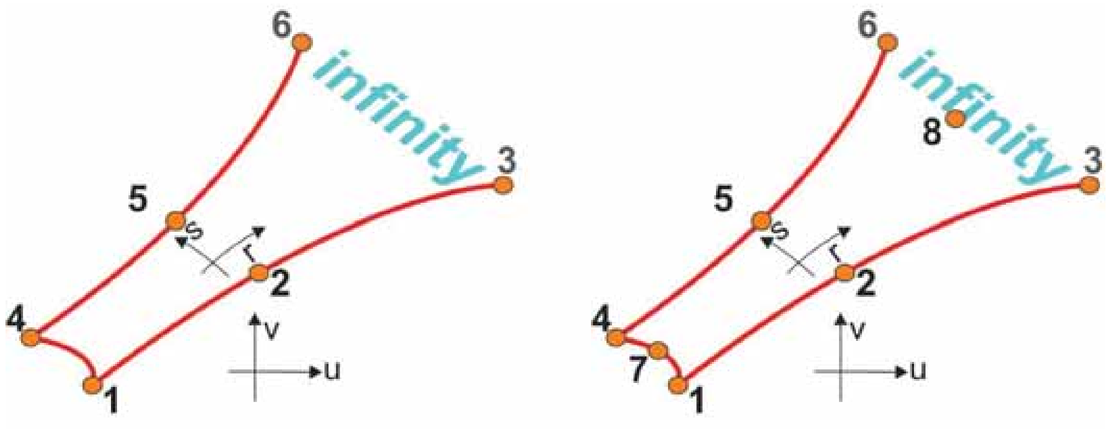

Fig. 2. Infinite element with 6 nodes and 8 nodes

where

$$M_1 = -\frac{(1-s)r}{1-r}$$
$$M_2 = -\frac{1}{2}\frac{(1-s)(1+r)}{1-r}$$
$$M_4 = -\frac{(1+s)r}{1-r} \qquad (4)$$
$$M_5 = -\frac{1}{2}\frac{(1+s)(1+r)}{1-r}$$

In eight node infinite element, the element displacement in *u* and *v* direction is interpolated with the usual shape functions as given below for 8 node infinite element:

$$u = [N_u^1 \quad N_u^2 \quad 0 \quad N_u^4 \quad N_u^5 \quad 0 \quad N_u^7 \quad 0]\overline{\mathbf{u}}$$
$$v = [N_u^1 \quad N_u^2 \quad 0 \quad N_u^4 \quad N_u^5 \quad 0 \quad N_u^7 \quad 0]\overline{\mathbf{v}} \qquad (5)$$

The shape functions are given as follows:

$$N_u^1 = -(r-1)(-1+s)(s+1+r)/4$$
$$N_u^2 = (r-1)(1+r)(-1+s)/2$$
$$N_u^4 = -(r-1)(1+s)(s-1-r)/4$$
$$N_u^5 = -(r-1)(1+r)(1+s)/2 \qquad (6)$$
$$N_u^7 = (-1+s)(1+s)(r-1)/2$$
$$N_p^1 = (s-1)(r-1)/4$$
$$N_p^4 = -(s+1)(r-1)/4$$

The coordinate interpolation in the infinite element from global to local is completed using the expressions (5) and (6). The infinite element is one sided meaning that only the positive r direction extends to infinity. Following Fig. 1 the mapping functions for coordinate interpolation considering displacement degrees of freedom are defined as follows:

$$r = [M_u^1 \quad M_u^2 \quad 0 \quad M_u^4 \quad M_u^5 \quad 0 \quad M_u^7 \quad 0]\overline{\mathbf{r}}$$
$$s = [M_u^1 \quad M_u^2 \quad 0 \quad M_u^4 \quad M_u^5 \quad 0 \quad M_u^7 \quad 0]\overline{\mathbf{s}} \qquad (7)$$

Where the mapping functions are given as:

$$M_u^1 = -\frac{(1-s)rs}{1-r}$$
$$M_u^2 = -\frac{(1-s)(1+r)}{2(1-r)}$$
$$M_u^4 = -\frac{(1+s)rs}{1-r} \qquad (8)$$
$$M_u^5 = -\frac{(1+s)(1+r)}{2(1-r)}$$
$$M_u^7 = -\frac{2r(1+s)(1-s)}{(1-r)}$$

In expressions (7) and (8), *u* and *r* stand for vectors of nodal point displacement. On the infinity side where values of *r* approach unity (*r*=1), no mappings are defined. The number and location of the common nodes connecting finite and infinite elements should coincide to guarantee the continuity condition between the elements. The proposed infinite elements have possibility of assigning different number of nodes for displacement allowing coupling with different finite elements. Last but not the least, the newly developed infinite elements are advantageous in correct representation of the boundary conditions by user defined number of integration points in the infinite elements. The only disadvantage of the developed infinite elements is in the fact that the more integration points are used the slower the calculation is performed.

3 VERIFICATION OF STATIC INFINITE ELEMENTS - PLATE WITH CIRCULAR HOLE

In geotechnical problems extending to infinity one of the most difficult tasks is to model the infinite region. In the next problem, an infinite plate having a circular hole of radius R=1.0 m length is subjected to a pressure p=1kPa which is uniformly distributed. The domain is presented in Fig. 3.

The domain being a plane strain space has the following material properties: Young's modulus E=1kPa and Poisson's ratio n=0.25. The discretization of the domain is done using 80 finite elements in total. The infinite elements of 6 and 8 nodes are used to simulate the boundaries. The results comparing the analytical solution as given in the work of T.T. Abdel-Fattah [21] are given in Fig. 4.

As it is seen from the Fig. 4 the correctness of the analytical results with infinite elements is adequately good although; the 8-node infinite elements have better correctness in the results. Thus, in absorbing infinite elements, the 8-node infinite elements should be used further.

4 ABSORBING INFINITE ELEMENTS IN ABAQUS

In the study, efficiency of the developed infinite element is also compared with the results of the numerical simulations conducted by the FE-code ABAQUS [21]. ABAQUS is a general-purpose analysis software that can solve a wide range of linear and nonlinear problems comprising the static and dynamic response of the components [22].

Built-in infinite elements are provided in ABAQUSto to solve boundary value problems defined in unbounded domains or problems in which the region of interest is small compared to the dimensions of the surrounding medium. While standard finite elements are used to model the region of interest, the infinite elements are utilized to model the far-field region. Infinite elements can be used together with first- and second-order planar, axisymmetric, and three-dimensional finite elements [22].

The infinite elements provided in ABAQUS are based on the study of Zienkiewicz et al.[23]for static response and of Lysmer and Kuhlemeyer [9] for dynamic response. They provide stiffness in static solid continuum analyses and quiet boundaries to the FE model in dynamic analyses. The static behaviour of the infinite elements is based on modelling the basic solution variable u according to spatial distance r measured from a "pole" of the solution, so that $u \to 0$ as $r \to \infty$, and $u \to \infty$ as $r \to 0$. The interpolation provides terms of order $1/r$, $1/r^2$ and, when the solution variable is a stress-like variable $1/r^3$ as $r \to 0$. Additionally, dynamic response of the infinite elements is considered in case of plane body waves travelling out of the domain. All assumptions near to the boundary are of small amplitude to develop responds only in a linear elastic domain [22].

Infinite elements available in ABAQUS are given and defined in Table1 and their naming convention is depicted in Fig. 5.

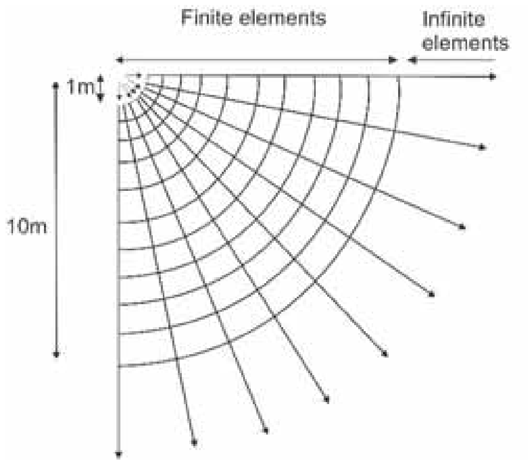

Fig. 3. Mesh of finite and infinite elements

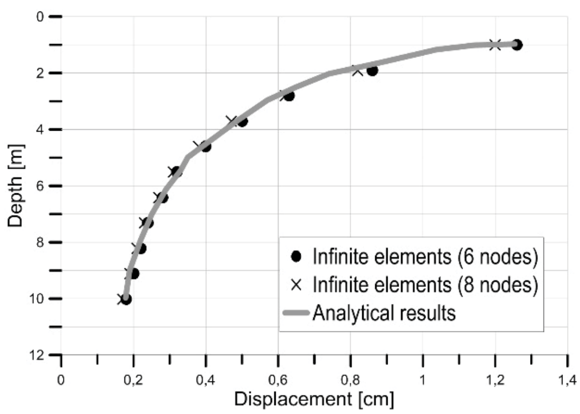

Fig. 4. Comparison of analytical and numerical results

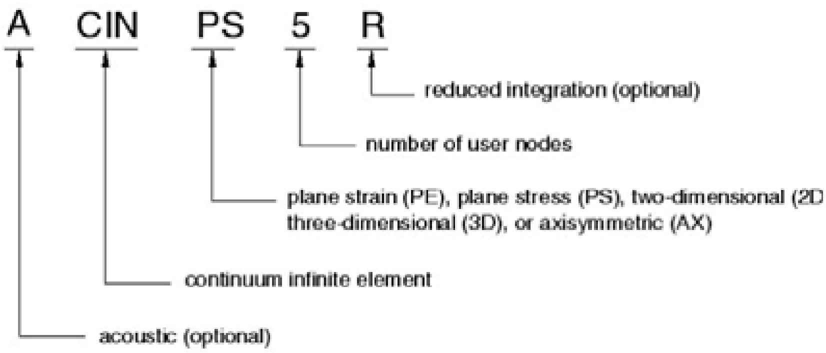

Fig. 5. Naming Convention of Infinite Elements in ABAQUS [22]

Table 1. Infinite Elements provided in ABAQUS

Type of Infinite Element	Naming Convention	Definition
Plane strain solid continuum	CINPE4	4-node linear, one-way infinite
	CINPE5R(S)	5-node quadratic, one-way infinite
Plane stress solid continuum	CINPS4	4-node linear, one-way infinite
	CINPS5R(S)	5-node quadratic, one-way infinite
3D solid continuum	CIN3D8	8-node linear, one-way infinite
	CIN3D12R(S)	12-node quadratic, one-way infinite
	CIN3D18R(S)	18-node quadratic, one-way infinite
Axisymmetric solid continuum	CINAX4	4-node linear, one-way infinite
	CINAX5R(S)	5-node quadratic, one-way infinite

A solid section definition is used to define the element's section properties which should be associated with a region of the model. A thickness should be defined for two-dimensional, plane strain, and plane stress elements as an element property definition. By default, a unit thickness is assumed. On the contrary, it needless to specify a thickness for three-dimensional and axisymmetric solid elements. Material definition of infinite elements is assumed to be linear, therefore only linear behaviour can be associated with infinite elements. Moreover the material response of the infinite elements in dynamic analysis is assumed to be isotropic and it should also match the material properties of the adjacent finite elements in the linear domain [22].

The node numbering of infinite elements should be assigned in a way that the first face is the face that is connected to the finite element part of the mesh. Node ordering and face numbering on elements, and numbering of integration points for output is depicted in Fig. 6 for PS and PE solid continuum elements. The formulation of the solid medium elements is based on the fact that the far-field solution along each element edge that stretches to infinity is centred about an origin, called the “pole”. The position of the nodes in the infinite direction should be selected appropriately with respect to the pole. It is important to position the second node along each edge pointing in the infinite direction in order that it is twice as far from the pole as the node on the same edge at the boundary between the finite and the infinite elements. In addition to this length consideration, the second node in the infinite direction should be specified in the way that the element edges in the infinite direction do not cross over, which would give non-unique mappings (Fig. 7). ABAQUS will give an error message if such a problem occurs. These second nodes in the infinite direction can be projected conveniently from a pole node. The positions of the pole and the nodes on the boundary between the finite and the infinite elements are used. However, in explicit dynamic analysis the infinite element nodes that are not part of the first face are treated differently. Those nodes are located away from the finite element mesh in the infinite direction. Loads and boundary conditions should not be specified using these nodes since the location of these nodes is not meaningful for explicit dynamic analysis [22].

In the study of 4-node linear, one-way plane strain solid continuum infinite elements (CINPE4) are used to simulate the propagation of waves in a soil domain in which the region of interest is small in size compared to the surrounding medium. Linear dynamic behaviour of the soil is analyzed by ABAQUS/Explicit analysis procedure. A solid section definition is used to define the element's section properties and it is associated with the region of the model. Unit thickness is assumed for thickness of the two-dimensional plane strain elements. Moreover, similar mesh size and material properties given in the reference studies are assigned to the numerical models.

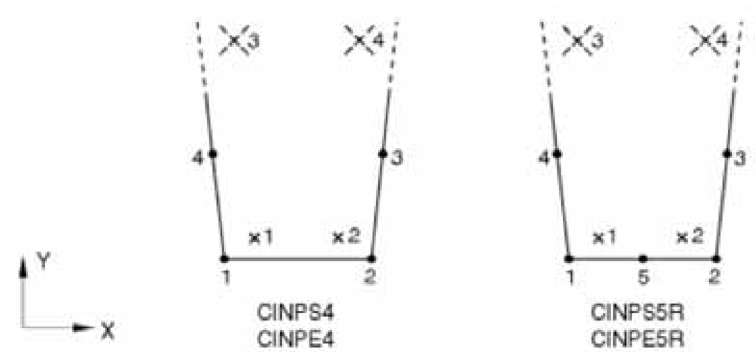

Fig. 6. Node ordering and face numbering on elements, and numbering of integration points for PS and PE solid continuum elements [22].

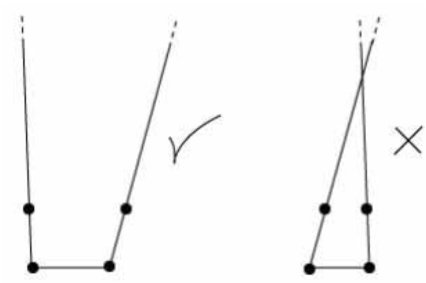

Fig. 7. Examples of an acceptable and an unacceptable two-dimensional infinite element [22].

5 VERIFICATION OF ABSORBING INFINITE ELEMENTS

The newly developed absorbing infinite elements are verified by several examples. Comparisons are made with the software ABAQUS.

5.1 Wave propagation in 1D

First, wave propagation in one dimensional medium is simulated to verify the newly programmed infinite elements. The soil parameters are taken from Plaxis [22] example and comparisons are made accordingly. Simulation is done using a soil column composed of finite elements with fixed and infinite element boundaries. Soil domain is presented in Figure 8. It has a length of 10m and is discretized with 40 elements. In the middle of the soil column a point A is chosen as a reference point for the comparison of the results. The soil domain of interest has a length of 10m and is discretized with 40 elements. The properties of soil are taken as: Young's modulus E=18000kPa, Poisson's ratio=0.2 and Density=2.04ton/m^3. The p wave velocity is given in PLAXIS manual [22]. The p-wave velocity is given in the equation 9 below as follows:

$$V_p = \sqrt{\frac{(1-\upsilon)E}{\rho(1+\upsilon)(1-2\upsilon)}} \tag{9}$$

Using the values above, the p wave velocity can be computed as *Vp*=99m/s. In simulation of wave propagation the application of vertical displacement on the top of the domain is done in three different types. Namely,

- Heaviside step function
- Impulse function
- Sine function

In this case the applied displacement is considered to be of Heaviside step type with a magnitude of uy=0.001m. Time history of the travelling P wave at point A is given in Figure 9.

In Figure 9, it is clearly shown that in the case of fixed boundaries the P wave is reflected while using the infinite elements the P wave is absorbed in the boundary hindering the back propagation of the wave. When estimated the time needed for the P-wave to reach the point A it is easily seen that the wave velocity equals the

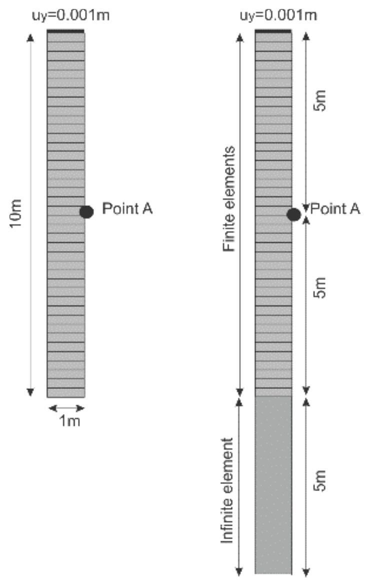

Fig. 8. Domain of soil column

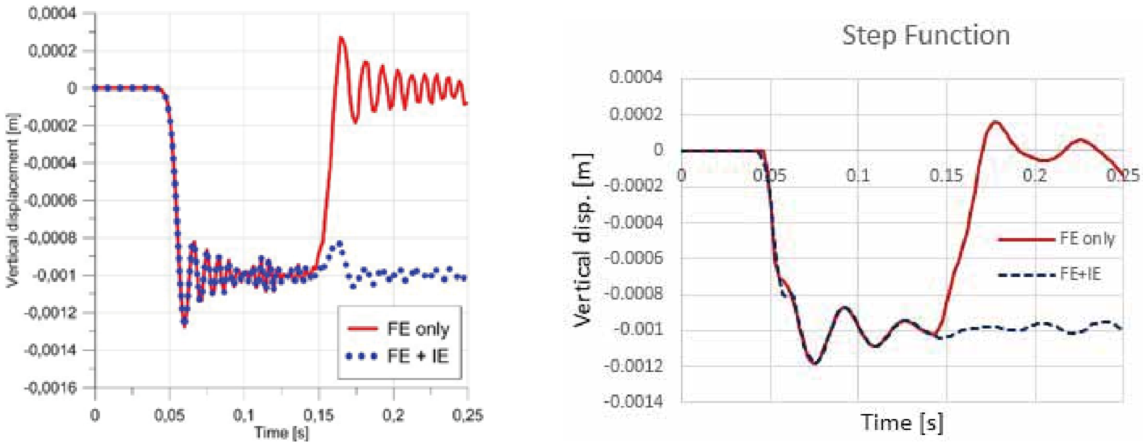

Fig. 9. Time displacement history-Heaviside step function ANSYS left, ABAQUS right

value of equation 9 (*Vp*=99m/s). On the other hand, the simulation with ABAQUS reveals similar results proving that the newly developed infinite elements in ANSYS provide correct results.

Displacement as an Impulse function

In applying the displacement as an impulse function interesting results have been found. The impulse function is applied only for *0.00166s* and then the domain is left to vibrate freely up to 0.3seconds. In Figure 10, displacement comparison is given in the mid-point of the domain (Point A).

As can be seen from Fig. 10 that infinite elements absorb the wave in a correct manner not letting the reflection to take place back in the domain. The first impulse occurs at time=0.05 seconds which ensures that the velocity of P-wave is 99m/s and is in accordance with equation (9). The comparison between the infinite elements used in ANSYS and ABAQUS software shows that both infinite elements absorb the wave in a correct manner although the newly developed infinite elements in ANSYS software seem to decrease the oscillations back in the domain of finite elements. This is mainly due to the reason of the increased number of integration points which are used in the newly developed infinite elements.

Displacement as a sine function

In order to evaluate the simulation of the applied displacement as a sine function a circular frequency of 0.5Hz has been selected. The sine function is applied at the top of the model for 10 seconds and the results are compared accordingly.

As can be seen form Fig. 11 the time displacement histories of sine functions have different magnitudes. This proves that boundary conditions play an important role in simulation of wave propagation. The values that are compared occur at the middle of the domain in the way that the wave magnitude in the case of fixed boundaries is doubled. Once more, the usage of infinite elements proves to play important role in simulation of the wave propagation problems. The comparison between ANSYS and ABAQUS show similar magnitudes although in ABAQUS the frequency is considered as 0.1Hz.

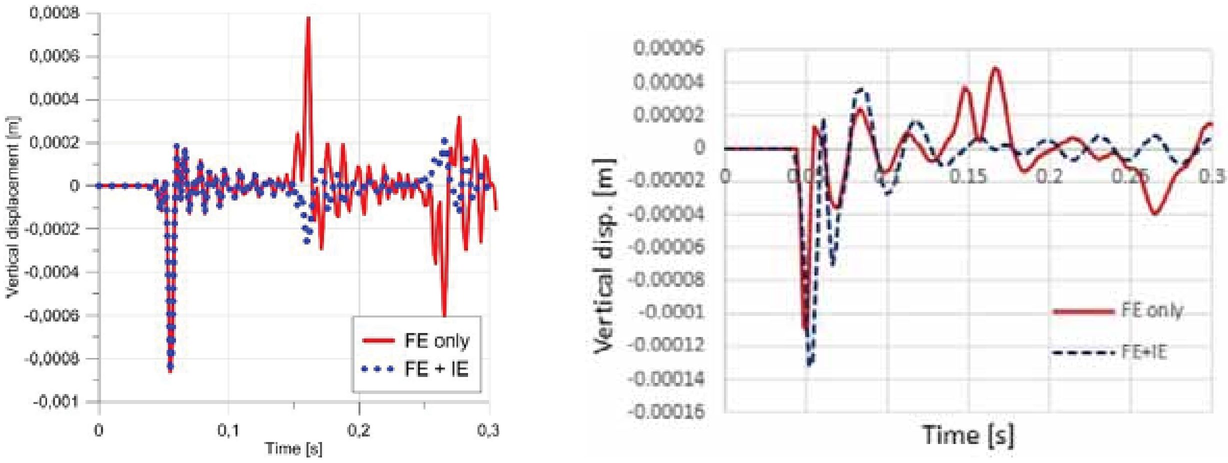

Fig. 10. Time displacement history-impulse function ANSYS left, ABAQUS right

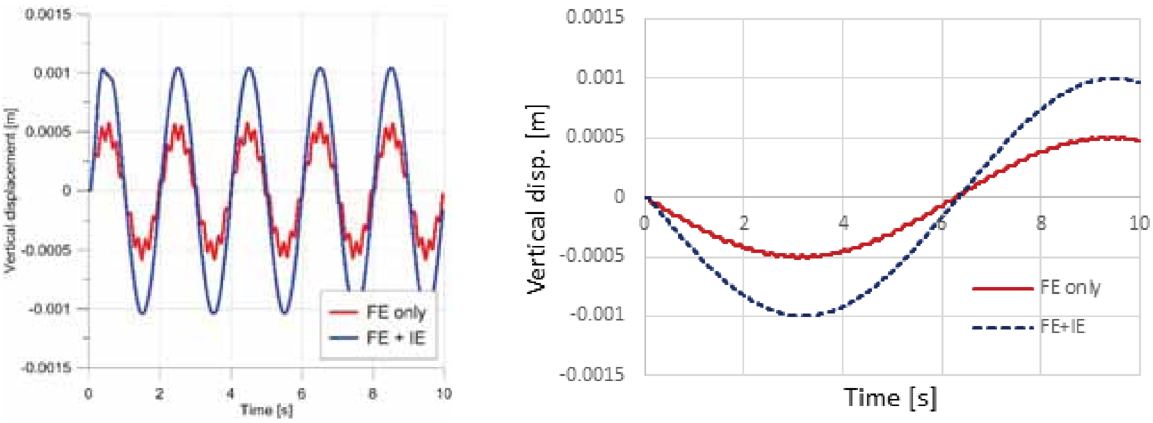

Fig. 11. Time displacement history-sine function ANSYS left, ABAQUS right

5.2 Two dimensional wave propagation

Two dimensional wave propagation through a quarter-space is considered for the sake of completeness. The material parameters are the same as in the case of 1D simulations above. The soil medium as given in Figure 12, and it is a combination of finite and infinite elements. There are 15 infinite elements in total. At the uppermost part a prescribed displacement of magnitude 0.001m is prescribed. Comparisons of the results are given in Fig.13.

In Fig. 13 simulation of wave propagation using both software of ANSYS and ABAQUS is shown. The wave propagation is smooth up to the point where the wave arrives at the boundary, as can be seen from Fig. 13. In the case of finite elements only the wave reflects back to the medium, thus, colliding with the other waves propagating in the medium. In the case of boundaries represented by infinite elements, the wave does not return back to the medium. Namely, the wave is absorbed at the infinite elements. The comparison of newly programmed infinite elements provides acceptable results when compared with the infinite elements in ABAQUS software.

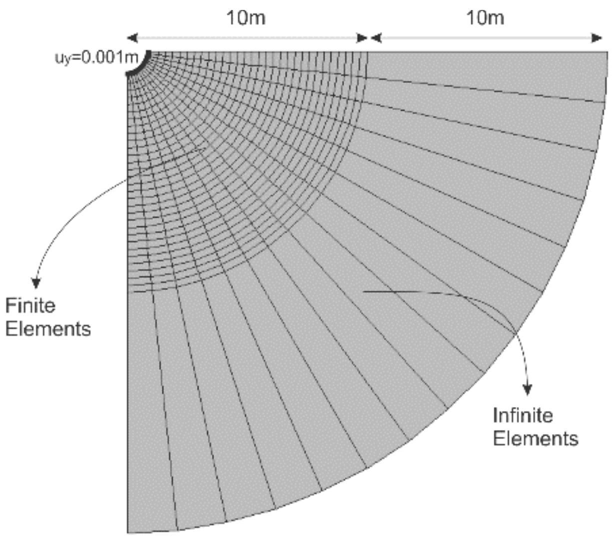

Fig. 12. 2D Domain of finite and infinite elements

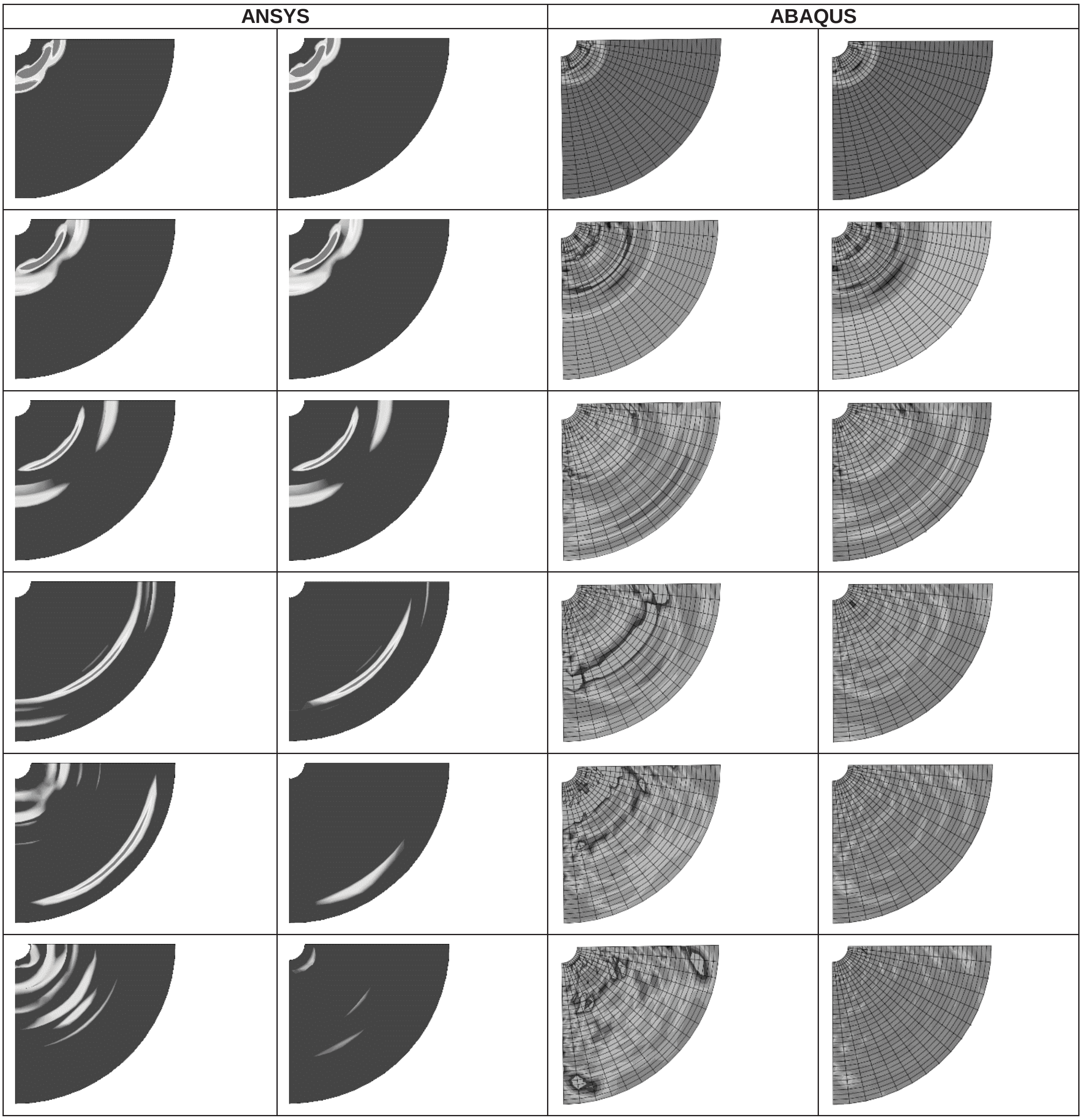

Fig. 13. Wave propagation at time: t=0.04s,t=0.06s,t=0.15s,t=0.18s,t=0.21s,t=0.24s (left only finite elements; right finite and infinite elements)

6 CONCLUSION

In this work, new type of infinite elements with both six and eight nodes having a 1/*n* type decay function have been developed. In simulation of static problems the infinite elements have been shown to give satisfactory results. On the other hand, in dynamic conditions the same infinite elements have been added absorbing layer in order to prevent reflection of the displacement waves back to the region of interest i.e. finite elements. In the case of 1D and 2D wave propagation, the obtained results show that the usage of absorbent infinite elements improves the results greatly.

The obtained numerical results from ANSYS and ABAQUS software are reliable and further application of coupled finite and infinite elements could be considered in the field of soil structure interaction. Moreover, the newly developed absorbent infinite elements are in time domain which allow non-linearity of materials to be considered in the finite elements region.

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SUMMARY

DEVELOPMENT OF INFINITE ELEMENTS FOR SIMULATION OF UNBOUNDED MEDIA

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Based on the elastic theory assumptions, an infinite element boundary which is frequency independent is derived. The infinite element development is based on mapping functions and viscous layer for damping propagating waves. In numerical modelling the general finite element software ANSYS using its User Programmable Features (UPF) is used. Related comparisons are done with PLAXIS and ABAQUS software. In simulation of propagating waves, the numerical approach is done considering several one-dimensional and two-dimensional wave propagation.

Key words: Infinite elements, numerical analysis, wave propagation

APSTRAKT

RAZVOJ BESKONAČNIH ELEMENATA ZA SIMULACIJU NEOGRANIČENOG MEDIJA

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Na osnovu pretpostavki elastične teorije izveden je granica beskonačnog elementa koja je nezavisna od frekvencije. Razvoj beskonačnog elementa zasnovan je na kartografskim funkcijama i viskoznom sloju za prigušivanje propagirajućih talasa. U numeričkom modeliranju koristi se opšti softver konačnih elemenata ANSIS koji koristi svoje korisničke programabilne funkcije (UPF). Za odgovarajuće uporedne analize korišćeni su rezultati dobijeni softverskim paketima PLAKSIS i ABAKUS. U simulaciji propagirajućih talasa, a numerički pristup je obavljen uzimajući u obzir nekoliko jedno-dimenzionalnih i dvodimenzionalnih propagacija talasa.

Ključne reči: beskonačni elementi, numeričke analize, propagacija talasa

SISTEM ZA MONITORING NOVOG ŽELEZNIČKO-DRUMSKOG MOSTA U NOVOM SADU

MONITORING SYSTEM FOR NEW RAIL-ROAD BRIDGE NOVI SAD

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1 UVOD

Projekat "Monitoring sistem i probno opterećenje Železničko-drumskog mosta u Novom Sadu" je konačno prihvaćen u martu 2016. godine od strane izvođača radova (AZVI/Taddei/Horta/Coslada), projektanta (A. Bojović, kompanija "Deling", Beograd) kao sofisticirana, racionalna i modifikovana verzija inicijalnog plana aktivnosti "Oprema za monitoring" i "Probno opterećenje", nakon brojnih priprema, od 2014. godine. Ovaj projekat je realizovan u okviru FTN konzorcijuma čiji su partneri:

- Departman za građevinarstvo i geodeziju, Fakultet tehničkih nauka (FTN), Univerzitet u Novom Sadu (glavni partner konzorcijuma),
- Građevinsko-arhitektonski fakultet Univerziteta u Nišu - Niš (pridruženi partner),
- TRCpro - Petrovaradin (partner za opremu i logistiku),
- GeoGIS Consultants - Beograd (partner za geodetsko merenje),
- Creative Tree i IK Solutions - Novi Sad (partneri za razvoj softvera) i
- Wiss, Janney, Elstner Associates, Inc. - Čikago, SAD (konsalting partner).

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1 INTRODUCTION

Optimized project for "Monitoring Equipment and Test Load of Railway Road Bridge in Novi Sad" was finaly accepted in March 2016, both by Contractor (AZVI/Taddei/Horta JV) and Designer (A. Bojović, "Deling" company, Belgrade) as a sophisticated, rational and modified version of initial "Monitoring Equipment" and "Test Load" plan of activities, after many preparations, since 2014. This project is realized by the following FTN Joint venture:

- Department for Civil Engineering and Geodesy, Faculty of Technical Sciences (FTN), University of Novi Sad (main partner of Joint venture),
- Faculty of Civil Engineering and Architecture, University of Niš (consulting partner),
- TRC Pro - Petrovaradin (hardware installation and logistics partner),
- GeoGIS Consultants - Belgrade (geodesy partner in test by load),
- Creative Tree - Novi Sad (software development partner) and
- Wiss, Janney, Elstner Associates, Inc. - Chicago, USA (consulting partner).

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Poštovani su i ispunjeni sledeći dokumenti:

- SRPS U.M1.046 - Tehnička regulativa za ispitivanje mostova probnim opterećenjem [1],
- inicijalni "Metod rada za monitoring" i "Metod rada za probno opterećenje" ([4] i [5]),
- konačni "Metod rada za monitoring i probno opterećenje" [2], i
- zahtevi Investitora, Projektanta, Izvođača radova, Podizvođača radova i Inženjera.

Naše opšte primedbe i preporuke su bile:

- dugotrajni monitoring i ispitivanje probnim opterećenjem treba realizovati u istoj konfiguraciji mernih mesta, senzora i opreme, s izuzetkom nekih zona koje su značajne samo u fazi lansiranja oba lučna mosta,
- isti radni tim treba da bude odgovoran za opremu, monitoring i ispitivanje probnim opterećenjem i
- snabdevanje i ugradnja opreme, instalacija monitoring sistema i ispitivanje probnim opterećenjem bi trebalo organizovati kao zadatak FTN konzorcijuma po sistemu "ključ u ruke", a obezbeđenje teretnih vozila kamiona/vagona/lokomotiva, kao i logistike na gradilištu treba da organizuje AZVI kao Izvođač radova, prema preporukama FTN tima.

2 OPIS KONSTRUKCIJE ŽELEZNIČKO-DRUMSKOG MOSTA U NOVOM SADU

Most se nalazi na lokaciji starog "Žeželjevog mosta, na trasi međunarodne magistralne elektrificirane pruge “Beograd - Budimpešta”. Most ima dva koloseka, dve drumske trake i dve pešačko-biciklističke trake, izveden je kao čelična konstrukcija, u skladu sa urbanističkim zahtevima grada Novog Sada.

Ukupna dužina mosta je 474.0m i sastoji se od četiri, u konstrukcijskom smislu, potpuno nezavisne celine sledećih karakteristika:

- raspon 25,3m + 1,7m (prilazna konstrukcija mosta 1-2A na strani Petrovaradina),
- raspon 177,0m (lučna konstrukcija mosta 2-3A na strani Petrovaradina),
- raspon 3,0m (prelazna konstrukcija u zoni centralnog stuba)
- raspon 219,0m + 1,7m (lučna konstrukcija mosta 3B-4 na Novosadskoj strani),
- raspon 46,3m (prilazna konstrukcija mosta 4B-5 na Novosadskoj strani),
- razmak između osa zatega = 23,5m,
- razmak između osa luka 2-3 na vrhu = 12,978m,
- razmak između osa luka 3-4 na vrhu = 10,5m,
- razmak između spoljašnjih ivica maski = 31,4m i
- visine lukova su 34,0m i 42,0m.

Prilazne konstrukcije mosta su sistema proste grede sa sledećim karakteristikama:

- bočne grede: čelične konstrukcije, istog oblika kao zatege susednog lučnog mosta,
- srednja greda: spregnuta konstrukcija čelik-beton,
- kolovozna ploča: armiranobetonska, spregnuta vertikalno sa poprečnim nosačima kolovozne konstrukcije i srednjom gredom, dok je sa bočnim gredama spregnuta horizontalno i
- primenjeni materijali: čelik S355, beton C35/45, armatura B500B (ili C).

Respected and fulfilled documents were:

- SRPS U.M1.046 - Serbian technical regulation for testing of bridges by load [1],
- initial "Method Statement for Monitoring and Test Load" ([4] and [5])
- final "Method Statement for Monitoring and Test Load" [2] and
- requirements of Employer, Designer, Contractor, Subcontractor and Engineer.

Our general remarks and recommendations were:

- Long time monitoring and test by load should be performed by same configuration of measurement points, gauges and equipment, with except of some points which are important only in launch phase of both of arch bridges,
- same working team could be in charge for equipment, monitoring and test by load and
- supply and installation of equipment, building of monitoring system and test by load should be organized as a "turn-key" task by FTN Joint venture and obtaining of loaded trucks/wagons/locomotives as well as construction site logistics should be organized by AZVI as Contractor, according to recommendations from FTN team.

2 BASIC STRUCTURAL DESCRIPTION OF THE RAILWAY ROAD BRIDGE IN NOVI SAD

The bridge is located on the place of the old Žeželj Bridge, on the way of the major international electrified railroad "Belgrade - Budapest". Bridge has two tracks, two road lanes and two foot-cycle paths with steel bridge structure according to the requirements of urban conditions of the city of Novi Sad.

Total length of the bridge is 474.0m and it consists of four, in structural manner, completely independent parts with the following dimensions:

- span 25.3m+1.7m (approach bridge part 1-2A on Petrovaradin side),
- span 177.0m (arch bridge part 2-3A on Petrovaradin side),
- span 3.0m (transition structure on central pier zone)
- span 219.0m+1.7m (arch bridge part 3B-4 on Novi Sad side),
- span 46.3m (approach bridge part 4B-5 on Novi Sad side),
- spacing of the ties axes = 23.5m,
- spacing of the arches axes 2-3 at the top = 12.978m,
- spacing of the arches axes 3-4 at the top = 10.5m,
- spacing between the outer edges of the masks = 31.4m and
- height of arches are 34.0m and42.0m.

Approach bridges are simply supported beam systems with following girders and characteristics:

- side girders: steel structure, same shape as tie adjacent tied-arch bridges,
- middle girder: composite structure steel /concrete,
- deck plate: reinforced concrete, part of composite cross-beams and middle girder for verticalactions: coupled with side girders for horizontal actions and
- structural materials are steel S355, concrete

Prelazna konstrukcija je sistema roštilja gde su podužni i poprečni nosači spregnuti sa AB pločom.

Lučni mostovi su slobodno oslonjeni prostorni lukovi sa zategom i sa sledećim karakteristikama i segmentima:

- lukovi, poprečne grede za vezu lukova, zatege (čelična konstrukcija),
- vešaljke (kablovi sa paralelnim strukovima),
- poprečne grede (čelična konstrukcija),
- betonska kolovozna ploča (armiranobetonska spregnuta sa poprečnim nosačima) i
- primenjeni materijali: čelik S355 i S460, beton C35/45 i C40/50, kablovi f_y=1860MPa, armatura B500B (ili C).

Svi čelični delovi konstrukcije su zavareni u radionici, spojevi su zavareni na licu mesta, AB ploča je betonirana na licu mesta. Svi zahtevi pravilnika za projektovanje koji se odnose na trajnost, granična stanja nosivosti (GSN), granična stanja upotrebljivosti (GSU) i aeroelastičnu stabilnost su zadovoljeni.

3 MONITORING PARAMETARA KONSTRUKCIJE MOSTA

Monitoring obuhvata niz aktivnosti osmatranja, prikupljanja podataka, transfer, analizu i prezentaciju podataka dobijenih dugotrajnim merenjem tokom eksploatacije mosta. Cilj monitoringa je formiranje baze podataka za praćenje ponašanja konstrukcije mosta čime se izbegava potencijalna degradacija konstrukcijskih performansi mosta (nosivost, krutost, upotrebljivost i trajnost).

Monitoring mosta uključuje sledeće aktivnosti:

- monitoring utezanja vešaljki,
- monitoring lansiranja lučnih mostova,
- monitoring lansiranja i nanošenja stalnog opterećenja na prilazne rampe i uklanjanje privremenih oslonaca prilaznih rampi,
- monitoring nanošenja stalnog opterećenja na lučne mostove,
- monitoring izgrađenog mosta u testu probnog opterećenja i
- monitoring izgrađenog mosta tokom eksploatacije (tj. dugotrajni monitoring).

4 SPECIFIKACIJE PROCEDURE I OPREME ZA MERENJE

Naš optimizovani Projekat obuhvata sledeću konfiguraciju posmatranih zona/preseka mosta:

- Z-pomeranja: 12 zona u polju i 8 oslonačkih zona,
- X-pomeranja: 4 oslonačke zone,
- Nagibi: 12 zona u polju i 9 oslonačkih zona,
- Naponi: 4 zona u polju, 8 oslonačkih zona i 2 zone za vreme navlačenja mosta,
- sile u 80 vešaljki,
- ubrzanja, frekvencije i parametri prigušenja: 12 zona u polju i 9 oslonačkih zona i
- temperatura u konstrukciji mosta: 12 zona u polju i 9 oslonačkih zona.

C35/45 and reinforcement B500B (or C).

Transition structure is the system of cross and connection beams with RC deck plate.

Arch bridges are simply supported arch-tie space structural systems with the following parts and characteristics:

- arches, transversal arch connecting beams, ties (steel structures),
- hangers (cables with parallel strands),
- cross beams (steel structure) and
- concrete deck plate (reinforced concrete coupled with cross beams).
- structural materials: steel S355 and S460, concrete C35/45 and C40/50, cables f_y=1860MPa and reinforcement B500B (or C).

All steel structural parts are welded at workshop, connection joints are welded at site, and RC deck plate are concreted at site. All design code requirements related to durability, ultimate limit states (ULS), serviceability limit states (SLS) and aero elastic stability, are satisfied.

3 MONITORING OF BRIDGE STRUCTURAL PARAMETERS

Monitoring was performed through the set of activities that include observation, acquisition, transfer, analysis and presentation of data obtained by long time measurement during bridge exploitation. Monitoring target was database formation for observing bridge structure behaviour due to avoid potential deterioration of bridge structural performance (bearing capacity, stiffness, serviceability and durability).

Bridge monitoring comprehends the following:

- monitoring during tensioning of hangers,
- monitoring during launching of arch bridges,
- monitoring during installation of permanent load on approach bridges and releasing of approach bridges from temporary supports,
- monitoring during installation of permanent load on arch bridges,
- monitoring of completed bridge during test by load and
- monitoring of completed bridge during exploitation (i.e. long time monitoring).

4 SPECIFICATION OF MEASUREMENT PROCEDURES AND EQUIPMENT

Our optimized project comprehends the following configuration of observed zones/sections of the bridge:

- Z-deflections: 12 mid span zones and 8 support zones,
- X-deflections: 4 support zones,
- Inclinations:12midspan zones and 9 support zones,
- Stresses: 4midspan zones, 8 support zones and 2 zones during launching
- forces in 80 hangers,
- acceleration, frequency and damping parameters: 12midspan zones and 9 support zones and
- temperature in bridge structure: 12midspan zones and 9 support zones.

Oprema za monitoring, softver i vozila za ispitivanje probnim opterećenjem su:

• 328 mernih traka u 14 preseka (za napone u konstrukciji),

• 80 merača sile (isporučenih od strane proizvođača vešaljki, za sile u vešaljkama)

• 12 deflektometara u 4 preseka pokretnih oslonaca (za horizontalna pomeranja),

• 32 dvoosna inklinometra (za merenje promene vertikalnog nagiba i indirektno registrovanje vertikalnih pomeranja) sa ugrađenim troosnim akcelerometrom i senzorom za merenje temperature u 20 preseka konstrukcije i u jednom preseku zone centralnog stuba (za merenje ubrzanja u svim pravcima i merenje temperature u konstrukciji)

• meteorološka stanica za merenje temperature i vlažnosti vazduha i brzine vetra,

• 28 akvizicionih i kontrolnih uređaja (14 zona),

• 2 PC sistema (van mosta),

• Ethernet (1.2km) i signal kablovi (8.6km),

• Originalno razvijeni i fabrički softver za upravljanje mernim podacima i

• 38 kamiona (235kN), 32 E/4 (720kN) vagona, 10 E/2 (360kN) vagona i 3 lokomotive (1009kN svaka) u 28 šema opterećenja: 24 statičke i 4 dinamičke.

Sva pomenuta oprema je obaveza FTN osim merača sile u vešaljkama (obaveza dobavljača vešaljki - VSL) i vozila za test probnim opterećenjem (obaveza AZVI kao izvođača radova).

Cilj praćenja različitih mehaničkih i fizičkih veličina može se opisati u sledećem:

• naponi, izračunati iz registrovanih dilatacija, ukazuju na nosivost celokupne konstrukcije (sve merne trake će biti uparene sa "kompenzacionim mernim trakama" za poništavanje uticaja temperature u tačkama registrovanja dilatacija),

• sile u vešaljkama treba da budu osnova za proveru pravilne funkcije vešaljki u takvom tipu konstrukcijskog sistema i promene sila tokom eksploatacije (relaksacija i slični problemi mogu biti otkriveni smanjenjem sile u vešaljkama),

• horizontalna pomeranja u oslonačkim zonama će biti mera uzdužnih deformacija konstrukcijskih delova (pre od promene temperature) i funkcionisanja pokretnih elemenata oslonca,

• nagibi preseka konstrukcije će ukazati na kapacitet krutosti u smislu strukturalne upotrebljivosti u kontaktnim zonama između četiri glavna dela mosta,

• vertikalna pomeranja će se izračunati iz "5 nagiba u liniji" (jedna linija za oba prilazna mosta i dve linije za oba lučna mosta), dobijajući "polinom petog stepena pomeranja" od "polinoma četvrtog stepena nagiba ", što je pristupačan postupak u potpunosti prema zahtevima praćenja u realnom vremenu i potrebne tačnosti (greška je manja od rezolucije merenja mernih traka i mnogo preciznija od GPS procedura),

• vibracije i ubrzanja u sva tri pravca će se koristiti za procenu dinamičkih faktora, svojstvenih frekvencija i vrednosti prigušenja, što su parametri za proveru globalnog ponašanja konstrukcijskog sistema mosta u kratkom i dužem vremenskom periodu,

• temperature u konstrukciji će se posmatrati zbog poznavanja temperaturnih gradijenata koji će pomoći da se objasne različiti fenomeni ponašanja u potpunosti i

Monitoring equipment, software and test by load vehicles are:

• 328 strain gauges in 14 sections (for structural stresses),

• 80 force gauges (for forces in hangers, delivered by "VSL" company)

• 12 deflection gauges in 4 movable support sections (for horizontal deflections),

• 32 bi-axial inclinometers (for vertical inclinations and vertical deflections in indirect manner) with embedded tri-axial accelerometers and temperature gauges in 20 structural sections and in one section of central pier zone (for accelerations and structural temperature),

• air temperature, humidity and windspeed gauges and devices for recognition of traffic circumstances,

• 28 Acquisition and Control devices (14 zones),

• 2 PC systems (out of bridge),

• Ethernet (1.2km) and signal cables (8.6km),

• custom and OEM software for management of measurement data and

• 38 trucks (235kN), 32 E/4 (720kN) wagons, 10 E/2 (360kN) wagons and 3 locomotives (1009kN each) in 28 load schemes: 24 static and 4 dynamic.

All mentioned equipment is duty of FTN except force gauges in hangers (obligation of supplier of hangers - "VSL") and loaded vehicles for Test Load (obligation of AZVI as Contactor).

The aim of observation of various mechanical and physical quantities could be described in the following:

• stresses, calculated from registered strains, indicate a bearing capacity state of the whole structure (all strain gauges are coupled by "compensation strain gauges" for annul influence of temperature in strain registering points),

• forces in hangers should be base for check of proper function of hangers in such type of structural system and changes of forces during exploitation (relaxation and similar problems may be diagnosed by decreasing forces in hangers),

• horizontal deflections in support zones are indicators of longitudinal deformations of structural parts (mainly from temperature changes) and function of movable supports,

• inclinations of structural sections indicate stiffness capacity in the sense of structural serviceability in contact zones between four main bridges parts,

• vertical deflections are calculated from "5 inclinations-in-line" (one line for both approach bridges and two lines for both arch bridges), obtaining the "5th degree deflection polynomial" from "4th degree inclination polynomial", what is fully affordable procedure according to the requirements of the real time monitoring and needed accuracy (errors scale is less than measurement resolution of gauges and much precise than GPS based procedures),

• vibration and acceleration in all three directions are used for estimation of dynamic factors, natural frequencies and damping values what are parameters for checking global bridge structures systems work during the short time and long time periods,

• by the knowledge of structural temperatures it is possible to obtain temperature gradients for right explanation of some structural behaviour phenomenon and

• parametri sredine (meteorološki podaci) zajedno sa uslovima saobraćaja će se koristiti za dobijanje potpunog pregleda mogućih uzroka potencijalnih problema koji su relevantni za eksploataciju mosta.

5 OPŠTE SPECIFIKACIJE MERENJA

Svi predloženi merači, uređaji i oprema imaju merne performanse na višem nivou od realno potrebnih konstrukcijskih i inženjerskih zahteva ovog monitoringa i isporučeni su od istaknutih proizvođača sa referencama za srodne građevinske konstrukcije.

FTN tim je u potpunosti sposoban za odgovarajući rad sa “Opremom za monitoring” i “Probnim opterećenjem” i profesionalno korišćenje svih predviđenih merača, uređaja i opreme, što se potvrđuje brojem i vrstom njihovih referenci, naučnim i inženjerskim iskustvom.

Sistem za merenje za sve mostovske konstrukcije se sastoji od tri podsistema:

• podsistem merača (merne trake, merači sile, inklinometri, akcelerometri, termometri i deflektometri), koji je dat u Tabeli 1,

• podsistem za akviziciju podataka (digitalnih višekanalni mernih pojačala sa fabrički ugrađenim softverom i namenskim računarskim sistemima sa softverom za prikupljanje podataka) i

• podsistem za procesiranje podataka (mrežno orijentisan višenamenski računarski sistem za prikupljanje, prenošenje i obradu podataka stečenih iz prethodno spomenutog podsistema sa originalnim "user fiendly" orijentisanim softverom za proračun i prikazivanje podataka).

• meteorological data together with traffic flow circumstances will be used for obtaining full view on possible causes for all issues relevant for bridge exploitation.

5 GENERAL MEASUREMENT SPECIFICATIONS

All proposed gauges, devices and equipment are with measurement performances on higher level than real needed structural and engineering issues of this monitoring case and from eminent manufacturers which have references for related civil engineering structures.

FTN team is completely capable for competent work on "Monitoring Equipment" and "Test Load" tasks and professional use of all proposed gauges, devices and equipment what are verified by quantity and kind of their references, scientific and engineering experience.

Measurement system for all bridges consists of three subsystem parts:

• subsystem of gauges (strain gauges, force gauges, inclinometers, accelerometers, thermometers and deflectometers), what is given in Table 1,

• subsystem of data acquisition devices (digital multichannel measuring amplifiers with factory embedded software and dedicated computer systems with software for data acquisition) and

• subsystem for data processing (multipurpose computer system for collection, transfer and processing of data acquired from previously mentioned subsystem with custom developed user friendly software for data presentation).

Tabela 1: Sumarni raspored mernih mesta
Table 1: Summary configuration of strain gauges

Deo mosta ***Part of bridge***	**Merne trake na čeliku** ***Strain gauges on steel***	**Merne trake na čeliku (rozete)** ***Strain gauges on steel (rosettes)***	**Merne trake na betonu** *Strain gauges (concrete)*	**Merne trake na armaturi** *Strain gauges (RF bars)*	**Senzori sila u vešaljkama** *Force gauges (hangers)*	**Inklinometri (akcelerometri + termometri)** *Inclinometers (accelerometers + thermometers*	**Horizontalni deflektometri** *Horizontal deflectometers*
1-2A	**17**	**42**	**3**	**2**	**-**	**5**	**3**
2-3A	**91**	**-**	**3**	**6**	**36**	**11**	**3**
3B-4	**91**	**-**	**3**	**6**	**44**	**11**	**3**
4B-5	**17**	**42**	**3**	**2**	**-**	**5**	**3**
Ukupno	**328**				**80**	**32**	**12**

Neophodno je naglasiti da svi uređaji podsistema za akviziciju podataka i podsistema za obradu podataka imaju veću tačnost merenja i obrade od svih korištenih merača i senzora zbog digitalne rezolucije koja pokriva interval izmerenih i registrovanih vrednosti više nego dovoljno dobro u odnosu na stvarne inženjerske potrebe u ovom slučaju.

5.1 Oprema za registrovanje normalnih i smičućih napona

FTN projekat obuhvata 328 mernih traka na sledeći način:

It is necessary to emphasize that all the devices of data acquisition subsystem and data processing subsystem have greater measurement and processing accuracy than all used gauges and sensors, because of digital resolution which covers interval of measured and registered values more than sufficient in relation to the real engineering need in such case.

5.1 Equipment for Registering axial and shear stresses

FTN project undertakes 328 items of strain gauges in the following manner:

- prilazni most 1-2A: 64 senzora (17+42+3+2, čelik + rozete + beton + arm. šipke),
- lučni most 2-3A: 100 senzora (91+3+6, čelik + beton + arm. šipke),
- lučni most 3B-4: 100 senzora (91+3+6, čelik + beton + arm. šipke) i
- prilazni most 4B-5: 64 senzora (17+42+3+2, čelik + rozete + beton + arm. šipke).

Sve merne trake isporučuje kompanija "Hottinger-Baldwin Messtechnik" (HBM, Nemačka) na tri sledeća tipa:

- merne trake za čelik (jednoosna konfiguracija): LY11-6/120,
- merne trake za beton: LY41-50/120 (pre-wired verzija od LY11) i
- merne trake za šipke armature: LY11-6/120.

Svaka pojedinačna merna traka će biti spojena sa odgovarajućom "kompenzacionom mernom trakom" za kompenzaciju uticaja temperature u tački za registraciju, povezivanjem pomoću 5-žičnih kablova i podešavanjem mernih pojačala u podešavanjima "polovina mosta". Deklarisana tačnost merenja sa pomenutim tipovima mernih traka je 1μm/m.

5.2 Oprema za registrovanje vertikalnih pomeranja

Za posmatranje vertikalnih pomeranja, monitoring sistem koristi 30 dvoosnih inklinometara sa ugrađenim troosnim akcelerometarima i senzorima za merenje temperature u sledećem rasporedu

- prilazni most 1-2A: 5 komada (u osi centralnog sanduka),
- lučni most 2-3A: 10 komada (5 komada u osama svake zatege),
- lučni most 3B-4: 10 komada (5 komada u osama svake zatege),
- prilazni most 4B-5: 5 komada (u osi centralnog sanduka).

Svi inklinometri je isporučila kompanija "Sensr" (SAD), a tip "CX1 Structural Response Monitor" se koristi za sve mostove. Veza između CX1 i namenskog računarskog podsistema je zasnovana na Ethernet/IP.

Kao što je pomenuto, vertikalna Z-pomeranja se izračunavaju iz nagiba. Ovo je jedini mogući način za tačno dobijanje Z-pomeranja u "realnom vremenu" i standardna procedura za monitoring ovakvog tipa konstrukcije.

Zbog toga što se svaki CX1 sastoji ne samo od inklinometra, već i od senzora za merenje temperature, moguće je postići vrlo dobre rezultate temperaturne kompenzacije za dugotrajno praćenje. Tačnost CX1 je ±0.0001°, što drži apsolutnu grešku u granicama od ±0.19mm za ugib većeg Lučnog mosta 3B-4.

Dodatni razvoj u poređenju sa drugim slučajevima monitoringa je uvođenje 5 inklinometara i liniji što obezbeđuje tačnost potrebnog inženjerskog nivoa. Za upoređenje, najbolji komercijalno dostupni GPS sistemi imaju apsolutnu grešku od 3.5mm i 15mm za statička i dinamička merenja Z-pomeranja, što je potpuno neodgovarajuće za potrebe monitoringa ovog mosta.

- approach bridge 1-2A: 64 gauges (17+42+3+2, steel+rosettes + concrete + bars),
- arch bridge 2-3A: 100 gauges (91+3+6, steel+concretes +bars),
- arch bridge 3B-4: 100 gauges (91+3+6, steel+concretes +bars) and
- approach bridge 4B-5: 64 gauges (17+42+3+2, steel+rosettes +concrete + bars).

All strain gauges are delivered from "Hottinger-Baldwin Messtechnik" (HBM, Germany) company in three following types:

- strain gauges for steel (single or rosette configuration): LY11-6/120,
- strain gauges for concrete: LY41-50/120 and
- strain gauges for reinforcement bars: LY11-6/120.

Each single strain gauge is coupled with "compensation strain gauge" to eliminate the influence of temperature in measurement point, with connection by 5-wire cables and adjustment of measurement amplifiers in "half bridge" settings. Declared accuracy of measurement with mentioned types of strain gauges is 1μm/m.

5.2 Equipment for Observation of vertical deflections

For observation of vertical deflection our project acclaims use of 30 bi-axial inclinometers with embedded tri-axial accelerometers and temperature gauges in the following arrangement:

- Approach bridge 1-2A: 5 items (in one central box axis),
- Arch bridge 2-3A: 10 items (5 items in axes per each tie),
- Arch bridge 3B-4: 10 items (5 items in axes per each tie),
- Approach bridge 4B-5: 5 items (in one central box axis).

All inclinometers are delivered from "Sensr" company (USA) and type "CX1 Structural Response Monitor" are used for all bridges. Connection between CX1 and dedicated computer subsystem is based on Ethernet/IP.

It is already mentioned that vertical Z-deflections are calculated from inclinations. This is the only possible way for "real time" and accurate observation of Z-deflection and standard procedure for monitoring of this kind of structures.

It is possible to achieve very good results in temperature compensation for long time monitoring since each CX1 consists of both inclinometer and temperature gauge as well. Accuracy of CX1 is ±0.0001°, what makes the absolute error of approximately 0.19mm for observation of larger arch bridge.

Additional development in comparison of other monitoring cases is introduction of 5 inclinometers in line what increase needed accuracy to reasonable engineering level. As comparison example, the best commercially available GPS based systems have absolute accuracy between 3.5mm and 15mm for static and dynamic measurements of Z-deflections, what is completely inappropriate for our needs.

5.3 Oprema za merenje ugla rotacije

Za merenje ugla rotacije Monitoring sistem obuhvata pomenuti "CX1 Structural Response Monitor" koji u osnovi sadrži dvoosni inklinometar. Koristi se sledeći raspored inklinometara:

- prilazni most 1-2A: 5 komada (u osi centralnog sanduka),
- lučni most 2-3A: 11 komada (5 komada u osama svake zatege, jedan u zoni centralnog stuba),
- lučni most 3B-4: 11 komada (5 komada u osama svake zatege, jedan u zoni centralnog stuba),
- prilazni most 4B-5: 5 items (in one central box axis).

Svi komentari, objašnjenja i detalji dati u prethodnom poglavlju važe i u ovom slučaju merenja.

5.4 Oprema za merenje horizontalnih pomeranja

Za posmatranje horizontalnih X-pomeranja u zonama pokretnih oslonaca, FTN projekat predviđa 12 induktivnih deflektometara u sledećem rasporedu

- prilazni most 1-2A (zona "1"): 3 komada,
- lučni most 2-3A (zona "2"): 3 komada,
- lučni most 3B-4 (zona "4"): 3 komada i
- prilazni most 4B-5 (zona "5a"): 3 komada.

Svi deflektometri su od "Hottinger-Baldwin Messtechnik" (HBM) i koriste se tipovi WA500 (za lučne mostove) i WA200 (za prilazne mostove). WA500/WA200 će biti povezani pomoću 5-žičnih kablova sa mernim pojačalima. Tačnost merenja je 0.01mm.

5.5 Oprema za merenje ubrzanja konstrukcije

Za merenje ubrzanja tačke konstrukcijskog sistema, Monitoring sistem koristi pomenuti "CKS1 Structural Response Monitor " koji se sastoji od jednog triosnog akcelerometra. Sledeći je raspored akcelerometara:

- prilazni most 1-2A: 5 komada (u osi centralnog sanduka),
- lučni most 2-3A: 11 komada (5 komada u osama svake zatege,
- jedan u zoni centralnog stuba),
- lučni most 3B-4: 11 komada (5 komada u osama svake zatege,
- jedan u zoni centralnog stuba),
- prilazni most 4B-5: 5 komada (u osi centralnog sanduka).

Tačnost CX1 ugrađenog akcelerometra je u rasponu od 1.0mm/s^2 (sa rezolucijom od 0.1mm/s^2, što čini ovaj uređaj potpuno pogodnim za merenje svih komponenti konstrukcijskog ubrzanja, posebno u slučaju tzv. "ambijentalnih" vibracija, koje su osnova za procenu svojstvenih frekvencija i konstrukcijskih parametara prigušenja). Predviđeni broj akcelerometara daje mogućnost "mapiranja promene dinamičkih parametara" kroz vreme praćenja, što će biti izvor za procenu promene krutosti i konstrukcijskih parametara upotrebljivosti.

5.3 Equipment for Measurement of angle rotations

The abovementioned "CX1 Structural Response Monitor" which basically consists of bi-axial inclinometer was adopted for measuring angle rotation. The following pattern of 32 items of inclinometers is used:

- Approach bridge 1-2A: 5 items (in one central box axis),
- Arch bridge 2-3A: 11 items (5 items in axes of each tie, one in central pier zone),
- Arch bridge 3B-4: 11 items (5 items in axes of each tie, one in central pier zone),
- Approach bridge 4B-5: 5 items (in one central box axis).

All comments, explanations and details given in previous chapter are valid in this case of measurement.

5.4 Equipment for Measuring horizontal deflections

For observation of horizontal X-deflection in zones of movable supports FTN project assumes 12 inductive deflectometers in the following arrangement:

- Approach bridge 1-2A (zone "1"): 3 items,
- Arch bridge 2-3A (zone "2"): 3 items,
- Arch bridge 3B-4 (zone "4"): 3 items and
- Approach bridge 4B-5 (zone "5a"): 3 items.

All deflectometers are from "HBM" company: type WA500 for arch bridges and type WA200 for approach bridges. WA500/WA200 are connected by 5-wire cables with measurement amplifiers. Measurement accuracy of these gauges is 0.01mm.

5.5 Equipment for Measuring structural accelerations

The abovementioned "CX1 Structural Response Monitor" which consists one tri-axial accelerometer was used for measuring accelerations of structural point. The following pattern of 32 items of such embedded accelerometers is used:

- Approach bridge 1-2A: 5 items (in one central box axis),
- Arch bridge 2-3A: 11 items (5 items in axes of each tie, one in central pier zone),
- Arch bridge 3B-4: 11 items (5 items in axes of each tie, one in central pier zone),
- Approach bridge 4B-5: 5 items (in one central box axis).

Accuracy of CX1 embedded accelerometer is in range of 1.0mm/s^2 (with resolution of 0.1mm/ s^2, which makes this device completely suitable for measurement of all components of structural acceleration, especially in the case of so-called "ambient" vibration, which are the bases for estimation of natural frequencies and structural damping parameters. This number of accelerometers provides the possibility for defining the "map of change of dynamic parameters" through the time of monitoring, which will be the source of estimation of change of stiffness and structural serviceability parameters.

5.6 Oprema za merenje temperature konstrukcije

Za merenje temperature u tačkama konstrukcije monitoring sistem predviđa isti "CX1 Structural Response Monitor" koji sadrži jedan termometar u sledećem rasporedu:

- prilazni most 1-2A: 5 komada (u osi centralnog sanduka),
- lučni most 2-3A: 11 komada (5 komada u osama svake zatege,
- jedan u zoni centralnog stuba),
- lučni most 3B-4: 11 komada (5 komada u osama svake zatege,
- jedan u zoni centralnog stuba),
- prilazni most 4B-5: 5 komada (u osi centralnog sanduka).

Tačnost CX1 ugrađenog termometra je 1°C (sa rezolucijom od 0.1°C, što čini ovaj uređaj potpuno pogodnim za merenje temperature u konstrukciji). Predviđeni broj ugrađenih termometara daje mogućnost za "mapiranje temperature u konstrukciji", što će biti osnova za analizu i procenu promene ponašanja konstrukcije.

5.7 Oprema za merenje sila u vešaljkama

Oprema za merenje sila u vešaljkama je obaveza dobavljača vešaljki (VSL), a FTN preuzima obavezu da uključi VSL monitoring podsistem sa monitoring sistemom celog mosta.

5.8 Registrovanje vremenskih uslova

Ovi tipovi i brend opreme će biti kompatibilni sa zvaničnim zahtevima Republičkog hidrometeorološkog zavoda Srbije (RHMS) zbog mogućeg sukoba interesa i zakonskih propisa u ovoj oblasti. Zbog toga će informacije o konačnom izboru opreme podsistema za registraciju vremenskih uslova biti predstavljene nakon konačnog dogovora između Investora (Železnice Srbije) i RHMS.

Ova okolnost je uobičajena za svaku zgradu ili konstrukciju koja je vlasništvo države, imovina državnog preduzeća ili javne službe.

5.9 Snimanje toka saobraćaja

Snimanje toka saobraćaja vrši se sinhronizovanim radom podsistema kamera za snimanje i podsistema za akviziciju podataka nekom vrstom "značajnog okidača" koji se dobija kao prekoračenje prethodno definisanih izmerenih vrednosti iz podsistema određenog broja senzora.

U svakodnevnim "normalnim" i "neincidentnim" okolnostima saobraćaja snimanje saobraćajnog toka će se vršiti uz pomoć podsistem kamera za snimanje koji snima delove konstrukcije mosta i koloseke i drumske trake u vremenskim intervalima koji predstavljaju kompromis između potrebe za ispravnim pregledom saobraćaja i racionalne upotrebe memorije. Jedna slika u sekundi (1FPS) je u tom smislu optimalna brzina snimanja za dobijanje dovoljne količine informacija o položaju vozila ako voze na maksimalnoj granici brzine u

5.6 Equipment for Measuring structure temperature

Measurement of temperatures is predicted by the same "CX1 Structural Response Monitor" which consists of one thermometer. The following pattern of 32 items of such embedded thermometers is used:

- Approach bridge 1-2A: 5 items (in one central box axis),
- Arch bridge 2-3A: 11 items (5 items in axes of each tie, one in central pier zone),
- Arch bridge 3B-4: 11 items (5 items in axes of each tie, one in central pier zone),
- Approach bridge 4B-5: 5 items (in one central box axis).

Accuracy of CX1 embedded thermometer is in range of 1°C (with resolution of 0.1°C, what make this device completely suitable for measurement of structural temperature. Predicted number of embedded thermometers gives opportunity to obtain the "map of structural temperatures" through time of monitoring, which will be the basis for analyzing and estimating the change of structural behaviour.

5.7 Equipment for Measuring forces in hangers

Equipment for measuring forces in hangers is obligation of supplier of hangers ("VSL") and FTN takes the responsibility to harmonize "VSL" monitoring subsystem with the whole monitoring system of the bridge.

5.8 Registering of weather conditions

This type and brand of equipment will comply with official requirements of Republic Hydrometeorological Service of Serbia (RHMS of Serbia) because of possible conflict of interest and law regulations in this area. Thus, information about the final choice of weather conditions registering equipment subsystem will be presented after the final agreement between Investor (Railways of Serbia) and RHMS of Serbia.

This circumstance is usual for any building or structure which is the property of state, property of state company or public service.

5.9 Recording traffic flow

Recording traffic flow will be performed through synchronized work of camera recording subsystem and dedicated data acquisition subsystem by some kind of "significant trigger" obtained as exceed of previously defined measured values from number of sensors and gauges subsystem.

In everyday "normal" and "no accidental" traffic circumstances recording of traffic flow will be carried out by camera recording subsystem which records bridge structural parts and rail and road tracks in the timing which is a compromise between a need for correct traffic observation and rational memory usage. One picture frame in second (1FPS) is in that sense optimal recording speed for obtaining enough amount of information about position of vehicles if they drive on maximum city speed limit (50km/h or 13.9m/s). Only last uslovima gradske vožnje (50km/h ili 13,9m/s). Samo poslednjih 60min saobraćaja biće zabeleženo u povećanoj rezoluciji vremena (24FPS) za moguće "događaje od većeg značaja". Ako se to ne pojavi, prethodna istorija će se snimiti u 1FPS vremenskoj rezoluciji.

U slučaju "događaja od većeg značaja", što bi moglo da predstavlja neku pobudu registrovanih vrednosti napona i/ili izmerenih vrednosti ugiba i/ili ugla rotacije, ova pojava će biti pokretač za snimanje u povećanoj vremenskoj rezoluciji. Kasnija analiza sinhronizovanog snimanja i serija podataka izmerenih vrednosti može biti osnova za zaključke o uzrocima mogućeg konstrukcijskog problema.

Važno je naglasiti da tipovi i marke opreme moraju biti u skladu sa zvaničnim zahtevima Ministarstva unutrašnjih poslova Republike Srbije (MUP Srbije) zbog mogućeg sukoba interesa i zakonskih propisa u ovoj oblasti. Zbog toga će informacije o konačnom izboru podsistema opreme za snimanje biti predstavljene nakon konačnog dogovora između Investora (Železnice Srbije) i MUP-a Srbije. Ovo je uobičajen pristup za konstrukcije koje su vlasništvo države.

6 SPECIFIKACIJE SISTEMA ZA OBRADU PODATAKA

Sistem za obradu podataka je organizovan u dva podsistema:

- podsistem za akviziciju podataka (digitalnih višekanalni mernih pojačala sa fabrički ugrađenim softverom i namenskim računarskim sistemima sa softverom za prikupljanje podataka) i
- podsistem za procesiranje podataka (mrežno orijentisan višenamenski računarski sistem za prikupljanje, prenošenje i obradu podataka stečenih iz prethodno spomenutog podsistema sa prilagođenim “user fiendly” softverom za proračun i prikazivanje podataka)

Neophodno je naglasiti da tim zadužen za sistem za obradu podataka ima adekvatne kompetencije u oblasti projektovanja mostova, ispitivanju konstrukcija i informacionim tehnologijama. Ovo je očigledno zbog potrebe za prezentacijom, analizom i tumačenjem velike količine podataka, kao i mogućim servisiranjem, popravkom i daljim razvojem sistema.

6.1 Akvizicija, transfer, skladištenje i upravljanje podacima

Prikupljanje podataka se realizuje mrežom HBM univerzalnih industrijskih mernih pojačala tipa PMX koji se nalaze u odgovarajućoj konfiguraciji i sa frekvencijama snimanja u zavisnosti od prirode odgovora konstrukcije. "Standardni" svakodnevni odgovor biće zabeležen frekvencijom "jednom u svakih 5s" i sa "posebnim" snimanjem slučaja "jednom u sekundi", što je dovoljno za naknadnu analizu. Odluka o prelazu sa "standardnog" na "poseban" način snimanja biće zasnovana na funkciji okidača. Okidači će biti veće od uobičajenih vrednosti nekih relevantnih parametara. Tipično ubrzanja i/ili napori će biti okidači, ali bi izbor bilo koje izmerene veličine kao okidača trebao biti moguć.

Vremensko sinhronizovanje merenja i/ili prikupljanje podataka vršiće se mrežnim upravljanjem

60min of traffic will be recorded in increased time resolution (24FPS) for the possible "event of greater attention". If it fails, the previous history will be recorded in 1FPS time resolution.

In the case of "event of greater attention" which could be some excitation of registered values of stress and/or measured values of deflection and/or angle rotation these phenomenon will be a trigger for recording in increased time resolution. Later analysis of synchronized recording and data series of measured values can be the basis for conclusions on the cause of structural issue.

It is important to emphasize that types and brands of equipment should comply with official requirements of Ministry of Internal Affairs Republic of Serbia (MUP of Serbia) because of possible conflict of interest and law regulations in this area. Thus, information about final choice of recording equipment subsystem will be presented after final agreement between Investor (Railways of Serbia) and MUP of Serbia. This is usual approach for buildings which are the property of state.

6 SPECIFICATION OF DATA PROCESSING SYSTEM

Data processing system is organized into two subsystems:

- subsystem of data acquisition devices (digital multichannel measuring amplifiers with factory embedded software and dedicated computer systems with software for data acquisition) and
- subsystem for data processing (multipurpose computer system for collection, transfer and processing of data acquired from previously mentioned subsystem with custom developed user friendly software for data presentation).

It is necessary to emphasize that the team in charge of data processing system has adequate expert knowledge and skills on bridge design, testing structures and computer technologies. This is obvious because of the need for competent presentation, analysis and interpretation of large amounts of data as well as potential servicing, repair and further development of the system.

6.1 Data acquisition, transfer, storage and management

Data acquisition is realized by HBM universal measurement amplifiers located in appropriate configuration and with recording frequencies depending on the nature of structural response. "Standard" everyday response will be recorded by frequency of "one in every 5s" and with "special" case recording of "one in second", sufficient for subsequent analysis. Decision to switch from "standard" to "special" mode of recording shall be based on trigger functionality. Triggers will be larger than usual values of some relevant parameters. Typically accelerations and/or stresses can be triggers, but choice of any measured quantity as trigger should be possible.

Time synchronization of measurement and/or data collection will be performed by network operation of components of this subsystem, which is a standard komponentama ovog podsistema, što je standardna opcija u specijalizovanom softveru dopunjenom od strane HBM univerzalne jedinice mernog pojačala (HBM). Slično tome, kompanija Sensr isporučuje sopstveni softver za prikupljanje podataka za upravljanje vezom između CX1 inklinometara i računara.

Od pojačala za akviziciju, podaci će biti preneti preko Ethernet/IP konekcija. U nekim slučajevima i na nekoj lokaciji ova veza će biti bežična.

Podaci, dobijeni na prethodno opisan način, biće sačuvani na uređajima za skladištenje na namenskim računarskim jedinicama sa tzv. "mirrored" i "striped" konfiguracijom što predstavlja prvi nivo zaštite podataka.

Sledeća faza obrade podataka će istovremeno predstavljati drugi nivo zaštite podataka.

6.2 Prezentacija, analiza i interpertacija podataka

Iz ranije opisanog namenskog računarskog sistema (namenjenog za skladištenje podataka) podaci će biti prebačeni u završnu fazu - višenamenski personalni računarski sistem namenjen prezentaciji, analizi i interpretaciji podataka prikupljenih iz mernih mesta. Ovaj računarski sistem će zabeležiti podatke u drugoj tzv. "mirrored" i "striped" konfiguraciji skladištenja, koji služi kao drugi nivo zaštite podataka.

Ovaj sistem automatski generiše dokument izveštaja sa rezimeom rezultata, sa različitim opcijama za alarm i obaveštavanje o hitnim slučajevima, kao i vremensku sinhronizaciju snimljenih putnih i šinskih vozila pomoću sistema kamere.

Izmereni podaci će biti predstavljeni na numerički i grafički način koji su kompatibilni sa široko korišćenim softverom - internet pretraživačima.

Internet pretraživač ima za cilj prikazivanje svih relevantnih podataka sa mogućnostima potrebnog proračuna i obrade u tzv. pozadinskom okruženju koje je transparentno i otvoreno za posvećenog korisnika i sa ograničenim pristupom običnog korisnika.

U ovom slučaju neophodne nadgledane vrednosti i podaci će biti dostupni svim zaduženim osobama u svakom trenutku (24/7) na bilo kojoj lokaciji sa Internet konekcijom i bilo kom sistemskom softverskom okruženju. Jedini neophodan preduslov za korišćenje podataka dobijenih od strane našeg sistema jeste prosečno tehničko obrazovanje u građevinarstvu.

Za osnovnu upotrebu predloženog sistema (prikaz dijagrama podataka, istorije ponašanja mosta, kretanja mogućeg budućeg odgovora mosta, itd.) dovoljan je skroman nivo znanja upotrebe računara. Naše dosadašnje iskustvo je dovoljan dokaz da je ovaj sistem optimalan u smislu korisničkih zahteva.

7 KONFIGURACIJA UREĐAJA ZA MONITORING

Sledeća poglavlja se bave važnim detaljima o konfiguraciji i lokaciji svih merača i senzora za posmatranje konstrukcijske faze mosta tokom probnog opterećenja i eksploatacije (dugotrajno nadgledanje). Ukupan broj mernih senzora je dat u prethodnim poglavljima za sve delove mosta.

option in specialized software supplemented by HBM universal measurement amplifier units (HBM Cotman and HBM Quantum Assistant). Similarly, "Sensr" company delivers its own data acquisition software for management of connection between CX1 inclinometers and computers.

Data will be transferred by Ethernet/IP connections from acquisition amplifier devices. In some cases in bridge inner this connection will be wireless.

Data, acquired as described previously, will be saved in memory storage devices in dedicated computer units with so-called "mirrored" and "striped" disc configuration which represents the first level of data protection.

Next stage in data processing will, at the same time, represent the second level of data protection.

6.2 Presentation, analysis and interpretation of data

From previously described dedicated computer system (dedicated to data storage) data will be transferred to the final stage - multipurpose personal computer system intended for presentation, analysis and interpretation of data collected from measurement points. This computer system records data in another "mirrored" and "striped" storage configuration, serving as a second level of data protection.

This system is capable to generate a report document i.e. summary of results, with various options for alarm and emergency notification as well as time synchronization of recorded road and rail vehicles by camera system.

Measured data will be presented in numerical and graphical manner compatible with widely used web browser software.

Browser is aimed for presentation of all relevant data with abilities of necessary calculation and processing in so-called background environment which is transparent and open for dedicated user and with limited approach of common user.

In this case necessary monitored values and data will be available to all "in charge" personnel at all times (24/7) in any location with Internet connectivity and on any system software environment. The only necessary qualification for use of data obtained by our system is an advanced civil engineering technical education.

For basic use of proposed system (view of data diagrams, history of bridge behaviour, trends of possible future bridge response, triggered points, etc.) the modest skill level of computer use is sufficient. Our previous experience is sufficient proof that this system is optimal in the sense of user-friendly requirements.

7 CONFIGURATION OF MONITORING ITEMS

The following chapters deal with important details on configuration and location of all gauges and sensors for the observation of structural stage of bridge during Test Load and exploitation (long time monitoring). Summary number of measuring gauges and sensors items were given in previous chapters for all bridge parts.

7.1 Monitoring mosta 1-2A

Prilazni most 1-2A (Petrovaradinska strana) će se posmatrati u tri zone/preseka:

- blizu zone oslonca na Petrovaradinskoj strani,
- zona sredine raspona (≈12.00m od oslonačke zone)
- blizu zone sledećeg oslonca.

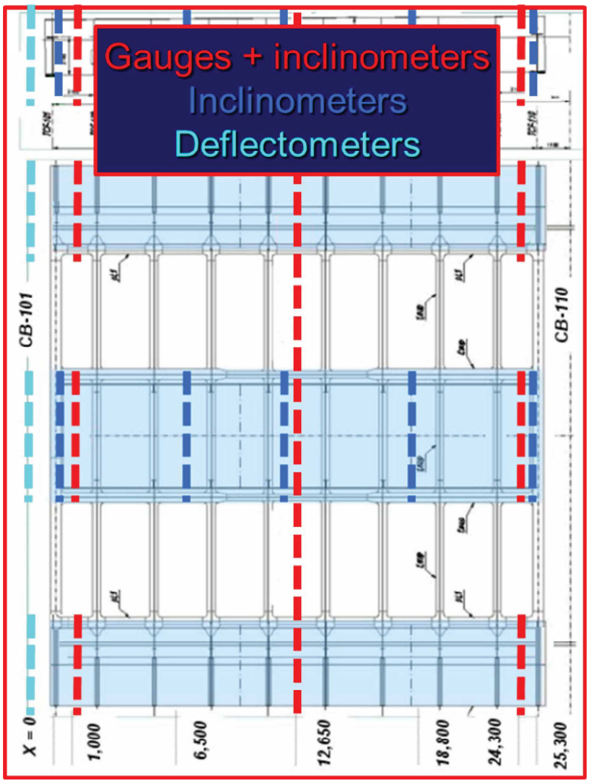
Konfiguracija mernih tačaka za obe oslonačke zone je ista i razlikuje se u odnosu na zonu sredine raspona. Slike 1-4 prikazuju ove konfiguracije.

7.1 Monitoring of the bridge 1-2A

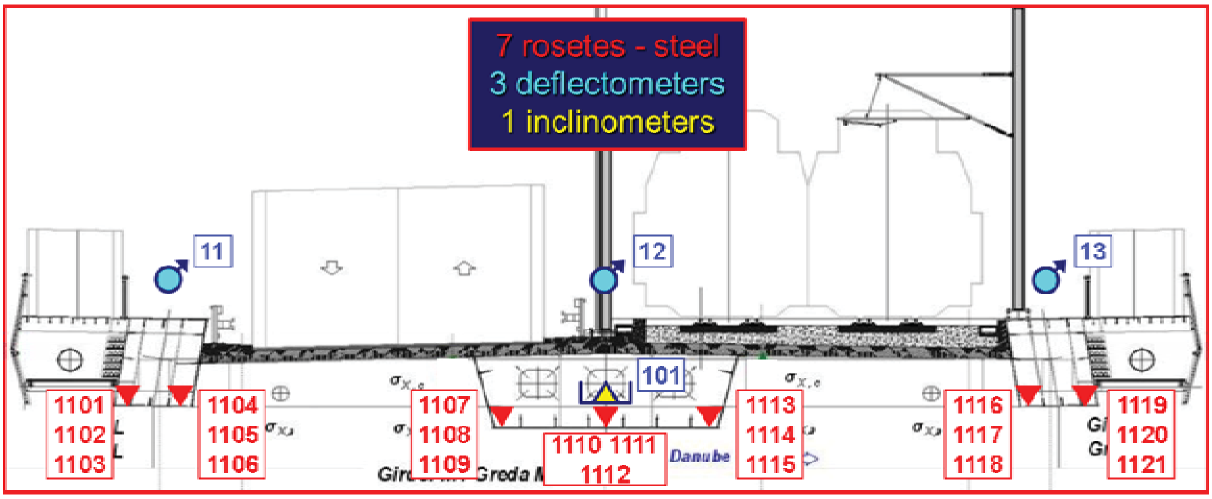
Approach bridge 1-2A is observed in three zones/sections:

- near to support zone on Petrovaradin side,
- mid span zone (≈12.00m from support section) and
- near to next support zone.

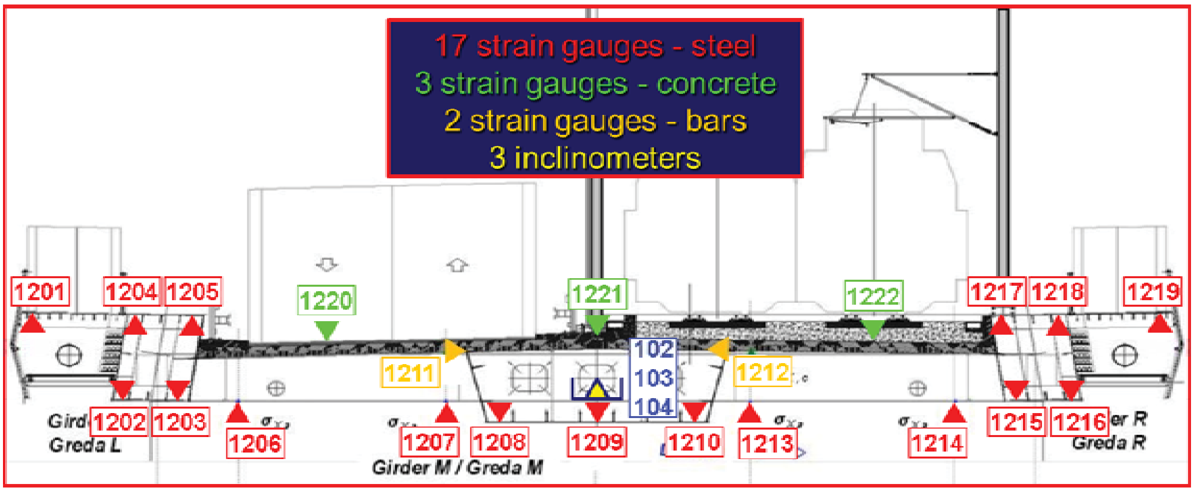
Configuration of measurement points for both of support zones is the same and it is different in comparison with mid span zone. Figures 1-4 show these configurations.



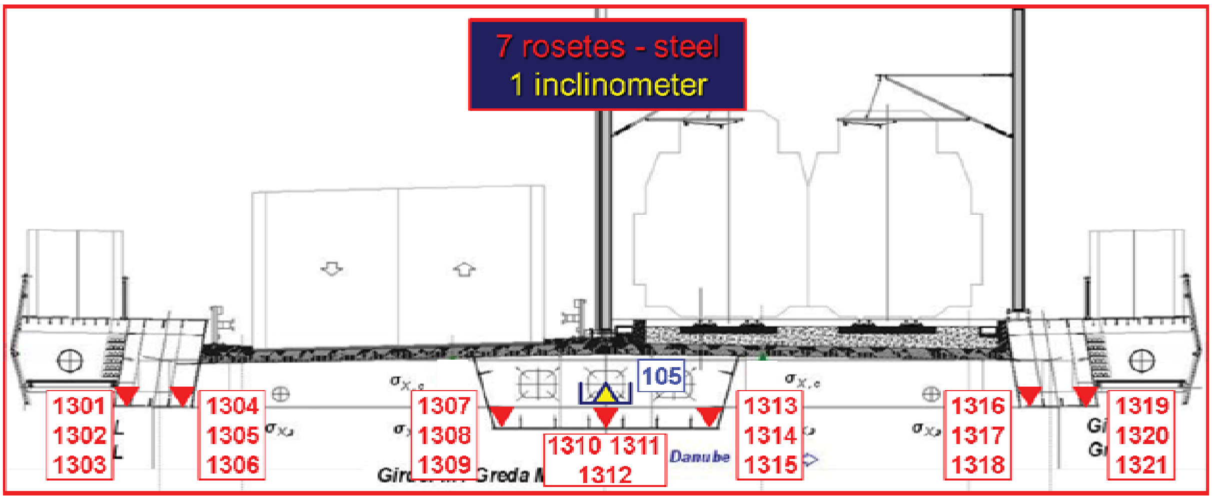
Slika 1. Prilazni most 1-2A - konfiguracija zona posmatranja u osnovi
Figure 1. Approach bridge 1-2A - layout of observation zones



Slika 2. Prilazni most 1-2A – oslonačka zona 1 - konfiguracija mernih mesta
Figure 2. Approach Bridge 1-2A - support zone 1 - configuration of measurement points



Slika 3. Prilazni most 1-2A – srednja zona - konfiguracija mernih mesta
Figure 3. Approach Bridge 1-2A - mid span zone - configuration of measurement points



Slika 4. Prilazni most 1-2A – oslonačka zona 2A - konfiguracija mernih mesta
Figure 4. Approach Bridge 1-2A - support zone 2A - configuration of measurement points

7.2 Monitoring mosta 2-3A (180m, "mali" luk)

Lučni most 2-3A će se posmatrati u četiri zone/preseka:

- blizu zone oslonca na stubu na petrovaradinskoj strani,
- zona privremenog stuba za vreme lansiranja (≈68.50m od oslonca),
- zona sredine raspona (≈88.50m od oslonačke zone),
- blizu zone oslonca na centralnom stubu.

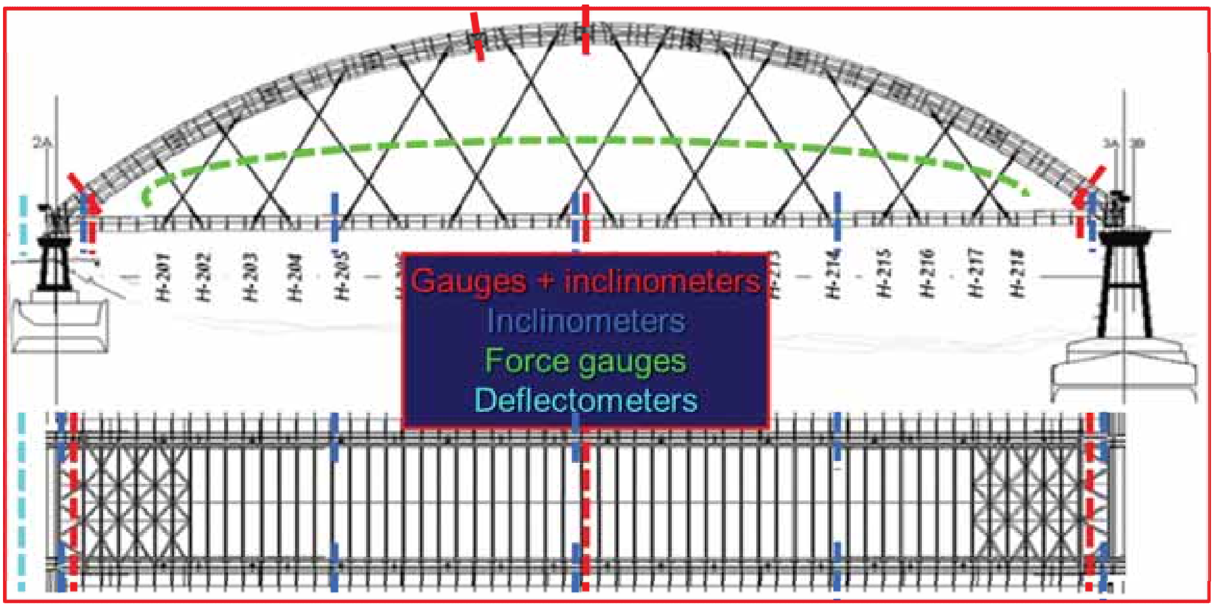
Konfiguracija mernih tačaka za obe oslonačke zone je ista i razlikuje se u odnosu na zonu sredine raspona i zonu privremenog stuba. Slike 5-9 prikazuju ove konfiguracije.

7.2 Monitoring of the bridge 2-3A (180m, "small" arch)

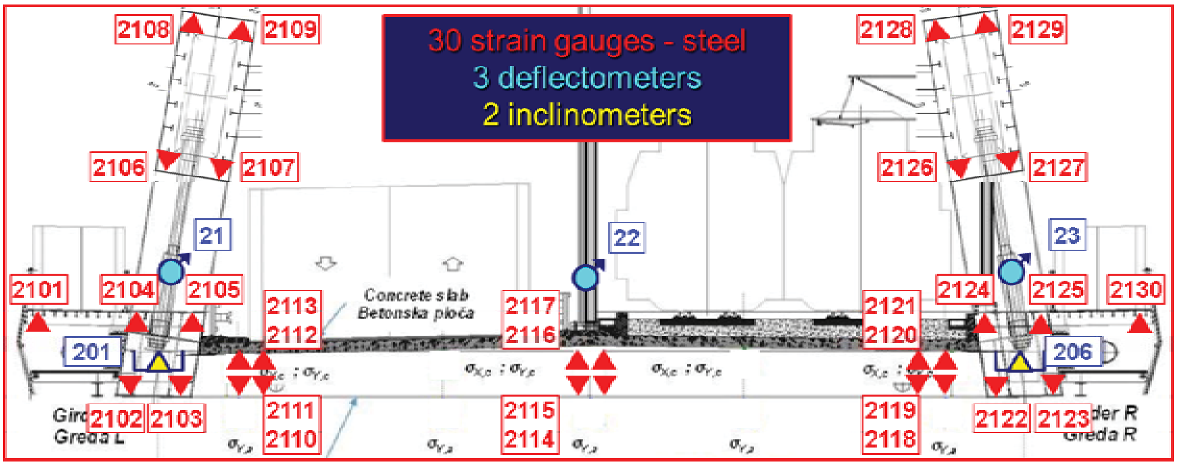
Arch bridge 2-3A is observed in four zones/sections:

– near to support zone on pier in Petrovaradin side,
– zone of temporary column for launching (≈68.50m from support),
– mid span zone (≈88.50m from support zone),
– near to support zone on area of central pier.

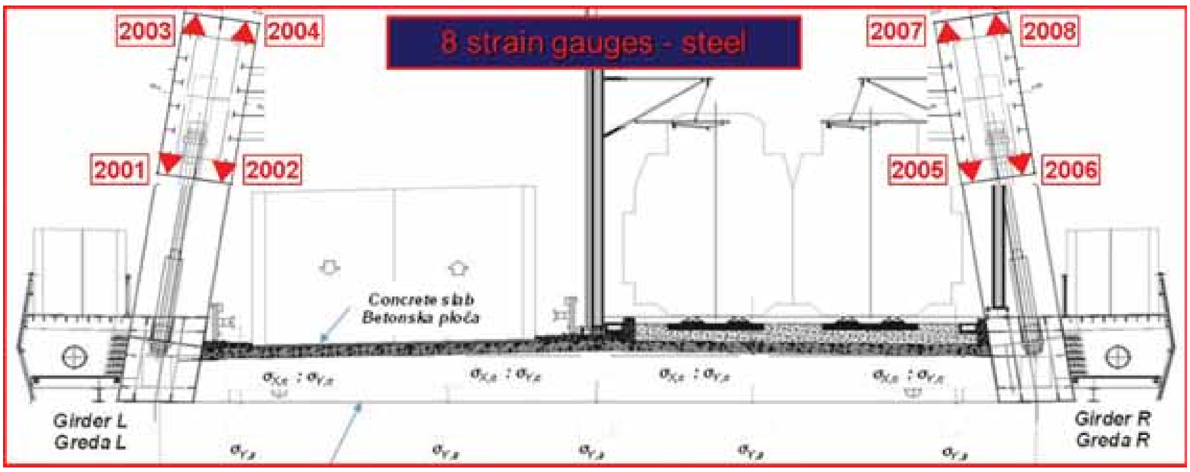
Configuration of measurement points for both support zones is the same and it is different in comparison with mid span zone and zone of temporary column. Figures 5-9 show these configurations.



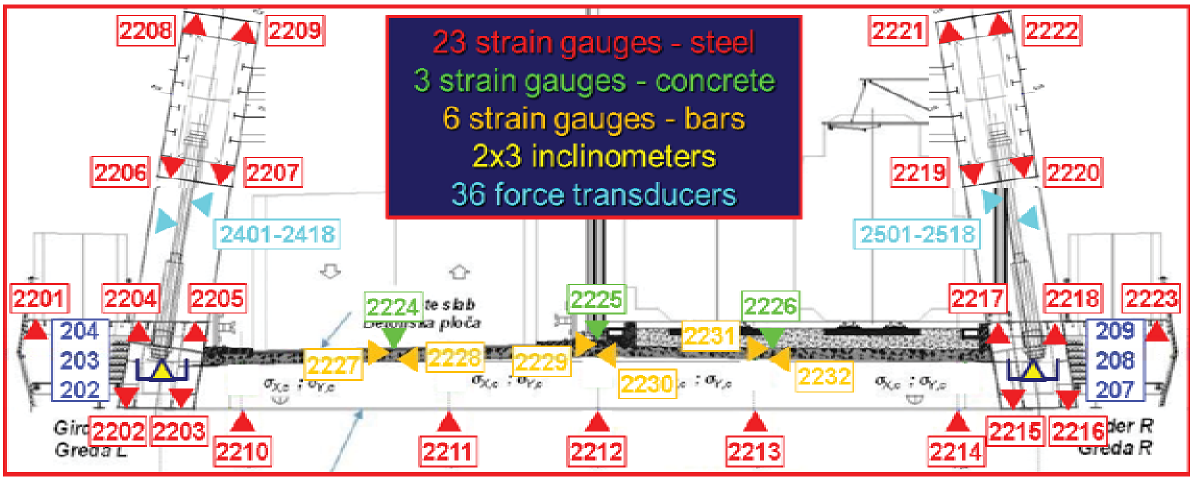
Slika 5. Lučni most 2-3A - konfiguracija zona posmatranja
Figure 5. Arch bridge 2-3A - layout of observation zones



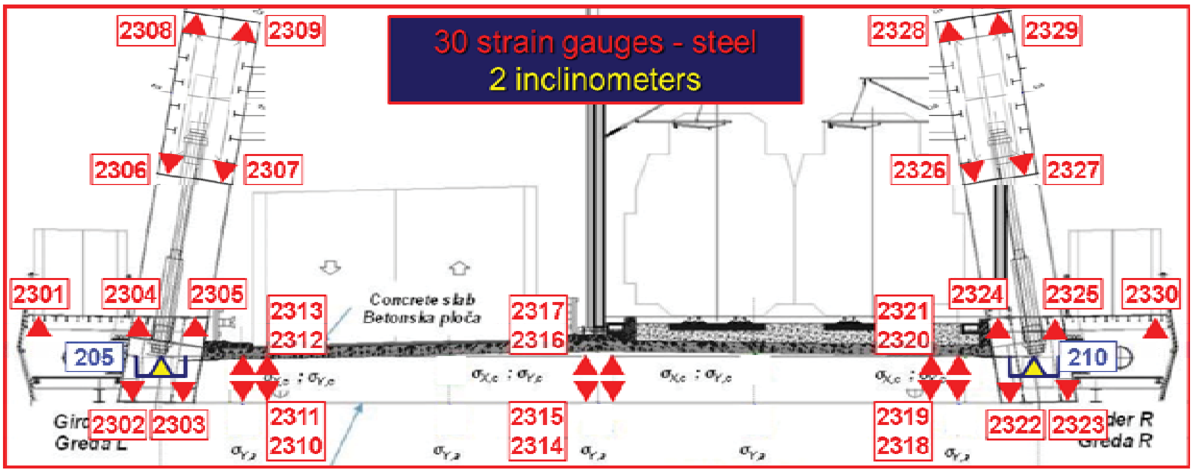
Slika 6. Lučni most 2-3A – oslonačka zona 2 - konfiguracija mernih mesta
Figure 6. Arch Bridge 2-3A - support zone 2 - configuration of measurement points



Slika 7. Lučni most 2-3A – zona privremenog oslonca – merna mesta
Figure 7. Arch Bridge 2-3A - temporary column zone - measurement points



Slika 8. Lučni most 2-3A – srednja zona - konfiguracija mernih mesta
Figure 8. Arch Bridge 2-3A - mid span zone - configuration of measurement points



Slika 9. Lučni most 2-3A – oslonačka zona 3A - konfiguracija mernih mesta
Figure 9. Arch Bridge 2-3A - support zone 3A - configuration of measurement points

7.3 Monitoring mosta 3B-4 (220m, "veliki" luk)

Lučni most 3B-4 će se posmatrati u četiri zone/preseka:

- blizu zone oslonca na centralnom stubu,
- zona privremenog stuba za vreme lansiranja (≈35.0m od zone oslonca na centralnom stubu),
- zona sredine raspona (≈110.0m od oslonačke zone),
- blizu zone oslonca na novosadskoj strani.

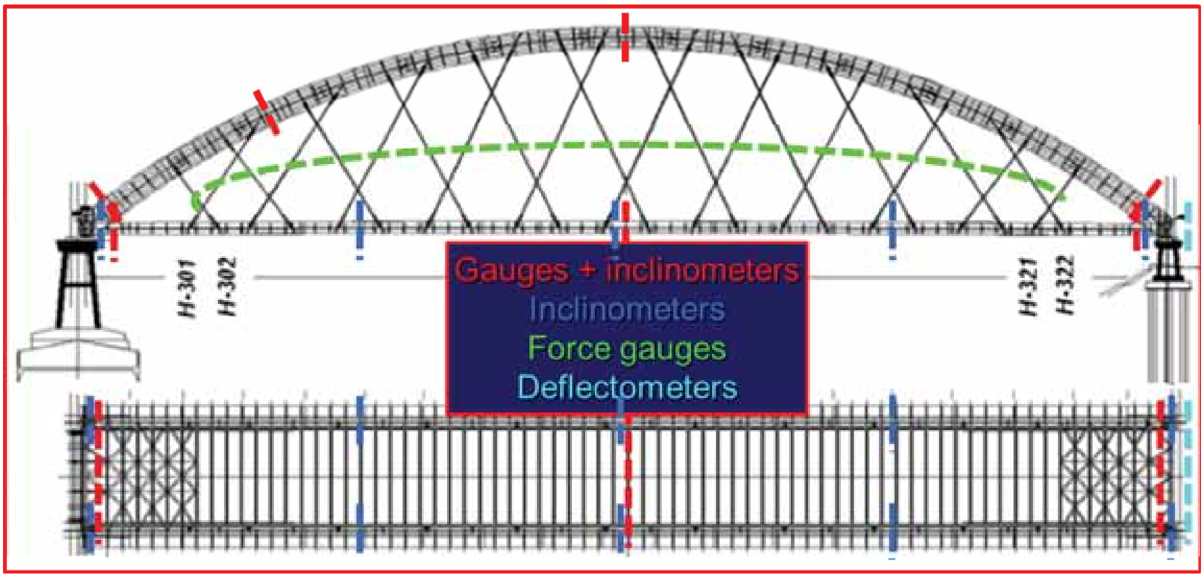
Konfiguracija mernih tačaka za obe oslonačke zone je ista i razlikuje se u odnosu na zonu sredine raspona i zonu privremenog stuba. Slike 10-14 prikazuju ove konfiguracije.

7.3 Monitoring the bridge 3B-4 (220m, "big" arch)

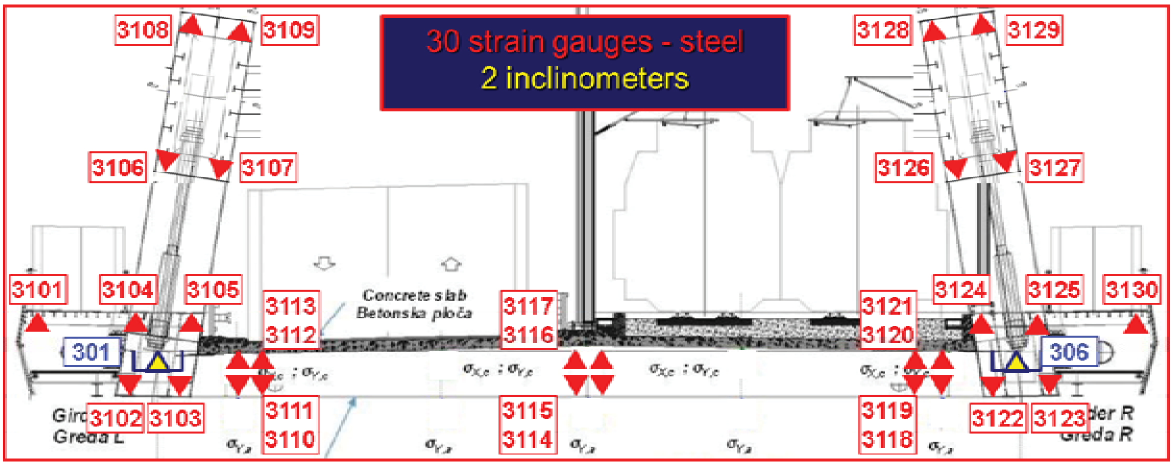
Arch bridge 3B-4 is observed in four zones/sections:

- near to central pier support zone,
- zone of temporary column for launching (≈35.0m from central pier support zone),
- mid span zone (≈110.0m from support zone),
- near to support zone on Novi Sad side.

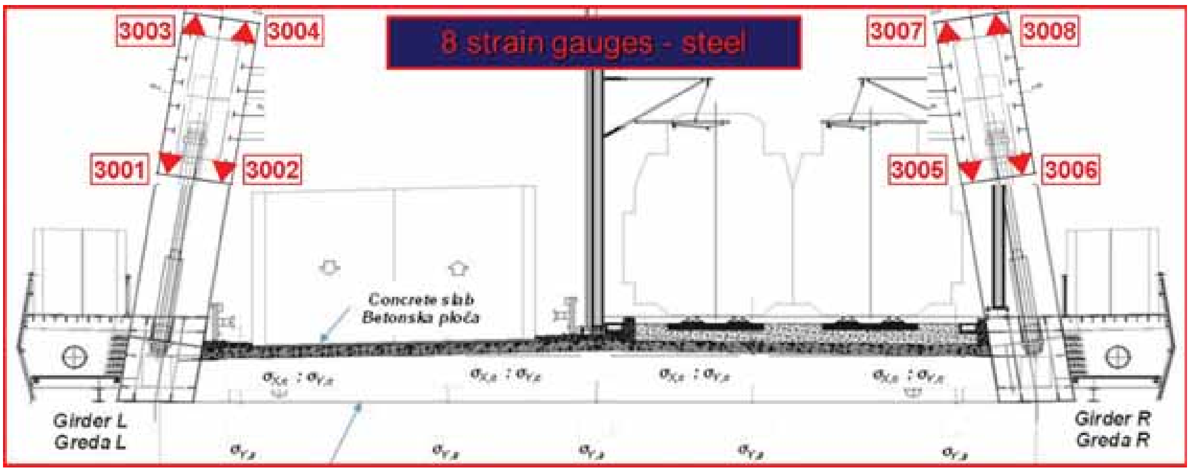
Configuration of measurement points for both support zones is the same and it is different in comparison with mid span zone and zone of temporary column. Figures 10-14 show these configurations.



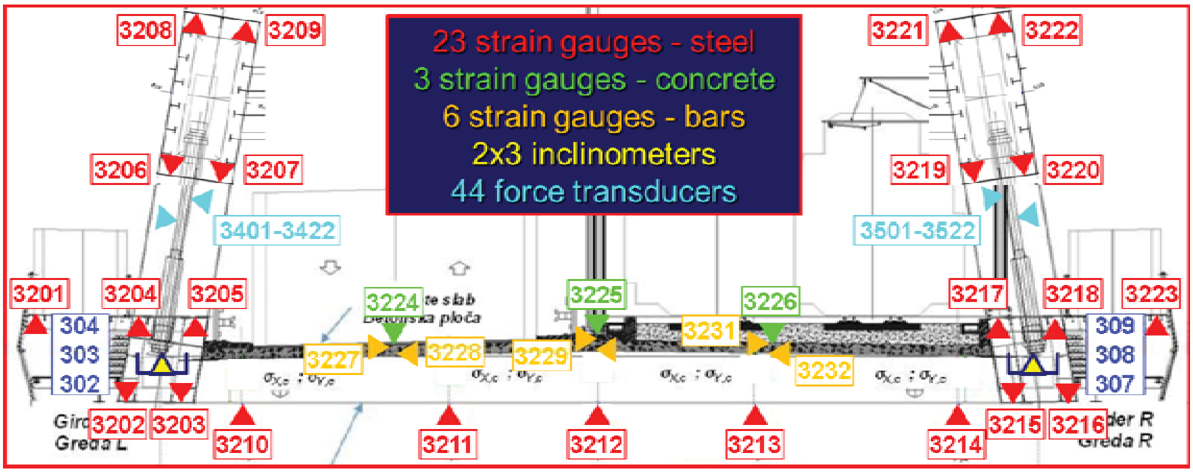
Slika 10. Lučni most 3-B4 - konfiguracija zona posmatranja
Figure 10. Arch bridge 3-B4 - layout configuration of observation zones



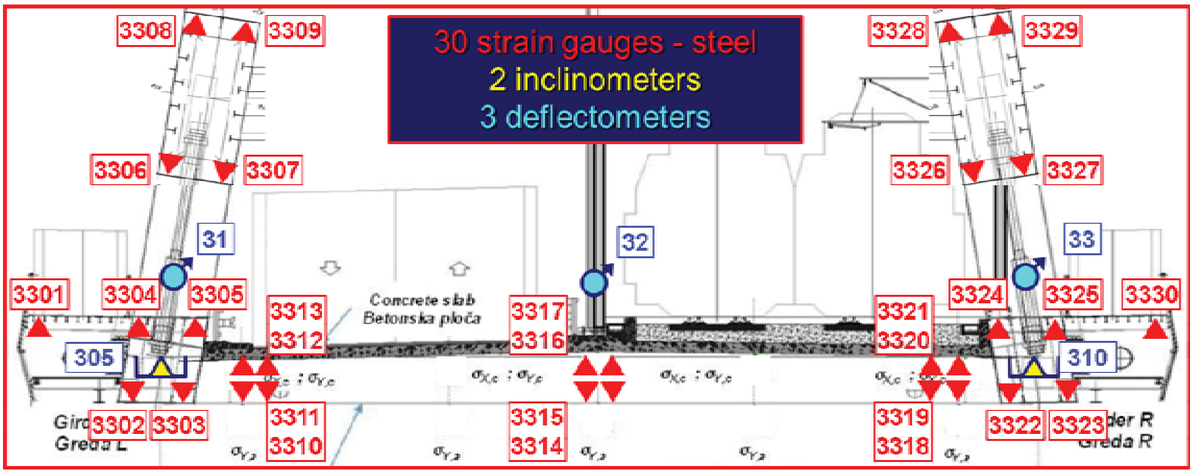
Slika 11. Lučni most 3-B4 – oslonačka zona 3 - konfiguracija mernih mesta
Figure 11. Arch Bridge 3-B4 - support zone 3 - configuration of measurement points



Slika 12. Lučni most 3-B4 – zona srednjeg oslonca – merna mesta
Figure 12. Arch Bridge 3-B4 - temporary column zone - measurement points



Slika 13. Lučni most 3-B4 – srednja zona - konfiguracija mernih mesta
Figure 13. Arch Bridge 3-B4 - midspan zone - configuration of measurement points



Slika 14. Lučni most 3-B4 – oslonačka zona B4 - konfiguracija mernih mesta
Figure 14. Arch Bridge 3-B4 - support zone B4 - configuration of measurement points

7.4 Monitoring mosta 4B-5

Prilazni most 4B-5 će se posmatrati u tri zone/preseka:

- blizu zone oslonca na novosadskoj strani,
- zona sredine raspona (≈23.50m od oslonačke zone),
- blizu zone sledećeg oslonca.

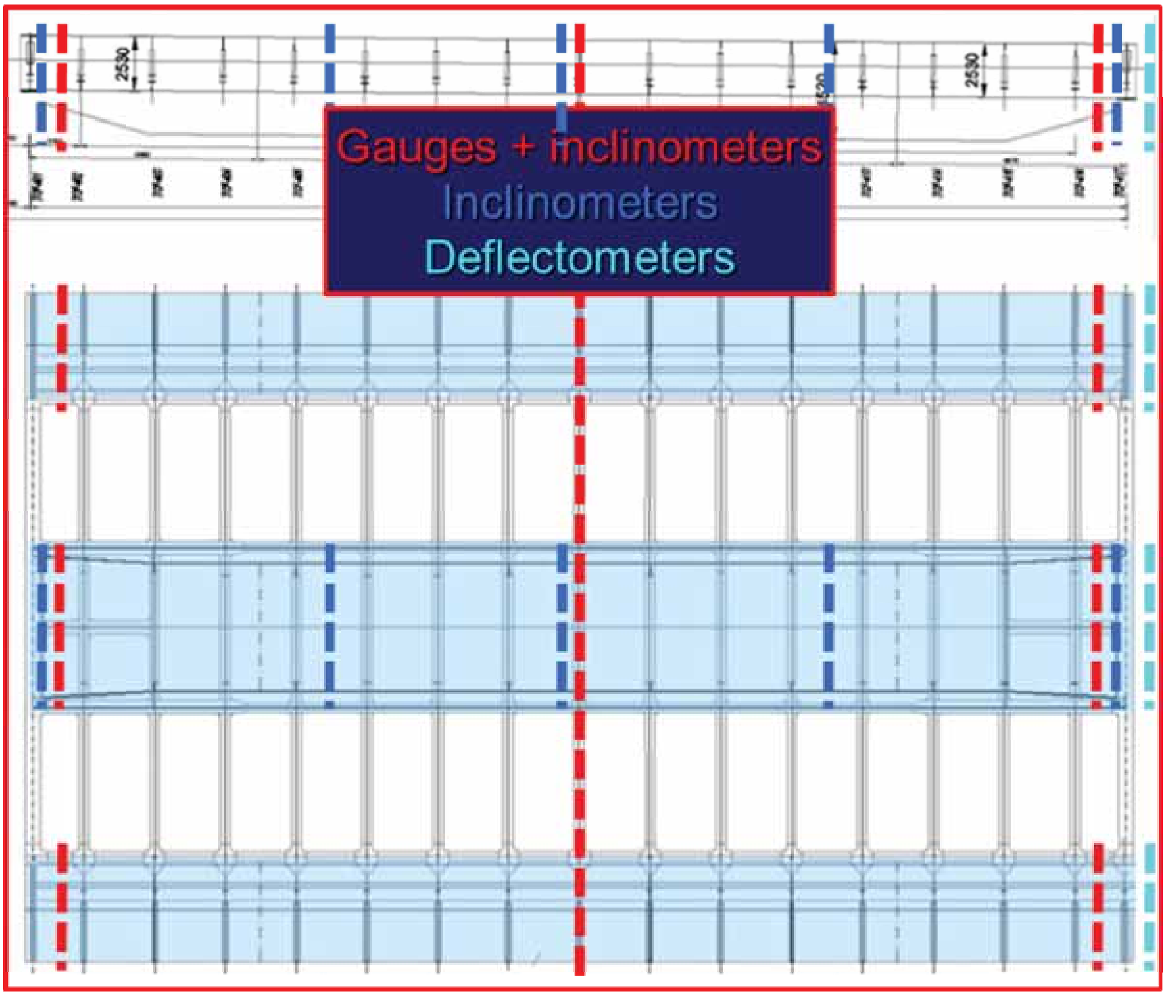
Konfiguracija mernih tačaka za obe oslonačke zone je ista i razlikuje se u odnosu na zonu sredine raspona. Slike 15-18 prikazuju ove konfiguracije. Slika 19 daje sumarni prikaz mernih zona duž mosta.

7.4 Monitoring of the bridge 4B-5

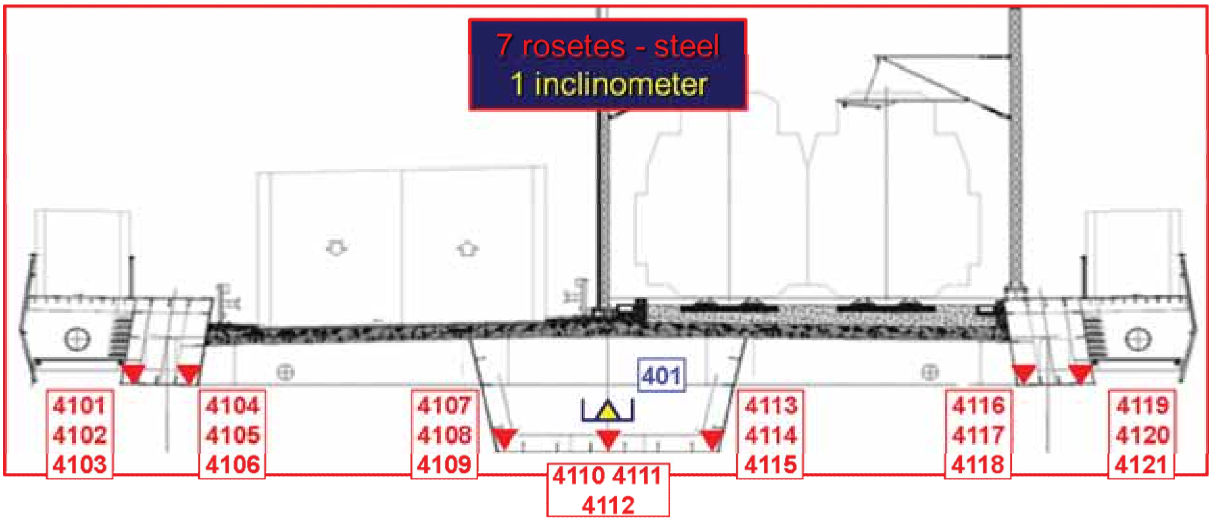
Approach bridge 4B-5 is observed in three zones/sections:

- near to support zone on Novi Sad side,
- mid span zone (≈23.50m from support section) and
- near to next support zone.

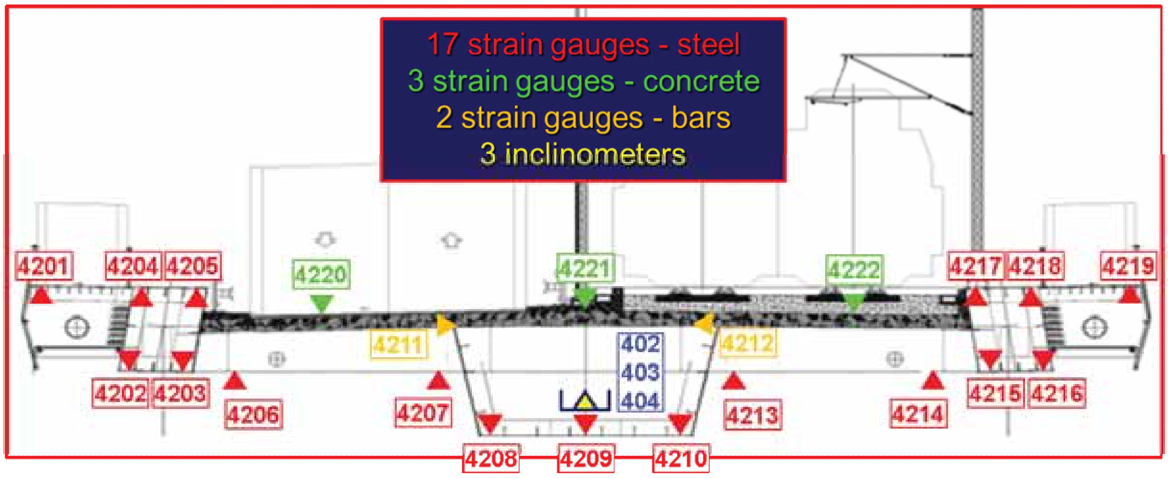
Configuration of measurement points for both support zones is the same and it is different in comparison with mid span zone. Figures 15-18 show these configurations. Figure 19 shows summary of measurement zones along the bridge.



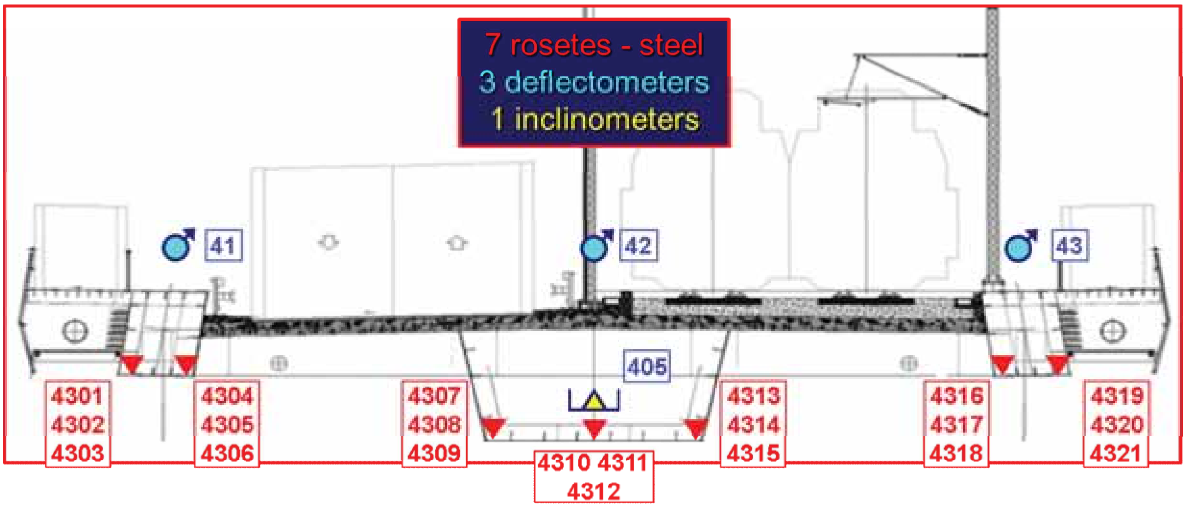
Slika 15. Prilazni most 4B-5 - konfiguracija zona posmatranja u osnovi
Figure 15. Approach bridge 4B-5 - layout configuration of observation zones



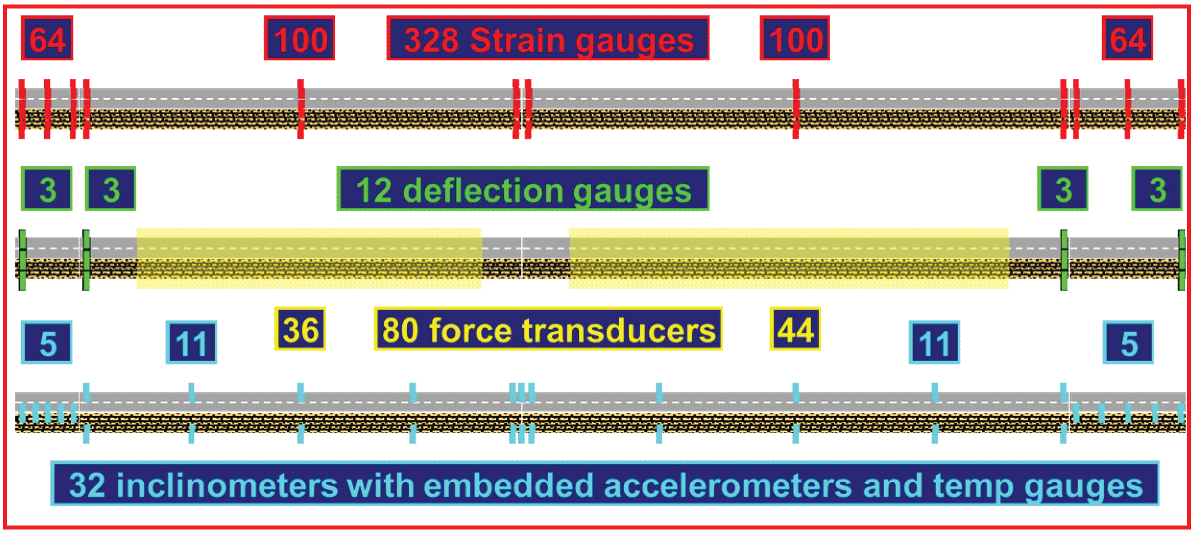
Slika 16. Prilazni most 4B-5 – oslonačka zona 4 - konfiguracija mernih mesta
Figure 16. Approach Bridge 4B-5 - support zone 4 - configuration of measurement points



Slika 17. Prilazni most 4B-5 – srednja zona - konfiguracija mernih mesta
Figure 17. Approach Bridge 4B-5 - mid span zone - configuration of measurement points



Slika 18. Prilazni most 4B-5 – oslonačka zona 5A - konfiguracija mernih mesta
Figure 18. Approach Bridge 4B-5 - support zone 5A - configuration of measurement points



Slika 19. Rezime konfiguracija mernih zona duž mosta
Figure 19. Summary configuration of measurement zones along the bridge

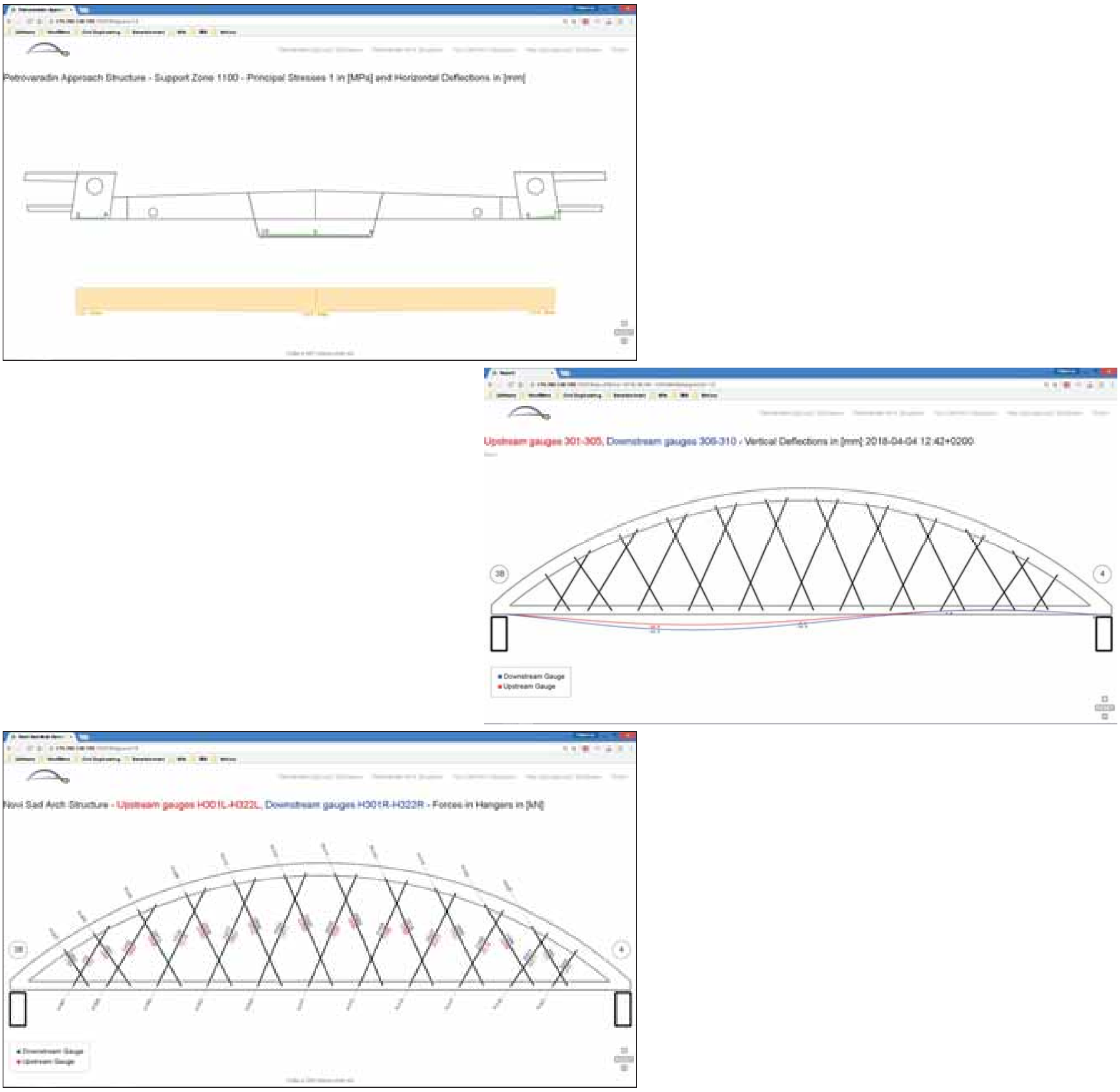
Slika 20 prikazuje neke delove opreme monitoring sistema mosta (merne trake u konfiguraciji rozete, dvoosni inklinometri sa ugrađenim aksijalnim akcelerometrom i termometrom, induktivni deflektometar, kutija sa mernim višekanalnim uređajem, jednostruka merna traka sa kompenzacionom mernom trakom).

Fig. 20 shows some parts of equipment of monitoring system of the bridge (strain gauges in rosette configuration, two-axis inclinometers with embedded -- axial accelerometer and thermometer, inductive deflectometer, box with measuring multichannel device, single strain gauge in single configuration with compensational strain gauge).

Slika 20. Neki uređaji i senzori korišćeni u monitoring sistemu
Figure 20. Some devices and gauges used in monitoring system

Slika 21 ilustruje radne ekrane originalno razvijenog softvera za praćenje ponašanja mosta usled saobraćajnih dejstava i ispitivanja probnim opterećenjem.

Fig. 21. illustrates working screens of originally developed software for monitoring behaviour of the bridge under traffic actions and test by load.



Slika 21. Ekrani rada softvera korišćenog za prikupljanje i prezentaciju podataka monitoring sistema
Figure 21. Some working screens of software used for acquisition and presentation of data from monitoring system

Više detalja je objašnjeno u opširnoj tehničkoj dokumentaciji mosta, posebno u [3].

8 ZAKLJUČCI

U poređenju sa drugim sistemima slične vrste i namene, Monitoring sistem Železničko-drumskog mosta u Novom Sadu jedan je od najvećih naučno-inženjerskih poduhvata Departmana za građevinarstvo i geodeziju Fakulteta tehničkih nauka sa mnogim inovativnim aspektima u oblasti konstrukcijskog monitoringa. Napori naših partnera u konzorcijumu, "TRC Pro" za hardver i "Creative Tree" za softver, doprineli su da je ranije

Much more details are explained in comprehensive technical documentation of bridge, especially in [3].

8 CONCLUSIONS

In comparisson with other systems with similar kind and purpose Monitoring system of Railway Road Bridge in Novi Sad is one of the largest scientific-engineering enterprise of Department of Civil Engineering and Geodesy of Faculty of Technical Sciences with many innovative aspects in structural monitoring field. Efforts of our joint venture partners, "TRC Pro" for hardware and "Creative Tree" for software, contributed that pomenuto postalo stvarnost. Očigledno je da ovakav složeni sistem praćenja zahteva ekspertski nivo multidisciplinarnog znanja za izradu i pravilnu upotrebu i istovremeno pruža velike mogućnosti za dobijanje vrednih podataka za naučne, konstrukterske i obrazovne svrhe.

previously mentioned becomes reality. It is obvious that such complex monitoring system needs expert level of multidisciplinary knowledge for building and proper use and in the same time provides large oportunity for obtaining valuable data for scientific, structural engineering and educational purposes.

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REZIME

SISTEM ZA MONITORING NOVOG ŽELEZNIČKO-DRUMSKOG MOSTA U NOVOM SADU

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Đ. LAĐINOVIĆ
S. RANKOVIĆ
S. RADIŠIĆ
I. KOVAČEVIĆ

Ovo je prikaz monitoring sistema za "Železničko-drumski most Novi Sad" koji je sagrađen na mestu čuvenog "Žeželjevog" mosta srušenog 1999. Monitoring sistem je mrežno orijentisani računarski sistem za akviziciju podataka sa ciljem praćenja parametara koji su od značaja za procenu konstrukcijskih performansi mosta. Sistem se sastoji od hardverskog dela (merni uređaji, prateća oprema, kablovi) nabavljenog iz više izvora i softverskog dela originalno razvijenog za potrebe monitoringa probnog opterećenja i eksploatacije mosta. Prema trenutno raspoloživim informacijama ovaj monitoring sistem je jedan od najvećih ove vrste, s obzirom na broj i vrstu mernih mesta, količinu obrađenih i prikazanih podataka, kompleksnost strukture i topologije, kao i na osnovu specijalizovanog softverskog okruženja. Glavni učesnici u razvoju ovog sistema su Departman za građevinarstvo i geodeziju, Fakulteta tehničkih nauka iz Novog Sada, firma "TRC Pro" iz Petrovaradina i softverska firma "Creative Tree" iz Novog Sada.

Ključne reči: Monitoring sistem mosta, akvizicija podataka, probno opterećenje

SUMMARY

MONITORING SYSTEM FOR NEW RAIL-ROAD BRIDGE NOVI SAD

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This is a review of the Monitoring System for "Rail Road Bridge Novi Sad" constructed on the place of famous "Žeželj" bridge, which is demolished in 1999. Monitoring system is a network based computer system for data acquisition with a goal of real-time observing of parameters, which are important for assessment of structural performances of the bridge. The system consists hardware parts (devices, equipment, cables) which delivered by various company sources and software part, which is originally developed and customized for purpose of test by load and exploitation of the bridge. In accordance to currently available information this monitoring system is one of the largest system of this type considering the number and kind of measuring points, quantity of processed and presented data, complexity and topology of its structure, as well as dedicated software environment. Department for Civil Engineering and Geodesy of Faculty of Technical Sciences in Novi Sad, company "TRC Pro" from Petrovaradin and software company "Creative Tree" from Novi Sad are main participants in development of this system.

Key words: Bridge monitoring system, data acquisition, test by load

EKONOMSKA ANALIZA POJAČANOG ODRŽAVANJA DRŽAVNOG PUTA IB21, DEONICA IRIG - RUMA

ECONOMIC ANALYSES OF HEAVY MAINTENANCE (UPGRADING) OF STATE ROAD IB21, SECTION IRIG-RUMA

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STRUČNI RAD
PROFESSIONAL PAPER
UDK: 625.765
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1 UVOD

Putna infrastruktura je meću najvrednijim dobrima jednog društva i indikator je razvoja nacionalne ekonomije. Ulaganja u održavanje, rekonstrukciju i modernizaciju puteva u svetu, u poslednjih dvadesetak godina, veca su nego u izgradnju novih puteva. Upravljanje održavanjem putne mreže predstavlja proces donošenja odluka o investicijama, u kojem je veoma znađajno razrešiti brojna tehniđka i ekonomska pitanja i obezbediti što više objektivnih tehniđkih i ekonomskih informacija za konađno donošenje odluke. Planiranje održavanja putne mreže jedan je od osnovnih zadataka za svakog upravljađa putnom mrežom [1].

Za potrebe efikasnog planiranja i upravljanja održavanjem putne mreže neophodno je raspolagati ažurnom informacionom osnovom i odgovarajucim modelom za donošenje odluka [2]. Model za analizu investicija u razvoj i upravljanje putevima HDM-4 (*The Highway Development and Management Model*) predstavlja kompleksan softverski alat za tehniđko-ekonomsku ocenu

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1 INTRODUCTION

Road infrastructure is one of the most valuable assets of a society and a good indicator of development of national economy. Over the past two decades, worldwide investments in the maintenance, reconstruction and modernization of roads have been significantly higher than the investments made in the construction of new roads. The management of the road network presents the process of decision making in investments, where it is very important to solve numerous technical and economic problems and provide as much objective technical and economic information as possible for final decision making. Planning the maintenance of the road network is one of the basic tasks for each road network manager [1].

A properly updated road information system, as well as an adequate decision model, should be established and put in operation so as to enable an effective management of road maintenance activities [2]. The HDM-4 model (Highway Development and Management

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projekata i analizu investicija u radove na putnoj mreži, opšteprihvaćen od strane međunarodnih finansijskih institucija. Pomoću HDM-4 modela moguće je sprovoditi: strateške analize na nivou putne mreže (ili dela putne mreže), programiranje radova na održavanju/poboljšanju putne mreže i analize na nivou projekta. Strateške i programske analize putne mreže sprovode se na osnovu adekvatne i ažurne informacione osnove o putnoj mreži (baza podataka o putevima), dok je za analize na nivou projekta potrebno postojanje odgovarajuće projektno-tehničke dokumentacije (glavni projekat). Nakon sprovedene strateške i/ili programske analize putne mreže (ili dela putne mreže) potrebno je izraditi odgovarajuću projektno-tehničku dokumentaciju za selektirane prioritetne deonice u skladu sa zakonskom procedurom [3].

Projekat rehabilitacije puteva i unapređivanja bezbednosti saobraćaja (*Road Rehabilitation and Safety Project – RRSP*) jeste projekat podrške međunarodnih finansijskih institucija (Svetske banke, Evropske investicione banke i Evropske banke za obnovu i razvoj) Vladi Republike Srbije u implementaciji Nacionalnog programa rehabilitacije državne putne mreže. Deonica državnog puta IB21, Irig–Ruma, u ukupnoj dužini od 15.580 km deo je RRSP projekta i predviđena je za realizaciju u 2017. godini.

U radu se daje prikaz metodološkog postupka za izradu ekonomske analize i ocene investicije za radove na periodičnom održavanju puta s primerom predmetne deonice puta.

2 PRIMENJENA METODOLOGIJA

2.1 Tehničko-ekonomska analiza projekta

Tehničko-ekonomska analiza opravdanosti pojačanog održavanja državnog puta IB-21 na deonici: Irig 2 - Ruma 1 u ukupnoj dužini od 15.580 km sprovedena je pomoću HDM-4 modela (*Highway Development Management Model, v2.08*). Korišćen je postupak projektne analize na nivou projekta (*project analyses by project*).

Nakon opšte analize cele razmatrane deonice izvršena je podela na homogene poteze. Svaki izabrani homogeni potez posebno je obrađen i analiziran na nivou projekta.

Cela analizirana deonica podeljena je na homogene poteze prema [4,5]:

- saobraćajnom opterećenju;
- dominantnoj geometriji puta;
- utvrđenoj strukturi kolovozne konstrukcije;
- utvrđenom stanju kolovozne konstrukcije;
- predviđenim radovima na pojačanom održavanju.

Razlika u troškovima i koristima između varijante „projektno rešenje radova na pojačanom održavanju” u skladu sa Glavnim projektom pojačanog održavanja i varijante „minimum radova na održavanju” izračunata je za svaku godinu posebno za period eksploatacije puta od deset godina. Neto sadašnja vrednost (NSV) i interna stopa rentabiliteta (ISR) za projekat izračunate su, kao i odnos neto sadašnje vrednosti prema investicionim

Model) for the analysis of investments in the development and management of roads is a complex software tool for the technical and economic evaluation of road projects, and for analyzing investments in the existing road network. The model is widely accepted by the International Financial Institutions (IFIs).The HDM-4 model can be used to: conduct strategic analyses at the level of the road network (or part of the road network), program road maintenance and improvement activities on the road network, and make analyses at the project level. The strategic and programme analyses of the road network are carried out on the basis of adequate and updated road network information base (RDB - Road Data Base), while the project-level analysis requires preparation of appropriate design and technical documentation (Final/Detailed Design). After the conduct of strategic and/or programme analyses of the road network, appropriate design and technical documentation should be prepared for selected priority sections, in accordance with the legal procedure [3].

Road Rehabilitation and Safety Project (RRSP) is a project of support of international financing institutions (World Bank, European Investment Bank and European Bank for Reconstruction and Development) to the Government of the Republic of Serbia in implementation of the National State Road Network Rehabilitation Program. The section of the state road IB21, Irig–Ruma, in the total length of 15,580 km is part of the RRSP project and is planned for realization in 2018.

This paper presents a methodological procedure for the preparation of economic analysis and assessment of investments for the periodic maintenance of roads with example of the state road IB 21, section Irig–Ruma.

2 APPLIED METHODOLOGY

2.1 Technical – economic analysis of the design

Technical - economic analysis of the justification for heavy maintenance of the state road of the road IB-21 on the section: Irig 2 – Ruma 1 in the total length of 15,580 km was carried out using the HDM-4 model (*Highway Development Management Model, v2*.08) in the project analysis.

Upon the general analysis of the entire considered section, it was divided into homogeneous subsections. Each selected homogeneous subsection is specifically processed and analyzed at the project level. The whole analyzed section is divided into homogeneous moves according to [4,5]:

- traffic load,
- dominant road geometry,
- determined structure of the pavement structure,
- determined condition of the pavement structure, and
- planned works on heavy maintenance

The difference in costs and benefits between the variant "design solution for heavy maintenance" in accordance with the Main design for heavy maintenance and the "minimum works on maintenance" variant is calculated for each year, in particular for the 10-year period of exploitation. Net present value (NPV) and the internal rate of return (IRR) for the design are calculated, as well as the ratio of net present value and investment (kapitalnim) troškovima radova (NSV/CAP).

Analiza osetljivosti rezultata urađena je da bi ilustrovala važnost promena u troškovima izvođenja radova na pojačanom održavanju puta kao i u promenama prognoziranih saobraćajnih tokova. Ekonomska analiza bazirana je na sledećim postavkama:

– početna godina analize je 2017. godina;
– period analize (eksploatacije) jeste 1+10=11 godina;
– inicijalni period radova na pojačanom održavanju deonice puta traju od 2017. godine (100%);
– početna godina eksploatacije puta je 2018. godina;
– troškovi radova na pojačanom održavanju državnog puta IB21 na deonici: Irig 2 - Ruma 1 (Autoput) preuzeti su iz Glavnog projekta pojačanog održavanja državnog puta IB-21 na deonici: Irig 2 - Ruma 1 (Autoput), mart/jul 2017 [6];
– diskontna stopa iznosi 8%;
– odnos ekonomske prema finansijskoj vrednosti troškova iznosi 0.80;
– egzogeni troškovi i koristi od socijalnih aspekata nisu uključeni u ekonomsku analizu projekta usled nedostatka podataka i detaljnijih studija;
– egzogeni troškovi i koristi od zaštite od uticaja puta na životnu sredinu nisu uključeni u ekonomsku analizu projekta usled nedostatka podataka i detaljnijih studija;
– preostala vrednost koristi (*salvage value*) prilikom poboljšanja puta iznosi 10%.

Period od 1+10 godina podrazumeva jednu godinu za izvođenje radova (odnosno, to je period u kojem se izvode radovi na pojačanom održavanju na predmetnoj deonici) dok je period od deset godina period eksploatacije puta nakon završetka radova, u kojem se ostvaruju potpune koristi u vidu smanjenih operativnih troškova vozila i smanjenog vremena putovanja.

2.2 Kalibracija modela HDM-4 za primenu u lokalnim uslovima

Za potrebe adekvatne primene HDM-4 modela, izvršeno je prilagođavanje HDM-4 modela za primenu u lokalnim uslovima koji su karakteristični za Republiku Srbiju.

U izradi ekonomske analize i kalibracije HDM-4 modela za primenu u lokalnim uslovima korišćene su preporuke i rezultati istraživanja na putnoj mreži Republike Srbije, koja su sprovedena za potrebe realizacije projekta baze podataka o putevima [7-9].

3 OPIS PROJEKTA – KARAKTERISTIKE DEONICE

3.1 Lokacija

Predmetna deonica nalazi se na putnom pravcu Novi Sad – Irig – Ruma – Šabac – Koceljeva – Valjevo – Kosjerić – Požega – Arilje – Ivanjica – Sjenica, koji je prema uredbi o klasifikaciji državnih puteva („Sl. glasnik RS" br. 105/2013 i br. 119/2013) svrstan u državni put IB reda i nosi oznaku IB-21. U funkcionalnom smislu, prema „Pravilniku o uslovima koje sa aspekta

(capital) costs of works (NPV/CAP).

The sensitivity analysis of the results was made to illustrate the importance of changes in the cost of carrying out works on heavy road maintenance as well as changes in forecasted traffic flows. The economic analysis is based on the following assumptions:

– the starting year of the analysis is 2017.
– analysis (exploitation) period is 1+10=11,
– the initial period of works on heavy maintenance of the road section is during 2017. (100%),
– the starting year for road exploitation is 2018.
– the costs of works on heavy maintenance of the state road IB-21 on the section: Irig 2 –Ruma 1 (Motorway) are taken from the Main design of heavy maintenance of the state road of the road IB-21 on the section: Irig 2 –Ruma 1 (Motorway), March/July 2017 [6],
– discount rate is 8%,
– the ratio of the economic towards the financial value of costs is 0.80,
– exogenous costs and benefits from social aspects are excluded from the economic analysis of the design due to the lack of data and detailed studies,
– exogenous costs and benefits of the impact of the road on the environment are excluded from the economic analysis of the design due to the lack of data and detailed studies,
– salvage value for road improvement is 10%.

The period of 1+10 years implies one year for the execution of works (period in which the enhanced maintenance works are carried out), while the period of 10 years is the period of exploitation of the road after the completion of the works and in which full benefits are achieved in the form of reduced operating costs of vehicles and reduced travel time.

2.2 Calibration model HDM-4 for application in the local conditions

For the needs of adequate application of the HDM-4 model, the HDM-4 model was adapted for use in local conditions that are characteristic for the Republic of Serbia.

In the elaboration of the economic analysis and calibration of the HDM-4 model for application in the local conditions, recommendations and results of the research on the road network of the Republic of Serbia, implemented for the needs of the realization of the project of the database of roads, were used[7-9].

3 DESIGN DESCRIPTION – SECTION CHARACTERISTICS

3.1 Location

The subject section is located on the road Novi Sad – Irig – Ruma – Sabac – Koceljeva – Valjevo – Kosjeric – Pozega – Arilje – Ivanjica - Sjenica which was classified according to the regulation on state road classification (Official Gazette of the Republic of Serbia no. 105/2013, 119/2013 and 93/2015), as a state road IB class. More precisely, it is named IB-21. Functionally speaking, this section can be classified as the long distance interregional road, according to the "Regulabezbednosti saobraćaja moraju da ispunjavaju putni objekti i drugi elementi javnog puta" [10], deonica se može svrstati u vezni međuregionalni put.

Deonica pripada regionu Vojvodine i nalazi se u Sremskom upravnom okrugu. Opštine na kojim se deonica pruža jesu Ruma i Irig. Putna deonica vodi se po ravničarskom i brežuljkastom terenu s nadmorskim visinama u proseku oko ~ 150 mnm. Osnovna trasa je duga 15.580 km i ide od km 26+280 do km 42+260.

Prema referentnom sistemu mreže državnih puteva Republike Srbije [11], razmatrana deonica za pojačano održavanje obuhvata sledeće primarne saobraćajne deonice referentnog sistema koje su prikazane u tabeli 1.

tions on the conditions that must be met by road structures and other elements of public roads from safety aspects" [10] which is in the further text called Regulations on road design. The section belongs to Vojvodina region and is situated in Srem administrative district, and stretches in Ruma and Irig municipalities. The road section runs along a plain and hilly terrain with an altitude of about ~150 m a.s.l. on average. Main roadway is 15.580 km long and it stretches from km 26+280 to km 42+260.

According to the new reference system of the national road network of the Republic of Serbia [11], the considered section for heavy maintenance includes the following primary traffic sections of the reference system shown in Table 1.

Tabela 1. Primarne saobraćajne deonice predviđene za pojačano održavanje [11]
Table 1. Primary traffic sections for heavy maintenance [11]

Redni broj *Order*	Oznaka deonice *Mark of Section*	Naziv početnog čvora *Mark of start node*	Naziv završnog čvora *Mark of end node*	Početna stacionaža *Start chainage*	Završna stacionaža *End chainage*	Dužina deonice *Section Length* (km)
1	02105	Irig (Vrdnik)	Ruma (Putnici)	**26.680**	35.890	9.210
2	02106	Ruma (Putnici)	Ruma (Pećinci)	35.890	36.638	0.748
3	02107	Ruma (Pećinci)	Ruma (Voganj)	36.638	37.915	1.277
4	02108	Ruma (Voganj)	Ruma (veza sa A3)	37.915	41.975	4.060
5	02109	Ruma (veza sa A3)	Jarak	41.975	**42.260**	0.285
					Ukupno /*Total* (km):	**15.580**

3.2 Geometrijski elementi plana i profila

Računska brzina deonice je 80 km/h. U sledećoj tabeli prikazani su granični elementi plana i profila za predmetnu deonicu, dati u tabeli 2.

3.2 Geometrical elements of horizontal and vertical alignment

The overall design speed of the section is 80 km/h. The following table shows the boundary elements of the plan and profile for the given section which are show in Table 2.

Tabela 2. Granični elementi plana i profila [9]
Table 2. Boundary elements of the plan and profile [9]

Granični elementi plana i profila deonice / *Boundary elements of the plan and profile of the section*		Računska brzina deonice *Overall design speed of the section* Vri (km/h) 60*	80
Situacioni plan/ *Site plan*	Najveća dužina pravca (m) *The longest straight section* (m)	1200	1600
	Najmanja dužina pravca (m) *The shortest straight section (m)*	120 (240)	160 (320)
	Minimalni poluprečnik (m) *The minimum radius minR (m)*	120	250
	Minimalni poluprečnik za ipk=-2.5% (m) *The minimum radius for ipk=-2.5% (m)*	-	2500
	Minimalni parametar klotoide A (m) *The minimum clothoide parameter A (m)*	75	125 (80)
	Minimalna dužina kružne krivine (m) *The minimum length of the circular curve (m)*	33	44
Podužni profil/ *Longitudinal profile*	Maksimalni podužni nagib (%) *The maximum longitudinal grade (%)*	8	6
	Minimalni podužni nagib (%) *The minimum longitudinal grade (%)*	0	0
	Minimalni radijus konkavnog zaobljenja minRv konk.(m) *The minimum radius of sag vertical curve minRv sag.(m)*	900	2500

Granični elementi plana i profila deonice / *Boundary elements of the plan and profile of the section*		Računska brzina deonice *Overall design speed of the section* Vri (km/h)	
		60*	80
	Minimalni radijus konveksnog zaobljenja minRv konv. (m) *The minimum radius of crest vertical curve minRv crest. (m)*	800	3500
Poprečni profil/ *Cross-section*	Maksimalni poprečni nagib (%) / *The maximum crossfall (%)*	7	7
	Minimalni poprečni nagib (%) / *The minimum crossfall (%)*	2.5	2.5
	Širina vozne trake (m) / *Width of the driving lane (m)*	3.00	3.25
	Širina ivične trake (m) / *Width of the paved shoulder (m)*	0.25	0.35
	Širina bankine (m) / *Width of the road shoulder (m)*	1.50	1.50
	Širina trake za postrojavanje (m) *The width of the lane for vehicles line-up (m)*	3.5	3.5
	Širina ulivno-izlivnih traka / *Width of merging – diverging lanes*	3.5	3.5
Preglednost/ *Sight distance*	Minimalna dužina zaustavne preglednosti (m) *The minimal length of the brake sight distance (m)*	55	115
	Minimalna dužina preticajne preglednosti (m) *The minimal length of the overtaking sight distance (m)*	320	480
	Minimalni procenat preticajne preglednosti (%) *The minimal percentage of overtaking sight distance (%)*	20	20

* Računska brzina na celoj deonici je 80 km/h, osim na delu od km 26+880 do km 26+960 gde se put nalazi u vertikalnoj krivini koja ne zadovoljava računsku brzinu od 80 km/h. Za taj potez su prikazani podaci u tabeli 2 za računsku brzinu 60 km/h. S obzirom na to što se radi o projektu pojačanog održavanja i o relativno kratkom potezu (l=80m) isti podaci nisu značajno uticali na utvrđivanje intervencija i na troškove radova.

* The design speed on the whole section is 80 km/h, except for the section from km 26 + 880 to km 26 + 960 where the path is in a vertical curve that fails to satisfy the design speed of 80 km/h. For this stretch, the data in Table 2 for the design speed of 60 km / h is displayed. Given that this is an enhanced maintenance project and a relatively short subsection (l = 80m), the same data insignificantly affects the interventions and the costs of the works.

3.2.1 Poprečni profil

Širine kolovoza na otvorenoj deonici mogu da se podele na tri poddeonice. Od km 26+680 do km 37+000 gde je širina kolovoza oko 7.2 m, zatim od km 37+000 do km 40+360 gde je širina kolovoza u proseku 8.5 m (autoputski profil) i na kraju od km 40+360 do km 42+260 gde je širina kolovoza u proseku 6.5 m.

3.2.1 Cross-section

Carriageway widths on open section can be divided into three subsections. From km 26+800 to km 37+000 where carriageway width is about 7.2m, then from km 37+000 to km 40+360 where carriageway width is about 8.5m (highway profile), and finally from km 40+360 to km 42+260 where carriageway width is about 6.5m.

Tabela 3. Podaci o karakteristikama poprečnog profila [9]
Table 3. Cross section data [9]

R.br. *Ord.*	Stacionaža *Chainage*	Dužina *Length* (km)	Broj saob. traka *No. of traffic lanes*	Prosečna širina kolovoza saob. trake *Average traffic lane pavement width* (m)	Prosečna širina bankine *Average shoulder width (m)*	Ukupna širina kolovoza *Total pavement width* (m)
1.	26+680 - 37+000	10.320	2	3.60	1.00	7.20
2.	37+000 - 40+360	3.360	2	4.25	1.00	8.50
3.	40+360 - 42+260	1.900	2	3.25	1.00	6.50

3.2.2 Geometrijske i vozno-dinamičke analize

<u>Krivinska karakteristika i analiza brzine</u>

Krivinska karakteristika predstavlja srednju vrednost skretnog ugla na posmatranoj deonici. Za predmetnu deonicu sračunati su krivinska karakteristika, srednje kvadratno odstupanje i koeficijent varijacije:

krivinska karakteristika: *K*=42.612 g/km,
srednje kvadratno odstupanje: *S*=29.992 g/km,
koeficijent varijacije: *KV*=70.38%.

3.2.2 Geometrical and driving-dynamical analysis

<u>Bendiness and speed analysis</u>

Bendiness represents absolute angular deviation measured in gradian/kilometre. For section in subject bendiness ratio, standard deviation and variation coefficient are calculated:

Bendiness ratio: *K*=42.612g/km
Standard deviation: *S*=29.992g/km
Variation coefficient: *KV*=70.38%

Vrlo visoki koeficijent varijacije posledica je dugih pravaca odnosno krivina velikih radijusa, a malih skretnih uglova na trasi.

3.2.3 Usvojene karakteristike deonice po homogenim potezima

U tabeli 4 prikazane su glavne geometrijske karakteristike deonice po homogenim potezima.

Very high variation coefficient is the result of long straight lines and horizontal curves with large radii and small deflection angles.

3.2.3 Adopted characteristics of the section by homogenous sub-sections

In Table 4 shows the characteristics of the existing section Irig – Ruma which are presented per homogenous subsections:

Tabela 4. Geometrijske karakteristike deonice po homogenim potezima [9]
Table 4. Geometric characteristics of the section by homogeneous sub-sections [9]

R.b. *Ord.*	Homogeni potez *Homogeneous sub-section*	Dužina *Length* (km)	Prosečna zakrivljenost *Average curvature* (deg/km)	$\sum$ (R+F)/L (m/km)	N° (R+F)/km	Prosečan poprečni nagib *Average elevation* %	Nadmorska visina *Altitude* mnm
H1	km 26+680 – km 28+680	2.000	24.17	1.63	3.64	2.5	150
H2.	km 28+680 – km 35+470	6.790	23.16	1.51	2.81	2.5	150
H3.	km 35+470 – km 36+680	1.210	99.60	0.30	4.03	3.0	150
H4.	km 36+680 – km 37+680	1.000	21.77	0.26	5.49	2.5	150
H5.	km 37+680 – km 40+070	2.390	57.50	0.62	2.01	3.0	150
H6.	km 40+070 – km 41+370	1.300	24.57	0.33	1.01	2.5	150
H7.	km 41+370 – km 42+260	0.890	18.10	0.23	1.02	2.5	150

3.3 Kolovozna konstrukcija

3.3.1 Postojeća kolovozna konstrukcija

Podaci o strukturi i karakteristikama postojeće kolovozne konstrukcije na deonici državnog puta IB-21, deonica: Irig 2 - Ruma 1 dobijeni su na osnovu arhivskih podataka iz 2004. i istražnih radova koji su sprovedeni za potrebe izrade Glavnog projekta pojačanog održavanja u junu 2016. godine.

3.3 Pavement Structure

3.3.1 Existing Pavement Structure

Composition of pavement was analyzed based on the historical data from 2004 as well as based on additional test pits drilling done in June 2016.

Tabela 5. Struktura kolovozne konstrukcije po homogenim potezima [9]
Table 5. Pavement structure by homogeneous sub-sections [9]

Potez *Sub-section*	Debljine asfaltnih slojeva *Thickness of asphalt layers(cm)*		Debljine sloja od cementom stabilizovanog kamenog agregata *Thickness of cement stabilized layer* (cm)	Debljine sloja od nevezanog kamenog agregata *Thickness of stone base layers* (cm)	Ukupne debljine kolovozne konstrukcije *Total thickness of pavement structure* (cm)	
	Levo *Left*	Desno *Right*			Levo *Left*	Desno *Right*
km 26+680 – km 28+680	18	33	/	38	56	71
km 28+680 – km 32+680	21	32	/	32	53	64
km 32+680 – km 34+680	16	20	/	25	41	45
km 34+680 – km 36+680	18	35	10	22	50	67
km 36+680 – km 39+480	20	20	15	37	72	72
km 39+480 – km 42+260	24	28	/	24	48	52

Svojstva materijala u posteljici

U sklopu geotehničkih istraživanja vršeni su istražni radovi na utvrđivanju fizičko-mehaničkih karakteristika materijala u posteljici postojeće kolovozne konstrukcije. Uzorci su dati za geomehanička ispitivanja i to standardnim metodama (standardi iz grupe SRPS U.B1 i SRPS EN 13286-47:2012).

Na uzetim uzorcima obavljena su sledeća laboratorijska geomehanička ispitivanja:

- granulometrijski sastav;
- Atterberg-ove granice konsistencije;
- sadržaj prirodne vlažnosti;
- Proctor-ov opit.

Properties of materials in capping layer

Within geotechnical investigations geo-mechanical properties of capping layer was determined. Samples were taken in accordance to standard methods (standards from group SRPS U.B1 and SRPS EN 13286-47:2012).

Determination of geo-mechanical properties included the following:

- determination of material particle size distribution,
- determination of consistency limits of the material,
- determination of bulk density and natural moisture,
- Proctor's test.

3.3.2 Projektno rešenje kolovozne konstrukcije

Metodološki pristup proračuna potrebnog pojačanja

Analiza nosivosti postojeće kolovozne konstrukcije i proračun potrebnog pojačanja, u ovom projektu, zasnivaju se na – REVISED AASHTO OVERLAY DESIGN PROCEDURE (1993) [12].

Proračun čini definisanje nosivosti postojeće kolovozne konstrukcije i definisanje potrebne nosivosti kolovozne konstrukcije za buduće eksploatacione uslove. Potrebno pojačanje se proračunava po sledećoj jednačini:

3.3.2 Pavement dimensioning

Methodological approach of the necessary reinforcement analysis

The analysis of the existing pavement bearing capacity and the calculation of required overlay in this design is based on – REVISED AASHTO OVERLAY DESIGN PROCEDURE (1993) [12].

The analysis is comprised of defining existing pavement bearing capacity and defining required bearing capacity for future operational conditions. The required overlay is calculated according to the following equation:

$$d_{poj} = \frac{SN_{fut} - SN_{eff}}{a_1} \quad (1)$$

gde je

SN_{fut} – potreban strukturni broj;

SN_{eff} – efektivan strukturni broj postojeće kolovozne konstrukcije;

a_1 – koeficijent zamene sloja za pojačanje.

Potrebno pojačanje od bitumeniziranog materijala, sračunato je iz razlike potrebne i efektivne nosivosti:

where:

SN_{fut} – required structural number,

SN_{eff} – effective structural number of existing pavement,

a_1 – coefficient of the replacement of reinforcing layer (overlay).

The required overlay of bituminous material is calculated from the difference between the required and the effective bearing capacity:

$$d_{poj} = \frac{SN - SN_{eff}}{a_{poj}} \quad (2)$$

U sledećoj tabeli prikazani su rezultati proračuna:

Results of the analysis are as follows:

Tabela 6. Efektivan i potreban strukturni broj [9]
Table 6. An Effective and required structural number [9]

Potez *Sub-section*	Stacionaža /*Chainage* (km)	SNeff (cm)	SNpotr (cm)	dpoj (cm)
I	km 26+680 – km 28+470	11.68	13.98	6.56
II	km 28+470 – km 32+970	9.60	14.23	13.23
III	km 32+970 – km 35+470	9.52	13.54	11.50
IV	km 35+470 – km 36+670	10.59	13.68	8.83
V	km 36+670 – km 37+680	13.19	13.58	1.00
VI	km 37+680 – km 40+070	13.38	14.02	2.00
VII	km 40+070 – km 41+370	10.52	14.76	12.11
VIII	km 41+370 – km 42+260	10.99	13.79	8.01

Za novi sloj od bitumeniziranog materijala usvojen je koeficijent zamene materijala a_{poj}=0.40. Za postojeću kolovoznu konstrukciju korišćeni su sledeći koeficijenti zamene materijala:

- asfaltni slojevi a_{asf}=0.35
- cementno stablizovani kameni agregat, a_{cs}=0.20
- sloj od nevezanog kamenog agregata a_{dk}=0.10

Na osnovu utvrđenog stanja kolovozne konstrukcije (vrsta i obim oštećenja) kao i na osnovu ESO (ekvivalentnog saobraćajnog opterećenja) predložene su odgovarajuće mere sanacije kolovozne konstrukcije.

For the new layer of bituminous materials, the coefficient of material substitution a_{poj} = 0.40 was adopted. For the existing pavement structure, the following coefficients of material substitution were used:

- asphalt layers a_{asf} = 0.35
- cement stabilized stone aggregate, a_{cs} = 0.20
- unbound stone aggregate layer a_{dk} = 0.10

Based on the established condition of the pavement structure (type and extent of damage) and on the basis of the ETL (Equivalent Traffic Load), appropriate measures have been proposed for the rehabilitation of the pavement structure.

3.4 Stanje kolovoza

3.4.1 Podužna neravnost površine kolovoza

Performansa podužne neravnosti kolovoza - Internacionalni indeks neravnosti (IRI) predstavlja meru udobnosti vožnje i utvrđuje se kontinualnim merenjem na odgovarajućem rastojanju [13]. Merenje je izvršeno profilometrom - laserskom gredom montiranom na prednjem delu vozila, koje se kreće brzinom većom od 40km/h (u svemu prema standardu SRPS EN 13036-6:2012).

Na osnovu dijagrama kumulativnih razlika dobijeni su homogeni potezi. U sledećoj tabeli date su srednje vrednosti za IRI i 85-procentne vrednosti po homogenim potezima, kao i ocena stanja prema navedenom kriterijumu:

3.4 Pavement condition

3.4.1 Pavement longitudinal roughness

A performance of the pavement longitudinal roughness - International Roughness Index (IRI) represents a measure of driving comfort and is determined by a continual measurement made at certain distances [13]. Measurement is performed by a profilometer – laser beam installed on front part of a vehicle moving at speed higher than 40 km/h (fully in compliance with the standard SRPS EN 13036-6:2012).

Based on Cumulative difference chart homogeneous sections have been identified. Average values of IRI and 85% values by homogeneous sections and condition assessment by stated criteria are shown in the following table:

Tabela 7. Ocena stanja kolovozne konstrukcije po homogenim potezima – IRI [9]
Table 7. Assessment of the pavement condition by homogeneous subsections – IRI [9]

Položaj *Location*	IRIsr (m/km)	IRI 85% (m/km)	Ocena stanja *Assessment of condition*
Desna strana / *Right side*			
km 26+520 – km 27+680	3.09	4.25	Loše / *Bad*
km 27+680 – km 28+880	2.96	3.95	Osrednje / *Fair*
km 28+880 – km 33+130	2.69	3.72	
km 33+130 – km 37+630	1.71	2.37	Dobro / *Good*
km 37+630 – km 39+760	4.31	6.11	Vrlo loše / *Very Bad*
km 39+760 – km 41+400	2.31	3.29	Osrednje / *Fair*
km 41+400 – km 42+240	3.01	3.97	
Leva strana / *Left side*			
km 26+520 – km 27+900	3.04	4.34	Loše / *Bad*
km 27+900 – km 29+180	4.01	5.55	Vrlo loše / *Very Bad*
km 29+180 – km 33+100	3.30	4.43	Loše / *Bad*
km 33+100 – km 37+620	1.70	2.43	Dobro / *Good*
km 37+620 – km 39+620	5.08	7.16	Vrlo loše / *Very bad*
km 39+620 – km 40+930	2.76	3.76	Osrednje / *Fair*
km 40+930 – km 42+240	3.24	4.54	Loše / *Bad*

3.4.2 Nosivost kolovozne konstrukcije

Defleksije, kao pokazatelji stanja strukture utvrđeni nedestruktivnom metodom, izmerene su deflektometrom s padajućim teretom (FWD 8002-236 - Dynatest), u maju, 2016. godine. Defleksija pri svakom udarcu merena je geofonima postavljenim na sledećim udaljenjima od centra kružne ploče: r=0 mm, 200 mm, 300 mm, 450 mm, 600mm, 900 mm, 1200 mm, 1500 mm i 1800 mm.

3.4.2 Pavement structural condition

Deflections, as indicators of the structure condition determined by a non-destructive method, were measured by a heavy falling weight deflectometer (FWD 8002-236 - Dynatest) in May 2016. Deflection measurement with every drop was done by geophones placed at the following distances from centre of the round plate: r=0 mm, 200 mm, 300 mm, 450 mm, 600 mm, 900 mm, Merenje je rađeno u tragu točka na svakih 100 m po saobraćajnoj traci, odnosno naizmenično na svakih 50 m.

Ukupno je urađeno 313 opita. Defleksije su korigovane odgovarajućim faktorom korekcije u skladu sa: Protocol 3 (CROW Report D11-07) – Short Term Repeatability Verification i Protocol 10 (CROW Report D11-07) – Falling Weight Deflectometer correlation trial.

Metodom kumulativnih razlika (AASHTO) definisani su homogeni potezi prema defleksijama površine kolovoza d0. U narednoj tabeli prikazane su izmerene defleksije po homogenim potezima:

1200 mm, 1500 mm and 1800 mm. Measurement was done in a wheel trace at every 100 m per lane, i.e. intermittently at every 50 m.

Total of 313 tests was done. Deflections were adjusted by a correction factor 0.865 in accordance with the Protocol 3 (CROW Report D11-07) – Short Term Repeatability Verification and Protocol 10 (CROW Report D11-07) – Falling Weight Deflectometer correlation trial.

By use of the method of cumulative differences (AASHTO), homogeneous sections according to pavement surface deflections d0 have been defined. The following homogeneous sections have been identified:

Tabela 8. Izmerene defleksije kolovoza po homogenim potezima [9]
Table 8. Measured pavement deflections by homogenous sub-sections [9]

Hom. potez *Hom. Sub-section*	Stat. podat./ *Stat. data*	Izmerene defleksije / *Measured deflections* (10^{-3}mm)								
		d0	d200	d300	d450	d600	d900	d1200	d1500	d1800
I	avg	318	252	216	176	144	102	75	57	45
	stdev	127	92	72	49	34	18	10	7	5
	kv	0.40	0.36	0.33	0.28	0.23	0.17	0.14	0.13	0.11
	85%	407	302	261	210	170	120	87	64	49
II	avg	416	326	273	213	169	112	79	60	48
	stdev	112	80	60	41	29	16	9	6	5
	kv	0.27	0.25	0.22	0.19	0.17	0.14	0.12	0.10	0.09
	85%	524	406	326	253	195	127	89	67	53
III	avg	335	274	239	190	148	96	65	49	39
	stdev	39	31	25	17	14	11	9	7	6
	kv	0.12	0.11	0.10	0.09	0.09	0.11	0.13	0.14	0.15
	85%	382	317	279	214	161	105	73	56	46
IV	avg	298	246	218	176	140	95	67	51	40
	stdev	87	72	60	42	28	12	5	4	2
	kv	0.29	0.29	0.28	0.24	0.20	0.12	0.08	0.07	0.06
	85%	370	300	267	216	166	104	71	53	41
V	avg	241	200	180	153	128	92	66	50	39
	stdev	82	67	57	43	31	20	13	9	6
	kv	0.34	0.33	0.32	0.28	0.24	0.21	0.19	0.18	0.16
	85%	315	259	228	190	153	110	81	61	46
VI	avg	370	284	240	195	161	117	88	68	54
	stdev	88	60	44	30	23	15	10	7	5
	kv	0.24	0.21	0.18	0.16	0.14	0.13	0.11	0.10	0.09
	85%	415	311	261	217	184	133	97	74	58
VII	avg	239	199	171	135	110	83	64	50	40
	stdev	118	110	80	46	30	20	12	8	5
	kv	0.49	0.55	0.47	0.34	0.27	0.24	0.20	0.16	0.13
	85%	351	311	260	184	146	107	74	57	45

Analizirani su indeks zakrivljenosti površine SCI, indeks oštećenja podloge BDI i d0 (20^0C), takođe po homogenim potezima.

3.4.3 Zbirni prikaz stanja kolovoza

Na osnovu analiziranih parametara:

- defleksija površine kolovoza;
- nosivosti posteljice kolovozne konstrukcije;
- postojeće strukture kolovozne konstrukcije;
- stanja oštećenosti površine kolovoza;

Surface Curvature Index SCI, Base Damage Index BDI and d0 (20ºC) were analyzed, also by homogeneous sections.

3.4.3 Summary overview of pavement condition

Based on the following analyzed parameters:

- deflection of pavement surface,
- bearing capacity of pavement subgrade,
- current composition of the pavement,
- severity of pavement damage,

– podužne ravnosti površine kolovoza;
– poprečne ravnosti površine kolovoza;
– zaštite od mraza.

Definisani su sledeći homogeni potezi sa stanovišta ocene stanja kolovoza i predviđenih radova na pojačanom održavanju.

– longitudinal evenness of pavement,
– transverse evenness of pavement,
– friction ability,
– protection against frost.

The following homogeneous sections based on pavement condition assessment and needed works on heavy maintenance were defined.

Tabela 9. Karakteristični homogeni potez – zbirni prikaz stanja kolovoza [9]
Table 9. Characteristic homogenous subsections pavement-conditipon summary [9]

Homogen potez *Homogenous sub-section*	Stacionaža *Chainage*	Dužina hom. poteza *Length of hom. sub-section* (km)
I homogen potez *I Homogenous sub-section*	km 26+680 – km 33+000	6.320
II homogen potez *II Homogenous sub-section*	km 33+000 – km 35+500	2.500
III homogen potez *III Homogenous sub-section*	km 35+500 – km 36+680	1.180
IV homogen potez *IV Homogenous sub-section*	km 36+500 – km 37+680	1.000
V homogen potez *V Homogenous sub-section*	km 37+680 – km 40+070	2.390
VI homogen potez *VI Homogenous sub-section*	km 40+070 – km 41+370	1.300
VII homogen potez *VII Homogenous sub-section*	km 41+370 – km 42+260	0.890
	Ukupna dužina / *Total length* (km):	**15.580**

4 SAOBRAĆAJNA ANALIZA

Informacionu osnovu za izradu predmetnog izveštaja čine sledeći podaci o saobraćajnom opterećenju:

– podaci određeni u projektnom zadatku za izradu Glavnog projekta pojačanog održavanja državnog puta IB 21, deonica: Irig 2 – Ruma 1 (Autoput), L=15.460 km;
– podaci prikupljeni kontrolnim brojanjem saobraćaja;
– podaci preuzeti sa internet stranice JP Putevi Srbije;
– podaci sa brojača saobraćaja broj 2072 preuzeti od JP Putevi Srbije.

4.1 Projekcije saobraćajnog opterećenja

Saobraćajno opterećenje je neophodno za proces projektovanja puteva i odnosi se na vremenske preseke u budućnosti, pa je projektnim zadatkom i pripadajućim metodologijama definisan planski period prema funkcionalnom tipu puta i vrsti i obimu planiranih građevinskih intervencija od deset godina. U daljoj analizi će biti prikazano saobraćajno opterećenje za desetogodišnji planski period.

Merodavno saobraćajno opterećenje na deonici ID 02105 u planskom periodu i u baznoj 2016. godini, prikazano je u tabeli 10.

Merodavno saobraćajno opterećenje na deonicama ID 02106, ID 02107 i ID 02108 u planskom periodu i u baznoj 2016. godini, prikazano je u tabeli 11.

4 TRAFFIC ANALYSIS

The information base for the preparation of this report is the following data on traffic load:

– data specified in the project task for the preparation of the Main Project for Improved Maintenance of the State Road IB 21, section: Irig 2 - Ruma 1 (Highway), L = 15,460 km;
– data collected by control counting of traffic;
– the data is downloaded from the website of PE Roads of Serbia;
– data from the traffic counter number 2072 taken from PE Roads of Serbia.

4.1 Traffic load projection

Traffic load is necessary for the road design process and refers to the time sections in the future, so the terms of reference and the associated methodologies define the planning period according to the functional type of a road and the type and scope of planned construction interventions of 10 years. A further analysis will show the traffic load for a ten-year planning period.

Relevant traffic load on the section ID 02105 during the planned period in the base year of 2016 is shown in Table 10.

Relevant traffic load on sections ID 02106, ID 02107 and ID 02108 during the planned period within the base year of 2016 is shown in Table 11.

Tabela 10. Projekcija rasta saobraćaja na deonici ID 02105 [9]
Table 10. Projection of traffic growth at section ID 02105 [9]

Godina *Year*	PA	BUS	LT	ST	TT	AV	Ukupno *Total*
2016	7,741	157	141	197	115	770	**9,121**
2017	8,066	164	147	205	120	802	9,504
2018	8,405	170	153	214	125	836	9,903
2019	8,758	178	160	223	130	871	10,319
2020	9,126	185	166	232	136	908	10,753
2021	9,509	193	173	242	141	946	11,204
2022	9,908	201	180	252	147	986	11,675
2023	10,325	209	188	263	153	1,027	12,165
2024	10,758	218	196	274	160	1,070	12,676
2025	11,210	227	204	285	167	1,115	13,208
2026	11,681	237	213	297	174	1,162	**13,763**

Tabela 11. Projekcija rasta saobraćaja na deonicama ID 02106, ID 02107 i ID 02108 [9]
Table 11. Projection of traffic growth at sections ID 02106, ID 02107 and ID 02108 [9]

Godina *Year*	PA	BUS	LT	ST	TT	AV	Ukupno *Total*
2016	7,430	115	152	198	165	932	**8,992**
2017	7,742	120	158	206	172	971	9,370
2018	8,067	125	165	215	179	1,012	9,763
2019	8,406	130	172	224	187	1,054	10,173
2020	8,759	136	179	233	195	1,099	10,601
2021	9,127	141	187	243	203	1,145	11,046
2022	9,510	147	195	253	211	1,193	11,510
2023	9,910	153	203	264	220	1,243	11,993
2024	10,326	160	211	275	229	1,295	12,497
2025	10,760	167	220	287	239	1,350	13,022
2026	11,212	174	229	299	249	1,406	**13,569**

Ukupno ekvivalentno saobraćajno opterećenje od 80kN odnosno 100kN za projektni period od deset, odnosno dvadeset godina:

- Deonica: ID 02105
  ESO80kN (10 god.) = 7.9 x 106 standardnih osovina od 80kN.
  ESO80kN (20 god.) = 20 x 106 standardnih osovina od 80kN.
- Deonica: ID 02106, ID 02107 i ID 02108
  ESO80kN (10 god.) = 9.2 x 106 standardnih osovina od 80kN.
  ESO80kN (20 god.) = 23 x 106 standardnih osovina od 80kN.

The total equivalent traffic load of 80кN or 100кN for the design period of 10, and 20 years:

- Section: ID 02105:
  ECO80kN (10years) = 7.9 x 106 standard axle load of 80кN.
  ECO80kN (20 years) = 20 x 106 standard axle load of 80кN.
- Section: ID 02106, ID 02107 и ID 02108:
  ECO80kN (10years) = 9.2 x 106 standard axle load of 80кN.
  ECO80kN (20years) = 23 x 106 standard axle load of 80кN.

4.2 Troškovi saobraćajnih nezgoda

Za potrebe izrade ekonomske analize usvojene su sledeći ulazni podaci za analizu troškova od saobraćajnih nezgoda na predmetnoj deonici državnog puta IB-21, Irig 2 – Ruma 1, u ukupnoj dužini od 15.580 km:

– prosečna stopa saobraćajnih nezgoda na 10^8 vozila-km iznosi: 32.78

– prosečna stopa poginulih na 10^8 vozila-km iznosi: 1.93

– prosečna stopa povređenih na 10^8 vozila-km iznosi: 11.57

4.2 Traffic accidents analysis

For the needs of the economic analysis development, the following input data were adopted for analyzing the costs of traffic accidents on the section of the state road IB-21, Irig 2 - Ruma 1, total length of 15.580 km:

– average rate of traffic accidents per 108 vehicles-km is: 32.78

– average rate of fatalities per 108 vehicles-km is: 1.93

– average rate of bodily injuries per 108 vehicles-km is: 11.57

– prosečna stopa nezgoda s materijalnom štetom na 10^8 vozila-km iznosi: 21.21
– prosečan broj saobraćajnih nezgoda iznosi: 17
– prosečan broj saobraćajnih nezgoda po km iznosi: 1.09

Prosečne vrednosti saobraćajnih nezgoda prikazane su u tabeli 12.

– average rate of traffic accidents with mat. damage per 10^8 vehicles-km is: 21.21
– the average number of traffic accidents is: 17
– the average number of traffic accidents per km is: 1.09

The average costs of traffic accidents are presented in the following Table 12.

Tabela 12. Prosečne vrednosti saobraćajnih nezgoda u Srbiji (2016) [9]
Table 12. Average values of traffic accidents in Serbia (2016) [9]

Godina *Year*	Prosečna vrednost za poginulo lice u Srbiji *Average value for death person in Serbia*	Prosečna vrednost za teške telesne povrede u Srbiji *Average value for serious body injury in Serbia*	Prosečna vrednost za lake telesne povrede u Srbiji *Average value for light body injury in Serbia*	Prosečna vrednost za materijalnu štetu u Srbiji *Average Value for Material Damage in Serbia*	Prosečna vrednost nezgode u Srbiji *Average value of traffic accidents in Serbia*
	(€)	(€)	(€)	(€)	(€)
2016	400,000	50,000	4,250	5,000	125,000

Navedene vrednosti usvojene su na osnovu preporuka datih u „Priručniku za analizu troškova i koristi za Srbiju”, JP Putevi Srbije, Beograd, decembar 2010. [14]. Na osnovu prethodnih podataka procenjeni su broj i troškovi saobraćajnih nezgoda na predmetnoj deonici Irig 2 - Ruma 1 (L=15.580 km) u periodu analize (2017-2027). Zbog same prirode projekta (pojačano održavanje) ne smanjuje se broj saobraćajnih nezgoda, već on raste proporcionalno s porastom PGDS-a [15].

Ukupni troškovi saobraćajnih nezgoda (nediskontovani) u periodu analize (2017-2027) procenjeni su na 8,335,000 €. Troškovi saobraćajnih nezgoda nisu uključeni u Ekonomsku analizu.

These values were adopted on the basis of the recommendations given in the "Cost and Benefit Analysis Manual for Serbia", PE "Roads of Serbia", Belgrade, December 2010 [14].Based on the previous data, the number and costs of traffic accidents on the Irig 2 - Ruma 1 section (L = 15,580 km) for the analyzed period (2017-2027) were estimated. Due to the nature of the design (heavy maintenance) there is no reduction in the number of traffic accidents, but it increases in proportion to the increase in AADT[15].

The total costs of traffic accidents (undiscounted) in the analyzed period (2017-2027) were estimated at 8,335,000 €. The costs of traffic accidents are not included in the Economic Analysis.

5 PREDLOŽENI RADOVI – VARIJANTNA REŠENJA

5.1 Osnovna varijanta: minimum radova na održavanju deonice

5.1.1 Radovi na redovnom održavanju puta

U okviru definisanja „scenarija” osnovne varijante za upoređenje („minimum radova na održavanju kolovoza”), uključeni su radovi na redovnom održavanju puta. Ovi radovi u modelu HDM-4 ne utiču na model promene stanja kolovoza u toku vremena, već ekonomsku analizu opterećuju samo dodatnim troškovima uređenja putnog pojasa (*miscellaneous operations*) [16]. Radovima na redovnom održavanju puta generalno su obuhvatili sledeće radove [17]:

– pregled i praćenje stanja puteva i objekata;
– mestimično popravljanje i obnavljanje trupa puta;
– čišćenje kolovoza u granicama putnog zemljišta, odnosno zaštitnog pojasa gde se radi o erozivnom terenu;
– zaštita kosina nasipa, useka i zaseka;
– uređenje bankina;
– čišćenje i uređenje jarkova, propusta i drugih delova puta;
– popravka mostova;
– zaštita mostova i objekata od korozije;

5 PROPOSED WORKS – ALTERNATIVES

5.1 Base alternative: minimal works on the maintenance of the section

5.1.1 Routine maintenance

Within the framework of defining the "scenarios" of the basic variants for comparison ("minimum work on carriageway maintenance"), works on regular road maintenance are included. These works in the HDM-4 model do not affect the model of the change in the condition of the carriageway during the time, but they only burden economic analysis with the additional costs of the arrangement of the roadside area ("*miscellaneous operations*")[16].Routine maintenance works generally include the following works[17]:

– reviewing and monitoring the condition of roads and structures;
– partly repairing and renewing the road bed;
– cleaning the carriageway within the boundaries of the roadside area, or the protection zone where the field is erosive;
– protection of slopes of the embankments, cuts and side cuts;
– road shoulder arrangement;
– cleaning and arranging ditches, culverts and other

– zamena, čišćenje i opravka saobraćajnih znakova i druge opreme puta;
– obnova horizontalne signalizacije;
– košenje trave i održavanje zelenih površina na zemljišnom pojasu;
– zimsko održavanje puteva.

parts of the road;
– repair of bridges;
– protection of bridges and structures from corrosion;
– replacement, cleaning and fixing traffic signs and other road equipment;
– renovation of horizontal signage;
– mowing grass and maintaining green areas on the soil patch;
– winter road maintenance

Tabela 13. Troškovi redovnog održavanja puta
Table 13. Routine maintenance costs

R.b.	Standard održavanja *Maintenance Standard*	Kôd standarda *Standard Code*	Jed. mera *Unit*	Ekonom-ska cena *Economic Cost* (€/km)	Finansijska cena *Financial Cost* (€/km)	Kriterijum za primenu *Appling criteria*	Efekat primene *Effects*
1.	REDOVNO ODRŽAVANJE *(ROUTINE MAINTENANCE)*	RM	km	5,000	6,250	svake godine every year	-

5.1.2 Radovi na redovnom održavanju kolovoza

Radovima na redovnom održavanju kolovoza predviđeno je:
– zalivanje pukotina;
– krpljenje udarnih rupa;
– popravke ivice kolovoza.

5.1.2 Works on regular pavement maintenance

Works on regular maintenance of the carriageway anticipate:
– crack sealing,
– pothole patching and
– edge repair.

Tabela 14. Troškovi redovnog održavanja kolovoza
Table 14. Routine maintenance costs

R.b. *Or.*	Standard održavanja *Maintenance Standard*	Kôd standarda *Standard Code*	Jed. mera *Unit*	Ekonomska cena *Economic Cost* (€/km)	Finansijska cena *Financial Cost* (€/km)	Kriterijum za primenu *Apliing Criteria*	Efekat primene *Effects*
1.	ZALIVANjE PUKOTINA (*CRACK SEALING*)	CRKSL	m^2	2.26	3.04	Wide Structural Cracking ≥ 1%	Wide and trans. cracks 100%
2.	KRPLJENJE UDARNIH RUPA (*POTHOLE PATCHING*)	POTPAT	m^2	10.01	13.50	Potholing ≥1 no./km	Patching 100%
3.	POPRAVKA IVICA KOLOVOZA *(EDGE REPAIR)*	EDGRPR	m^2	9.70	13.09	Edge break ≥1 m^2./km	Patching 100%

5.2 Varijanta za poređenje: predloženi radovi na pojačanom održavanju

5.2.1 Radovi na pojačanom održavanju puta

Prema projektnoj dokumentaciji, ukupna finansijska vrednost radova na pojačanom održavanju državnog puta IB-21 na deonici Irig 2 - Ruma 1, u ukupnoj dužini od 15.580 km, iznosi 5,175,240.12 €, odnosno 332,172.02 € po km puta.

5.2 Comparison alternative: proposed works for heavy maintenance

5.2.1 Works on heavy road maintenance

According to the design documentation, total financial value of works on heavy maintenance of the state road IB21 on the section Irig 2 - Ruma 1 in the total length of 15.580 km is 5,175,240.12 €, in other words approx 332,172.02 € per km of road.

Odnos ekonomske prema finansijskoj vrednosti radova iznosi 0.80, tako da ekonomska vrednost radova iznosi 4,140,192.09 €, odnosno 265,737.62 € po km puta.

Navedeni troškovi radova obuhvataju ve troškove radova na pojačanom održavanju koji su predviđeni Glavnim projektom pojačanog održavanja:

- građevinski deo;
- geodetski deo;
- objekti;
- saobraćajna signalizacija i oprema;
- regulisanje saobraćaja za vreme radova;
- odvodnjavanje;
- rasveta.

Radovi na pojačanom održavanju puta predviđeni su tokom 2017. godine (100%).

The ratio of the economic towards financial value of works is 0.80, so that economic value of works is 4,140,192.09 €, in other words approx. 265,737.62 € per km of road.

The abovementioned costs of the works include all the expenses of the enhanced maintenance works that are foreseen in the Main Design of the enhanced maintenance:

- the building parts,
- geodetic part,
- objects,
- traffic signalization and equipment,
- regulation of traffic during works,
- drainage and
- lighting.

Works on heavy road maintenance are planned during the year 2017 (100%).

6 EKONOMSKA ANALIZA

6.1 Analiza ekonomskih pokazatelja

Ekonomska analiza urađena je pomoću modela HDM-4. Ovaj model izračunava diskontovane tokove čistih koristi (ušteda) tokom perioda analize. Ekonomska analiza sprovedena je za svaki homogeni potez, kao i kumulativno za celu deonicu.

6 ECONOMIC ANALYS

6.1 Analysis of economic indicators

Economic analysis is based on model HDM-4. This model calculates discounted flows of pure benefits during analysis period. Economic analysis is conducted for every homogenous section and cumulatively for the whole section.

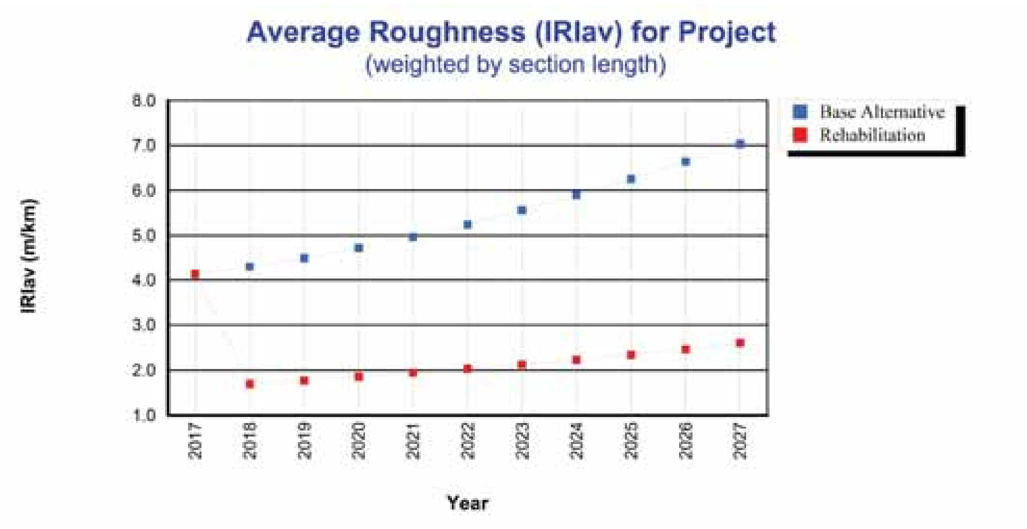
Tabela 15. Rezultati ekonomske analize
Table 15. Results of Economic Analyses

Pregled ekonomskih indikatora / *Economic indicators summary*	
Uštede u troškovima eksploatacije vozila / *Vehicle Operating Costs* (mil. €)	8.37
Uštede u vremenu putovanja / *Travel Time Savings* (mil. €)	3.63
Interna stopa rentabiliteta ISR / *Internal Rate of Return IRR* (%)	31.5
Neto sadašnja vrednost NSV / *Net Present Value* (mil. €)	7.94
NSV / *KAP*	1.93

** diskontovane vrednosti /discounted values*

Na slici broj 1 prikazana je promena stanja površine kolovoza u zavisnosti od projektnog rešenja.

Figure 1 shows a change of pavement surface condition depending on the design solution.



Slika 1. Promena stanja površine kolovoza
Figure 1. Pavement surface condtion change

6.2 Analiza osetljivosti rezultata

Analiza osetljivosti rezultata sprovedena je za sledeće slučajeve:

- smanjenje obima saobraćaja za -20%,
- povećanje ukupnih troškova radova za +20%,
- smanjenje obima saobraćaja za -20% i povećanje ukupnih troškova radova za +20%.

6.2 Sensitivity Analyses

Analysis of data sensitivity is conducted for following cases:

- Traffic volume reduction for -20%,
- Increase of total costs of the works for +20%,
- Traffic volume reduction for -20% with increase of total costs of the works for +20%.

Tabela 16. Analiza osetljivosti rezultata
Table 16. Sensitivity Analyses

Ekonomski indikator/*Economic Indicator*	**IRS (%)**	**NSV (mil. €)**	**NSV / KAP**
Referentna vrednost / *Reference Value*	**31.5**	**7.94**	**1.93**
Povećanje troškova radova za +20% *Increase of Work Costs +20%*	26.6	7.12	1.73
Smanjenje stope saobraćaja za -20% *Decrease of traffic growth -20%*	30.3	7.26	1.76
Smanjenje stope saobraćaja za -20% i povećanje troškova radova za +20% *Decrease of traffic growth -20% and Increase of Work Costs +20%*	25.4	6.45	1.56

6.3 Analiza troškova zagađenja vazduha

Troškovi zagađenja odnose se na korišćenje energije drumskog saobraćaja. Sledeće emisije štetnih gasova i materija izračunavaju se na osnovu korišćenja energije: CO, NOx, CO_2, SOx. Brzina kretanja vozila i dužina putne veze određuju potrošnju goriva (benzina ili dizela), u zavisnosti od tipa vozila.

Emisija vozila i troškovi zagađenja vazduha proračunati su pomoću HDM-4 modela. Zbog same prirode projekta (pojačano održavanje) ne nastaju značajne promene u režimu kretanja vozila, pa su i uštede koje se ostvaruju od smanjenja zagađenja vazduha relativno male i procenjene su na 28,035 € (nediskontovana vrednost) tokom perioda analize (2017-2027).

6.3 Air pollution costs analysis

Pollution costs refer to the energy usage of road traffic. The following emissions of pollutants are calculate based on energy usage: CO, NOx, CO2, SOx. Speed of the vehicle and length of the road connection determines fuel consumption (gasoline or diesel), based on the type of the vehicle.

Calculation of vehicle emission and air pollution costs are calculated with HDM-4 model. Because of the nature of the design (heavy maintenance) there is no significant changes in vehicle movement regime so savings are relatively small and estimated on 28,035 € (undiscounted value) during analysis period (2017.-2027).

7 ZAKLJUČCI I PREPORUKE

- Ekonomska analiza je urađena pomoću modela HDM-4. Ovaj model izračunava diskontovane tokove čistih koristi (ušteda) tokom perioda analize. Ekonomska analiza sprovedena je za period eksploatacije od deset godina. Ukupan period analize obuhvata 1+10=11 god. (2017-2027. godine).
- Radovi na pojačanom održavanju puta predviđeni su tokom 2017. godine (100%).
- Početna godina eksploatacije rehabilitovane deonice jeste 2018. godina.
- Ukupna vrednost investicije s primenom u prvoj godini analize (2017) procenjena je na 5,175,240 €, odnosno 332,172 € po km puta (finansijska vrednost).
- Dobijeni rezultati ekonomske analize projektnog rešenja radova na pojačanom održavanju razmatrane deonice, iskazani pre svega putem Interne stope rentabiliteta (ISR= 31.5%) i Neto sadašnje vrednosti (NSV= 7.94 mil. €) ukazuju na opravdanost investicionih ulaganja u radove na pojačanom održavanju.
- Rezultati analize osetljivosti ukazuju na prihvatljivu stabilnost projektnog rešenja, pogotovu ako se ima u

7 CONCLUSIONS AND RECOMMENDATIONS

- Economic analysis is based on the model HDM-4. This model calculates discounted flows of pure benefits during the analyzed period. Economic analysis is conducted for the period of exploitation of 10 years. Total period of analysis is 1+10=11 years (2017-2027 year)
- Works on heavy maintenance will be executed during the year 2017. (100%)
- Exploitation begins in 2018.
- Total value of investment in the first year of analysis is estimated on 5,175,240 €, or 332,172 €/km (financial value).
- The results of economic analysis for works on heavy maintenance of section in subject expressed through Internal Rate of Return (IRR=31.5%) and Net Present Value (NPV=7.94 mil. €) show that investment for works on heavy maintenance are justified.
- The results of sensitivity analysis show that designed solution is acceptable, especially when social aspect requirements were not considered as it was the case in this analysis.

vidu da u okviru ove analize nisu razmatrane egzogene koristi iz socijalnog aspekta.

– Nažalost, zbog same prirode projekta koji se prvenstveno odnosi samo na održavanje puta (pojačano održavanje), ne smanjuje se broj saobraćajnih nezgoda, već on raste proporcionalno s porastom PGDS-a. Ukupni troškovi saobraćajnih nezgoda (nediskontovani) u periodu analize (2017-2027) procenjeni su na 8,335,000 €. Troškovi saobraćajnih nezgoda nisu uključeni u ekonomsku analizu.

– Uštede koje se ostvaruju smanjenjem zagađenja vazduha relativno su male i procenjene su na 28,034 € tokom perioda analize (2017-2027). Ove koristi nisu uključene u ekonomsku analizu.

– Na osnovu ovih rezultata može se zaključiti da je ulaganje u predložene radove pojačanog održavanja na razmatranoj deonici državnog puta IB-21, Irig 2 – Ruma 1 u ukupnoj dužini od 15,580 km ekonomski opravdano.

– Unfortunately, due to the very nature of the project, primarily referring to road maintenance (heavy maintenance), there is no reduction in the number of traffic accidents, but it increases in proportion to the increase of AADT. The total cost of traffic accidents (undiscounted) in the analyzed period (2017-2027) was estimated at 8,335,000 €. The cost of traffic accidents is excluded from the economic analysis.

– Savings generated through reduced air pollution are relatively small and estimated at € 28,034 during the analysis period (2017-2027). These benefits are excluded from economic analysis.

– Based on the results it can be concluded that investment in proposed measures for heavy maintenance on road section of the state road IB-21, Irig 2 – Ruma 1 in total length of 15.580 km is economically justified.

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REZIME

EKONOMSKA ANALIZA POJAČANOG ODRŽAVANJA DRŽAVNOG PUTA IB21, DEONICA IRIG-RUMA

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Upravljanje održavanjem putne mreže predstavlja proces donošenja odluka o investicijama, u kojem je veoma značajno razrešiti brojna tehnička i ekonomska pitanja i obezbediti što više objektivnih tehničkih i ekonomskih informacija za konačno donošenje odluke. Planiranje održavanja putne mreže predstavlja jedan od osnovnih zadataka za svakog upravljača putnom mrežom. U radu se daje prikaz metodološkog postupka za izradu ekonomske analize i ocene investicije za radove na periodičnom održavanju puta s primerom deonice državnog puta IB 21, Irig–Ruma, u ukupnoj dužini od 15,580 km, kao deo nacionalnog projekta rehabilitacije puteva i unapređivanja bezbednosti saobraćaja u Republici Srbiji.

Ključne reči: upravljanje putevima, održavanje puteva, HDM-4 model, ekonomska analiza

SUMMARY

ECONOMIC ANALYSES OF HEAVY MAINTENANCE (UPGRADING) OF STATE ROAD IB21, SECTION IRIG-RUMA

Milos SESLIJA
Igor VUKOBRATOVIC
Miodrag POCUC
Igor PESKO

The management of the road network presents the process of decision making on investments, where it is very important to solve numerous technical and economic issues and to provide as much objective technical and economic information as possible for final decision making. Planning the maintenance of the road network is one of the basic tasks for each road network manager. This paper presents a methodological procedure for the preparation of economic analysis and assessment of investments for the periodic maintenance of roads with example of the state road IB 21, section Irig - Ruma, in the total length of 15,580 km as a part of the national road rehabilitation project and the improvement of road safety in the Republic Serbia.

Key words: road management, road maintenance, HDM-4 model, economic analysis

PROCENA ČVRSTOĆE BETONA PRI PRITISKU, KORIŠĆENJEM RAZLIČITIH FUNKCIJA ZRELOSTI BETONA: PRIMER IZ PRAKSE

ASSESMENT OF CONCRETE COMPRESSIVE STRENGTH USING DIFFERENT MATURITY FUNCTIONS: CASE STUDY

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1 UVOD

Čvrstoća pri pritisku jeste svojstvo betona, najvažnije prilikom projektovanja i izvočenja konstrukcija. Često se ostala svojstva – poput đvrstoće pri zatezanju, modula elastiđnosti i trajnosti – povezuju s đvrstoćom pri pritisku betona. U nauđnoj i struđnoj zajednici, najviše se poklanjala pažnja modelovanju razvoja đvrstoće pri pritisku betona tokom vremena. Većina modela uključuje u razmatranje više parametara od kojih su najznađajniji oni koji se odnose na svež beton, kao što su vrsta i kolidina pojedinih komponentnih materijala. Ipak, na razvoj đvrstoće betona veliki uticaj ima i temperatura, koja se uglavnom ne razmatra, jer je većina modela zasnovana na ispitivanjima u laboratoriji pri nekoj konstantnoj temperaturi.

Kada je beton u pitanju, neophodno je razdvojiti uticaj temperature kao uslova sredine odnosno nege betona od temperature koja je posledica hidratacije cementa. Posledice delovanja povišene temperature umnogome se razlikuju u zavisnosti od mesta nastanka. Ovo je posebno bitno u sluđaju masivnih betona, gde se povećana temperatura usled hidratacije cementa ne može zanemariti.

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1 NTRODUCTION

Compressive strength is a property of concrete of the highest importance throughout design and construction stage. Other properties, such as tensile strength, modulus of elasticity and durability are often associated with concrete compressive strength. Consequently, scientific and practitioners' communities pay most attention to the development of models for this particular concrete property. Most of these developed models take into account two or more parameters among which the parameters related to fresh concrete such as type and quantity of component materials are the most significant. In addition, temperature has great influence on the development of concrete strength. However, this parameter is almost never taken into consideration since most models are based on laboratory tests performed at a constant temperature.

When it comes to concrete, it is necessary to separate the impact of temperature as an environmental condition, i.e., concrete curing condition, and temperature generated by cement's hydration. Consequences of elevated temperature differ substantially depending on the place of origin. This is especially important in the case of massive concrete elements, in which temperature increases since the hydration of cement cannot be ignored.

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Kontrola čvrstoće betona u konstrukciji, prema američkim propisima, podeljena je prema vrstama i veličini konstrukcije. Propisane su metode koje se primenjuju za pločaste elemente do 300 mm debljine, kao i više metoda za sve ostale tipove i veličine konstrukcija. Najčešće primenjivane metode jesu otpornost na utiskivanje, *pullout* i metode na bazi zrelosti betona. Za svaki od navedenih pristupa, standardom su propisane metode ispitivanja i izračunavanja čvrstoće betona u konstrukciji.

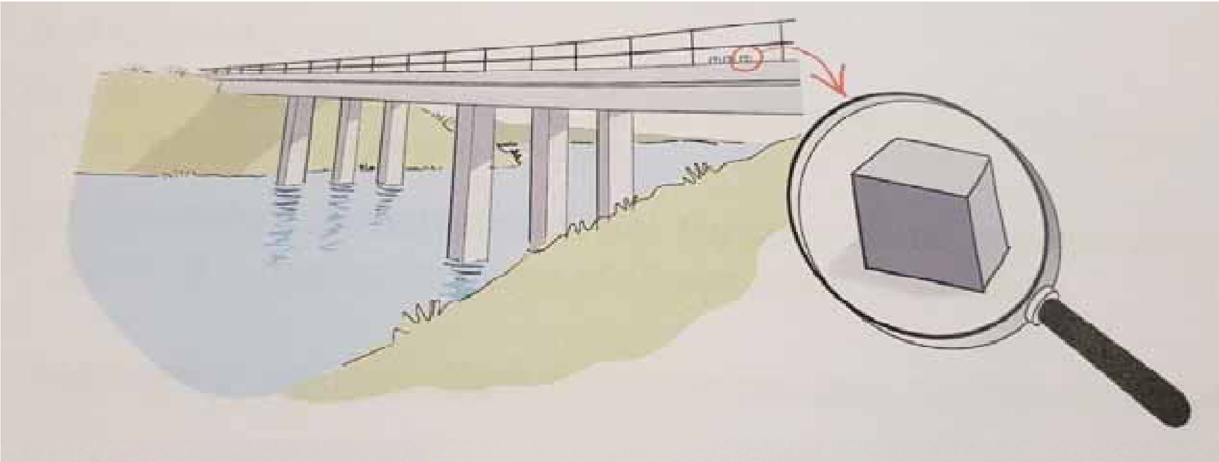
Kontrola saglasnosti sa uslovima projekta konstrukcije pomaže u tome da se obezbedi sigurnost da proizvod – beton – ispunjava očekivanja odnosno propisane kriterijume [1]. Prema zvaničnim zakonskim propisima Republike Srbije u oblasti betona, za dokaz čvrstoće betona mogu da se koriste uzorci kao što su kocke, prizme i cilindri različitih dimenzija. Za konačni dokaz, svi rezultati preračunavaju se na kocke ivice 20 cm. Uvođenjem evropskih propisa, u Republici Srbiji – na gradilištima i u laboratorijama – osnovni uzorci će biti kocke ivice 15 cm. U skladu s važećim standardima, za ocenu betona u konstrukciji propisana je odgovarajuća nega koja je u potpunosti drugačija od nege elementa u konstrukciji. Za neke faze građenja konstrukcije uzimaju se dodatni uzorci koji se čuvaju u istim uslovima kao odgovarajući elementi u konstrukciji. Oni se koriste kako bi se odredilo optimalno vreme oslobađanja elementa od oplate, utezanja konstrukcije i slično. Ipak, u slučaju masivnih konstrukcija i elemenata konstrukcije sa značajnim dimenzijama, poređenje betona u kocki i konstruktivnom elementu pod znakom je pitanja. O kakvom disparitetu je reč, prikazano je na slici 1, na kojoj se jasno vidi kolika može biti razlika u veličini između kontrolnog uzorka i konstrukcije. U slučaju, na primer, prednapregnutih konstrukcija, broj uzoraka na gradilištu znatno se povećava i neophodna je dobra koordinacija kontrolne laboratorije sa izvođačem radova, kako bi se na vreme dobio podatak o čvrstoći betona.

Zakonska regulativa Republike Srbije, u oblasti armiranog betona, oslanja se u svemu na još uvek važeći pravilnik BAB'87 [2]. Kada je u pitanju temperatura u betonu, važeći pravilnik BAB'87 definiše maksimalnu temperaturu u masivnim betonskim elementima na nivou od 60°C. Evropske norme su nešto blaže, pa maksimalnu temperaturu u betonu ograničavaju na 70°C [3]. Američki propis za beton ACI 318 [4] ograničava maksimalnu temeperaturu u betonu na svega 55°C. Izgradnja masivnih delova konstrucija posebno je kritična u zemljama hladnih klimatskih prilika. Tako, propisima u Švedskoj, definisana je maksimalna dozvoljena temperatura u betonu svega 55°C, a ograničen je i maksimalni temperaturni gradijent u elementu konstrukcije na 24°C [4–7]. Pored ograničenja temperature i temperaturnog gradijenta, u Švedskoj su propisana tri nivoa proračuna uticaja temperature na konstrukciju pre početka izgradnje, u zavisnosti od vrste i veličine konstrukcije koja se gradi [7].

According to US regulations the control of in-place concrete strength depends on the types and size of structures. There are special methods which are applicable to plate-like elements, whose thickness goes up to 300mm thick, as well as several different ones for all other types and sizes of structures. The most often applied methods are the pull-through resistance test method, the pull-out method and methods based on maturity of concrete. For each of these approaches, there are standard prescribing methods for testing and calculating in-place concrete strength.

The control of compliance with the structure design requirements help to ensure that the product – concrete meets the requirements, i.e., prescribed criteria. [1] According to the legislation of the Republic of Serbia relevant to concrete, samples in the form of cubes, prisms and cylinders of various dimensions are used for the purpose of proving required concrete strength. The final proof is presented as the strength of concrete obtained in 20cm cubes. With the introduction of European regulations, the construction sites across the Republic of Serbia will take a 15cm cube as the basic test cube. For the purpose of evaluation of in-place concrete strength, appropriate curing has been prescribed, according to the applicable standards. The curing prescribed by applicable standards is entirely different from the curing of elements in-situ. For some phases in construction stage additional samples should be taken and kept under the same conditions as the corresponding in-place elements. Such samples are used to determine the optimum time for stripping formwork, for tightening the structure, etc. However, in the case of massive structures and structural elements of significant dimensions, comparing concrete cured in test cubes to in-place concrete is questionable. The kind of required disparity is shown in Figure 1 which clearly shows how much the difference can be in size between the control sample and the construction. For instance, if prestressed structures are used at a construction site, the number of samples is significantly increased and it is necessary to have a good coordination between the activities of the test lab and the contractor of the works for obtaining reliable and timely data on concrete strength.

Serbian Republic regulations related to reinforced concrete rely on the still applicable Rulebook BAB'87 [2]. Regarding temperature in the concrete, the Rulebook BAB'87 allows the maximum temperature in massive concrete elements of 60°C. European norms are a bit more relaxed, limiting the maximum temperature in concrete to 70°C [3]. American concrete institute standard, ACI 318 [4] limits the maximum concrete temperature to only 55°C. The execution of massive parts of structures is critical in the cold climate countries. Thus, Swedish regulations set the maximum concrete temperature at only 55°C, at the same time also limiting the maximum temperature gradient in a structural elements to 24°C [4,7]. Beside maximum temperature and temperature gradient, the Swedish regulations before construction stage also prescribe three levels of calculations of the impact of temperature on the structure, depending on the type and size of the structure. [7].



Slika 1. Uzorci za kontrolu čvrstoće betona, negovani u uslovima kao elementi konstrukcije
Figure 1. Samples for concrete strength testing cured under the same conditions as in-place members

Ocena saglasnosti s propisanim uslovima kvaliteta betona na mestu ugrađivanja – putem uzoraka kocki i bez uzimanja u obzir uticaja temperature – jeste diskutabilna. Rađena su brojna istraživanja i razvijene su metode koje povezuju čvrstoću pri pritisku i temperaturu betona u starostima do 28 dana [8,9]. U istraživanjima su prikazani različiti rezultati i pouzdanost usvojenih metoda, jer su ulazni parametri različiti, a samim tim i zaključci se razlikuju. U prikazanim istraživanjima, različito je i dobijanje ulaznih parametara, kao i njihovo usvajanje, što je najznačajniji uzrok razlika u analizama i zaključcima.

Cilj rada jeste da se na primeru iz prakse građenja masivnih konstrukcija uporedi više predloženih pristupa kontrole i procene čvrstoće betona. Prvo, potrebno je uraditi laboratorijske probe pri konstantnim temperaturama nege, a nakon toga sprovesti merenja temperature u masivnim delovima konstrukcije mosta, uraditi proračun čvrstoće betona i nakon toga uporediti dobijene rezultate. Pored teorijskih pristupa za procenu čvrstoće, koristiće se uređaj *ConReg* 706, pomoću kog može da se procenjuje čvrstoća betona.

The evaluation of conformity with prescribed concrete quality requirements for in-place concrete via test cubes is questionable without taking into account the impact of temperature. Numerous researches have been done and methods have been developed to connect compressive strength and temperature in concrete aged up to 28 days [8,9]. The research shows the different results and reliability of the adopted methods, since the input parameters are different, and thus, the conclusions differ. In the presented research, the acquisition and adoption of input parameters is different, which is the most significant cause of differences in analyzes and conclusions.

The aim of this paper is to compare the proposed approaches to the control and assessment of the concrete strength in the case study of the construction of mass concrete constructions. First, it is necessary to do laboratory tests at constant temperature of curing, and then perform temperature measurements in massive parts of the bridge construction, perform a calculation of concrete strength and then, compare the results obtained. In addition to theoretical approaches for strength assessment, the ConReg 706 will be used to assess the strength of the concrete.

2 TEORIJSKE POSTAVKE

Kvalitet ugrađenog betona, po pravilu, u praksi se kontroliše na uzorcima koji se uzorkuju prilikom betoniranja konstrukcije. Uzorci se neguju u svemu prema standardu. Kada su u pitanju uzorci betona za kritične faze tokom građenja, oni se uglavnom čuvaju u uslovima istim kao i elementi u konstrukciji. Nakon dostizanja zahtevane starosti, uzorci se transportuju u laboratorije radi ispitivanja; nakon dobijanja rezultata, donosi se odluka o izvođenju planiranih faza tokom gradnje. Uzorci – koji se čuvaju u uslovima kao i elementi u konstrukciji – koriste se kako bi se dokazala čvrstoća betona, neophodna za skidanje oplate, faze utezanja i/ili skidanje potpornih elemenata u slučaju ploča i sličnih elemenata.

Osnovno pitanje koje se postavlja jeste da li takvi uzorci (kocke ili cilindri koji se neguju na gradilištu) na

2 THEORETICAL POSTULATES

As a rule, the quality of in-place concrete in practice is controlled using samples taken during the building works. For the first 24 hours, the samples are cured under conditions applicable to in-place elements, i.e., under conditions as similar as possible to those prescribed by the applicable standard. Thereafter, the samples are cured fully in accordance with prescribed standards. Samples of concrete taken in critical phases of building works are kept, as a rule, under the same conditions as in-place elements. When reaching the required age, such samples are transported to laboratories for further testing and, based on the obtained results, decisions are made on proceeding with planned stages in building works. The samples cured under the same conditions as in-built elements are used to prove the strength of the concrete required for strip-pravi način reprezentuju stanje u betonskoj konstrukciji. Ukoliko se razmatra betoniranje u uslovima niskih temperatura, uzorci koji se neguju na gradilištu imaju znatno niže temperature. U takvim uslovima, uzorci mogu imati drastično manje čvrstoće betona od betona u masivnim delovima konstrukcije. Ako se, pak, razmatra beton u predelima s visokim temperaturama, može doći do znatno viših temperatura u betonskim telima za kontrolu, nego u samoj konstrukciji. U tim slučajevima, mogu se očekivati uočljivo veće čvrstoće betona na uzorcima za kontrolu kvaliteta od betona u konstrukciji. Opisane situacije ukazuju na to da je neophodno kontrolisati temperaturu betona, kako bi se stvorila jasna slika o dostignutim čvrstoćama betona i uporedilo stanje u uzorcima s konstrukcijom.

Istraživači i brojni proizvođači opreme razvili su niz metoda za kontrolu postignute čvrstoće betona u konstrukciji, u zavisnosti od temperature koja se javlja u elementu. Sve razvijene metode zasnivaju se na principu zrelosti betona. Smatra se da hidratacija cementa prestaje na temperaturama oko -10°C, a zrelost betona zavisi od starosti i temperature kojoj je beton bio izložen. Osnova za primenu zrelosti betona u određivanju čvrstoće betona jesu laboratorijska ispitivanja pomoću kojih se određuje zavisnost čvrstoće i zrelosti, nakon čega se dobijena funkcija može primenjivati prilikom izgradnje na terenu, odnosno gradilištu. Funkcije zrelosti betona jesu matematički izrazi za računanje kombinovanog efekta vremena i temperature na razvoj čvrstoće betonskih mešavina odnosno cementnih kompozita. Dva u svetu najviše prihvaćena pristupa jesu: da je nivo razvoja čvrstoće linearno zavisan od temperature odnosno da se razvoj čvrstoće odvija po eksponencijalnoj Arrhenius jednačini. Oba pristupa imaju svoje prednosti, kao i nedostatke. Prvi pristup je veoma jednostavan za korišćenje, ali je manje pouzdan, dok je drugi pristup nešto složeniji, jer zahteva određene dodatne parametre na osnovu većeg broja laboratorijskih ispitivanja, ali je precizniji od prvog pristupa.

Prvi pristup određivanja faktora temperatura–vreme zasnovan je na funkciji zrelosti (1), koju su pedesetih godina prošlog veka predložili Nurse & Saul [8], usvajajući to da je T_0 u rasponu od -8 do -10°C, kao temperatura na kojoj prestaje hidratacija cementa.

ping the formwork, for re-tightening and/or removing supporting structures in the case of slabs and similar members.

The basic question is: whether a cube or a cylinder sampled at the construction site properly reflects the state within the concrete structure. This issue is of particular importance from the aspect of in-place concrete strength, and achieving designed in-place concrete strength. If laying concrete is considered under low environment temperatures, the samples taken in situ would be also considerably cooler. In such cases, the strength of the sampled concrete can be significantly lower than that of the concrete built in massive parts of building structures. On the other hand, in areas characterized by high daily temperatures, concrete in test cubes can be exposed to much higher temperatures than in-place concrete. Hence, test cube concrete can reach much higher strengths than in-built concrete. This proves that in order to obtain a clear and realistic picture of achieved in-place concrete strength and to be able to compare in-place and test concrete samples it is necessary to control the temperature in concrete.

Researchers and manufactures of concrete-related equipment have developed a number of methods for testing in-place concrete strength, depending on temperatures inside the element. All these methods are based on the principle of concrete maturity. The idea of concrete maturity is quite old and based on simple principles. The basic principle is that cement hydration stops at around -10°C, and that maturity of concrete depends on the age, as well as on the temperature that concrete has been exposed to. Laboratory tests, which make correlation between concrete strength and maturity, serve as the basis for using concrete maturity to define concrete strength and later applied in situ, i.e., at the construction site. The functions of concrete maturity are mathematical expressions used for calculating the time-temperature effects on the strength development of concrete mixtures, i.e., cement composites. In general, there are two widely-used approaches; one assumes that the rate of the strength development is a linear function of temperature, and the other assumes that the rate of the strength development follows the exponential Arrhenius equation. Both approaches have advantages and weaknesses. The first is very simple to use but is less reliable while the second is more complex requiring certain additional parameters based on more extensive lab tests but its accuracy is much higher compared to the first approach.

The first approach for defining the time-temperature factor is based on the maturity function (1) proposed in 1950's, by Nurse & Saul [8], which is adopting $T_{0,}$ in the range between -8 and -10°C, as temperature below which hydration stops.

$$M(t) = \sum (T_a - T_0) * \Delta t \tag{1}$$

gde su: *M(t)* – faktor temperatura – vreme koji se izražava u stepen–dan ili stepen–sat, T_a – srednja temperatura u usvojenim vremenskim intervalima, T_0 – početna temperatura odnosno temperatura nulte hidratacije u betonu, Δt – usvojeni vremenski interval merenja temperature.

Drugi pristup, dosta kasnije predstavljen, zasnovan je na određivanju ekvivalentne starosti pomoću Arrhenius-ove [8] funkcije (2).

where: *M(t)* = temperature-time factor expressed as degree-days or degree-hours, T_a = average temperature in adopted time intervals, T_0 = starting temperature, i.e., temperature for staring concrete hydration, Δt – adopted time interval for temperature measurement.

The second approach, presented much later, is based on determination of equivalent age using Arrhenius [8] function (2).

$$t_e = \sum e^{-Q\left(\frac{1}{T_a}-\frac{1}{T_s}\right)} \Delta t \quad (2)$$

gde su: t_e – ekvivalentna starost pri specificiranoj temperaturi T_s izražena u danima ili satima, Q – aktivaciona energija, podeljena s gasnom konstantom, u granicama je od 4800 do 5000°K, u zavisnosti od vrste primenjenog cementa u betonu, T_a – srednja temperatura betona u intervalu Δt (°K), T_s – usvojena ili specificirana temperatura izražena u °K i usvaja se na nivou od 20±2°C, Δt – interval merenja, a izražava se u danima ili satima.

Oba pristupa zahtevaju prethodna ispitivanja u laboratorijskim uslovima i na recepturama za beton koje će biti korišćene prilikom betoniranja elemenata konstrukcije.

3 EKSPERIMENTALNI RAD

Kao što je već prethodno rečeno, kontrola postignute čvrstoće betona u konstrukciji jeste obavezna za pojedine faze izgradnje. Naročito je značajno kontrolisati postignutu čvrstoću betona u masivnim elementima, odnosno elementima čija je najmanja dimenzija veća od 1 m. Kada su u pitanju ovakvi elementi, posebno su značajni vremenski uslovi u kojima se radovi izvode, odnosno da li su visoke ili niske ambijentalne temperature. Prilikom izgradnje mostova, svi delovi konstrukcije – osim ploča i glavnih nosača – svrstavaju se u masivne konstrukcije, odnosno primenjuju se pravila za masivni beton.

Prilikom izgradnje mosta preko reke Save kod Ostružnice, za naglavne grede, stubove i ležišne grede najmanja dimenzija elemenata bila je veća od 1 m. Samim tim, ovi elementi morali su se razmatrati kao masivni betonski elementi. Zbog ubrzanja dinamike izvođenja radova i boljeg iskorišćenja oplata, neophodno je bilo da se ovi elementi što pre oslobađaju od oplate.

Urađene su analize receptura za beton klase C30/37 (MB35 i MB40), kao i laboratorijska ispitivanja za dobijanje odnosa čvrstoće pri pritisku i faktora vreme–temperatura ili ekvivalentne starosti.

Za izradu betona, korišćeni su: cement CEM II A/L 42,5R, agregat iz reke Morave, separisan u četiri frakcije s maksimalnim zrnom agregata 32 mm, voda iz vodovoda i superplastifikator na bazi polikarboksilata. Količina cementa bila je 370 kg/m^3 i 400 kg/m^3 za beton MB35 i MB40 respektivno. Količina superplastifikatora bila je konstantna 0.6% u odnosu na masu cementa. Voda je usvojena tako da se dobije beton konzistencije 19 cm ± 2 cm. Spravljanje betona u laboratoriji rađeno je u mešalici kapaciteta 60 l, dok je na gradilištu bila angažovana fabrika betona s kapacitetom mešanja 2 m^3 u mešalici.

Laboratorijska ispitivanja obuvatila su izradu receptura pri spoljašnjoj temperaturi od 20°C i određivanje čvrstoće pri pritisku u starostima od 12h, 18h, 24h (jedan dan), tri dana, sedam dana, 14 dana i 28 dana. Komponentalni materijali za beton čuvani su u laboratorijskim uslovima na temperaturi od 20°C, pa je spravljeni beton, pri mešanju, imao temperaturu od 22°C ± 2°C. Nakon 24 sata nege na vazduhu pri temperaturi od 20°C, dalja nega sprovođena je u vodi konstantne temperature 20 ± 1°C. Temperatura u uzorcima je kontrolisana; već nakon 12 sati od izrade, bila je do

where: t_e = equivalent age at specified temperature, T_s = the same expressed in days or hours, Q = activation energy divided by the gas constant, (°K), T_a = average concrete temperature in time interval Δt, (°K), T_s = adopted and specified temperature, (°K), Δt = time interval of measurement, days or hours.

Both of the above approaches require prior testing in laboratory on the concrete mixtures that will be used during the casting.

3 EXPERIMENTAL WORK

As already mentioned, the control of achieved in-place concrete strength is mandatory in some building stages. It is very important to test concrete strength in massive elements, i.e., in elements whose minimum dimension is 1m or more. Weather conditions at the time of building works have particular importance for such elements, i.e., whether ambient temperatures are high or low. In the bridge construction industry, apart deck slab and main girders, all other elements are considered to be massive parts, i.e., massive concrete elements.

During the construction of the bridge over the river Sava near Ostružnica, the smallest dimensions of built elements, pile cup, piers, and bearing beams, were more than 1m. Therefore, these parts had to be viewed as massive concrete elements. However, for the purpose of acceleration of the works, and better utilization of formwork, it was necessary to strip formwork as soon as possible.

The mix design analyses were carried out and used to prepare concrete class C30/37 (Serbian: MB40 and MB 35), as well as laboratory tests in order to establish the relation between compressive strength and time-temperature or equivalent age factors.

For the production of concrete we used: CEM II A/L 42,5R cement, aggregate from river Velika Morava separated into four fractions with a maximum aggregate grain 32mm, water from water supply and a polycarboxylate based superplasticizer. The amount of cement was 370 kg/m^3 and 400 kg/m^3 for concrete MB35 and MB40 respectively. The amount of superplasticizer was constant at 0.6% relative to the weight of the cement. The water was adopted so as to obtain a concrete consistency of 19cm ± 2cm. Concrete preparation in the laboratory was done in a 60 l mixer, while a concrete plant with a mixing capacity of 2 m^3 in the mixer was engaged on the construction site.

Laboratory tests included production of concrete using the recipes at 20°C and determining compressive strength for concretes aged 12h, 18h, 24h (1 day), 3 days, 7 days, 14 days and 28 days. The constitutive materials for concrete were stored under laboratory conditions at a temperature of 20°C, and the produced concrete was at a temperature of 22°C+2°C at most. After 24 hours of air cure at a temperature of 20°C, the further curing was carried out in a water with constant temperature of 20°C±1°C. The temperature in the samples was controlled and after 12 hours of production it was up to a maximum of 22°C. A constant temperature of 20°C in the case of laboratory tests is taken for the calculation. Three 150mm-test cubes were examined for najviše 22°C. Za proračun je uzeta konstantna temperatura od 20°C u slučaju laboratorijskih proba. U svakoj od predviđenih starosti betona, ispitane su tri kocke ivice 150 mm. Kao rezultat ispitivanja, uzeta je srednja vrednost od tri uzorka, s tim što je rasipanje rezultata ograničeno na 15% od srednje vrednosti. Na osnovu dobijenih rezultata, dobijene su funkcije čvrstoće pri pritisku i faktora vreme–temperatura. Takođe, na osnovu istih rezultata dobijena je i funkcija čvrstoće pri pritisku i ekvivalentne starosti betona. Laboratorijski dobijene funkcije prikazane su na slici 2 za odnos čvrstoće i faktora vreme–temperatura i na slici 3 odnos čvrstoće i starosti betona, a eksperimentalne vrednosti date su u tabeli 1. Za izračunavanje faktora vreme–temperatura, kao referentna temperatura korišćeno je -3°C prema uputstvima brojnih autora [8].

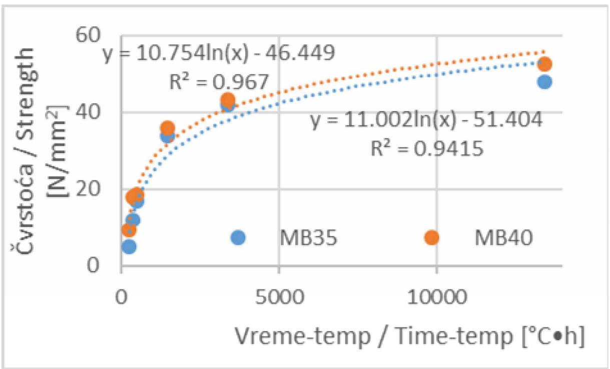
Kompletan eksperimentalni rad urađen je na dve recepture betona – MB35 i MB40. Recepture za beton date su u tabeli 1, kao i postignute čvrstoće betona u predviđenim starostima.

each of the above listed concrete ages. The average value of the results obtained from all three cubes was used as the final result, with scattering of results limited to 15%. The functions of compressive strength and time-temperature factors were calculated based on these obtained results. Also, these results were used to generate the function of concrete compressive strength and equivalent age. The functions obtained by lab testing are shown in Figure 2 for the strength and time-temperature factor relation and in Figure 3 for the concrete strength and age relation, and experimental values are shown in Table 1. Reference temperature of -3°C was used for calculating the time-temperature factor following recommendations of numerous authors [8].

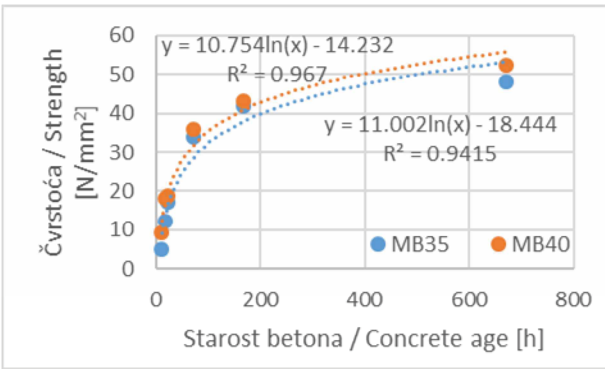
The entire experimental work was done for two concrete recipes, MB35 and MB40. The concrete recipes are given in table 1 as well as achieved concrete strengths at specified age.

Tabela 1. Rezultati laboratorijskih ispitivanja za MB35 i MB40
Table 1. Results of laboratory tests for MB35 and MB40

Marka betona *Concrete*	Cement *Cement* kg/m^3	Voda *Water* kg/m^3	Agregat *Aggregate* kg/m^3	Plastifik. *Plast.* kg/m^3	Aerant *"Aerant" additive* kg/m^3	12h MPa	18h MPa	24h MPa	3d MPa	7d MPa	28d MPa
MB35	371	162	1795	2.6	0.03	5.1	12.1	17.1	34.1	42.0	48.1
MB40	400	170	1742	2.8	0.032	9.3	18.1	18.7	35.9	43.2	52.5



Slika 2. Odnos čvrstoće i vreme–temperatura
Figure 2 Strength and time-temperature relation



Slika 3. Odnos čvrstoće i starosti betona
Figure 3 Strength and concrete age relation

Kada je završena faza laboratorijskih ispitivanja betona za dve marke betona, pristupilo se merenjima na gradilištu. Merenje je sprovedeno pomoću aparata *ConReg* 706 firme ASTM iz Švedske. Uređaj ima mogućnost da meri temperature na maksimalno šest mesta u konstrukciji i – na osnovu sopstvene funkcije za određivanje zrelosti betona i čvrstoća određenih u laboratorijskim uslovima – daje procenu čvrstoće u svakom momentu. Funkcija zrelosti betona zasnovana je na principu određivanja ekvivalentne starosti koju su razvili proizvođači opreme, a koja predstavlja modifikovanu Arrhenius funkciju (3).

In situ measurements started once the laboratory testing for both above mentioned concrete mixtures was finished. Measurements were taken using a device ConReg 706 provided by ASTM, a Swedish company. The device has a possibility to take temperature measurements at up to 6 points on the structure and to produce its own evaluation of concrete strength at all times based on its ability to determine concrete maturity and taking into account strengths determined under lab conditions. The concrete maturity function is based on the principle of establishing equivalent age developed by the equipment manufacturer and it represents a modified Arrhenius function (3).

$$t_e = e^{\left\{\left(\left(\frac{\theta}{T+10}\right)^{k_3}\right)*\left(\frac{1}{293}-\frac{1}{T+273}\right)\right\}} \quad (3)$$

gde se koeficijenti k_3 i θ izračunavaju iz laboratorijskih ispitivanja cementa i betona.

Merenja su urađena na više vrsta elemenata - na kolovoznoj ploči, stubu, naglavnoj gredi i ležišnoj gredi. Od izabranih elemenata, samo kolovozna ploča ne pripada masivnim delovima konstrukcije, jer je njena najmanja dimenzija svega 22 cm, što je daleko manje od uslova da najmanja dimenzija elementa bude veća od 1 m.

Kao proba, prvo su urađena merenja temperature betona na kolovoznoj ploči za koju je korišćen beton MB40. Rezultati ispitivanja na kockama čuvanim u uslovima elementa i prognozirane čvrstoće pomoću aparata *ConReg* 706 firme ASTM dati su u tabeli 2 za prva 24 sata starosti betona.

where coefficients k_3 and θ are derived based on the results of laboratory tests of cement and concrete.

Measurements were taken on several types of members: deck slab, pile cup and bearing beam. Among all these elements, only the deck slab does not belong to massive parts of a structure since its shortest edge is only 22cm long, that is, far below the 1m requirement for considering a structure to be a massive one.

Temperature measurements were taken on the deck slab first. The results of tests performed on cubes kept under the same conditions as elements and strengths forecasted by ConReg 706 devices provided by ASTM company are shown in table 2 for the fists 24 h of concrete aging process.

Tabela 2. Uporedna ispitivanja na kolovoznoj ploči
Table 2 Comparative tests for deck slab

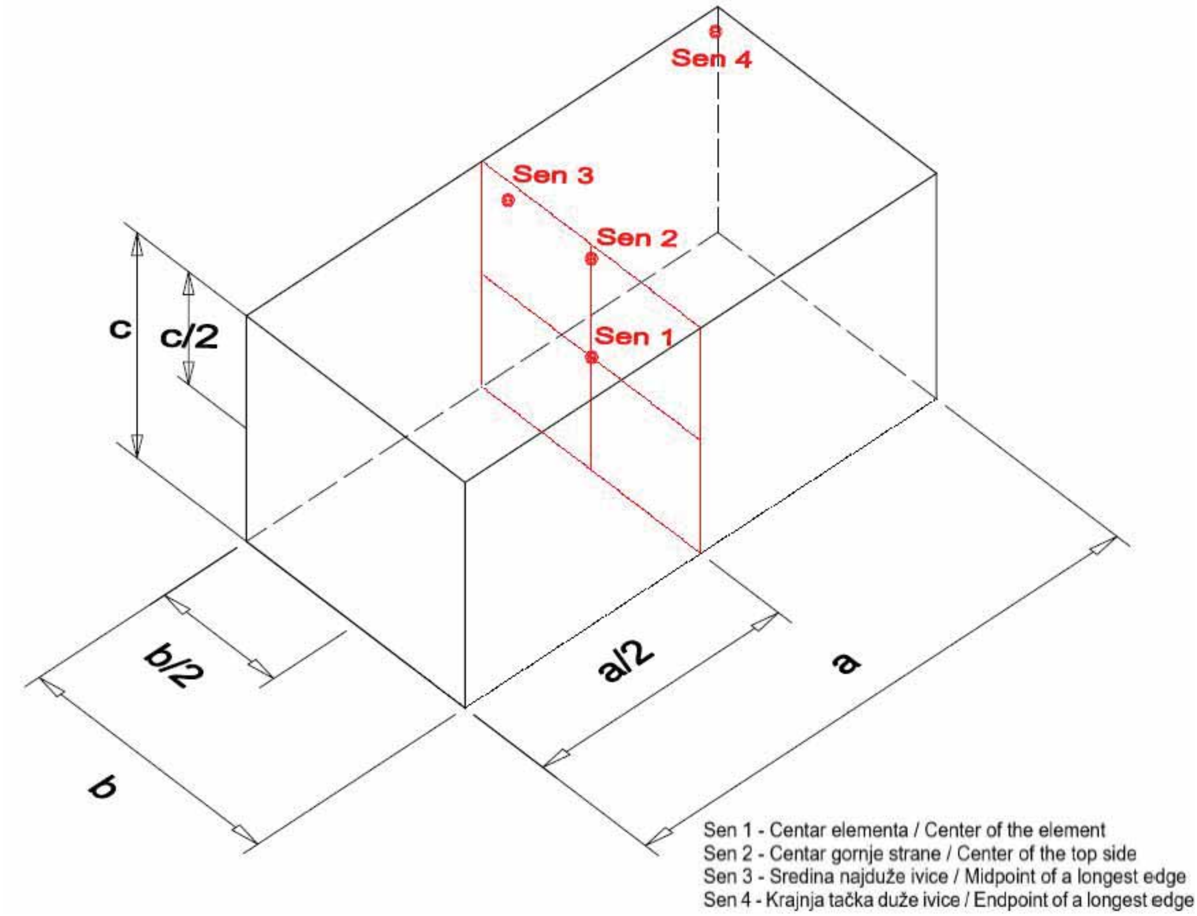
Marka betona Concrete Class	*Vreme Time*	*Čvrstoća na kockama Strength on cube*	*Procena na ConReg Evalution on ConReg*
MB40	*12h*	*13.75 N/mm²*	*14.61 N/mm²*
	18h	*24.16 N/mm²*	*23.13 N/mm²*
	24h	*30.14 N/mm²*	*30.05 N/mm²*

Nakon ispitivanja urađenih na kolovoznoj ploči, pristupilo se pripremi i ispitivanjima na naglavnoj i ležišnoj gredi koje su betonirane betonom MB35. Tokom pripremnih radova, urađena je analiza oba elementa i određena su potencijalna mesta na kojima će biti rađeno merenje i paralelno ispitivani kontrolni uzorci. Naglavna i ležišna greda su izabrane jer je reč o dva potpuno različita elementa iz aspekta temperaturnih uticaja. Naglavna greda je ukopan element, odnosno radi se u širokom iskopu, ali je donja strana kompletno na zemlji, odnosno na mršavom betonu, te s donje strane nema oplate. Bočne strane su na 1–1.5 m od iskopa i ovakav element, osim s gornje strane, zaštićen je od direktnog uticaja sunca. Gornja površina se na svim elementima posle 6 do 8 sati od betoniranja zaštićuje geotekstilom i počinje se s negom betona već posle 12 sati. Drugi izabrani element – ležišna greda – jeste deo konstrukcije iznad stuba i za takav element, osim na relativno malom delu stuba na koji se oslanja, oplata je neophodna sa svih strana. Kod ležišne grede vazduh je sa svih strana. Kod ovakvog elementa konstrukcije spoljašnji uticaji su vrlo važni, naročito leti kada direktni sunčevi zraci mogu povisiti temperaturu oplate, a samim tim i betona.

Prvo je urađeno ispitivanje na naglavnoj gredi dimenzija 9.5x2.4x2.5 m, a potom i na ležišnoj gredi dimenzija 12.6x2x (~2 m) – širina grede promenljiva je od 2 do 1.5 m. Temperatura je merena na četiri mesta u konstruktivnom elementu i u okolini elementa koji je betoniran. Šematski prikaz rasporeda senzora u konstrukciji tokom merenja temperature u oba elementa dat je na slici 4.

After the tests on the deck slab were performed, there have been some preparations and testing on the pile cup and bearing beam. The preparation works included an analysis of both elements and choosing potential spots in the elements suitable for measurements and parallel control of test samples. These components had been selected because they were completely different from the aspect of temperature impact. The first component was the pile cup that is an embedded structure. More precisely, there was a wider excavation and the bottom side of the component was laid completely on the ground, i.e., lean concrete surface which means no formwork was placed there. The sides of the components were located 1-1.5 m far from the excavation and this member, save for its upper side is completely protected from direct impact of the sun. The upper surface of all these elements should be protected from the sun 6 to 8 hours after concreting with geotextile fabric material and the curing process should start 12 hours after casting. The second structural component selected for the test – the bearing beam is a part of the structure above the pillar and as such it requires formwork to be placed from all sides except for a relatively small part where the component rests of the pillar. The bearing beam is exposed to air from all sides. In the case of such element, external impacts are significant, especially in summer when direct sun exposure can increase the temperature of formwork and thus, of the concrete as well.

Measurements were taken first on the pile cup dim. 9.5x2.4x2.5m, and then on the beam dim. 12.6x2x(~2m) (the width of the beam varies between 2 and 1.5m). Temperature was taken at four points in the element as well as the temperature of the external air close to the casting place. Schematic diagram of measurement points in both elements is shown in Figure 4.



Slika 4. Raspored senzora u ispitivanim elementima
Figure 4. Disposition of sensors in tested elements

Pored prikazanih senzora, korišćen je i peti senzor za merenje temperature vazduha u okolini elementa. Taj senzor postavljen je u zaštitnu drvenu kutiju koja je sprečavala direktni uticaj sunca i na taj način omogućeno je pravilno merenje temperature vazduha u okolini elementa.

Sva merenja rađena su tokom sedam dana. Uređaj firme ASTM *ConReg* 706 podešen je da beleži rezultate u intervalu od 30 minuta, pa je dobijena baza od oko 300 merenja po razmatranom elementu. Uređaj beleži temepraturu i daje procenu čvrstoće prilikom svakog merenja.

Na osnovu merenja temperature, urađen je proračun čvrstoće betona pri pritisku na osnovu dva opisana pristupa. Pored ova dva pristupa, uređaj *ConReg* 706 dao je procenu čvrstoće betona. Na osnovu dobijenih rezultata, data su tri para krivih za procenu čvrstoće betona: prva korišćenjem Nurse & Saul funkcije, druga korišćenjem Arrhenius funkcije i treća je dobijena iz uređaja *ConReg* 706. Za sve navedene pristupe, dobijene su po dve funkcije: za mesta s najnižom i najvišom temperaturom u elementu. Svi dobijeni rezultati prikazani su u obliku dijagrama na slikama 5 i 6. Na slikama su prikazane krive dobijene korišćenjem Nurse & Saul pristupa (Str-1 i Str-3), krive na osnovu Arrhenius-ove formule (Str-1 Arrh i Str-3 Arrh) i krive

In addition to the above displayed sensors, a fifth sensor was also used for measuring environmental air temperature. This sensor was encased in a protective wooden box preventing direct exposure to the sun, thus enabling proper measurement of air temperature close to the tested component.

The entire measurement lasted for 7 days. The ASTM supplied device, ConReg 706 was adjusted to record results at 30-minute intervals, thus creating a database containing 300 measurements per tested element. The device is designed to record temperature and produce its own evaluation in terms of strength after each measurement.

Based on temperatures taken on the elements the compressive strength of concrete was calculated using two traditional approaches. In addition to these approaches, the ConReg 706 device also produced its own concrete strength evaluation. On the basis of the obtained results, three pairs of curves for the concrete strength assessment were given: first using the Nurse & Saul function, the second one using the Arrhenius function, and the third was obtained from the ConReg 706. For all the foregoing approaches, two functions have been obtained: for the places with the highest and for the places with the lowest temperature in the member. All of the results thus obtained are shown in dobijene iz uređaja *ConReg* 706 (ConR1 i ConR2). Na slikama su paralelno prikazana i merenja spoljašnje temperature (AirTemp) u okolini predmetnog elementa.

4 ANALIZA REZULTATA I ZAKLJUČCI

Prikazani rezultati ispitivanja navode na više zaključaka u razmatranju uticaja temperature na razvoj čvrstoće betona.

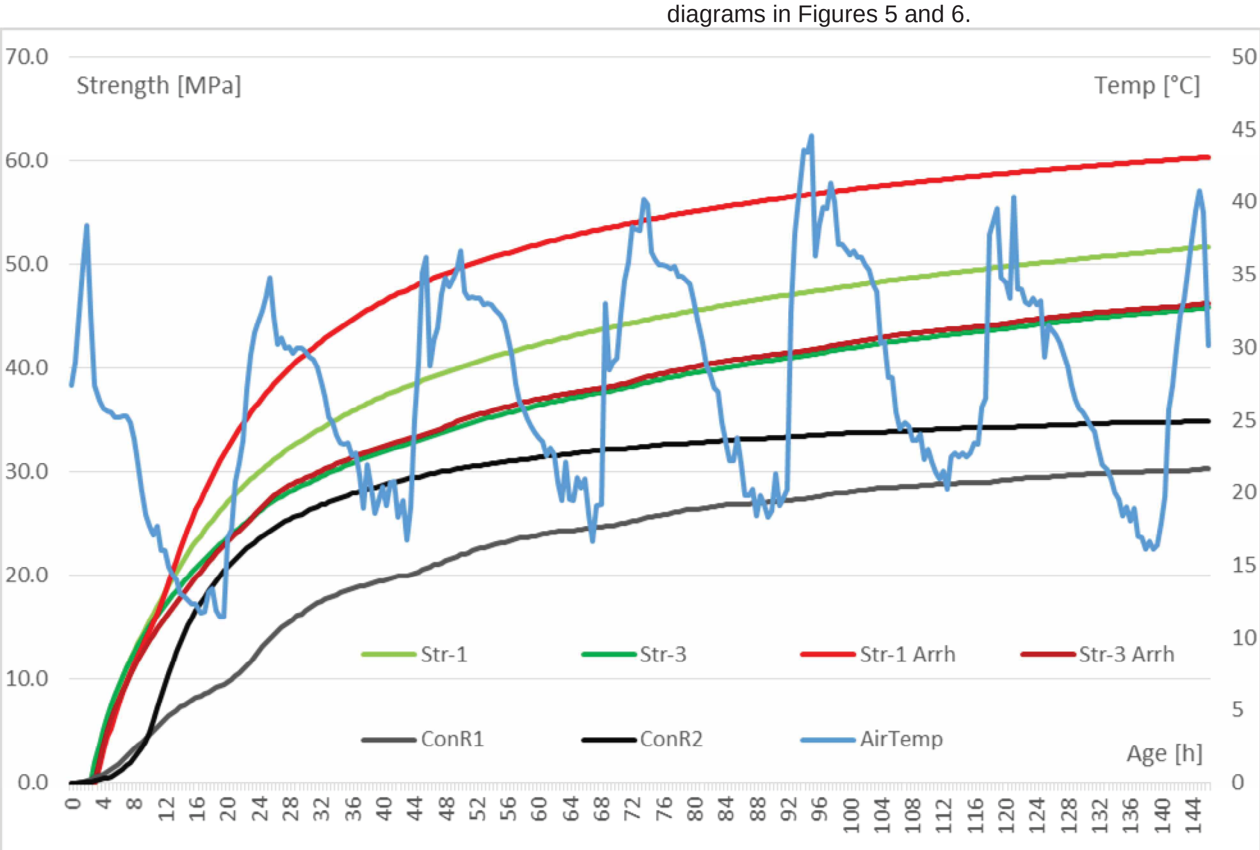
Izabrane metode ispitivanja veoma su osetljive na izbor mesta merenja temperature betona. Iz prikazanih rezultata vidi se da u okviru svakog pristupa postoje znatna odstupanja, u zavisnosti od mesta merenja. Na dijagramima sa slike 5 i slike 6, vide se razlike za svaki od korišćenih pristupa. Ako se pojedinačno posmatraju primenjene analitičke metode za procenu čvrstoće, za mesta s najnižom temperaturom dobijaju se i preko 15% manji rezultati čvrstoće pri pritisku nego za mesta s najvišom izmerenom temperaturom u elementu. Čvrstoća betona, ako se procenjuje na bazi Arrhenius-ove formule, osetljivija je na promene temperature. Za iste rezultate merenja temperature ovaj pristup daje mnogo veći raspon rezultata nego Nurse & Saul pristup, što se jasno vidi sa dijagrama na slikama 5 i 6.

the form of diagrams in Figures 5 and 6. Figures show the curves obtained using the Nurse & Saul approach (Str-1 and Str-3), curves based on the Arrhenius formula (Str-1 Arrh and Str-3 Arrh) and the curves obtained from ConReg 706 (ConR1 and ConR2). The figures also show the external temperature measurements (AirTemp) in the surroundings of the subject element.

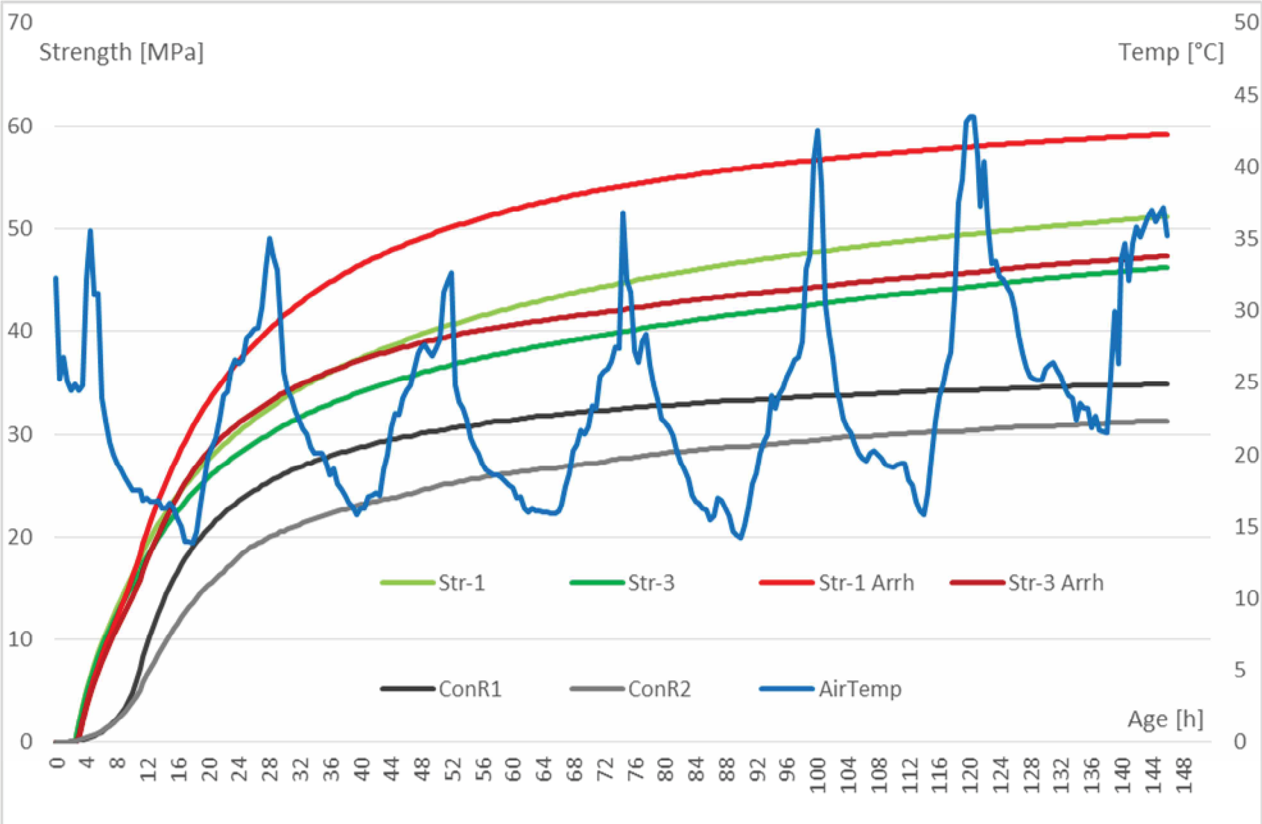
4 THE ANALYSIS OF THE RESULTS AND CONCLUSIONS

Based on the found results, several conclusions can be drawn when considering the influence of temperature on concrete strength.

The selected test methods are very sensitive to the choice of spots for measuring concrete temperatures. The above results clearly show that each approach has significant deviations depending on the measurement place. Figures 5 and 6 clearly show the differences for each of the applied approaches. If the applied analytical methods for assessing the strength for places with the lowest temperature are observed individually, more than 15% less results of compressive strength are obtained in relation to the sites with the highest emission temperature in the element. The strength of the concrete, if assessed on the basis of the Arrhenius formula, is more sensitive to temperature changes. For the same temperature measurement results, this approach gives a much greater range of the results than the Nurse & Saul approach, which is clearly seen in the diagrams in Figures 5 and 6.



Slika 5. Merenja temperature i procena čvrstoće betona u naglavnoj gredi
Figure 5. Temperature measurements and evaluation of concrete strength in pile cup



Slika 6. Merenja temperature i procena čvrstoće betona u ležišnoj gredi
Figure 6. Temperature measurements and evaluation of concrete strength in the bearing beam

Analizirajući rezultate dobijene primenom tri pristupa, uočavaju se znatne razlike u proceni čvrstoće pri pritisku. Generalno uzevši, od svih proračunskih modela, najmanje rezultate daje Nurse & Saul pristup, dok su najveći rezultati dobijeni pristupom koji je koristio Arrhenius-ovu formulu. Proračunske metode veoma su osetljive na temperaturne razlike koje se svakako javljaju u masivnim betonskim elementima. Razlike između klasičnih metoda i proračunskog modela koji koristi uređaj *ConReg* 706 jesu značajne, što svakako treba imati u vidu prilikom odabira metode koja će se koristiti.

Uređaji, kao što je i korišćeni *ConReg* 706 Švedske firme ASTM, paralelno mere temparaturu i daju procenu čvrstoće betona, pa samim tim mogu umnogome olakšati procenu postignute čvrstoće betona u konstrukciji.

Najveće dobijene temperature u elementima dostigle su 70°C, što je daleko više od 60°C, koliko je propisano u Pravilniku BAB’87. Ipak, nije premašena temperatura propisana evropskim normama, te stoga nisu primenjivane mere za smanjenje temperature betona u posmatranim elementima. Ukoliko se kao referentne norme usvoje Švedske norme, premašena je maksimalna temperatura u elementima od 55°C, kao i temperaturni gradijent u elementu od 24°C. Sve to ukazuje na potrebu da se važeća regulativa Republike Srbije mora revidirati u pogledu temperaturnih uticaja u betonskim elementima i približiti savremenim pogledima i istraživanjima u ovoj oblasti.

Analyzing the results obtained using the three approaches, significant differences in pressure strength assessment are observed. Generally speaking, from calculating models, the least results are provided by the Nurse & Saul approach, while the highest results are derived from the approach used by the Arrhenius formula. The classic calculating methods are very sensitive to temperature differences that certainly occur in massive concrete elements. Differences between conventional methods and calculation model which uses a device ConReg 706 are significant which should certainly be kept in mind when selecting the method.

Instruments, as well as the used ASTM ConReg 706 from Sweden, are simultaneously measuring the temperature and providing an estimate of the strength of the concrete, and therefore can significantly facilitate the estimate of the strength of the concrete in the construction.

The highest measured temperature in the elements reached 70°C, which is far more then 60°C maximum allowed in Serbian regulations, Rule book BAB’87. However, maximum temperature defined by European standards was not exceeded, thus no measures were taken to reduce the concrete temperature in tested elements. If the standard adoption of the Swedish standard, the maximum temperature in the elements of 55°C is exceeded as well as the temperature gradient in the element of 24°C is exceeded. All this points to the need for the valid regulations of the Republic of Serbia to be revised in terms of temperature influences in concrete elements and bring them closer to contemporary views and research in this area.

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REZIME

PROCENA ČVRSTOĆE BETONA PRI PRITISKU, KORIŠĆENJEM RAZLIČITIH FUNKCIJA ZRELOSTI BETONA: PRIMER IZ PRAKSE

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Aleksandar SENIĆ

Čvrstoća pri pritisku jeste svojstvo koje je veoma značajno u građevinarstvu, te postoji izražena potreba da se razviju metode za praćenje prirasta čvrstoće pri pritisku betona u konstrukciji. Prema zakonskim propisima Republike Srbije, procena čvrstoće pri pritisku betona u konstrukciji radi se na osnovu rezultata dobijenih tokom laboratorijskih ispitivanja u konstantnim uslovima.

U radu se koriste rezultati dobijeni u laboratoriji i porede se rezultati dobijeni pomoću metode za merenje zrelosti betona, koje se baziraju na korelaciji između čvrstoće betona, starosti betona i temperaturnih uslova i rezultata dobijenih pomoću *ConReg* 706 uređaja, koji takođe uzima u obzir temperaturu van betona. Primenjena su dva pristupa za određivanje zrelosti betona – Nurse & Saul i Arrhenius.

Za potrebe ovog istaživanja, pripremljene su dve različite betonske mešavine – MB 35 i MB 40, obe klase C30/37. Odabrani konstrukcijski elementi betonirani su tokom leta, na mostu preko reke Save, kod Ostružnice, u blizini Beograda. Testirani elementi mosta jesu kolovozna ploča, naglavna greda i ležišna greda.

Ispitivanje je pokazalo da temperatura koja se razvija u masivnim delovima konstrukcije znatno utiče na čvrstoću betona, pored već dobro poznatih faktora, kao što su vodo-cementni odnos, tip i kvalitet komponentnih materijala i drugi.

Ključne reči: zrelost betona, masivni beton, temperatura

SUMMARY

ASSESMENT OF CONCRETE COMPRESSIVE STRENGTH USING DIFFERENT MATURITY FUNCTIONS: CASE STUDY

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Compressive strength is a property of significant importance for civil engineering; consequently, there have been strong need for developing method, which will estimate rise of concrete compressive strength in construction. According to Serbian legislation, assessment of compressive strength in construction relies on laboratory results obtained under constant conditions.

This paper presents and compares results obtained in laboratory, results obtained by maturity method, which is based on correlation between concrete compressive strength, concrete age and ambient temperature, and the results obtained by ConReg 706 instrument, which also takes in consideration external environment and concrete temperature. Two approaches of maturity method, Nurse & Saul and Arrhenius have been applied.

For this research, concrete class C30/37 was used, prepared as two different mix designs, MB35 and MB 40. Casting was performed in summer time in Ostruznica bridge near Belgrade. Elements that were casted are deck slab, pile cup and bearing beam.

Key words: concrete maturity, mass concrete, temperature

MOGUĆNOST UPOTREBE ZGURE VISOKE PEĆI KAO AGREGATA U BETONU

THE POSSIBILITY OF USING BLAST FURNACE SLAG AS CONCRETE AGGREGATE

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STRUČNI RAD
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1 UVOD

Problem deponovanja otpadnog industrijskog materijala jedan je od najvećih u većini razvijenijih zemalja svijeta. Problem deponovanja posebno je naglašen ako se uzme u obzir da većina industrijski otpadnih čvrstih materijala zagađuje tlo i/ili vodu, a nerijetko i vazduh. Običan beton obično sadrži oko 12% cementa i 80% masenog agregata. To znači da na globalnom nivou, za proizvodnju betona, potrošimo godišnje od 10 do 11 milijardi tona agregata. Rukovanje, prerada i transport za tako velike količine agregata troše znatne količine energije i negativno utiču na ekologiju [1]. S druge strane, redovni izvori agregata su u velikoj mjeri iscrpljeni dok se u međuvremenu proizvedeni otpad iz industrije značajno širi [2]

Imajući u vidu gore rečeno, upotreba industrijskog otpadnog materijala u građevinske svrhe je posebno značajna. Otpad (npr. zgura, leteći pepeo, blokovi keramike i mermera) igra važnu ulogu u održivom razvoju građevinske industrije [3]. U svijetu se povećava potražnja i interesovanje za agregate iz netradicionalnih izvora kao što su industrijski nusprodukti i reciklirani otpad pri gradnji i rušenju [1]. Mnogi istraživači pokušavaju da prouče GBFS (granulirana zgura visoke peći) u proteklim godinama kako bi procijenili njene osobine i njeno ponašanje [4]. Naravno, neophodno je obezbijediti ekonomski isplativu i ekološki prihvatljivu gradnju.

Gvožđe se ne može pripremiti u visokoj peći bez proizvodnje njegovog suvog proizvoda, tj. zgure visoke peći. Korištenje ovog agregata u betonu zamjenom prirodnih agregata predstavlja obećavajući koncept jer

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1 INTRODUCTION

The problem of waste disposal is one of the greatest in most developed countries in the world. It is especially pronounced considering the fact that most industrial solid waste materials contaminate soil and/or water, often the air as well. Common concrete usually contains about 12 % of cement and 80% of mass aggregate. It means that globally 10-11 billion tons of aggregates are used annually for concrete manufacturing. Operating, processing and transportation of huge quantities of aggregate consume considerable amounts of energy and have negative effect on environment [1]. On the other hand, traditional sources of aggregate are largely exhausted, while the amount of produced industrial waste significantly increases [2].

Bearing in mind the above statements, the use of industrial waste for construction purposes is especially significant. Waste (e.g. slag, fly ash, ceramic and marble blocks) plays a significant role in sustainable development of construction industry [3]. The demand for interest in non-traditional aggregates such as industrial by-products and recycled waste from building and demolition increasingly spreads worldwide [1]. Many researchers studied GBFS (granulated blast furnace slag) in the previous years in order to assess its properties and behaviour [4]. Normally, it is necessary to provide economically profitable and ecologically acceptable construction.

Iron cannot be manufactured in blast furnace without the production of its dry product, i.e. blast furnace slag. The use of this aggregate in concrete by replacing natural aggregates is a promising concept, since the

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čvrstoća zgure je viša nego u prirodnog agregata [5]. Kako upravo agregat zauzima najveći udio u zapremini betona, primjenom zgure kao agregata znatno bi se više pridonijelo odlaganju tog otpadnog materijala [6].

Nedavno uvedeni evropski standardi za agregate ne prave diskriminaciju između različitih izvora, agregata iz prirodnih, recikliranih ili proizvedenih materijala [1].

U ovom radu razmatrana je mogućnost upotrebe industrijskog otpadnog materijala koji nastaje u procesu industrijske proizvodnje sirovog željeza u Zenici, R BiH.

Metalurška zgura (šljaka) sporedni je proizvod nastao u termičkom procesu dobijanja sirovog željeza i čelika. Po izgledu, načinu hlađenja i minerologiji, zgura je slična magmi iz koje su nastale silikatne eruptivne stijene kao što su bazalt, dijabaz, andezit, dacit, sijenit i druge, koje su cijenjen materijal u građevinarstvu.

Zgura odložena nedaleko od željezare u Zenici zauzima ogromnu površinu a pretpostavlja se da je u periodu od 1956. do 1992. godine na deponiji Rača odloženo cca 9.336.000 m^3 materijala ili oko 19 miliona tona, i to: zgura s prirodnim ili brzim hlađenjem sa sadržajem metalne supstance (berne), vatrostalni materijali, pepeo i šljaka, livački pijesak i drugi otpadni materijali iz tehnoloških procesa metalurškog kompleksa. Količine deponovanog otpadnog materijala, zgure, velike su s tendencijom brzog porasta. Tako, u željezari Arcelomittala Zenica u 2011. godini bilo je 185.000 tona otpadne zgure za preradu, dok se u narednim godinama pretpostavlja porast na 239.800 tona na godišnjem nivou.

U ovom radu razmatrana je mogućnost upotrebe visokopećne zgure kao agregata u betonu. Prikazani su rezultati ispitivanja zgure shodno evropskim propisima EN 12620:2002+A1:2008, a neke karakteristike zgure poređene su s prirodnim agregatima.

strength of slag is higher in comparison with natural aggregate [5]. Since aggregate has the greatest part in concrete volume, the use of slag as aggregate would more significantly help depositing this waste material [6].

The recently introduced European standards for aggregates ceased to discriminate various sources of aggregates as natural, recycled or produced [1].

This paper discusses the possibility of using industrial waste produced in base iron manufacturing in Zenica, Bosnia and Herzegovina.

Metallurgical slag is a by-product obtained in the process of base iron and steel manufacturing. In its appearance, mode of cooling and mineralogy, slag is similar to magma, from which silicate eruptive rocks originate such as basalt, diabase, andesite, dacite, syenite etc. which are appreciated materials in construction.

The slag, deposited nearby Iron Works in Zenica occupies a large area; it is supposed that 9,226,000 m^3 or about 19 million tons of material were deposited in landfill Rača in the period 1956-1992, including slag with natural and sudden cooling with the content of metal substance, fireproof materials, ash, slag, casting sand and other waste materials obtained in technological processes in the metallurgical complex. Thus in Iron Works Arceromittal Zenica, 185,000 tons of waste slag were processed in 2011, while in coming years the annual increase of 239,800 tons is assumed.

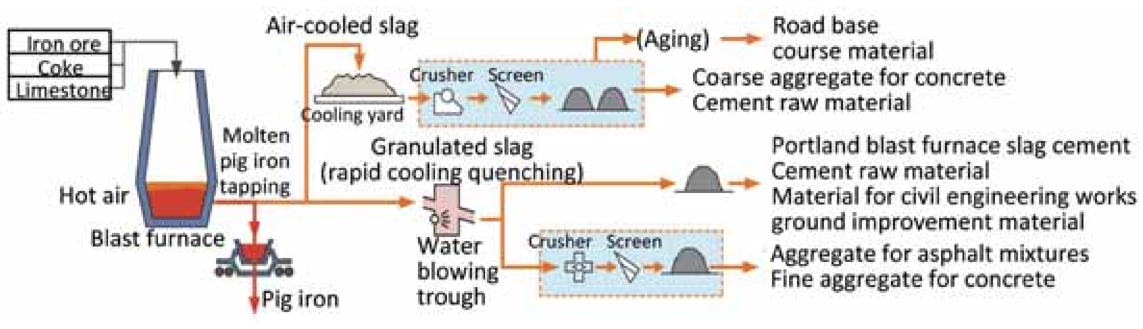
This paper considers the possibility of using blast furnace slag as concrete aggregate. The presented results of investigation are in accordance with European standards EN 12620:2002+A1:2008, and some characteristics of slag are compared to natural aggregates.

2 PROCES DOBIJANJA ZGURE

Kao što je već rečeno, metalurška zgura (šljaka) sporedni je proizvod nastao u procesu dobijanja sirovog željeza. U procesu proizvodnje sirovog željeza, sirovine (rude željeza, koks, krečnjak) kontinuirano se ubacuju kroz vrh visoke peći, a sirovo željezo i zgura se vade s dna. Naglim hlađenjem tekuće zgure koja pliva na rastaljenom željezu ona se granulira u zrna klinkerskog oblika.Tečna zgura iz peći direktno ulazi u granulacijsku komoru u mlaz vode. Tu se izvrši granuliranje zgure. Granulirana zgura i voda odlaze u bazen za zguru. Iz bazena granulirana zgura se transportuje do potrošača.

2 THE PROCESS OF OBTAINING SLAG

As it was previously said, metallurgical slag is a by-product obtained by manufacturing base iron. In the process of base iron manufacturing, the raw materials (iron ore, coke, and limestone) are continually inserted through the blast-furnace top, while base iron and slag are removed from the bottom. By sudden cooling, liquid slag that floats in melted iron granulates into clinker-shaped grains. From the blast furnace, liquid slag directly enters granulation chamber, under sprayed water where slag granulation is carried out. Granulated slag and water are removed to slag pool. From the pool, granulated slag is transported to customers.



Slika 1. Proces proizvodnje zgure visoke peći [7]
Figure 1. Manufacturing process of blast furnace slag [7]

Postoje dva oblika zgure: bazična i kisela. Bazična zgura sadrži najmanje 50% bazičnih oksida CaO i Al_2O_3 a ostatak je najvećim dijelom SiO_2. Kisela zgura sadrži znatno manje od 50% bazičnih oksida CaO i Al_2O_3 a prevladava SiO_2. Zgura visoke peći bogata vapnom (bazična zgura), upotrebljava se u proizvodnji cementa.

3 UPOTREBA ZGURE U SVIJETU

Upotreba zgure u razne namjene počinje još od davnina. Danas se skoro u svim zemljama u svijetu zgura koristi kao dodatak – punilo u cementu.
S druge strane, visoka gustoća visokopećne zgure karakterizira je kao jako pogodan materijal za hidrotehničke objekte. Naime, u Njemačkoj i Nizozemskoj oko 400 000 tona visokopećne zgure godišnje bude upotrijebljeno kao materijal za oblaganje pokosa. Osim toga, zgura je odlična za regulacije erodiranih vodotoka.

S obzirom na činjenicu da svojstva zgure zavise od njenog porijekla, mogućnost upotrebe domaće zgure kao agregata u betonu trebalo je potvrditi nizom ispitivanja [8].

Jedno od novijih područja primjene zgure jeste i njena upotreba kao agregata u betonu. Shodno postojećim podacima, upotreba zgure za beton je potpuno opravdana. Pojedine su zemlje, kao što je npr. Japan, u tome toliko daleko otišle da imaju i normu za primjenu zgure kao agregata u betonu. Kada su u pitanju evropske zemlje koje primjenjuju evropske propise, tada se ocjena karakteristika zgure pravi shodno odredbama standarda za agregat EN 12620:2002+A1:2008 – Agregati za beton, ili EN 13450:2003 – Agregati za željeznički tucanik, ili EN 13242:2002 – Agregati za nevezane i hidrauličkim vezivom vezane materijale za primjenu u građevinarstvu i u kolničkim konstrukcijama i tako dalje. Beton koji bi se spravio sa zgurom kao agregatom bio bi znatno teži od betona napravljenog s prirodnim agregatom, a samim tim stvara se mogućnost za široku upotrebu tako napravljenog betona.

U gradnji puteva, zgura se često koristi kao materijal za stabilizaciju tla. Osim u površinskim slojevima tla, granulirana visokopećna zgura uspješno je primijenjena i kao vezivo pri stabilizaciji dubljih slojeva tla, u slučaju slabe nosivosti tla na kojem je planirana gradnja inženjerskih građevina. Prema statističkim podacima, jedna od najučestalijih primjena jeste zgura u nevezanim mješavinama za donji ustroj puteva ili kao agregat u asfaltnim mješavinama.

Pored upotrebe zgure u građevinske svrhe danas je veoma česta upotreba zgure kao gnojiva u tlu. Ovo se odnosi na visokopećnu zguru koja sadrži veliki procenat kalcijum i magnezijum-oksida koji se koristi kao zamjena za kreč. Pored ovdje navedenih primjera moguće upotrebe zgure postoje i druga područja gdje je moguće upotrijebiti zguru, kao što je prečišćavanje vode, proizvodnja cementnog klinkera ili vraćanje u visoku peć radi ponovnog procesa proizvodnje sirovog željeza.

4 UPOTREBA ZGURE KAO AGREGATA U BETONU

Zgura visoke peći koja se postepeno hladi na vazduhu formira velike i veoma čvrste komade koje je prije svega neophodno samljeti na odgovarajuće frakcije. Mljevenje ove vrste zgure na jako sitnu frakciju (filer) nije ekonomski prihvatljivo jer je materijal jako tvrd. Za proiz-

Two types of slag are known: base and acid. Base slag contains not less than 50% of base oxides CaO and Al_2O_3, while the rest is mostly SiO_2. Acid slag consists of significantly less that 50% of base oxides CaO and Al_2O_3, while SiO_2 prevails. Blast furnace slag rich with lime (base slag) is used in the production of cement.

3 THE USE OF SLAG WORLDWIDE

The use of slag for different purposes began long time ago. Today, slag is used as additive (filler) in cement in all countries worldwide.

On the other hand, high density of blast furnace slag makes it suitable material for hydro-technical structures. Namely, in Germany and the Netherlands about 400,000 tons of blast furnace slag is used as a material for covering slopes. Besides, slag is perfect for regulation of eroded watercourses.

Due to the fact that the characteristics of slag depend on its origins, the possibility of using domestic slag as concrete aggregate should be confirmed by numerous tests [8].

One of the recent domains of application of slag is its use as concrete aggregate. According to the available data, the use of slag as concrete aggregate is completely justified. Certain countries such as Japan advanced in this field so much that they have standards related to application of slag as concrete aggregate. In European countries which apply European standards, the assessment of slag characteristics is made according to the standards for aggregate EN 12620:2002+A1:2008 – Concrete Aggregates or EN 13450:2003 – Aggregate for railway ballast or EN 13242:2002 Aggregates for unbound and hydraulically bound materials for application in civil engineering, road construction, etc. The concrete manufactured with slag as aggregate would be considerably heavier in comparison with the concrete made of natural aggregates, thus the possibility for wide application of such concrete is promising.

Slag is often used in road construction as a material for stabilisation of soil. Besides surface layers, granulated blast furnace slag is used as a binder at stabilisation of deeper layers, in cases of poor loading capacity of soil where construction is planned. According to statistical data, the slag in unbound mixtures for lower road layers is the most frequent one, or as aggregate in asphalt mixtures.

Besides using slag in civil engineering, it is also often used as soil fertilizer today. This refers to blast furnace slag with great percentage of calcium and magnesium oxides used as a replacement for lime. Besides these examples, slag can be used in other sectors such as purification of water, production of cement clinker or return to blast furnace for re-manufacturing of base iron.

4 THE USE OF SLAG AS CONCRETE AGGREGATE

Blast furnace slag that gradually cools in air forms large and very rigid pieces which should be grinded first into appropriate fractions. Grinding of this slag in very tiny fractions (filler) is not economically acceptable, since the material is very rigid. In cement production, other vodnju cementa sa zgurom koristi se druga vrsta zgure koja se nakon izlaska iz peći veoma brzo hladi sipanjem vode. Njena granulacija je 0-4 mm, a mljevenjem se može postići željena granulacija. Na slici 1. i 2. prikazani su primjeri zgure koja se postepeno hladi na vazduhu a koja je samljevena na frakcije koje se mogu koristiti za spravljanje betona i postrojenje za separaciju zgure.

Prerada zgure u tehnološkom smislu podrazumijeva:

- Dvostepeno drobljenje;
- Trostepenu magnetnu separaciju;
- Višestepeno prosijavanje;
- Odvojeno deponovanje pojedinih frakcija – agregata;
- Sortiranje izdvojene metalne komponente i odvoz u čeličanu, visoku peć i aglomeraciju.

kind of slag is used, which is cooled suddenly by pouring water. Its granulation is 0-4 mm, and the desired granulation can be obtained by grinding. Figures 1 and 2 show the slag obtained by sudden cooling in air, which is grinded into fractions that can be used for concrete manufacturing and the slag separation plant.

Slag processing in technological sense includes:

- Two-stage grinding
- Three-sage magnet separation
- Multi-stage filtering
- Separate depositing of certain fractions-aggregates
- Classifying separate metal components and transport to steel-works, blast furnace and agglomeration.

Slika 2. Uzorci materijala – frakcije zgure (lijevo) i postrojenje separacije (desno)
Figure 2. Samples of material – slag fractions (left) and separationplant (right)

Slika 3. Uzorci materijala – frakcije zgure (lijevo) i postrojenje separacije (desno)
Figure 3. Samples of material - slag fractions (left) and separation plant (right)

Nakon što je završen tehnološki proces obrade zgure, kao konačni proizvod dobiju su željene frakcije materijala: 0-4, 4-8, 8-16, 16-32, 32-64. Nakon formiranja frakcija od zgure, moguće je ispitati fizičko-meha-

After technological processing of slag, the desired fractions of material are obtained as follows: 0-4, 4-8, 8-16, 16-32, and 32-64. After slag fractions are formed, it is possible to examine their physical-mechanical and ničke i hemijske osobine zgure i uporediti te osobine sa zahtjevima datim u EN 12620:2002+AA1:2008. Zbog obimnosti rezultata ispitivanja ovdje će biti predstavljena samo ona svojstva koja su posebno važna za spravljanje betonskih uzoraka. Na slici 3. u nastavku prikazane su frakcije zgure granulacije 11,2-16 mm i 16-31,5 mm.

chemical properties and compare the properties with those given in EN 12620:2002+AA1:2008. Due to the extensive range of results of testing, only those that are especially important for concrete sample manufacturing will be presented here. Figure 4 below, shows the slag fraction granulation of 11.2–16 mm and 16-31.5 mm.

Slika 4. Uzorci materijala – frakcije zgure 11,2-16 (lijevo) i frakcije zgure 16-31,5 (desno)
Figure 4. Samples of material - slag fractions 11.2-16 (left) and slag fractions 16-31.5mm (right)

5 REZULTATI ISPITIVANJA FRAKCIONE ZGURE

Jedna od najvažnijih osobina koju je neophodno ispitati jeste granulometrijski sastav zgure shodno standardu EN 933-1 i 933-10. Rezultati ispitivanja granulometrijskog sastava, kao i ostalih osobina dati su u nastavku (Tabela 1. – Granulometrijski prikaz, Tabela 2. – Sadržaj sitnih čestica, Tabela 3. – Los Angeles koeficijent, Tabela 4. – Indeks oblika zrna, Tabela 5. – Gustoća agregata i upijanje vode, Tabela 6. – Sadržaj hlorida i sulfata, Tabela 7. – Ispitivanje radioaktivnosti).

5 RESULTS OF TESTING FRACTIONATED SLAG

One of the most significant properties which is necessary to test is granulometric composition of slag according to the standards EN 933-1 and 933-10. The results of testing granulometric composition and other characteristics are given below (Table 1 Granulometric presentation; Table 2 - Contents of small particles; Table 3 - Los Angeles coefficient; Table 4 - Index of grain shape; Table 5 - Aggregate density and water absorption; Table 6 - Contents of chlorides and sulphates; Table 7 - Testing of radiation)

Tabela 1. Granulometrijski sastav zgure - %
Table 1. Granulometric composition of slag - %

Frakcije / *Fractions* — Otvor sita / *Sieve opening*	**0/4 mm**	**4/8 mm**	**8/16 mm**	**16/31,5 mm**	**8-11,2 mm**	**11,2-16 mm**	**16-22,4 mm**
45,0 mm	-	-	-	100	-	-	100
31.5 mm	-	-	-	99	-	-	98
22.4 mm	-	-	100	70	-	100	70
16.0 mm	-	-	100	20	100	99	18
11.2 mm	100	100	91	2	100	68	1
8.0 mm	99	99	56	1	88	18	-
4.0 mm	95	62	13	-	30	-	-
2.0 mm	65	22	-	-	-	-	-
1.0 mm	23	-	-	-	-	-	-
0.71mm	12	-	-	-	-	-	-
0.5 mm	7	-	-	-	-	-	-
0.25 mm	4	-	-	-	-	-	-
0.125 mm	3	-	-	-	-	-	-
0.09 mm	2	-	-	-	-	-	-
Razred po EN 12620 ***Category by EN 12620***	**G_F85**	**G_C90/15**	**G_C90/15**	**G_C85/20**	**G_C85/20**	**G_C85/20**	**G_C85/20**

Tabela 2. Sadržaj sitnih čestica (prema EN 933-1)
Table 2. Contents of small particles (by EN 933-1)

Frakcije / *Fractions* — Otvor sita / *Sieve opening*	**0/4 mm**	**4/8 mm**	**8/16 mm**	**16/31,5 mm**	**8-11,2 mm**	**11,2-16 mm**	**16-22,4 mm**
Prolaz kroz sito 0,063 mm *Passage through sieve 0.063 mm*	3,40	2,19	1,21	0,39	2,09	2,45	0,33
Razred po EN 12620 *Category by EN 12620*	f_4	f_4	$f_{1,5}$	$f_{1,5}$	f_4	f_4	$f_{1,5}$

Tabela 3. Los Angeles koeficijent (prema EN 1097-2)
Table 3. Los Angeles coefficient (by EN 1097-2)

Frakcije / *Fractions* — Otvor sita / *Sieve opening*	**0/4 mm**	**4/8 mm**	**8/16 Mm**	**16/31,5 mm**	**8-11,2 mm**	**11,2-16 mm**	**16-22,4 mm**	**Dolomitni agregat *Dolomite aggregate***
Los Angeles koef. *Los Angeles coeff.*	16,73							24,7
Razred po EN 12620 *Category by EN 12620*	LA_{20}							LA_{25}
Napomena / *Note*	**Najviše LA_{35} za betone opće namjene** ***Most LA_{35} for general purpose concrete***							

Tabela 4. Indeks oblika zrna (prema EN 933-4)
Table 4. Index of grain shape (by EN 933-4)

Frakcije / *Fractions* — Otvor sita / *Sieve opening*	**0/4 mm**	**4/8 mm**	**8/16 mm**	**16/31,5 mm**	**8-11,2 mm**	**11,2-16 mm**	**16-22,4 mm**
Indeks oblika zrna *Index of grain shape*	-	4,489	4,270	0,781	3,576	2,733	2,414
Razred po EN 12620 *Category by EN 12620*	**-**	SI_{15}	SI_{15}	SI_{15}	SI_{15}	SI_{15}	SI_{15}

Tabela 5. Gustoća agregata od zgure i upijanje vode (prema EN 1097-6)
Table 5. Aggregate density and water absorption (by EN 1097-6)

Frakcije / *Fractions* — Otvor sita / *Sieve opening*	**0/4 Mm**	**4/8 mm**	**8/16 Mm**	**16/31,5 mm**	**8-11,2 mm**	**11,2-16 mm**	**16-22,4 mm**	**Dolomitni agregat *Dolomite aggregate***
Stvarna gustoća čestica agregata *Real density of aggregate particles* (Mg/m^3)	3.533	3.640	3.641	3.458	3.600	3.577	3.493	2,83
Upijanje vode WA_{24} *Water absorption WA_{24}*	2,513	1,516	1,257	1,136	1,492	1,108	1,171	0,85

Tabela 6. Sadržaj hlorida i sulfata
Table 6. Contents of chlorides and sulphates

Frakcije / *Fractions* — Otvor sita / *Sieve opening*	**0/4 mm**	**4/8 mm**	**8/16 mm**	**16/31,5 mm**	**8-11,2 mm**	**11,2-16 mm**	**16-22,4 mm**
Sadržaj hlorida (%) *Contents of chloride (%)*	0.0047						
Prema EN 12620 ***By EN 12620***	**ne sadrži hloride (maksimalno 0.06 za armirani beton)** **No chlorides (*maximum* 0.06 for reinforced concrete)**						
Sadržaj sulfata (%) *Contents of sulphates (%)*	0.057						
Prema EN 12620 ***By EN 12620***	**$AS_{1,0}$ (maksimalno 2% za zguru hlađenu na zraku)** ***$AS_{1,0}$ (maximum 2% for air cooled slag)***						

Tabela 7. Ispitivanje radioaktivnosti
Table 7. Testing of radiation

Frakcije / *Fractions* — Otvor sita / *Sieve opening*	**0/4 mm**	**4/8 mm**	**8/16 mm**	**16/31,5 mm**	**8-11,2 mm**	**11,2-16 mm**	**16-22,4 mm**
Radioaktivnost *Radioactivity*	0,123						
Dopuštena vrijednost ***Allowed value***	**1,0**						
Mišljenje *Opinion*	Proizvod nije radioaktivan *Product is not radioactive*						

Ispitivanje pH vrijednosti zgure nije urađeno iako bi ovaj podatak bio zanimljiv zbog sumnje na korozivno dejstvo zgure na armaturu. Zapreminska postojanost zgure usljed promjene vlažnosti ispitana je prema priručnoj (nenormiranoj) metodi, a rezultati su pokazali da se zapremina zgure nije promjenila.

6 SPRAVLJANJE UZORAKA BETONA SA AGREGATOM OD ZGURE

Pored ispitivanja fizičko-mehaničkih i hemijskih karakteristika zgure, autori rada su se odlučili za spravljanje uzoraka betona sa agregatom od zgure kako bi se izvršilo poređenje čvrstoća tako spravljenog betona sa čvrstoćom betona spravljenog od dolomitnog agregata. Na slici 4. data je kumulativna krivulja prosijavanja agregata od zgure.

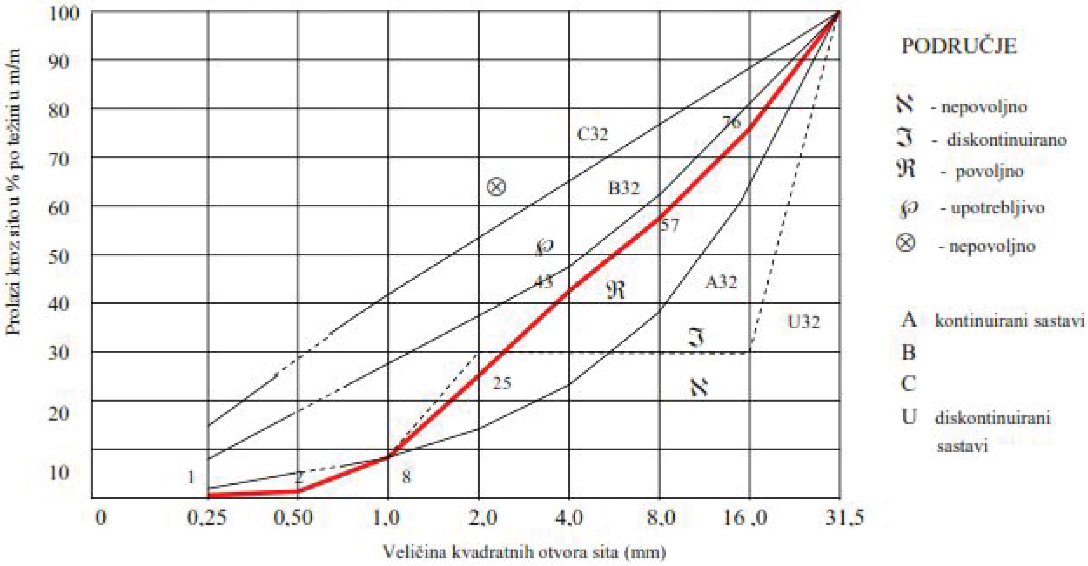
Kao što se vidi iz prethodno prikazanih ispitivanja granulometrijskog sastava zgure i kumulativne krive prikazane na prethodnoj slici krupne čestice zgure mogu se upotrebljavati kao agregat za beton, s malim problemom frakcije 0-4 mm. U frakciji zgure 0-4 mm javlja se neznatan procenat sitnih čestica, te je teško formirati granulometrijsku krivu između graničnih krivih EMPA i Fuller. Kako bi se ovaj problem riješio, upotrijebljen je dolomitni agregat frakcije 0-4 mm, a kumulativna kriva prosijavanja sa ovim dolomitnim agregatom frakcije 0-4 mm prikazana je na slici 5.

The testing of slag pH was not carried out, although this datum would be very interesting for doubt about corrosive effect of slag on reinforcement. Volume stability of slag due to the change of humidity was examined by using manual (non-standard) method, and the results showed that slag volume did not change.

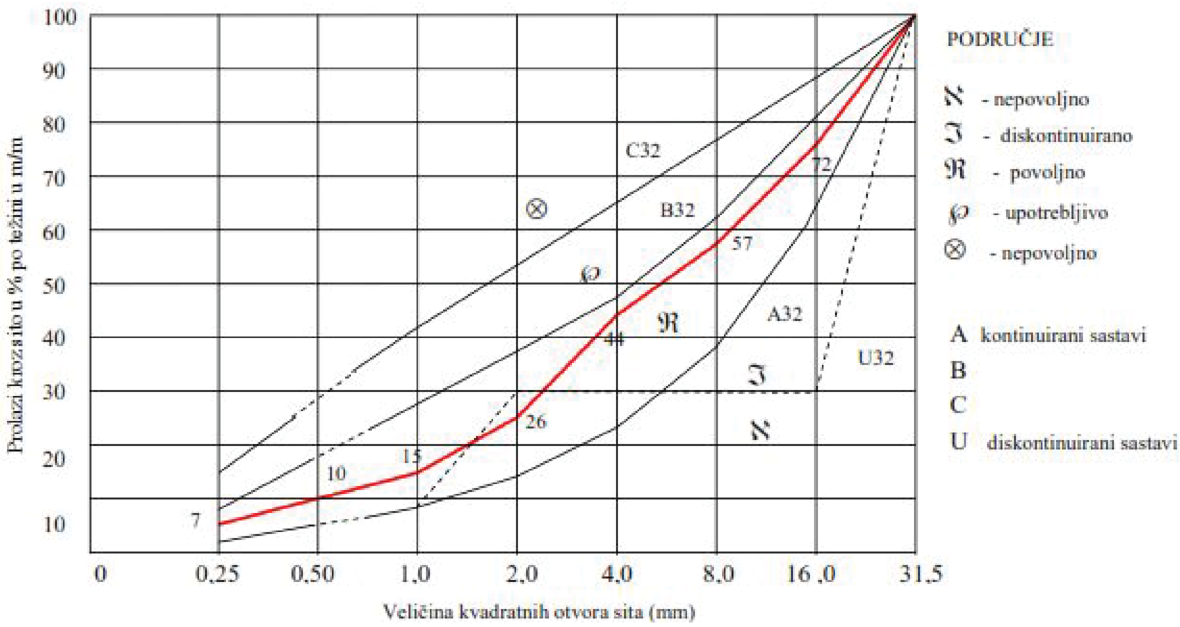
6 PREPARATION OF CONCRETE SAMPLES WITH SLAG AGGREGATE

In addition to testing physical-mechanical and chemical properties of slag, the authors of the paper decided to prepare concrete samples with slag aggregate in order to compare the strength of slag aggregate concrete with the strength of dolomite aggregate concrete. Figure 5 shows cumulative curve of sieving slag aggregate.

As it can be seen from the presented testing of granulometric composition of slag and the cumulative curve shown in the above Figure, large particles of slag can be used for concrete aggregate, with a small problem with fraction 0-4mm. In slag fraction 0-4 mm a slight percentage of tiny particles appear, thus it is difficult to create granulometric curve between boundary curves EMPA and Fuller. In order to solve this problem, dolomite aggregate in fraction 0-4 mm was used, and cumulative curve of sieving with the dolomite aggregate fraction 0-4 mm is shown in Figure 5.



Slika 5. Kumulativna krivulja prosijavanja agregata od zgure (0-4: 35%, 4-8: 12%, 8-16: 18%, 16-32: 35%)
Figure 5. Cumulative curve of sieving slag aggregate (0-4: 35%, 4-8: 12%, 8-16: 18%, 16-32: 35%)



Slika 6. Kumulativna krivulja prosijavanja agregata
(dolomitni agregat: 0-4: 35%, agregat od zgure: 4-8: 12%, 8-16: 18%, 16-32: 35%)

Figure 6. Cumulative curve of sieving aggregates
(Dolomite aggregate: 0-4: 35%, slag aggregate: 4-8: 12%, 8-16: 18%, 16-32: 35%)

Znači, napravljeni su uzorci betonskih kocki s dvije recepture (Tabela 8):

1. Receptura I sa četiri frakcije agregata od zgure (iako ne uklapaju u granične krive EMPA i Fuller);
2. Receptura II s tri frakcije agregata od zgure i jednom frakcijom dolomitnog agregata.

This means that the samples of concrete cubes are prepared following two recipes (Table 8):

1. Recipe I with four fractions of slag aggregate (although they do not fit into boundary curves EMPA and Fuller)
2. Recipe II with three fractions of slag aggregate and one fraction of dolomite aggregate

Tabela 8. Sastav betonskih mješavina
Table 8. Composition of concrete mixes

Mješavina *Mix*	**v/c**	**Voda** *Water* **(l)**	**Cement** *Cement* **(kg)**	**Agregat (kg)** ***Aggregate (kg)***				
				dolomitni agregat *dolomite aggregate* 0-4 mm	zgura *slag* 0-4 mm	zgura *slag* 4-8 mm	zgura *slag* 8-16 mm	zgura *slag* 16-32 mm
Receptura I *Recipe I*	0,62	205	330	-	753	258	387	753
Receptura II *Recipe II*	0,62	205	330	753	-	258	387	753

Za svaku navedenu recepturu napravljeno je po pet ispitnih uzoraka. Dva uzorka su ispitana nakon sedam dana, a preostala tri nakon 28 dana. Kasniji prirast čvrstoće betona nije kontrolisan.

Upotrijebljena količina cementa od 330 kg/m^3 dovoljna je kako bi se dobio beton čija čvrstoća odgovara klasi betona C25/30 kada se upotrebljavaju sve četiri frakcije od dolomitnog agregata. Za spravljanje betonskih uzoraka korišten je cement iz Lukavca (CEM II/B-M (V-W) 42,5N). Hemijski sastav upotrijebljenog cementa dat je u tabeli 9.

Five test samples were done for each recipe. Two samples were tested after 7 days, while the remaining 3 after 28 days. Further increase of concrete strength was not tested later.

The used amount of 330 km/m^3 of cement was sufficient for preparation of concrete with strength that corresponded to class C25/30 concrete, when all four fractions of dolomite aggregate were used. The cement from Lukavac (CEM II/B-M (V-W) 42.N) was used for preparation of concrete samples. Chemical composition of the obtained cement is shown in Table 9.

Tabela 9. Hemijski sastav cementa iz cementare Lukavac – CEM II/B-M(V-W) 42,5N (prema EN 196-2)
Table 9.Chemical composition of cement from cement plant Lukavac – CEM II/B-M (V-W) 42.5N (by EN 196-2)

Ispitana osobina ***The tested property***	**Ispitna metoda** ***Testing method***	**Rezultati ispitivanja** ***Results of testing*** **(%)**
Gubitak žarenjem *The loss by annealing*	EN 196-2, tačka 7 / *chapter* 7	2,25
Nerastvorivi ostatak u HCl i Na_2CO_3 *Insoluble residue in HCl and* Na_2CO_3	EN 196-2, tačka 9 / *chapter* 9	10,07
SiO_2	EN 196-2, tačka 13.6 / *chapter 13.6*	25,87
CaO	EN 196-2, tačka 13.14 / *chapter 13.14*	53,49
MgO	EN 196-2, tačka 13.15 / *chapter 13.15*	1,99
Fe_2O_3	EN 196-2, tačka 13.10 / *chapter 13.10*	4,02
Al_2O_3	EN 196-2, tačka 13.11 / *chapter 13.11*	2,20
SO_3	EN 196-2, tačka 8 / *chapter 8*	1,87
Cl	EN 196-2, tačka 14 / *chapter 14*	0,0053
Na_2O_3	-	0,219
K_2O	-	0,612

Važno je napomenuti da se prilikom izrade recepture i sa sve četiri frakcije od zgure javlja značajno slijeganje uzoraka, do 20 mm i da je ugradljivost betona u čelične uzorke otežana. S druge strane, upotrebom dolomitnog agregata, slijeganje se smanjuje a ugradljivost je poboljšana. Na slici 6. prikazan je postupak pripremanja uzoraka betona. Kao što se vidi na slici 6. pripremljene su kocke 15x15x15x cm.

It should be mentioned that during preparation of recipe, significant slump, up to 20 mm, occurred when all four slag fractions were used, thus workability of concrete in steel samples was hard to achieve. On the other hand, the use of dolomite aggregate reduced slump and workability improved. Figure 6 shows the procedure of concrete sample preparation. As it can be seen in Figure 6, the cubes 15x15x15cm were prepared.


Slika 7. Priprema uzoraka betona
Figure 7. Preparation of concrete samples


Slika 8. Priprema uzoraka betona
Figure 8. Preparation of concrete samples

Nakon propisnog spravljanja i njegovanja uzoraka izvršeno je ispitivanje, a rezultati ispitivanja dati su tabelarno u nastavku (Tabela 10. – Rezultati ispitivanja betonskih uzoraka kocki 15x15x15 cm – Receptura I, Tabela 11. – Rezultati ispitivanja betonskih uzoraka kocki 15x15x15 cm – Receptura II).

Testing was carried out after proper manufacturing and maintaining samples, and the results are shown in table below (Table 10 – Test results for concrete cube samples 15x15x15cm – Recipe I, Table 11 – Test results for concrete cube samples 15x15x15cm – Recipe II)

Tabela 10. Rezultati ispitivanja betonskih uzoraka kocki 15x15x15 cm – RECEPTURA I
Table 10. Test results for concrete cube samples 15x15x15cm – RECIPE I

Oznaka betonskog tijela ***Code of concrete cubes***	**Težina** ***Weight*** **(kg)**	**Zapr. masa** ***Volume mass*** **(kg/m^3)**	**Dimenzije (cm)** ***Dimensions (cm)***			**Površina** ***Area*** **(m^2)**	**Sila** ***Force*** **(kN)**	**Čvrstoća 7 dana** ***Strength 7 days*** **(MPa)**	**Čvrstoća 28 dana** ***Strength 28 days*** **(MPa)**
			a	b	c				
K-1	9,652	2860	15	15	15	0,0225	517,50	23,00	-
K-2	10,058	2980	15	15	15	0,0225	630,00	28,00	-
K-3	9,754	2890	15	15	15	0,0225	866,25	-	38,50
K-4	9,889	2930	15	15	15	0,0225	911,25	-	40,50
K-5	9,889	2930	15	15	15	0,0225	888,75	-	39,50
PROSJEČNO / *AVERAGE*								**25,50**	**39,50**

Tabela 11. *Rezultati ispitivanja betonskih uzoraka kocki 15x15x15 cm – RECEPTURA II*
Table 11. Test results for concrete cube samples 15x15x15 cm – RECIPE II

Oznaka betonskog tijela *Code of concrete cubes*	**Težina** *Weight* **(kg)**	**Zapr. masa** *Volume mass* **(kg/m^3)**	**Dimenzije (cm)** *Dimensions (cm)*			**Površina** *Area* **(m^2)**	**Sila** *Force* **(kN)**	**Čvrstoća 7 dana** *Strength 7 days* **(MPa)**	**Čvrstoća 28 dana** *Strength 28 days* **(MPa)**
			a	**b**	**c**				
K-6	9,180	2720	15	15	15	0,0225	506,25	22,50	-
K-7	9,315	2760	15	15	15	0,0225	472,50	21,00	-
K-8	9,281	2750	15	15	15	0,0225	798,75	-	35,50
K-9	9,754	2890	15	15	15	0,0225	843,75	-	37,50
K-10	9,450	2800	15	15	15	0,0225	821,25	-	36,50
							PROSJEČNO / ***AVERAGE***	**21,75**	**36,50**

7 ZAKLJUČAK

Na osnovu rezultata dobijenih prilikom ispitivanja uzoraka betona spravljenih sa zgurom iz željezare Zenica, a imajući u vidu kratak period ispitivanja i ograničena sredstva, ustanovljeno je sljedeće:

– Fizičko-mehaničke karakteristike zgure zadovoljavaju uslove definisane u evropskim normama za ovu vrstu materijala, naročito kada je u pitanju krupna frakcija zgure. Važno je napomenuti da materijal nije štetan za okolinu ili ljudsko zdravlje.

– Radioaktivnost zgure, promjena zapremine, procenat hlorida ili sulfata u dozvoljenim je granicama.

– Pripremljeni uzorci betona dali su vrijednosti čvrstoće na pritisak koje odgovaraju klasi betona oznake C25/30. Važno je napomenuti da se radi o betonu čija je zapreminska masa znatno veća od betona koji je napravljen sa dolomitnim agregatom. Zbog toga, betoni napravljeni sa agregatom od zgure najviše primjene nalaze kod hidrotehničkih objekata, kod temelja objekata, kod potpornih zidova i na drugim mjestima gdje je poželjna veća zapreminska masa betona.

– S obzirom da je zgura materijal koji ima povećanu otpornost na habanje poželjna je upotreba ovog materijala kao agregata za beton za saobraćajne površine.

– Zgura visoke peći se može koristiti kao agregat za betone koji su otporni na visoke temperature.

– Ugradljivost betona napravljenog od agregata od zgure otežana je, a slijeganje je povećano. Ovi problemi se mogu jednostavno riješiti dodavanjem aditiva za beton, kako bi se povećala ugradljivost, a samim tim smanjilo slijeganje.

– Kao što se vidi na krivuljama prosijavanja, ovom agregatu od zgure nedostaje sitna frakcija (fileri), nedostaje frakcija između 0 i 0,25 mm što može proizvesti niz negativnih posljedica po beton. Ove posljedice mogu biti loša ugradljivost, veća vodopropustljivost i slično.

Na kraju, sa sigurnošću tvrdimo da je moguća upotreba agregata od zgure za spravljanje betona kao građevinskog materijala. Naročito se preporučuje upotreba ovog materijala u izgradnji temeljnih konstrukcija, potpornih zidova, zaštiti kosina, regulaciji vodotoka i tako dalje, jer je zapreminska masa ovako

7 CONCLUSIONS

Based on the results obtained by testing slag concrete samples obtained from Iron Works Zenica, and bearing in mind a short period of investigation and limited finances, the following was found:

– Physical-chemical properties of slag fulfil the conditions defined by European standards for this kind of material, especially related to larger slag fractions. It is important to notify that the material is harmless for human health and environment.

– Radioactivity of slag, change of volume, percentage of chlorides or sulphates is within permissive boundaries.

– The prepared concrete samples have values of strength under pressure that correspond to the concrete category C25/30. It should be noted that this concrete has considerably larger mass in comparison with concrete manufactured with dolomite aggregate. Therefore slag aggregate concrete is mostly used for hydro-technical structures, structure foundations, sustaining walls and other places where larger volume of concrete mass is desirable.

– Since slag is a material with strong abrasive resistance, the use of this material as concrete aggregate for traffic surfaces is desirable.

– Blast furnace slag can be used for concrete that is resistant to high temperatures.

– Workability of concrete manufactured from slag aggregate is hard to achieve, and the slump increases. These problems can be solved easily by adding additives for concrete in order to increase its workability, and hence reduce its slump.

– As it can be seen from sieving curves of this slag aggregate, the small fractions (fillers) are missing. This lack of 0-0.25 fractions can cause a series of negative consequences in concrete. The consequences may be poor workability, higher water absorption etc.

Finally, it can be concluded that it is possible to use of slag aggregate for manufacturing concrete as civil engineering material. The use of this material is especially recommended for constructing foundations, sustainable walls, protection of slopes, regulation of watercourses etc., since volume mass of this manufactured concrete is significantly larger in comparison spravljenog betona znatno veća od betona s dolomitnim agregatom. Moguća je upotreba i drugih receptura, ali je neophodno dodatno ispitivanje. Upotreba ovog industrijskog nusproizvoda doprinosi očuvanju okoliša i smanjenju upotrebe agregata iz prirodnih izvora.

with concrete manufactured with dolomite aggregate. Application of other recipes is possible, but additional investigation is necessary. The use of this by-product contributes to the environmental protection process and reduced use of aggregates from natural sources.

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REZIME

MOGUĆNOST UPOTREBE ZGURE VISOKE PEĆI KAO AGREGATA U BETONU

Amir DŽANANOVIĆ
Nazim MANIĆ

Industrijskom proizvodnjom sirovog željeza kao sporedni proizvod dobijaju se velike količine otpadnog industrijskog materijala koji je neophodno deponovati. Dugo vremena otpadni materijal pri proizvodnji sirovog željeza deponovao se bez ikakve prethodne obrade ili selekcije. Na mjestima gdje se deponuje otpadni materijal veoma često bi došlo do zagađenja tla i/ili vode i do trajnog zauzimanja zemljišta, a nerijetko i do stvaranja vještačkih klizišta na mjestu deponovanja.

Iz tog razloga javila se ideja o istraživanju mogućnosti upotrebe industrijskog nusproizvoda pri proizvodnji željeza u građevinske svrhe, odnosno kao agregata u betonu. Kako bi se ustanovila mogućnost upotrebe zgure visoke peći kao agregata u betonu bilo je neophodno ispitati fizičko-mehaničke i hemijske osobine zgure, a nakon toga pripremati uzorke betona.

Eksperimentalno je dokazano da se zgura iz pogona „Željezare” (Arcelor Mittal) iz Zenice može koristiti kao agregat u betonu, što bi doprinijelo smanjenju količine ove vrste otpadnog materijala, a sačuvao bi se agregat iz prirode koji se obično koristi za spravljanje betona. Korišćenjem zgure za izradu betona smanjila bi se zagađenost prirode, a s druge strane – sačuvali bismo prirodu „nepovređivanjem”, jer bismo koristili manje količine krupnog agregata.

Ključne riječi: zgura, agregat, beton

SUMMARY

THE POSSIBILITY OF USING BLAST FURNACE SLAG AS CONCRETE AGGREGATE

Amir DZANANOVIC
Nazim MANIC

Large quantities of material are obtained for waste disposal in industrial production of basic iron. It is a long habit of waste management after industrial production of base iron without previous processing or selection. On the places of waste disposal, the contamination of soil and/or water is evident, and it resulted in permanent land degradation and frequent formation of artificial landslides.

These facts gave birth to the idea to investigate the possibility of using industrial by-products of iron manufacturing for construction purposes, i.e. concrete aggregate. In order to determine the possibility of blast furnace slag as concrete aggregate, it was necessary to examine physical and chemical properties of slag, and thereafter to prepare concrete samples.

The use of slag from “'Željezara“ Works (Arcelor Mital, Zenica) was experimentally proved as possible concrete aggregate, which could lead to reduction of this waste material, while preserving natural aggregate that was often used in production of concrete. By using slag in concrete production, environmental pollution will be reduced, and on the other hand, nature will remain “untouched”, since smaller quantities of natural aggregate will be used.

Key words: slag, aggregate, concrete

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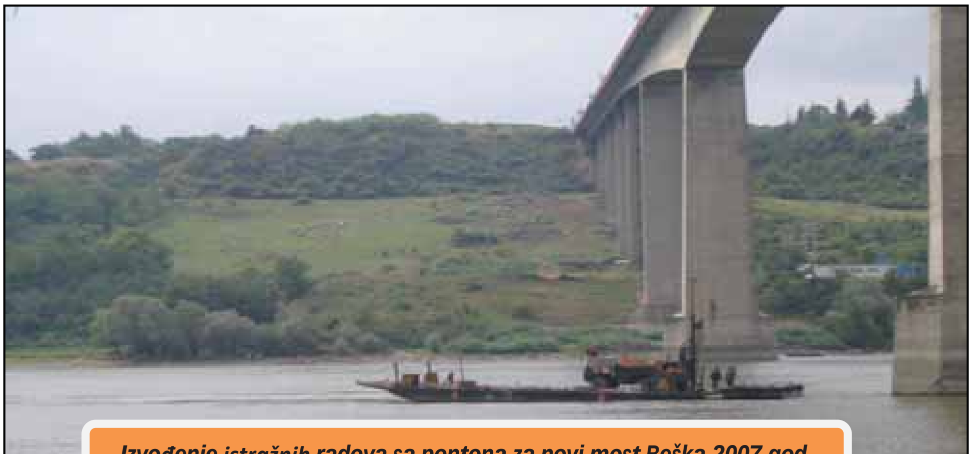


Izvođenje istražnih radova sa pontona za novi most Beška,2007.god.

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 protekloj deceniji.

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).

DLT-dinamičko ispitivanje šipova

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

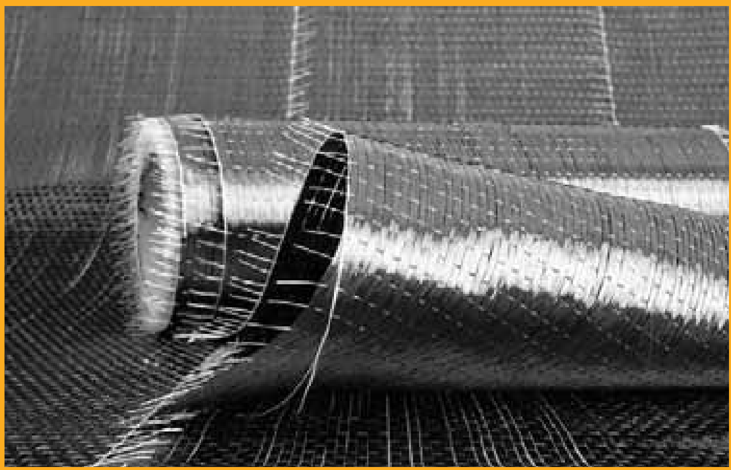
NAPREDNA SIKA REŠENJA U OBLASTI STRUKTURALNIH OJAČANJA

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

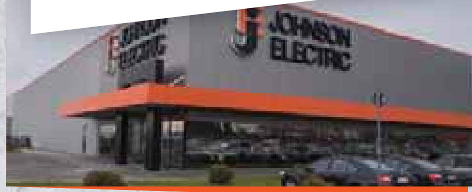
- Preko 40 godina iskustva u strukturalnim ojačanjima, sistemima i tehnikama
- Proizvodi i sistemi sa brojnim testovima i procenama kako internim tako i eksternim
- Najviši međunarodni standardi proizvodnje i kontrole kvaliteta

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 m^3 do 10 m^3 betonske mase. Za ugradnju betona posedujemo auto-pumpu za beton, radnog učinka 150 m^3/h, sa dužinom strele od 36 m.

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