

ODREĐIVANJE IN-SITU KOEFICIJENTA TRENJA I IMPERFEKCIJE KABLOVA ZA PREDNAPREZANJE

DETERMINATION OF THE IN SITU COEFFICIENT OF FRICTION AND IMPERFECTION OF PRESTRESSING CABLES

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1 UVOD

Savremena armiranobetonska konstrukcija značajnih raspona ne može se zamisliti bez njenog prednaprezanja. Projektovanje ustanovljeno na samim počecima ovakvih sistema, s malim izmenama nedavno uvedenim, u upotrebi je i danas širom sveta. Jedna od osnovnih premisa jeste to da sila u kابلu na aktivnom kraju za vreme zatezanja ne sme preći vrednost datu obrascem (1):

$$P_{\max} = A_p \cdot S_{p,\max} \quad (1)$$

gde A_p predstavlja površinu poprečnog preseka kabla i $S_{p,\max}$ maksimalni napon u kابلu. Vrednost $S_{p,\max}$ određena je manjom vrednošću od $k_1 \cdot f_{pk}$ i $k_2 \cdot f_{p0,1k}$. Vrednosti k_1 i k_2 definisane su nacionalnim standardima. Najčešće se koriste vrednosti $k_1=0,8$ i $k_2=0,9$ [1,2]. Prekoračenje najveće sile zatezanja dopušta se u posebnim slučajevima kada se koristi veoma precizna oprema za prednaprezanje. Tada se najveća sila prednaprezanja određuje pomoću obrasca $k_3 \cdot f_{p0,1k} \cdot A_p$, gde se za koeficijent k_3 usvaja vrednost 0,95.

1 INTRODUCTION

Modern reinforced concrete structure of significant spans cannot be imagined without its prestressing. Nowadays, the design established at the very beginning of such systems, with small changes introduced in the recent past, is in use worldwide. One of the basic premises is that the force in the cable at the active end during tensioning must not exceed the value given in the following formula (1):

where A_p represents the cross-sectional area of the cable and $S_{p,\max}$, the maximum stress in the cable. Value $S_{p,\max}$ is determined by the lower value of $k_1 \cdot f_{pk}$ and $k_2 \cdot f_{p0,1k}$. The values of k_1 and k_2 are defined by national standards. The most commonly used values are $k_1=0.8$ and $k_2=0.9$ [1,2]. Exceeding the highest tension force is allowed in special cases when highly accurate equipment for prestressing is used. Then the maximum tensioning force is determined by using the formula $k_3 \cdot f_{p0,1k} \cdot A_p$ where the coefficient k_3 adopts the value of 0.95.

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Za dobro projektovanje prednapregnutih konstrukcija u proračun se uvode i koeficijenti trenja i nepravilnosti, odnosno ugaonog odstupanja.

U proizvodnji čelika i plastičnih materijala, svakodnevno se uvode novine koje omogućavaju izradu bezbednijih konstrukcija. Tako, primenom savremenih čelika za prednaprezanje, relaksacija kablova svedena je na minimum. U građevinskoj praksi veoma često, u slučaju prednapregnutih konstrukcija, za trasiranje kablova upotrebljavaju se plastične orebljene cevi od novih vrsta plastike. Uticaj primene novih vrsta materijala na vrednosti koeficijenta trenja često se ostavlja na procenu projektantu. Najčešće se na nivou projekta uzimaju vrednosti koeficijenata iz važećih pravilnika i propisa koji možda i nisu uzeli u obzir primenu novih materijala u prednaprezanju. Dosadašnja iskustva na polju određivanja koeficijenata trenja i nepravilnosti izvođenja u slučaju prednaprezanja uglavnom su u vezi s teorijskim i laboratorijskim ispitivanjima. Kao što je već napomenuto, koeficijent trenja umnogome zavisi od primenjenih materijala, dok koeficijent nepravilnosti zavisi ponajviše od stepena obučenosti i savesnosti izvođača da izvede radove na prednaprezanju [3,4]. Parametri se usvajaju iskustveno, u granicama koje propisuju nacionalni standardi i propisi zemlje u kojoj se konstrukcija izvodi. Stvarno određivanje navedenih parametara jeste veoma komplikovano i zahteva dodatna sredstva od izvođača, kao i angažovanje specifične opreme. Samim tim, projektovani parametri najčešće se ne proveravaju.

Pri naknadnom utezanju kablova, sila prethodnog naprezanja i odgovarajuće izduženje kabla moraju da se provere merenjima, a moraju da se kontrolišu i stvarni gubici usled trenja. Pored ovih parametara, za projektante i izvođače na konstrukciji veoma bi korisno bilo da se analiziraju parametri u vezi s koeficijentom trenja i koeficijentom nepravilnosti izvođenja radova na prethodnom naprezanju [5].

2 TEORIJSKE POSTAVKE

Srednja vrednost sile prethodnog naprezanja $P_{m,t}(x)$ u datom trenutku vremena t , na rastojanju x od aktivnog kraja kabla, jednaka je najvećoj sili P_{max} kojom se kabl zateže na aktivnom kraju, umanjenoj za trenutne gubitke i gubitke koji zavise od vremena. Svi gubici razmatraju se u apsolutnim vrednostima.

Vrednost početne sile prednaprezanja $P_{m0}(x)$ za $t=t_0$, kojoj je beton izložen neposredno posle utezanja i ankerovanja kablova, ili posle prenošenja prethodnog naprezanja na beton, dobija se kada se sila prednaprezanja P_{max} umanjati za trenutne gubitke $\Delta P_i(x)$, i ne treba da prekorači vrednost dobijenu obrascem (2):

$$P_{m0}(x) = A_p \cdot s_{pm0}(x) \quad (2)$$

gde je $s_{pm0}(x)$ napon u kablju neposredno posle utezanja ili prenošenja sile kao manja vrednost od $k_7 \cdot f_{pk}$ i $k_8 \cdot f_{p0,1}$. Preporučene vrednosti za koeficijente jesu $k_7=0,75$ i $k_8=0,85$.

For good design of prestressed structures, the coefficients of friction and imperfection, or angular deviation are introduced in the calculation.

In the production of steel and plastic materials new things which enable the production of safer structures are introduced every day. Thus, with the application of modern steel for prestressing the relaxation of cables is reduced to a minimum. In construction practice in the case of prestressed structures for tracing cables plastic corugated pipes made of new types of plastics are used very often. The effect of the application of new types of materials on the values of the coefficient of friction is often left for the designer to estimate. Most often at the design level coefficient values are taken from applicable policies and regulations that may not take into account the application of new materials in prestressing. Previous experience in the field of determining the coefficients of friction and imperfection of the execution of prestressing are mainly related to the theoretical and laboratory testing. As it is already mentioned, the coefficient of friction depends largely on the applied materials, while the coefficient of imperfection depends largely on the level of training and conscientiousness of the contractor to perform work on the prestressing [3,4]. The parameters are adopted empirically within the limits prescribed by national standards and regulations of the country where the structure is performed. Actual determination of the aforementioned parameters is a very complicated process which requires additional resources from the contractor, as well as the involvement of specific equipment. Therefore the designed parameters are usually not checked.

In post-tensioning of the cables the prestressing force and the corresponding elongation of the cable must be checked by measurements, and actual losses since the friction have to be controlled. In addition to these parameters, it would be of great use for designers and contractors of the structure to analyze the parameters related to the coefficient of friction and the coefficient of imperfection of execution of work on prestressing [5].

2 THEORETICAL PREMISES

Mean value of prestressing force $P_{m,t}(x)$ at a given time t , at a distance x from the active end of the cable is equal to the maximum force P_{max} which tension the cable on the active end, reduced for current losses and losses that depend on the time. All losses are considered in absolute values.

The value of the initial prestressing force $P_{m0}(x)$ for $t=t_0$, where the concrete is exposed immediately after the tensioning and anchoring of the cables, or after the transmission of the prestressing to concrete, is obtained when the prestressing force P_{max} is reduced by the current loss $\Delta P_i(x)$, and should not exceed the value obtained by the equation (2):

where $s_{pm0}(x)$ is the stress in the cable immediately after the tensioning or transmitting the force as a smaller value of $k_7 \cdot f_{pk}$ and $k_8 \cdot f_{p0,1}$. The recommended values for the coefficients are $k_7=0,75$ and $k_8=0,85$.

Sila prednaprezanja najčešće nije konstantna duž kabla usled trenja kabla o zidove kanala kroz koji prolazi i trenja usled promene pravca kabla. Pored toga, sila prednaprezanja se tokom vremena i smanjuje usled relaksacije čelika, skupljanja i tečenja betona.

Prema tome, u jednom preseku kabla imamo početnu silu P_{m0} u trenutku prednaprezanja, silu $P_{m,t}$ u nekom vremenu „t” i trajnu silu za $t \rightarrow \infty$, $P_{m\infty}$. Za trajnu silu uzima se u obzir i promena sile usled dejstva stalnog i pokretnog opterećenja nakon prednaprezanja. Gubici koji se proračunavaju dati su u standardu SRPS EN:1992-1-1:2004 [6].

Kada se određuju trenutni $t=t_0$ gubici $\Delta P_i(x)$, razmatraju se sledeći trenutni uticaji usled kojih nastaju gubici pri utezanju, u zavisnosti koji od tih uticaja je relevantan:

- gubici pri ankerovanju - usled uvlačenja klina - ΔP_{sl} ;
- gubici usled elastičnih deformacija betona - ΔP_{el} ;
- gubici usled kratkotrajnog dejstva relaksacije - ΔP_r ;
- gubici usled trenja - $\Delta P_{\mu}(x)$.

Srednja vrednost sile prethodnog naprezanja $P_{m,t}(x)$ u vremenu $t > t_0$ određuje se u zavisnosti od metode utezanja. Pored navedenih trenutnih gubitaka, treba da se imaju u vidu i gubici prednaprezanja, koji zavise od vremena $\Delta P_{c+s+r}(x)$, a rezultat su tečenja i skupljanja betona i dugotrajne relaksacije čelika za prethodno naprezanje, tako da je

$$P_{m,t}(x) = P_{m0}(x) - \Delta P_{c+s+r}(x).$$

Početna sila u kablju (P_{po}) manja je od početne sile na presi (P_p), usled uvlačenja klinova u toku prenošenja sile s prese na kotvu. Prilikom uvlačenja klinova istovremeno, u približno istoj veličini, uvlače se i užad, što dovodi do pada sile u kablju usled izgubljenog izduženja. Uvlačenje klinova javlja se na strani aktivne i pasivne kotve. Uvlačenje klinova kod pasivne kotve ne mora uticati na smanjenje početne sile ukoliko se ukupno izduženje kod prese poveća za ovu vrednost. Uvlačenje klinova na strani prese, aktivne kotve, dovodi do smanjenja početne sile u kablju za veličinu izgubljenog izduženja, što može dati znatnu vrednost kod kratkih kablova. Uvlačenje klinova kod aktivne i pasivne kotve približno je isto i uzima se na nivou od 3 mm do 5 mm. Postoje načini da se ovaj gubitak delimično ili potpuno eliminiše, uz primenu posebnih procedura.

Elastično skraćanje konstrukcije dovodi do gubitka ukupne početne sile konstrukcije ukoliko se uteže više od jednog kabla. Gubitak je znatan u slučaju jako napregnutih elemenata malog preseka (npr. vešaljke, stubovi). Tada treba voditi računa o gubitku sile u kablju usled deformacije betona, kao i o zavisnosti od redosleda zatezanja kablova (prema SRPS EN:1992-1-1:2004).

Gubitak sile prednaprezanja javlja se u slučaju naknadno prednapregnutih elemenata usled trenja između kablova i zaštitnih cevi u betonu. Veličina ovog gubitka jeste funkcija oblika trase kabla - efekat zakrivljenosti i odstupanja prilikom montaže trase kablova - ugaono odstupanje. Vrednosti koeficijenata koji definišu gubitke sile često se preciziraju dok se

The prestressing force is usually not constant along the cable due to the friction of the cable on the walls of the channels through which it passes and friction due to the changes in the direction of the cable. In addition, the tensioning force is reduced over time due to relaxation of steel, shrinkage and creeping of concrete.

Accordingly, in a cross-section of the cable there is the initial force P_{m0} in the moment of prestressing, force $P_{m,t}$ in some time „t” and permanent force for $t \rightarrow \infty$, $P_{m\infty}$. For the permanent force the changes of the force due to the effect of permanent and moving load after prestressing should also be taken into account. Losses that are computed are presented in standard SRPS EN:1992-1-1:2004 [6].

When determining the current $t=t_0$ losses $\Delta P_i(x)$ the following current impacts which lead to losses in tensioning are considered, depending on which of these impacts is relevant:

- losses at anchorage - due to insertion of the wedge - ΔP_{sl} ,
- losses due to elastic deformation of concrete - ΔP_{el} ,
- losses due to the short-term effects of relaxation - ΔP_r ,
- losses due to friction - $\Delta P_{\mu}(x)$.

Mean value of prestressing force $P_{m,t}(x)$ at time $t > t_0$ is determined depending on the method of tensioning. In addition to these current losses, the losses of prestressing which depend on the time $\Delta P_{c+s+r}(x)$, which are the result of creeping and shrinkage of concrete and long-lasting relaxation of steel for prestressing should be taken into account, so that:

$$P_{m,t}(x) = P_{m0}(x) - \Delta P_{c+s+r}(x).$$

Initial force in cable (P_{po}) is less than the initial force on the press (P_p) due to the insertion of wedges during the transmission of force to the anchor. During the insertion of wedges simultaneously at approximately the same size, cables are also drawn, leading to a drop in force in the cable due to the lost elongation. Insertion of wedges occurs on the side of the active and passive anchor. Insertion of wedges in the passive anchor need not to affect the reduction of the initial force if total elongation at press is increased by this amount. Insertion of wedges on the side of the press, active anchor, leads to a reduction in the initial force in the cable for the size of the lost elongation, which can have significant value for short cables. Insertion of wedges of active and passive anchor is approximately the same and is taken at the level of 3-5mm. There are ways to partially or completely eliminate this loss with the use of special procedures.

Elastic deformation of structures, leads to a total loss of the initial force of the structure if more than one cable is being tensioned. The loss is significant with highly prestressed elements with small cross-section: hangers, piles and the like. Then the loss of force in the cable due to deformation of concrete, as well as dependence from the order of tensioning cables (according to EN: 1992-1-1: 2004) have to be taken into account.

Loss of tensioning force occurs in post-prestressed elements due to friction between the cables and protective pipes in concrete. The value of this loss is a function of the form of the route of the cable-effect of

obavlja priprema projekta izborom različitih tipova i oblika trase kablova. Pošto je efekat zakrivljenosti unapred određen, ugaono odstupanje jeste rezultat slučajnog ili neizbežnog odstupanja, pošto ne postoji mogućnost da se trasa zaštitnih cevi idealno montira [7].

Treba imati u vidu da će maksimalna vrednost gubitka sile usled trenja biti na drugom kraju elementa, ako se zateže s jednog kraja. Stoga, gubitak usled trenja se menja linearno duž raspona elementa i može se interpolirati za posebne položaje ako je potrebna veća tačnost.

Gubici usled trenja $\Delta P_{\mu}(x)$, pri utezanju kablova, mogu da se procene prema obrascu (3):

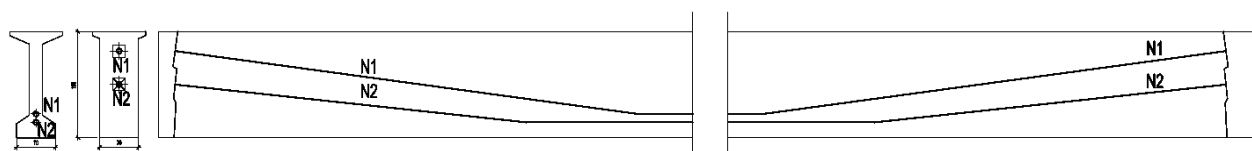
$$\Delta P_{\mu}(x) = P_{\max}(1 - e^{-m(q + kx)}) \quad (3)$$

U prethodnom obrascu q predstavlja zbir skretnih uglova na rastojanju x izražen u rad; m je koeficijent trenja između kabla i cevi u koju je postavljen izražen u rad^{-1} ; k određuje nenamerno ugaono skretanje unutrašnjih kablova izraženo u rad/m ; x predstavlja rastojanje izraženo u metrima duž kabla od tačke u kojoj je sila u kابلu jednaka P_{\max} to jest sila na aktivnom kraju kabla za vreme utezanja.

Za koeficijent trenja μ treba naglasiti da veoma zavisi od površinskih karakteristika kablova i cevi, a naročito od stepena korozije dodirnih površina. Veličina trenja zavisi i od vrste cevi koja se koristi i od tipa kabla. Postoje dva mehanizma koja proizvode trenje; prvi je zakrivljenost kabla, a drugi - slučajna razlika između težišta kablova i cevi.

3 IN-SITU EKSPERIMENTALNI RAD

Kompletan eksperiment urađen je na gradilištu, prilikom izgradnje mosta Borča-Zemun. Izvođač radova bio je CRBC (China Road and Bridge Corporation). Konstrukcija mosta van vode imala je dva sistema. Jedan od sistema uključivao je izradu prednapregnutih nosača statičke dužine 26 i 36 metara. U eksperimentu je korišćen nosač dužine 26 metara. Projektom je bilo predviđeno utezanje nosača sa četiri kabla od po sedam užadi prečnika 15,2 mm, dok je za trasu kablova korišćena plastična rebrasta cev. Karakteristični poprečni preseći i podužni presek nosača s trasama dva ispitivana kabla prikazani su na slici 1.



Slika 1. Karakteristični poprečni i podužni presek AB nosača
Figure 1. Typical cross section and longitudinal section of RC girders

curvature and deviation during the installation of cable route-angular deviation. The values of coefficients that define the losses of force is often specified while the preparation of the project by selecting different types and shapes of cable route is being done. As the effect of the curvature is predetermined, angular deviation is the result of accidental or unavoidable deviation, as there is no possibility for the trace of protective pipes to be ideally instaled [7].

It should be kept into account that the maximum value of the loss of force due to friction will be on the other end of the element, if it is tensioned from one end. Therefore, loss due to friction varies linearly along the element span and can be interpolated for specific positions if there is a need for greater accuracy.

Losses due to friction $\Delta P_{\mu}(x)$ when tensioning cables can be assessed according to the formula (3):

In previous formula q represents the sum of the diverting angles at a distance x expressed in rad; m is the coefficient of friction between the cable and pipes in which it is placed, expressed in rad^{-1} ; k determines accidental diverting angle of internal cables expressed in rad/m ; and x is the distance expressed in m along the cable from the point where the force in the cable is equal to P_{\max} i.e. the force on the active end of the cable during tension time.

For the friction coefficient μ it should be emphasized that it is highly dependent on surface characteristics of cables and pipes, in particular on the degree of corrosion of contact surfaces. Amount of friction also depends on the type of pipes used and the type of cable used. There are two mechanisms that produce friction. The first is the curvature of the cable, and the other is a random difference between the center of gravity of the cables and the pipe.

3 EXPERIMENTAL WORK IN SITU

The complete experiment was performed on construction site during the construction of the bridge Zemun-Borča. The contractor was the CRBC (China Road and Bridge Corporation). The construction of the bridge outside the water had two systems. One of the system included the making of prestressed girders with static length 26 and 36m. The experiment used the girder with the length of 26 meters. In the design tensioning of the girder with 4 cables of 7 ropes each with the diameter of 15,2mm was planned, while for the trace of cables corrugated plastic pipe was used. A typical cross-sections and longitudinal-section of the girder with traces of two tested cables are shown in Figure 1.



Slika 2. Aktivni kraj
Figure 2. Active end



Slika 3. Pasivni kraj
Figure 3. Passive end

Eksperiment je obuhvatio određivanje koeficijenta trenja i koeficijenta imperfekcije, s tim što nisu uzimani u obzir efekti zaklinjavanja i elastične deformacije betona. Efekti zaklinjavanja nisu se imali u vidu, jer su procedurama i modifikacijama IMS sistema prednaprezanja uticaji svedeni na minimum. Presa za utezanje modifikovana je tako da se zaklinjavanje vrši pre otpuštanja kablova. Poštujući proceduru upravljanja presom, efekat zaklinjavanja se može zanemariti. Projektom je predviđeno utezanje kompletnog nosača sa četiri kabla, a u eksperimentu je planirano utezanje s jednim kablom do ~90% projektovane sile. Efekat elastične deformacije betona na ovom nosaču i pri usvojenoj dispoziciji ispitivanja može se zanemariti, jer se vrši utezanje samo s jednim kablom koji se otpušta pre utezanja sledećeg kabla.

Planirano je da se prvo uteže kabl N1 do 95% projektovane sile u kablovima. Potom, vršeno je zaklinjavanje i praćenje sile naredna 24 sata. Pri utezanju kabla, merenja su sprovedena na svakih 20% maksimalno projektovane sile. Praktično, sila se merila na 20%, 40%, 60% i 80% maksimalne projektovane sile u kablovima. Merenja su navedena i nakon 24 sata. Potom, izvršeno je rasklinjavanje utegnuto kabla N1 i pristupilo se utezanju kabla N2. Merilo se sve, kao i u slučaju kabla N1. Nakon postizanja predviđene sile, vršeno je zaklinjavanje i praćenje sile naredna 24 sata. Naposljetku, izvršeno je rasklinjavanje kabla N2. Rezultati merenja sile utezanja na aktivnom i pasivnom kraju dati su u tabeli 1.

The experiment included the determination of the coefficient of friction and the coefficient of imperfection, except that the effects of wedging and elastic deformation of concrete were not taken into account. The effects of wedging were not taken into account because the procedures and modifications of the IMS system of prestressing minimized the impact. Press for tensioning has been modified so that wedge done before releasing the cables. By respecting procedures of using press wedging effect can be ignored. Design is anticipated tensioning of the complete girder with 4 cables, while the experiment tensioning with one cable up to ~90% designed force is planned. Effect of elastic deformation of concrete at such girders in adopted disposition tests can be ignored because it performs tensioning with only one cable which is released before tensioning second cable.

It was planned for cable N1 to be tensioned first and up to ~90% of the designed force in the cables. Then wedging was carried out and the force was monitored for the next 24 hours. While tensioning the cable measurements were conducted for every 20% of the maximum designed force. Practically force measurements were conducted at 20, 40, 60 and 85-95% of the maximum designed force in the cables. Measurements were also carried out after 24 hours. Then the released of tensioned cable N1 was performed and tensioning of cable N2 was started. All measurements were performed the same as for cable N1. After reaching the planned force wedging was performed and the force was followed for the next 24 hours. At the end released of cable N2 was performed. The results of the tensioning force measurements on the active and passive end are given in table 1.

Tabela 1. Rezultati merenja sile utezanja u kablovima N1 i N2
 Table 1. The results of tensioning force measurements in cables N1 and N2

Sila / Force	Kabal N1 / Cable N1			Kabal N2 / Cable N2		
	Aktivni kraj / Active end	Pasivni kraj / Passive end		Aktivni kraj / Active end	Pasivni kraj / Passive end	
	t→0	t→0	t→24h	t→0	t→0	t→24h
20%	347kN	314kN	-	348kN	312kN	-
40%	694kN	649kN	-	694kN	675kN	-
60%	1041kN	982kN	-	1041kN	1026kN	-
~90%	1379kN	1304kN	1302kN	1276kN	1180kN	1179kN

4 DISKUSIJA I ZAKLJUČCI

Rezultati ispitivanja obrađeni su na dva načina. Izračunati su koeficijenti trenja i koeficijenti imperfekcije na osnovu sila utezanja na dva kabla, kao i procena poređenja koeficijenta trenja za različite nivoe utezanja kablova. kabal

Proračun koeficijenta trenja i koeficijenta imperfekcije svodi se na rešavanje sistema jednačina s dve nepoznate. Jednačine su prikazane obrascima (4) i (5).

$$\ln(P_{1,x} / P_{1,max}) = -\mu * (\theta_1 + kx) \quad (4)$$

$$\ln(P_{2,x} / P_{2,max}) = -\mu * (\theta_2 + kx) \quad (5)$$

Ukupni skretni ugao θ_1 u kablju N1 iznosio je 15.346°, a θ_2 u kablju N2 iznosio - 12.136°. Dužina na kojoj je merena vrednost smanjenja sile jeste kraj kabla $x=26,097$ m. Na osnovu ulaznih podataka i rešavanja sistema jednačina s dve nepoznate, dobijene su vrednosti za koeficijent trenja kablova $\mu=0,22$ i koeficijent imperfekcije $k=0,004$.

Nakon rešavanja sistema jednačina, izvršen je i proračun koeficijenta trenja pojedinačno za kablove za različite nivoe utezanja kablova. Proračun je vršen posebno za svaki kabl i raspon koeficijenta imperfekcije od 0,001 do 0,01 s korakom 0,001. Dobijeni rezultati prikazani su na slikama 4 i 5.

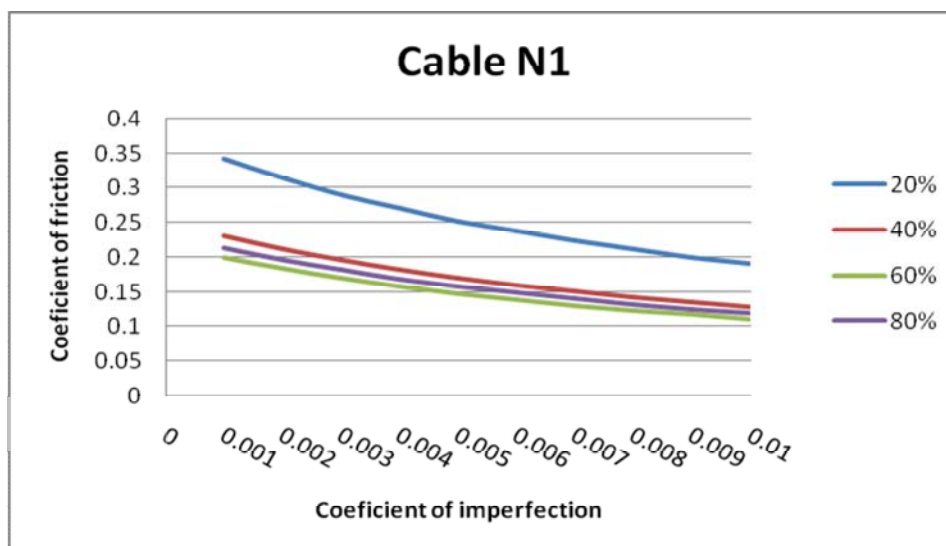
4 DISCUSION AND CONCLUSIONS

Test results processing was done in two ways. Coefficients of friction and coefficients of imperfection on the basis of tension forces in two cables as well as an evaluation of the comparison of the coefficient of friction for different levels of tension cables.

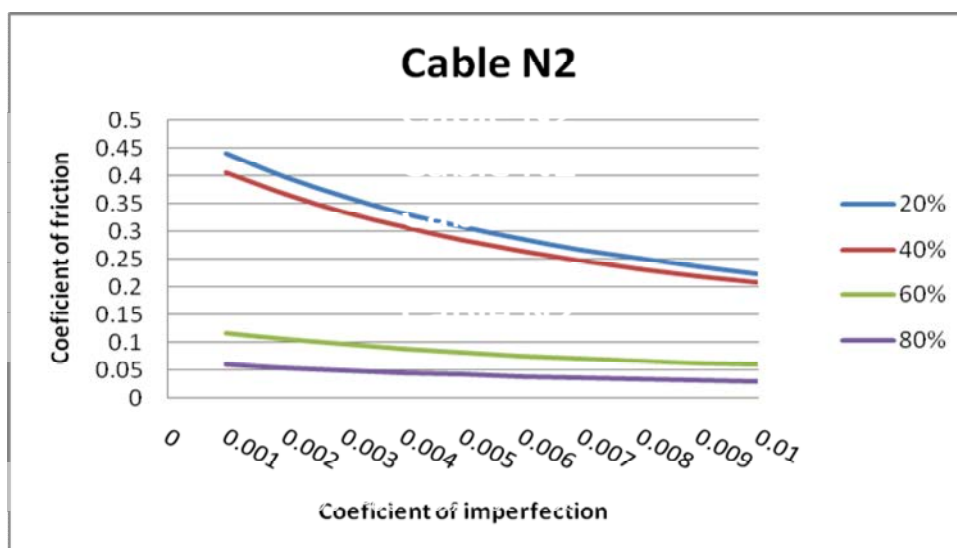
Calculation of the coefficient of friction and the coefficient of imperfection is reduced to solving a system of equations ((4) and (5)) with two unknowns.

Total deviation angle θ_1 in the cable N1 was 15.346°, and θ_2 in the cable N2 amounted to 12.136°. Length at which the measured value of the reduction in force is the end of the cable $x=26.097$ m. Based on the input data and solving the system of equations with two unknowns, the values for the coefficient of friction of cables $\mu=0.22$ and imperfection coefficient $k=0.004$ were obtained.

After solving the system of equations a calculation of the coefficient of friction of cables was made separately for different levels of cables tensioning. The calculation was done separately for each cable and imperfection coefficient ranging from 0.001 to 0.01 with step 0.001. The obtained results are shown in Figures 4 and 5.



Slika 4. Koeficijent trenja kabla N1 u zavisnosti od koeficijenta imperfekcije
 Figure 4. The coefficient of friction of the cable N1 depending on the coefficient of imperfection



Slika 5. Koeficijent trenja kabla N2 u zavisnosti od koeficijenta imperfekcije
 Figure 5. The coefficient of friction of the cable N2 depending on the coefficient of imperfection

Zajedničkom obradom rezultata ispitivanja dva kabla, dobijeni su rezultati koji se mogu uporediti sa standardom i preporukama definisanim vrednostima iz tabele 2. Kao što se može videti, dobijena vrednost za plastične rebraste cevi, koeficijenta trenja $\mu=0,22$ nešto je veća, dok je koeficijent imperfekcije $k=0,004$ u predloženim granicama. Koeficijent imperfekcije zavisi umnogome od izvođača radova i od njegove sposobnosti da što bolje postavi kabl. Time se imperfekcije znatno smanjuju i uticaj se može svesti na minimum. Koeficijent trenja jeste nešto na šta se ne može uticati i njegova vrednost će zavisiti najviše od materijala koji se koriste za vođenje kabla.

By joint processing of the test results for two cables the obtained results are comparable with the standard and recommendations defined by the values from Table 2. As it can be seen, the value obtained for plastic corrugated pipes, the friction coefficient $\mu=0.22$ is slightly higher, while the coefficient of imperfection $k=0.004$ is in the suggested limits. The coefficient of imperfections depends greatly on the contractor and its ability to instal the cord as good as possible. This significantly reduces the imperfections and the impact can be brought down to a minimum. The coefficient of friction cannot be influenced and its value depends the most on the materials used for tracing the cable.

Tabela 2. Preporučene vrednosti proizvođača za koeficijente trenja i imperfekcije
 Table 2. Manufacturers recommended values for the coefficients of friction and imperfection

Tip cevi Type of pipe	μ (rad ⁻¹)		k (rad/m)	
	Opseg vrednosti Value range	Preporuka za proračun Recommendation for design	Opseg vrednosti Value range	Preporuka za proračun Recommendation for design
Rebrasta metalna Corugated metal	0.18 ÷ 0.26	0.22	$(1-10) \cdot 10^{-3}$	$3 \cdot 10^{-3}$
Rebrasta plastična Corugated plastic	0.10 ÷ 0.14	0.12	$(1-10) \cdot 10^{-3}$	$4 \cdot 10^{-3}$
Plastična sa mašću Plastic with grease	0.05 ÷ 0.08	0.06	$(2-6) \cdot 10^{-3}$	$4 \cdot 10^{-3}$
Beton / Concrete	0.34 ÷ 0.62	0.48	$(1-10) \cdot 10^{-3}$	$5 \cdot 10^{-3}$

Razmatrajući rezultate po nivoima unošenja sile u kablove, jasno je da je na manjim silama utezanja koeficijent trenja daleko veći. Prilikom postavljanja kabla i manjih sila u kablovima, prvo dolazi do nameštanja kablova i gubici od aktivnog do pasivnog kraja su znatni. Kasnije, kada se kabl namesti u konačnu poziciju, trenje se smanjuje i dolazi na vrednosti koje se mogu pretpostaviti, u zavisnosti od materijala cevi za vođenje kablova.

Considering the results according to the levels of force application in the cables, it is clear that for lower tension forces coefficient of friction is far greater. When setting up the cable and lower forces in the cables, the cables are first being installed and losses from the active to the passive end are considerable. Later, when the cable is installed in the final position the friction decreased and the values that can be assumed depending on the material of the pipes for cables are obtained.

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REZIME

ODREĐIVANJE IN-SITU KOEFICIJENTA TRENJA I IMPERFEKCIJE KABLOVA ZA PREDNAPREZANJE

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Prednaprežanjem konstruktivnih elemenata omogućava se povećavanje raspona armiranobetonskih konstrukcija. Pri projektovanju i dimenzionisanju prednaprežnutih armiranobetonskih konstrukcija, neophodno je poznavanje, odnosno usvajanje većeg broja parametara koji su empirijski određeni. Za prednaprežnute konstrukcije od osnovnog je značaja da se odredi nivo sile naprežanja kablova. Nivo sile prednaprežanja, pored drugih parametara, umnogome zavisi od koeficijenta trenja kablova i koeficijenta imperfekcije izvođenja. Ovi koeficijenti definisani su standardima za projektovanje ili su ih definisali proizvođači sistema prednaprežanja. Koeficijenti su definisani u širokim opsezima, dok je za projektovanje neophodno poznavanje što tačnijih vrednosti, kako bi se dobio dobar projekat i jeftinija konstrukcija. Putem eksperimentalnog rada in-situ, određen je opseg vrednosti koeficijenta trenja kablova i upoređen je sa standardom definisanim opsezima.

Ključne reči: prednaprežanje, koeficijent trenja, koeficijent imperfekcije

SUMMARY

DETERMINATION OF THE IN SITU COEFFICIENT OF FRICTION AND IMPERFECTION OF PRESTRESSING CABLES

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Prestressing structural elements allows an increase in the spans of reinforced concrete structures. In the design and dimensioning of prestressed reinforced concrete structures it is necessary to know, that is to adopt a number of parameters which are empirically determined. Determining the level of the tension force of the cables is of primary importance for prestressed structures. The level of tensioning force, in addition to other parameters, greatly depends on the friction coefficient of cables and the imperfection coefficient of execution. These coefficients are defined by standards for the design or by the manufacturer of the prestressing system. The coefficients are defined in wide ranges, while for the design, the knowledge of the most accurate values is necessary in order to obtain a good design and cheaper structures. Through experimental work in-situ the range of the values of the coefficient of friction of cables is determined and compared with ranges defined by the standard.

Key words: prestressing, coefficient of friction, coefficient of imperfection