ISPITIVANJE INTEGRITETA ŠIPOVA: TESTIRANJE I ANALIZA REZULTATA

PILE INTEGRITY TESTING: TESTING AND RESULTS ANALYSIS

Mladen ĆOSIĆ
Kristina BOŽIĆ-TOMIĆ
Nenad ŠUŠIĆ

PRETHODNO SAOPŠTENJE
PRELIMINARY REPORT
UDK:624.154
doi:10.5937/GRMK1903039C

1 UVOD

Problematika ispitivanja integriteta šipova u poslednjih dvadesetak godina doživela je ekspanziju u pogledu: metodologije ispitivanja, tehnike i instrumentalizacije ispitivanja, raznovrsnosti tipova testova ispitivanja, softversko-hardverske podrške ispitivanju i teorije i obrade signala. U tom smislu, biti građevinski inženjer ili inženjer geotehnike sa iskustvom u oblasti projektovanja i izgradnje fundamenata nije dovoljan uslov, već se zahteva multidisciplinarnost u razmatranju problematike ispitivanja šipova. Pored standardnih naučnih disciplina, kao što su teorija elastičnosti, mehanika tla, dinamika tla, mehanika stena, fundiranje, ispitivanje konstrukcija, zahteva se i dobro poznavanje relativno novije naučne tematike interakcija konstrukcija–tlo, ali i drugih naučnih tematika (koje se primarno ne izučavaju u građevinarstvu ili u geotehnici), kao što su: talasna teorija, metoda karakteristika, teorija i obrada signala, termodinamička teorija i slično. U zavisnosti od stepena poznavanja određenih naučnih disciplina, zavisi i stepen pouzdanosti primenjene metodologije i interpretacije rezultata ispitivanja. Iskustva autora ovog rada pokazuju da se neretko nailazi na neadekvatnu interpretaciju standarda ispitivanja šipova, pa i kompletne metodologije ispitivanja. U tom smislu, težišta ovog rada jesu da se predstave određena iskustva autora rada i da se ukaže na potrebu za doslednošću u primeni metodologije ispitivanja šipova, koja je prikazana u radu [6]. S druge strane, primena nekoliko metoda u ispitivanju integriteta šipova omogućava bolje sagledavanje finalnog rešenja ispitivanja. Sve ove metode, primarno, zasnivaju se na talasnoj teoriji, ali i na procesiranju signala i na numeričkim analizama.

Dr Mladen Ćosić, Institut za ispitivanje materijala IMS, Beograd, Srbija, mladen.cosic@institutims.rs
Mr Kristina Božić-Tomić, Institut za ispitivanje materijala IMS, Beograd, Srbija, kristina.tomic@institutims.rs
Dr Nenad Šušić, Institut za ispitivanje materijala IMS, Beograd, Srbija, nenad.susic@institutims.rs

1 INTRODUCTION

The problem of pile integrity testing has expanded over the last twenty years in terms of: test methodology, test technique and instrumentalization, diversity of test types, software-hardware test support, and signal theory and processing. In this sense, being a civil engineer or geotechnical engineer with experience in the field of foundation design and construction is insufficient; a rather multidisciplinary consideration of pile testing is required. In addition to standard scientific disciplines, such as: theory of elasticity, soil mechanics, soil dynamics, rock mechanics, foundations, structural testing requires a good knowledge of relatively recent scientific topics of soil-structure interactions, but also other scientific topics which are not primarily studied in construction or geotechnics, such as: wave theory, method of characteristics, theory and signal processing, thermodynamic theory, etc. The degree of reliability of the applied methodology and interpretation of test results also depends on the degree of knowledge of particular scientific disciplines. The experience of the authors of this paper indicates that there is often an inadequate interpretation of the pile testing standards, even of the complete testing methodology. In this sense, the focus of this paper is to present some of the authors' experiences and to indicate the need for consistency in the implementation of the pile testing methodology presented in [6]. On the other hand, the application of several methods in pile integrity testing allows a better understanding of the final test solution. All of these methods are primarily based on the wave theory, but also on signal processing and numerical analyses.

Dr Mladen Cosic, Institute for testing of materials IMS, Belgrade, Serbia, mladen.cosic@institutims.rs
Mr Kristina Bozic-Tomic, Institute for testing of materials IMS, Belgrade, Serbia, kristina.tomic@institutims.rs
Dr Nenad Susic, Institute for testing of materials IMS, Belgrade, Serbia, nenad.susic@institutims.rs

Upoređivanje rešenja koja se dobijaju analizama reflektograma u vremenskom i frekventnom domenu prikazano je u radu [22], dok su u radovima [21] i [3] prikazane osnove ispitivanja integriteta šipova i procedure za procenu stanja integriteta šipova. U radu [9], razmatrana je analiza propagacije talasa prilikom testa integriteta šipa, dok se u radu [19], primenom teorije talasića, analizira integritet šipa. Numerička analiza defektnih šipova razmatrana je u istraživanjima [28] i [8], a numerička analiza integriteta šipa s promenljivim modulom elastičnosti u radu [26]. Analize 3D efekata, prilikom testa integriteta šipa, prikazane su u radovima [30] i [29]. Interpretacija rezultata testova integriteta šipova sa simuliranim defektima prikazana je u istraživanju [20], dok je interpretacija rezultata ispitivanja integriteta šipova, primenom metode mašinskog učenja, prikazana u istraživanju [5]. Razvoj sveobuhvatne metodologije za analizu integriteta i nosivosti šipova prezentovana je radu [7]. U odnosu na istraživanja koja se sprovode testom integriteta šipa sa senzorom (SIT), primenom testa integriteta šipa sa sondama (CSL) dobija se uočljivo bolji uvid o stanju integralnosti šipa [4], [25]. Pouzdanost testa integriteta šipa sa sondama (CSL), između ostalog, razmatrana je u radu [16].

Tim inženjera i tehničara Centra za puteve i geotehniku Instituta IMS sproveo je nekoliko hiljada ispitivanja testova integriteta šipa sa senzorom (SIT) i više od stotinu ispitivanja testova integriteta šipa sa sondama (CSL). Ispitivanja integriteta sprovedena su za šipove sledećih objekata (izdvojeno): mostovi na koridoru X i XI, Žeželjev most u Novom Sadu, poslovno-komercijalna zgrada-kula Ušće 2, obaloutvrde za projekat *Belgrade Waterfront*, železnička stanica Centar Beograd - Prokop, veći broj mostova na autoputu E 75 Novi Sad - Beograd - Niš, veći broj mostova na auto-putu E 763 Beograd - Južni Jadran, mostovi na auto-putu E 80 deonica Čiflik - Pirot, mostovi na obilaznici oko Beograda, modernizacija Rafinerije nafte Pančevo, silos pepela u TE Kostolac A, vetrogeneratori u vetroparko-vima Kula, Zagajica, Izbište, Malibunar i Alibunar, veći broj objekata na lokaciji ulice Stepa Stepanović u Beogradu, skladište mineralnih đubriva Victoria Zorka, poslovno-stambeni kompleks u ulici Dušana Jovanovića u Beogradu, poslovno-stambeni objekat u Univerzitet-skom naselju, kotlarnica toplane na Konjarniku, objekat u naselju dr Ivana Ribara na Novom Beogradu, Klinički centar u Nišu, objekat *dr Oetker* u Šimanovcima, postrojenje za prečišćavanje otpadnih voda u Šapcu i drugo. U ovom radu analiziraće se neki rezultati autorskih ispitivanja integriteta šipova, sprovedeni na velikim i značajnim objektima u Srbiji i u regionu.

The comparison of solutions obtained by the analysis of reflectograms in the time and frequency domains is presented in [22], while in [21] and [3] the basics of pile integrity testing and procedures for pile integrity state assessment were presented. In [9] the analysis of wave propagation in the pile integrity test was considered, while in [19] the pile integrity was analyzed using the wavelet theory. Numerical analysis of defective piles was considered in studies [28] and [8], and numerical analysis of pile integrity with variable modulus of elasticity in operation was considered in [26]. Analyses of 3D effects in pile integrity tests were presented in [30] and [29]. The interpretation of the results of pile integrity tests with simulated defects was presented in the study [20], while the interpretation of the results of pile integrity tests using machine learning method was presented in the study [5]. The development of a comprehensive methodology for analyzing the integrity and load-bearing capacity of piles was presented in [7]. In comparison with the research conducted with SIT, a significantly better insight into the state of integrity of the pile is obtained using CSL [4], [25]. The reliability of the CSL test, among others, was discussed in [16].

A team of engineers and technicians at the *Centre for Roads and Geotechnics of the IMS Institute* conducted several thousand SITs and more than a hundred CSLs. The integrity tests were carried out for piles of the following structures (selected): bridges on *CorridorX* and *XI*, *Žeželj* Bridge in *Novi Sad*, office-commercial building- tower *Ušće 2*, shoreline for the *Belgrade Waterfront* project, *Belgrade Centre - Prokop* railway station, a large number of bridges on the highway *E 75 Novi Sad-Belgrade-Nis*, a number of bridges on the highway *E 763 Belgrade-South Adriatic*, bridges on the highway *E 80* section *Čiflik-Pirot*, bridges on the *bypass around Belgrade*, modernization of the *Pančevo Oil Refinery*, fly ash silo at *Kostolac A TE*, wind turbines in *Kula, Zagajica, Izbište, Malbunar* and *Alibunar* wind farms, a large number of structures on the location of *Stepa Stepanović Street* in *Belgrade*, *Victoria Zorka* mineral fertilizer depot, office and residential complex in *Dušan Jovanović* Street in *Belgrade*, office and residential building in the *University District*, heating plant boiler room on *Konjarnik*, building in *dr Ivan Ribar* district in *New Belgrade*, clinical centre in *Niš*, *dr Oetker* building in *Šimanovci*, sewage treatment plant in *Šabac* et al. This paper analyzes some results of own pile integrity tests conducted on large and significant structures in Serbia and in the region.

2 ISPITIVANJE INTEGRITETA ŠIPOVA TESTOM INTEGRITETA ŠIPA SA SENZOROM (SIT)

Test integriteta šipa sa senzorom (SIT) u praksi se zove i test eha zvuka (SET) ili test eha šipa (PET), a pripada grupi niskodilatacionih testova (LST). Test integriteta šipa sa senzorom (SIT) zasniva se na teoriji jednodimenzionalne propagacije talasa kroz šip, s ciljem utvrđivanja: stvarne dužine šipa, postojanje defekata i diskontinuiteta i redukcije poprečnog preseka šipa [6]. Takođe, analiziraju se: promena signala u domenu glave šipa, kvalitet odziva signala u bazi šipa, promena

2 PILE INTEGRITY TESTING USING SONIC INTEGRITY TEST (SIT)

Sonic Integrity Test (SIT) is in practice also called the Sonic Echo Test (SET) or Pile Echo Test (PET), and it belongs to the group of Low Strain Tests (LST). SIT is based on the theory of one-dimensional wave propagation through the pile, with the aim of determining: the actual length of the pile, existence of defects and discontinuities and reduction of the pile cross-section [6]. In addition, it analyzes variation of signal in the pile head domain, signal response quality at impedance duž stabla šipa, promena slojeva tla u kojima je šip izgrađen i postojanje proširenja poprečnog preseka duž stabla šipa. Ovaj test, zapravo, jeste indirektna metoda analize integriteta šipa, s obzirom na to što se ispitivanje sprovodi analizirajući propagaciju talasa duž šipa, ali indukcijom talasa sa glave šipa. Test je brz, efikasan, sofisticiran i dovoljno pouzdan za praktičnu primenu. Ovim testom se ispituju integriteti svih tipova armiranobetonskih šipova: bušeni, CFA i pobijeni. Takođe, ispituju se i radni (eksploatacioni) i probni (testni) šipovi. Metodologija ispitivanja integriteta šipa sa senzorom (SIT) definisana je standardom ASTM D5882 [1]. Centar za puteve i geotehniku Instituta IMS poseduje licencirane opreme za test integriteta šipa sa senzorom (SIT) holandske firme *Profound* i američke firme *Pile Dynamics*. Obe opreme omogućavaju analizu reflektograma u vremenskom (TDA) i frekventnom domenu (FDA). Takođe, obe opreme imaju integrisane softverske module za: procesiranje, skaliranje (eksponencijalnu amplifikaciju) i filtriranje signala. Oprema SIT^{+} [15] za test integriteta šipa sa senzorom (SIT), holandske firme *Profound*, sastoji se iz: mehaničkog čekića, senzora (akcelerometra), hardverskog sistema za konvertovanje i akviziciju podataka i softverskog sistema (SIT i SITWAVE) za procesiranje i vizuelizaciju podataka. Akcelerometar je linearan u opsegu ±50g, rezonantne frekvencije 32kHz i nominalne osetljivosti 10mV/g. Konverzija AD signala se sprovodi primenom 24-bitnog konvertera (>48.6 kHz). Oprema PIT-QFV [12] za test integriteta šipa sa senzorom (SIT), američke firme *Pile Dynamics*, sastoji se iz: mehaničkog čekića povezanog električnim kablom za merenje karakteristika indukovanog signala, senzora (akcelerometra), hardverskog sistema za konvertovanje i akviziciju podataka i softverskog sistema (PIT-W *professional* i PIT-S) za procesiranje i vizuelizaciju podataka. Akcelerometar je linearan u opsegu ±100 g, rezonantne frekvencije 40 kHz i nominalne osetljivosti 50 mV/g. Konverzija AD signala se sprovodi primenom 24-bitnog konvertera (>32 kHz). Na slici 1 prikazane su opreme za ispitivanje integriteta šipova testom integriteta šipa sa senzorom (SIT): SIT^{+} oprema holandske firme *Profound* i PIT-QFV oprema američke firme *Pile Dynamics*.

the pile toe, variation of impedance along the pile shaft, variation of layers of soil in which the pile is constructed, and existence of expansions of cross-section along the pile shaft. This test is, in fact, an indirect method of pile integrity analysis, considering that the test is carried out by analyzing the wave propagation along the pile, via induction of waves from the pile head. The test is quick, efficient, sophisticated and sufficiently reliable for practical use. This test is used to test integrities of all types of reinforced concrete piles: bored, CFA and driven piles. It also tests both the service and test piles. The SIT methodology is defined with the ASTM D5882 standard [1]. The *Centre for Roads and Geotechnics of the IMS Institute* possesses the licensed equipment for SIT, manufactured by the Dutch *Profound* company and U.S. *Pile Dynamics* company. Both equipment sets facilitate reflectogram analysis in time (TDA) and frequency domains (FDA). In addition, both equipment sets have integrated software modules: processing, scaling (exponential amplification) and signal filtering. SIT^{+} equipment [15] for SIT, of the Dutch *Profound* company consists of: mechanical hammer, sensor (accelerometer), hardware system for data conversion and acquisition and software system (SIT and SITWAVE) for processing and visualization of data. The accelerometer is linear in the ±50g range, of resonant frequency 32kHz and nominal sensitivity 10mV/g. AD signal conversion is conducted using the 24-bit converter (>48.6kHz). PIT-QFV equipment [12] for SIT, by the U.S. *Pile Dynamics* company, consists of: mechanical hammer connected by an electric cable for measuring induced signal characteristics, sensor (accelerometer), hardware system for data conversion and acquisition and the software system (PIT-W *professional* and PIT-S) for data processing and visualization. The accelerometer is linear in the ±100g range, of resonant frequency 40kHz and nominal sensitivity 50mV/g. AD signal conversion is conducted using the 24-bit converter (>32kHz). Equipment sets for pile integrity testing using SIT: SIT^{+} equipment by the Dutch *Profound* company and PIT-QFV equipment by the U.S. *Pile Dynamics* company are shown in Figure 1.

a) 

b) 

Slika 1. Opreme za ispitivanje integriteta šipova testom integriteta šipa sa senzorom (SIT): a) SIT^{+} oprema holandske firme Profound [15]; b) PIT-QFV oprema američke firme Pile Dynamics [12]

Figure 1. Equipment sets for pile integrity testing using SIT: a) SIT^{+} Dutch Profound company equipment [15], b) PIT-QFV U.S. Pile Dynamics company equipment [12]

Institut IMS sproveo je nekoliko hiljada ispitivanja testova integriteta šipa sa senzorom (SIT) na različitim tipovima šipova izgrađenih u različitim geološkim uslovima, tako da poseduje sopstvenu bazu znanja, iskustva i bazu podataka ispitivanja. S obzirom na ovako veliki broj sprovedenih ispitivanja, s vremenom su se definisale karakteristične situacije u kojima su razmatrani aspekti dobijenih reflektograma. U tom smislu, generalno se mogu izdvojiti tri grupe reflektograma: klasični ili standardni reflektogrami koji ukazuju na dobar kvalitet integriteta šipa, reflektogrami koji ukazuju na moguću redukciju integriteta šipa, pa zahtevaju dodatne analize i reflektogrami koji jasno ukazuju na značajniji problem integriteta šipa. Detaljnija klasifikacija reflektograma može se sprovesti prema [17]:

- AA – ispravan šip s pozitivnim refleksijama ili kod koga se pre refleksije od baze šipa identifikuju manje promene brzine i odstupanja brzine propagacije talasa, ne veće od 5% od prosečne brzine propagacije talasa;
- AB – refleksija od baze se jasno ne identifikuje, ali i nema znatnih smanjenja impedance, pri čemu je moguć razlog za nepostojanje refleksije od baze velika krutost tla;
- PF – postoji jedna negativna refleksija ili više njih i/ili postoji bar jedno smanjenje impedance, a s obzirom na to što je refleksija od baze smanjena, impedanca je manja nego kod defekta kod koga nema refleksije od baze;
- PD – brzina propagacije talasa odstupa više od 5% od prosečne brzine propagacije talasa, a što ukazuje na moguć defekat šipa, pri čemu postoji jedna refleksija ili više njih koje maskiraju refleksiju od baze šipa;
- IR – znatno kompleksan signal (odgovor), a što, između ostalog, ukazuje na loš kvalitet betona pri vrhu šipa i/ili na to da je ispitivanje sprovedeno suviše rano da bi beton dostigao potrebnu čvrstoću.

Pre sprovođenja testa, okrajcuje se beton i glava šipa se očisti od prašine i ostataka odlomljenih delova betona. Na slici 2 su prikazani šipovi (glave šipova) pripremljeni za ispitivanje testom integriteta šipa sa senzorom (SIT): adekvanta priprema, neadekvatna priprema, adekvatna priprema, međutim rezultati SIT na ovako pripremljenim glavama šipa sa hidroizolacijom mogu biti diskutabilni i nastavci glava šipova koji mogu biti problematični u smislu interpretacije signala SIT.

The IMS Institute conducted several thousand tests of SIT on various types of piles constructed in different geological conditions, so it possesses its own database of knowledge, experience and testing database. In view of such a large number of tests conducted, over time, characteristic situations were defined in which aspects of the obtained reflectograms were considered. In this sense, three groups of reflectograms can be generally distinguished: classical or standard reflectograms indicating good quality of pile integrity, reflectograms indicating possible reduction of pile integrity, and thus require additional analyses and reflectograms that clearly indicate a more considerable problem of pile integrity. A more detailed classification of reflectograms can be made according to [17]:

- AA - a proper pile with positive reflections or such in which prior to reflection off the pile toe minor variations in velocity and deviations in the wave propagation velocity of not more than 5% of the average propagation velocity of the wave are identified,
- AB - the reflection from the toe is not clearly identified, but there are also no significant impedance reductions, the possible reason for the lack of reflection from the toe being the high stiffness of the ground,
- PF - there is one or more negative reflections and/or there is at least one impedance decrease, and since the reflection from the toe is reduced, the impedance is lower than in the case of a defect when there is no reflection from the toe,
- PD - the wave propagation velocity deviates more than 5% from the average wave propagation velocity, indicating a possible defect in the pile, with one or more reflections masking the reflection from the pile toe,
- IR - considerably complex signal (response), which indicates, among other things, the poor quality of the concrete at the head of the pile and/or the test was conducted too early for the concrete to reach the required strength.

Before the test, the concrete is trimmed and the pile head is cleared of dust and debris from broken concrete. Figure 2 shows the piles (pile heads) prepared for the SIT: adequate preparation, inadequate preparation, adequate preparation, however, the results of SIT on such a pile heads with waterproofing may be debatable and pile head extensions that can be problematic in terms of interpreting the SIT signal.

a) 

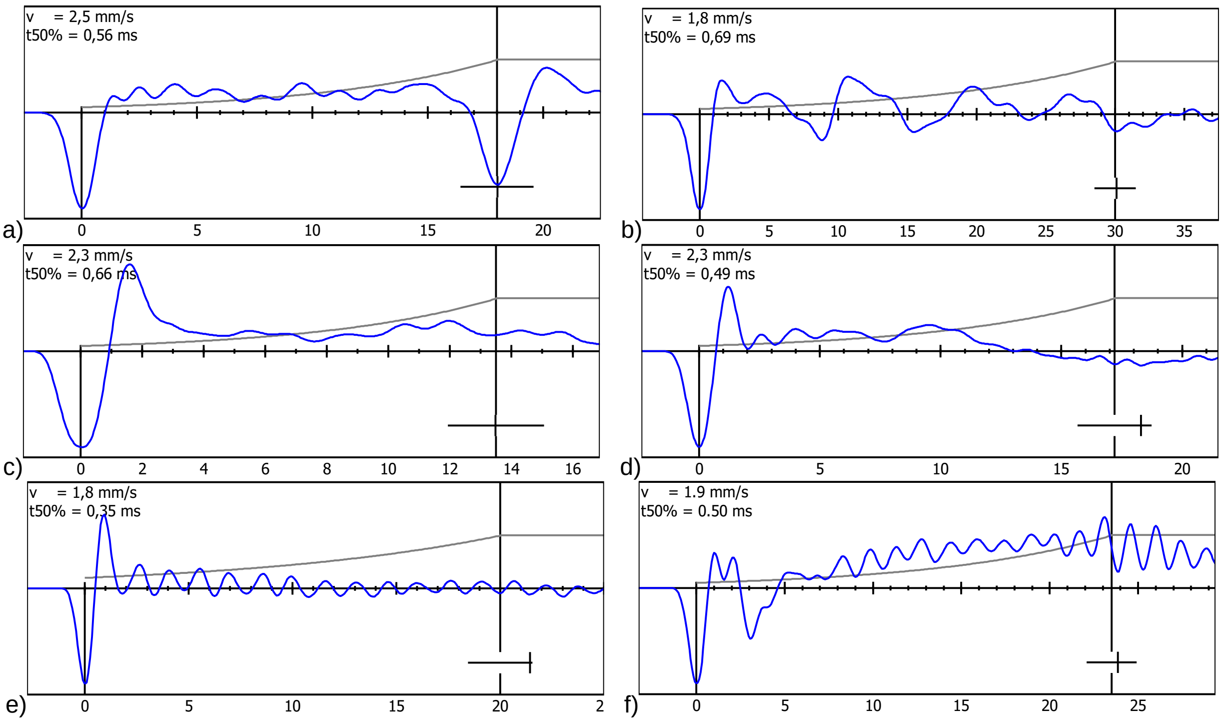
b) 

Slika 2. Šipovi (glave šipova) pripremljeni za ispitivanje testom integriteta šipa sa senzorom (SIT): a) adekvatna priprema; b) neadekvatna priprema; c) adekvatna priprema, međutim rezultati SIT na ovako pripremljenim glavama šipa sa hidroizolacijom mogu biti diskutabilni; d) nastavci glava šipova koji mogu biti problematični u smislu interpretacije signala SIT

Figure 2. Piles (pile heads) prepared for the SIT: a) adequate preparation, b) inadequate preparation, c) adequate preparation, however the results of SIT on such pile heads with waterproofing may be debatable, d) pile head extensions that can be problematic in terms of interpreting the SIT signal

Na slici 3 prikazani su reflektogrami SIT integriteta šipova dobijeni SIT+ holandskom opremom: regularan šip, šip sa značajnijim redukcijama impedance u određenim presecima, nejasan odziv baze šipa i nakon primene eksponencijalnog filtera, redukcija impedance

Figure 3 shows SIT reflectograms of pile integrity obtained by the Dutch equipment SIT+: regular pile, pile with significant impedance reductions in certain cross-sections, a vague pile toe response even after appli-cation of an exponential filter, the impedance reduction



Slika 3. Reflektogrami SIT integriteta šipova dobijeni SIT+ holandskom opremom: a) regularan šip; b) šip sa značajnijim redukcijama impedance u određenim presecima; c) nejasan odziv baze šipa i nakon primene eksponencijalnog filtera; d) redukcija impedance znatnije pre baze šipa; e) varijacija signala iz pozitivne u negativnu vrednost - posledica niskog modula elastičnosti glave šipa; f) značajna redukcija impedance u početnom delu šipa - defekat/diskontinuitet

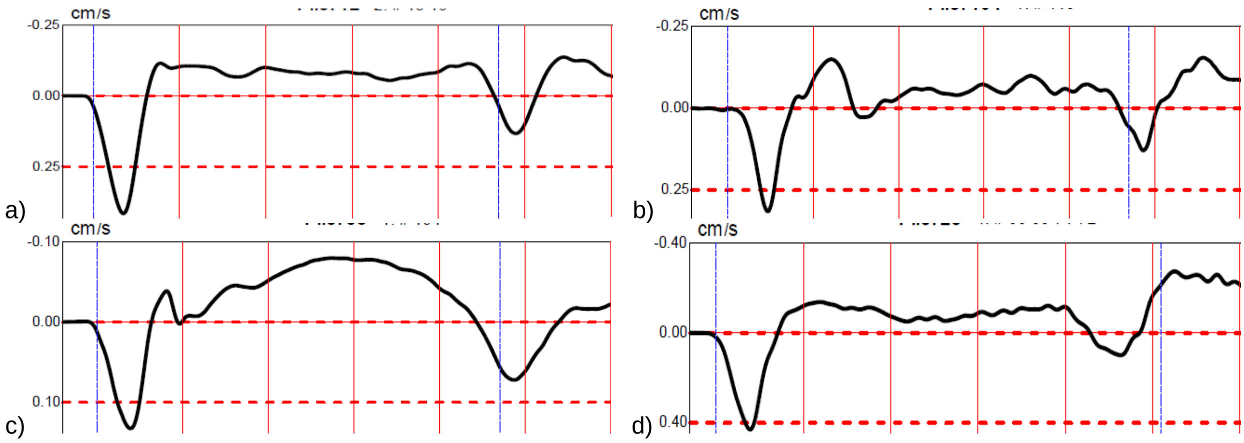
Figure 3. SIT reflectograms of pile integrity obtained by the Dutch equipment SIT+: a) regular pile, b) pile with significant impedance reductions in certain cross-sections, c) vague pile toe response even after application of an exponential filter, d) impedance reduction significantly before the pile toe, e) signal variation from positive to negative value - consequence of low modulus of elasticity of the pile head, f) significant impedance reduction in the initial part of the pile - defect/discontinuity

znatnije pre baze šipa, varijacija signala iz pozitivne u negativnu vrednost - posledica niskog modula elastičnosti glave šipa i značajna redukcija impedance u početnom delu šipa - defekat/diskontinuitet.

Na slici 4 prikazani su reflektogrami SIT integriteta šipova dobijeni PIT-QFV američkom opremom: regularan šip, šip s redukcijom impedance u početnom delu, efekat povećanja impedance i krutosti tla i šip izgrađen kraći nego što je projektom predviđeno.

significantly before the pile toe, signal variation from positive to negative value - consequence of low modulus of elasticity of the pile head and significant impedance reduction in the initial part of the pile - defect/discontinuity.

Figure 4 shows the SIT reflectograms obtained by the U.S. PIT-QFV equipment: regular pile, pile with impedance reduction in the initial part, an effect of increasing the impedance and soil stiffness, and pile built shorter than designed.



Slika 4. Reflektogrami SIT integriteta šipova dobijeni PIT-QFV američkom opremom: a) regularan šip; b) šip s redukcijom impedance u početnom delu; c) efekat povećanja impedance i krutosti tla; d) šip izgrađen kraći nego što je projektom predviđeno

Figure 4. SIT reflectograms obtained by the U.S. PIT-QFV equipment: a) regular pile, b) pile with impedance reduction in the initial part, c) effect of increasing the impedance and soil stiffness, d) pile built shorter than designed

Prilikom sprovođenja SIT integriteta šipa, kod određenih reflektograma, mogu se pojaviti značajnije redukcije impedance, što može biti jedan od pokazatelja defekta i/ili diskontinuiteta šipa. Da bi se detaljnije analizirao stepen defekta i/ili diskontinuiteta, sprovodi se dodatna analiza koja se zasniva na talasnoj teoriji i metodi karakteristika. Softver SITWAVE ima mogućnost analize promene impedance duž stabla šipa, tako da se efikasno može dobiti oblik šipa izgrađen u tlu, dok softver PIT-S ima mogućnost analize oblika šipa primenom *β* metode. S obzirom na veću pouzdanost rešenja koje se dobija primenom SITWAVE softvera, jer je, između ostalog, matematička analiza promene impedance kompleksnija i naučno utemeljenija, ovaj softver se i češće koristi za ovakve situacije. Jednačina propagacije talasa putem elastičnog medijuma, u opštem slučaju, jeste hiperbolična parcijalna diferencijalna jednačina drugog reda [23]:

During the implementation of pile integrity SIT, in certain reflectograms, considerable impedance reductions may occur, which may be one of the indicators of a defect and/or discontinuity of the pile. In order to analyze in more detail the degree of the defect and/or discontinuity, an additional analysis is conducted, which is based on the wave theory and method of characteristics. The SITWAVE software has the ability to analyze the impedance variations along the pile shaft, so that the pile shape built in the soil can be effectively obtained, while the PIT-S software has the ability to analyze the pile shape using the *β* method. Due to the higher reliability of the solution obtained by the application of SITWAVE software, because, among other things, the mathematical analysis of impedance variation is more complex and scientifically founded, this software is more often used in such situations. The wave propagation equation through an elastic medium is, in the general case, a hyperbolic partial differential equation of the second order [23]:

$$\frac{\partial^2 u}{\partial t^2} = v^2 \nabla^2 u, \tag{1}$$

gde je *v* brzina talasa, *u* pomeranje, *t* vreme. Ukoliko je dužina talasa veća od prečnika šipa ili jednaka prečniku šipa, tada se propagacija talasa u šipu može razmatrati primenom jednodimenzionalne teorije rasprostiranja talasa u čvrstom medijumu [11]. Jednodimenzionalna

where *v* is the wave velocity, *u* displacement, *t* time. If the wavelength is higher than or equal to the pile diameter, then the wave propagation in the pile can be analyzed by applying the one-dimensional theory of wave propagation in a solid medium [11]. The one-talasna jednačina (po x) predstavlja specijalan slučaj jednačine (1):

dimensional wave equation (by x) is a special case of equation (1):

$$\frac{\partial^2 u}{\partial t^2} = v^2 \frac{\partial^2 u}{\partial x^2}, \tag{2}$$

a opšte rešenje ove jednačine glasi:

and the general solution of this equation is:

$$u(x,t) = u_1(x - vt) + u_2(x + vt). \tag{3}$$

Brzina propagacije longitudinalnih talasa u čvrstom medijumu v jeste funkcija karakteristika materijala tog medijuma i određuje se prema:

The velocity of propagation of longitudinal waves in a solid medium v is the function of material characteristics of that medium and it is determined according to:

$$v = \sqrt{\frac{E}{\rho}}, \tag{4}$$

gde je E *Young*-ov modul elastičnosti, ρ zapreminska težina. Sada se jednačina (2) može pisati kao:

where E is the *Young* modulus of elasticity, ρ is density. Now equation (2) can be written as:

$$\rho \frac{\partial^2 u}{\partial t^2} - E \frac{\partial^2 u}{\partial x^2} = 0, \tag{5}$$

pri čemu se rešenje traži tako da su vreme i pomeranje nezavisne promenljive:

whereby solution is sought so that time and displacement are independent variables:

$$u(x,t) = \Psi(x) g(t), \tag{6}$$

a zatim zamenom izraza (6) u (2) dobija se:

and then, by the substitution of expression (6) in (2) is obtained:

$$\Psi(x) = Ae^{i\alpha x} \quad \text{i / and} \quad g(t) = Ae^{i\omega t}. \tag{7}$$

Rešenje problema (7) moguće je dobiti za jednostavnije sisteme i konturne uslove u zatvorenom obliku, međutim kod kompleksnijeg modeliranja šipa s diskontinuitetima i defektima potrebno je primeniti metodu konačnih elemenata. S druge strane, ukoliko se problem propagacije talasa u šipu razmatra u diskretnim segmentima, tada je rešenje jednačine (2) moguće odrediti metodom karakteristika, pri čemu se izraz (3) može pisati kao [24], [18]:

The solution of the problem (7) can be obtained for simpler systems and contour conditions in a closed form, however, in more complex modelling of a pile with discontinuities and defects, it is necessary to implement the finite element method. On the other hand, if the problem of wave propagation in a pile is considered in discrete segments, then the solution to the equation (2) could be determined using the method of characteristics, whereby expression (3) can be written as [24], [18]:

$$u(x,t) = u^{\downarrow}(x - vt) + u^{\uparrow}(x + vt), \tag{8}$$

gde je ↓ oznaka za talas koji se kreće od glave ka bazi šipa, a ↑ oznaka za talas koji se kreće od baze ka glavi šipa. Odgovarajuća brzina talasa v_p i sila F koja se indukuje u šipu, za diskretan element šipa, određuju se iz:

where ↓ is the designation for the wave propagating from the head to the toe of the pile, and ↑ the designation for the wave propagating from the toe to the head of the pile. The corresponding wave velocity v_p and force F induced in the pile, for the discrete element of the pile, are determined from:

$$v_p = \frac{\partial u}{\partial t} = \frac{\partial u^{\downarrow}}{\partial (x - vt)}(-v) + \frac{\partial u^{\uparrow}}{\partial (x + vt)}(+v) = v_p^{\downarrow} + v_p^{\uparrow}, \tag{9}$$

$$F = -EA\frac{\partial u}{\partial x} = -EA\frac{\partial u^{\downarrow}}{\partial (x - vt)} + \frac{\partial u^{\uparrow}}{\partial (x + vt)} = F^{\downarrow} + F^{\uparrow}, \tag{10}$$

gde je A površina poprečnog preseka šipa. Pošto su $v_p^{\downarrow}$ i $F^{\downarrow}$ samo funkcije od (x-vt) i $v_p^{\uparrow}$ i $F^{\uparrow}$ samo funkcije od (x+vt), brzina i sila mogu se pisati kao:

where A is the area of the pile cross section. Since $v_p^{\downarrow}$ and $F^{\downarrow}$ are only functions of (x-vt) and $v_p^{\uparrow}$ and $F^{\uparrow}$ only functions of (x+vt), the velocity and force can be written as:

$$F^{\downarrow} = Zv_p^{\downarrow} \quad \text{i / and} \quad F^{\uparrow} = -Zv_p^{\uparrow}, \tag{11}$$

gde je Z impedanca šipa:

where Z is the pile impedance:

$$Z = \frac{EA}{v} = A\sqrt{E\rho}, \tag{12}$$

Bilo koja promena *A*, *E* ili *ρ* parametra generiše promenu u odzivu brzina na reflektogramu. U slučaju diskontinuiteta, kada je na jednom delu prečnik šipa manji, jednačine ravnoteže za granicu dva medijuma glase:

Any variation of *A*, *E* or *ρ* parameters generates a variation in the response of velocities in the reflectogram. In case of a discontinuity, when a section of the pile has a smaller cross section, equilibrium equations for the interface of two media are:

$$F_1^{\downarrow} + F_1^{\uparrow} = F_2^{\downarrow} + F_2^{\uparrow} \quad \text{i / and} \quad v_{p1}^{\downarrow} + v_{p1}^{\uparrow} = v_{p2}^{\downarrow} + v_{p2}^{\uparrow}, \tag{13}$$

gde se indeksi 1 i 2 odnose na medijume. Zamenom (11) u (13) dobija se:

where indices 1 and 2 refer to the media. Substituting (11) for (13) the following is obtained:

$$\frac{F_1^{\downarrow}}{Z_1} - \frac{F_1^{\uparrow}}{Z_1} = \frac{F_2^{\downarrow}}{Z_2} + \frac{F_2^{\uparrow}}{Z_2}, \tag{14}$$

Kada je šip pobuđen na vibracije u tlu postoji kompleksna interakcija šip–tlo, gde se sila trenja po omotaču šipa *W* uzima u razmatranje kao:

When a pile is excited to soil vibrations, there is a complex soil-pile interaction, where the friction force along the pile surface *W* is taken into consideration as:

$$F = F_1^{\downarrow} + F_1^{\uparrow} = F_2^{\downarrow} + F_2^{\uparrow} + W\ , \tag{15}$$

tako da izraz (13) postaje:

so that expression (13) becomes:

$$v_p = \frac{F_1^{\downarrow}}{Z} - \frac{F_1^{\uparrow}}{Z} = \frac{F_2^{\downarrow}}{Z} + \frac{F_2^{\uparrow}}{Z} \quad \text{i / and} \quad Zv_p = F_1^{\downarrow} - F_1^{\uparrow} = F_2^{\downarrow} + F_2^{\uparrow}. \tag{16}$$

Komponente sila za medijume se sada određuju prema:

Force components for media are determined according to:

$$F_2^{\downarrow} = F_1^{\downarrow} - 0.5W \quad \text{i / and} \quad F_1^{\uparrow} = F_2^{\uparrow} + 0.5W. \tag{17}$$

U bazi, na kontaktu šipa i tla, jednačine ravnoteže glase:

At the toe, on the contact of the pile and the soil, equilibrium equations are:

$$F(L,t) = F^{\downarrow}(L,t) + F^{\uparrow}(L,t) = F_g \quad \text{i / and} \quad v_p(L,t) = v_p^{\downarrow}(L,t) + v_p^{\uparrow}(L,t) = \frac{2v_p^{\downarrow} - F_g}{Z}, \tag{18}$$

gde je *L* dužina šipa, a F_g sila reakcije tla. Ukoliko se šip diskretizira po dužini na *n* delova, pri čemu je dužina jednog diskretnog elementa *ΔL=vΔt*, a vreme propagacije talasa kroz šip razmatra se u diskretnim intervalima *Δt*, tada se za sile u diskretnim elementima $f^{\downarrow}_{n,i}$ i $f^{\uparrow}_{n,i}$ može pisati:

where *L* is the pile length, and F_g soil reaction force. If the pile is discretized along its length to *n* sections, whereby the length of one discrete element is *ΔL=vΔt*, and the time of wave propagation through the pile is considered in discrete intervals *Δt*, then, for the forces in the discrete elements $f^{\downarrow}_{n,i}$ and $f^{\uparrow}_{n,i}$ it can be written:

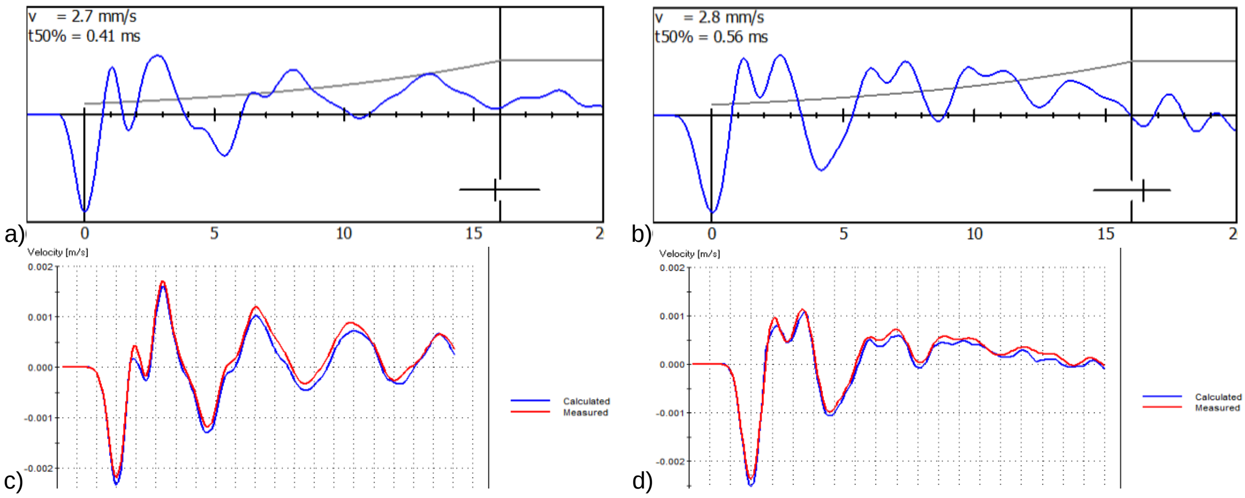
$$f_{n,i}^{\downarrow} = \left(\frac{Z_N - Z_{N+1}}{Z_N + Z_{N+1}}\right) f^{\uparrow} + \left(\frac{Z_{N+1}}{Z_N + Z_{N+1}}\right)\left(2f^{\downarrow} - W_{n,i}\right), \tag{19}$$

$$f_{n,i}^{\uparrow} = \left(-\frac{Z_N - Z_{N+1}}{Z_N + Z_{N+1}}\right) f^{\downarrow} + \left(\frac{Z_N}{Z_N + Z_{N+1}}\right)\left(2f^{\uparrow} + W_{n,i}\right), \tag{20}$$

gde je Z_N impedanca diskretnog *N* elementa šipa, Z_{N+1} impedanca diskretnog *N*+1 elementa šipa. Model interakcije šip-tlo jeste jednodimenzionalni kontinualni diskretan model, kod koga se tlo modelira kontinualno raspodeljenim oprugama duž šipa i koncentrisanom oprugom u bazi šipa. Konstitutivni model ponašanja tla je linearno-elastičan, a dodatno se modelira i prigušenje tla. Usklađivanje signala (odgovora), dobijenog primenom proračunskog modela i reflektograma *in-situ* SIT ispitivanja, sprovodi se iteracijama, a ovaj postupak je poznat kao kompatibilizacija. Prvo se iteriraju parametri tla, a zatim, nakon postizanja konvergencije rešenja putem ovih iteracija, sprovodi se iteriranje geometrijskih parametara (poprečnog preseka) šipa. Takođe, intervencija se sprovodi i korekcijom modula

where Z_N is the impedance of a discrete *N* element of the pile, Z_{N+1} impedance of the discrete *N*+1 element of the pile. The soil-pile interaction model is a one-dimensional continuous discrete model, in which the soil is modelled by continuously distributed springs along the pile and concentrated spring at the pile toe. The constitutive model of soil behaviour is linear-elastic, and soil damping is additionally modelled. When matching the signals (responses) obtained by applying the calculation model and from reflectograms of *in-situ* SIT testing is carried out through iterations, and this procedure is known as signal matching. The soil parameters are first iterated, and then, after achieving the convergence of the solutions through these iterations, iteration of the geometric parameters (cross-elastičnosti betona. Na taj način, direktno se utiče na promenu impedance šipa, gde se putem iteracija utvrđuje njena senzitivnost u domenima defekata i/ili diskontinuiteta. Na osnovu prethodno izložene procedure, primenom softvera SITWAVE, naknadno su analizirani reflektogrami dva šipa (oznake 1 i 2), kod kojih je primenom softvera SIT⁺ ukazano na mogućnosti postojanja defekata i/ili diskontinuiteta. Na slici 5 prikazani su reflektogrami šipova 1 i 2: reflektogram šipa 1, reflektogram šipa 2, kompatibilizovani signal šipa 1 (finalna iteracija), kompatibilizovani signal šipa 2 (finalna iteracija).

section) of the pile is performed. In addition, the intervention is implemented by correcting the modulus of elasticity of concrete. In this way, the variation in the impedance of the pile is directly caused, where its sensitivity in the domains of defects and/or discontinuities is determined through its iterations. Based on the procedure outlined above, the SITWAVE software was used subsequently to analyze reflectograms of two piles (designations 1 and 2), in which by using the SIT⁺ software the possibility of defects and/or discontinuities was indicated. Figure 5 shows the reflectograms of piles 1 and 2: pile 1 reflectogram, pile 2 reflectogram, pile 1 matched signal (final iteration), pile 2 matched signal (final iteration).

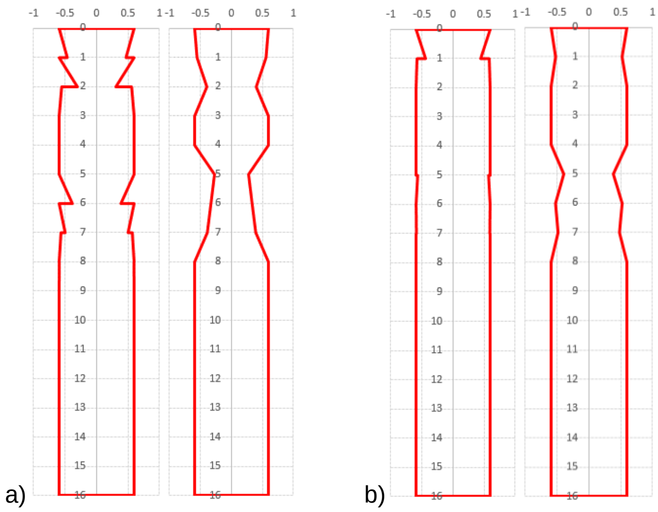


Slika 5. Reflektogrami šipova 1 i 2: a) reflektogram šipa 1; b) reflektogram šipa 2; c) kompatibilizovani signal šipa 1 - finalna iteracija; d) kompatibilizovani signal šipa 2 - finalna iteracija

Figure 5. Piles 1 and 2 reflectograms: a) pile 1 reflectogram 1, b) pile 2 reflectogram, c) pile 1 matched signal (final iteration), d) pile 2 matched signal (final iteration)

Na slici 6 prikazani su oblici defektnih šipova dobijeni primenom softvera SITWAVE: oblik šipa 1 dobijen putem početnih iteracija (slika levo) i oblik šipa 1 dobijen u poslednjoj iteraciji (slika desno), oblik šipa 2 dobijen putem početnih iteracija (slika levo) i oblik šipa 2 dobijen u poslednjoj iteraciji (slika desno). Dobijeni oblici su zapravo funkcija promene impedance, gde – pored promene geometrijskih karakteristika – učestvuju i mehaničke karakteristike šipa. To znači da se redukcija poprečnog preseka odnosi na promenu prečnika šipa i/ili na promenu modula elastičnosti betona. Na osnovu ovako sprovedenih analiza, primenom softvera SITWAVE, naknadno su izvedena bušenja i vađenja uzoraka šipova 1 i 2, tako da su ova ispitivanja potvrdila da postoje defekti u zonama koje su prethodno identifikovane kao domeni redukcije impedance šipova.

Figure 6 shows defective pile shapes obtained using the SITWAVE software: pile shape 1 obtained through initial iterations (figure left) and pile shape 1 obtained in the final iteration (figure right), pile shape 2 obtained through initial iterations (figure left) and shape pile 2 obtained in the final iteration (figure right). The resulting shapes are, in fact, a function of the impedance variation, where in addition to variation of the geometrical characteristics, the mechanical characteristics of the pile also participate. This means that the reduction in cross-section refers to the change in pile diameter and/or the change in modulus of elasticity of concrete. Based on the analyzes performed in this way, by using the SITWAVE software, the drilling and extraction of piles 1 and 2 samples were subsequently performed, and these tests confirmed that there were defects in the zones previously identified as domains of pile impedance reduction.



Slika 6. Oblici defektnih šipova dobijeni primenom softvera SITWAVE: a) oblik šipa 1 dobijen putem početnih iteracija (slika levo) i oblik šipa 1 dobijen u poslednjoj iteraciji (slika desno); b) oblik šipa 2 dobijen putem početnih iteracija (slika levo) i oblik šipa 2 dobijen u poslednjoj iteraciji (slika desno)

Figure 6. Defective pile shapes obtained using SITWAVE software: a) pile shape 1 obtained through initial iterations (figure left) and pile shape 1 obtained in the last iteration (figure right), b) pile shape 2 obtained through initial iterations (figure left) and pile 2 shape obtained in the last iteration (figure right)

3 NUMERIČKE ANALIZE INTEGRITETA ŠIPA SA SENZOROM

Numeričke analize integriteta šipa sprovode se promenom metode konačnih elemenata (FEM – *Finite Element Method*), pri čemu se šip i tlo modeliraju 2D površinskim konačnim elementima ili se koriste konačni elementi za rotacono simetrično stanje. U postupku određivanja ubrzanja, brzine i pomeranja šipa posmatraju se diferencijalne jednačine kretanja:

$$[M]\{A\}+[C]\{V\}+[K]\{U\}=\{Q\}, \tag{21}$$

gde je [*M*] matrica masa, {*A*} vektor ubrzanja, [*C*] matrica prigušenja, {*V*} vektor brzine, [*K*] matrica krutosti, {*U*} vektor pomeranja i {*Q*} vektor spoljašnjeg opterećenja. Rešavanje jednačina (21) se sprovodi numeričkom integracijom korak po korak *Hilber-Hughes-Taylor*-ovim (HHT) postupkom u modifikovanom obliku [10]:

$$[M]\{A\}_{i+1}+(1+\alpha)[C]\{V\}_{i+1}-\alpha[C]\{V\}_i+(1+\alpha)[K]\{U\}_{i+1}-\alpha[K]\{U\}_i=\{Q\}_{i+\alpha}, \tag{22}$$

za trenutak vremena:

$$t_{i+1}=t_i+\Delta t\,. \tag{23}$$

Numeričko modeliranje defekata šipa sprovodi se analizom šipa kroz faze oštećenja (SDA). SDA analiza se konstruiše tako da se povezivanjem individualnih analiza generišu i simuliraju uticaji defekata šipa. Ove analize se sukcesivno sprovode korišćenjem matrica krutosti sistema na kraju prethodne analize stanja defekata, kao inicijalne matrice krutosti sistema naredne analize stanja defekata. Matematička formulacija SDA analize izvedena je polazeći od izraza za stanje potpune integralnosti šipa [8]:

$$t=0:[K_0]\{U_0\}=\{P_0\}, \tag{24}$$

3 NUMERICAL SIT ANALYSES

Numerical SIT analyses are conducted by varying the finite element method (FEM), whereby the pile and the soil are modelled using 2D surface finite elements or finite elements for rotational symmetry. In the procedure of determining acceleration, velocity and displacement of the pile, differential motion equations are observed:

where [*M*] is mass matrix, {*A*} acceleration vector, [*C*] damping matrix, {*V*} velocity vector, [*K*] stiffness matrix, {*U*} displacement vector and {*Q*} external load vector. Solving equations (21) is conducted using step-by-step numerical integrations using the *Hilber-Hughes-Taylor* (HHT) procedure in a modified form [10]:

for the time instant:

Numerical modelling of pile defects is performed by pile stage degradation analysis (SDA). SDA analysis is constructed in such a way that the effects of pile defects are generated and simulated by linking individual analyses. These analyses are successively performed using the system stiffness matrix at the end of the previous defect state analysis as the initial stiffness matrix of the subsequent defect state analysis. The mathematical formulation of SDA was derived from the expression for the state of the complete pile integrity [8]:

gde je [K_0] matrica krutosti integralnog šipa (bez defekata). Za inicijalnu fazu defekata šipa analiza se sprovodi prema:

where [K_0] is the stiffness matrix of an integral pile (without defects). For the initial phase of pile defects, the analysis is conducted according to:

$$t = 1: [K_1]\{U_1\} = \{P_1\}, \quad [K_1] = [K_0] - [K_0'], [M_1] = [M_0] - [M_0'] , \tag{25}$$

gde je $[K_0']$ matrica krutosti eliminisanog domena konačnih elemenata šipa (simulacija defekata), [M_0] matrica masa integralnog šipa (bez defekata), $[M_0']$ matrica masa eliminisanog domena konačnih elemenata šipa (simulacija defekata). U *i*-toj fazi analize defekata šipa, proračun se sprovodi prema:

Where $[K_0']$ is the stiffness matrix of the eliminated domain of finite elements of the pile (defect simulation), [M_0] mass matrix of the integral pile (without defects), $[M_0']$ mass matrix of the eliminated domain of finite pile elements (defect simulation). In *i*-th phase of pile defect analysis, the calculation is conducted according to:

$$t = i: [K_i]\{U_i\} = \{P_i\}, \quad [K_i] = [K_{i-1}] - [K_{i-1}'], [M_i] = [M_{i-1}] - [M_{i-1}'], \tag{26}$$

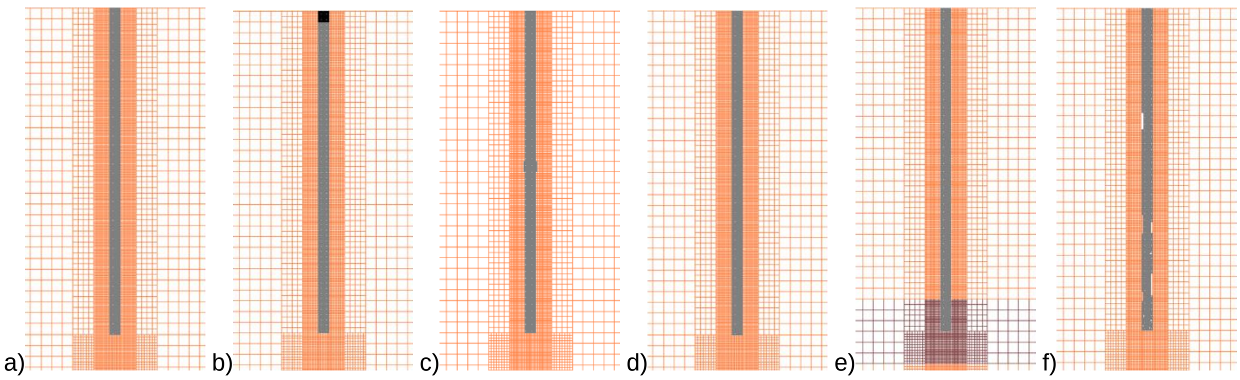
dok za *n*-tu fazu važi:

while for the *n*-th phase, it is:

$$t = n: [K_n]\{U_n\} = \{P_n\}, \quad [K_n] = [K_{n-1}] - [K_{n-1}'], [M_n] = [M_{n-1}] - [M_{n-1}'], \tag{27}$$

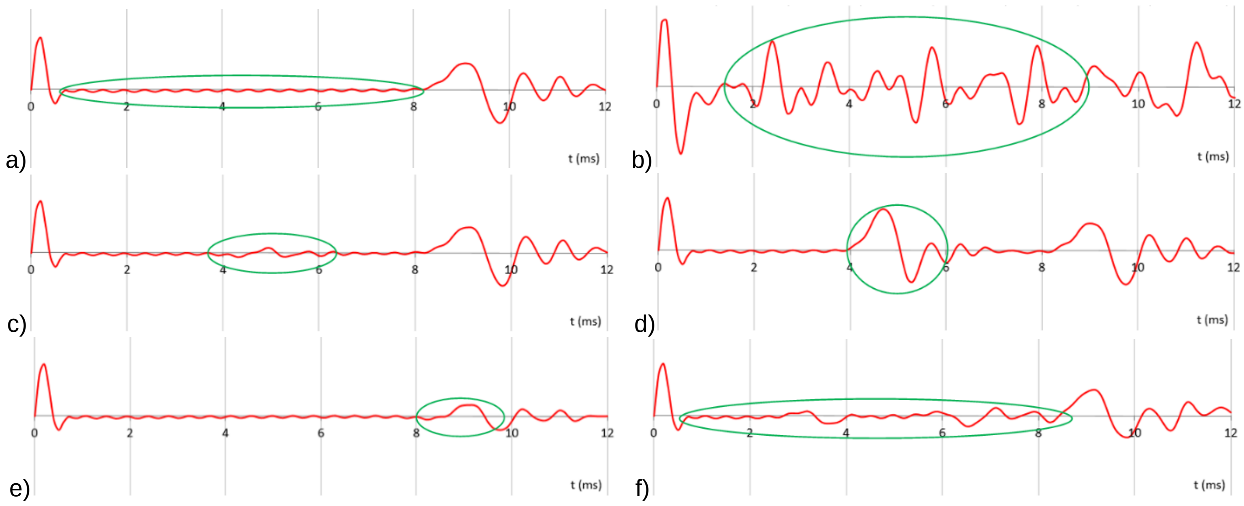
gde je [K_n] matrica krutosti defektnog šipa u finalnoj fazi proračuna, [M_n] matrica masa defektnog šipa u finalnoj fazi proračuna. Na slici 7 prikazani su modeli šipova s defektima i bez njih, dok su na slici 8 prikazani reflektogrami numeričkih modela šipova i tla: integralni šip (bez defekata), šip s redukovanim kvalitetom materijala glave, šip s proširenjem prečnika na polovini dužine stabla, šip s diskontinuitetom na polovini dužine stabla (prslina bez zatvaranja), šip u višeslojnoj sredini (sloj ispod baze šipa je boljih geomehaničkih karakteristika) i šip s randomiziranim diskontinuitetom prečnika duž stabla.

where [K_n] is the stiffness matrix of the defective pile in the final calculation phase, [M_n] the defective pile mass matrix in the final calculation phase. Figure 7 shows pile models with and without defects, while Figure 8 shows reflectograms of the numerical pile and soil models: integral pile (without defects), pile with reduced quality of head material, pile with a diameter expansion at half-length, pile with a discontinuity at half-length (a crack without closure), pile in a multilayered medium (the layer below the pile toe has better geomechanical characteristics) and pile with randomized discontinuity of diameter along the shaft.



Slika 7. Modeli šipova s defektima i bez njih: a) integralni šip (bez defekata); b) šip s redukovanim kvalitetom materijala glave; c) šip s proširenjem prečnika na polovini dužine stabla; d) šip s diskontinuitetom na polovini dužine stabla (prslina bez zatvaranja); e) šip u višeslojnoj sredini (sloj ispod baze šipa je boljih geomehaničkih karakteristika); f) šip s randomiziranim diskontinuitetom prečnika duž stabla

Figure 7. Models of piles with and without defects: a) integral pile (without defects), b) pile with reduced quality of head material, c) pile with a diameter expansion at half-length, d) pile with a discontinuity at half-length (a crack without closure), e) pile in a multilayered medium (the layer below the pile toe has better geomechanical characteristics), f) pile with randomized discontinuity of diameter along the shaft



Slika 8. Reflektogrami numeričkih modela šipova i tla: a) integralni šip (bez defekata); b) šip s redukovanim kvalitetom materijala glave; c) šip s proširenjem prečnika na polovini dužine stabla; d) šip s diskontinuitetom na polovini dužine stabla (prslina bez zatvaranja); e) šip u višeslojnoj sredini (sloj ispod baze šipa je boljih geomehaničkih karakteristika); f) šip s randomiziranim diskontinuitetom prečnika duž stabla

Figure 8. Reflectograms of numerical models of piles and soil: a) integral pile (without defects), b) pile with reduced quality of head material, c) pile with a diameter expansion at half-length, d) pile with a discontinuity at half-length (a crack without closure), e) pile in a multilayered medium (the layer below the pile toe has better geomechanical characteristics), f) pile with randomized discontinuity of diameter along the shaft

S obzirom na to što se prilikom sprovođenja testova integriteta šipa sa senzorom (SIT) i numeričkih analiza integriteta šipova (simulacija) dobijaju originalni (nekorigovani) reflektogrami, to se oni dodatno procesiraju s ciljem sprovođenja određenih korekcija i filtriranja. Najčešće se sprovode procedure filtriranja i skaliranja direktno u vremenskom domenu, međutim koriste se i metode filtriranja u frekventnom domenu. Filtriranjem se koriguje reflektogram radi jasnijeg uočavanja eventualnih defekata u šipu eliminacijom manje bitnih i konzervacijom bitnih diskretnih vrednosti pikova brzina reflektograma, dok se skaliranjem povećava intenzitet refleksije signala, prevashodno u bazi šipa s ciljem lakše identifikacije dužine šipa. Najčešće se primenjuje *n*-tostruki težinski filter kojim se signal direktno filtrira u vremenskom domenu [27]:

Given that when conducting SITs and numerical analyses of pile integrity (simulations), original (uncorrected) reflectograms are obtained, they are further processed in order to make certain corrections and filtering. Most often, filtering and scaling procedures are performed directly in the time domain, however, frequency filtering methods are also used. Filtration adjusts the reflectogram to more clearly detect possible defects in the pile by eliminating less significant and conserving essential discrete peak velocity values of the reflectograms, while scaling increases the signal reflection intensity, primarily at the pile toe, for an easier identification of the pile length. A *n*-times weight filter is most commonly used to filter the signal directly in the time domain [27]:

$$v_{f,1}(t) = \frac{v_0(t-1)+2v_0(t)+v_0(t+1)}{4}, \qquad (28)$$

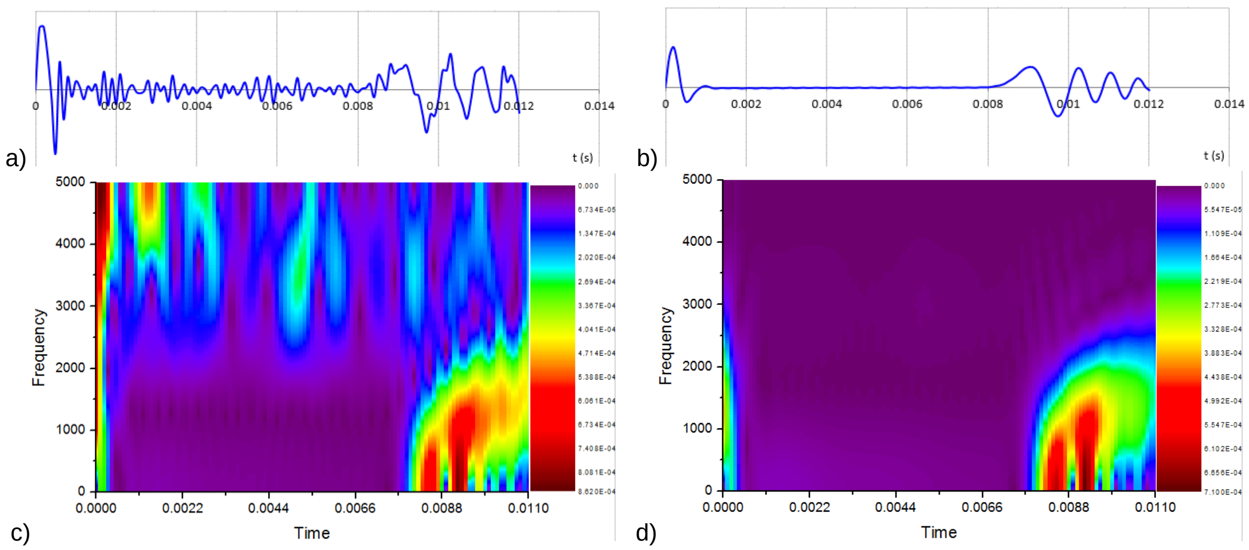
$$v_{f,i}(t) = \frac{v_{f,i-1}(t-1)+2v_{f,i-1}(t)+v_{f,i-1}(t+1)}{4}, \qquad (29)$$

$$v_{f,n}(t) = \frac{v_{f,n-1}(t-1)+2v_{f,n-1}(t)+v_{f,n-1}(t+1)}{4}, \qquad (30)$$

gde je $v_o(t)$ brzina originalnog (nefiltriranog) reflektograma u vremenu (*t*), dok su $v_{f,1}(t)$, $v_{f,i\text{-}1}(t)$, $v_{f,i}(t)$, $v_{f,n\text{-}1}(t)$, $v_{f,n}(t)$ brzine korigovanog (filtriranog) reflektograma u vremenu (*t*). Na slikama 9 i 10 prikazani su karakteristični primeri reflektograma i 2D spektrograma šipova s manjim diskontinuitetima i većim defektom u sredini šipa: bez primenjenog filtera i s primenjenim filterom. Spektrogrami su konstruisani primenom kratkotrajne *Fourier*-ove transformacije (STFT), tako da se u frekventnom domenu jasno može

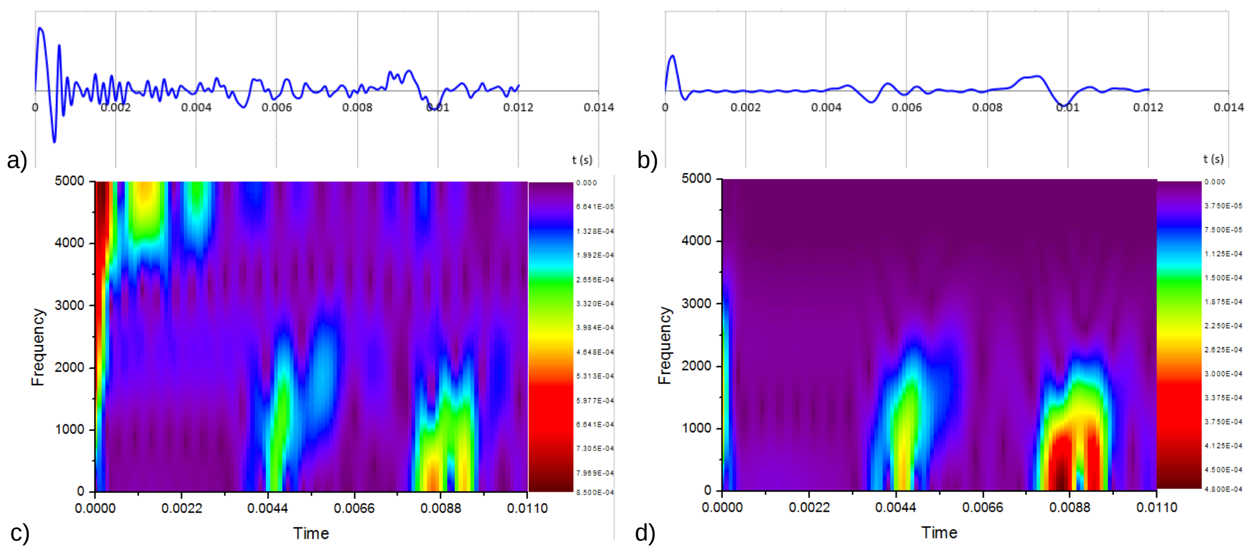
where $v_o(t)$ is the velocity of the original (unfiltered) reflectogram in time (*t*), while $v_{f,1}(t)$, $v_{f,i\text{-}1}(t)$, $v_{f,i}(t)$, $v_{f,n\text{-}1}(t)$, $v_{f,n}(t)$ are velocities of corrected (filtered) reflectogram in time (*t*). Figures 9 and 10 show characteristic examples of reflectograms and 2D spectrograms of piles with smaller discontinuities and larger defects in the middle of the pile: with no filter applied and with a filter applied. Spectrograms are constructed using the Short Time Fourier transform (STFT), so that in the frequency domain one can clearly observe the variation in sagledati promena amplituda u funkciji frekvencija odgovarajućeg signala (reflektograma), eliminacija i konzervacija određenih amplituda.

amplitudes as a function of the corresponding signal (reflectograms) frequencies, the elimination and conservation of certain amplitudes.



Slika 9. Reflektogrami i 2D spektrogrami šipa s manjim diskontinuitetima: a) reflektogram šipa bez primenjenog filtera; b) reflektogram šipa s primenjenim filterom; c) 2D spektrogram šipa bez primenjenog filtera; d) 2D spektrogram šipa s primenjenim filterom

Figure 9. Reflectograms and 2D spectrograms of a pile with smaller discontinuities: a) pile reflectogram without applied filter, b) pile reflectogram with applied filter, c) 2D pile spectrogram without applied filter, d) 2D pile spectrogram with applied filter



Slika 10. Reflektogrami i 2D spektrogrami šipa s većim defektom u sredini šipa: a) reflektogram šipa bez primenjenog filtera; b) reflektogram šipa s primenjenim filterom; c) 2D spektrogram šipa bez primenjenog filtera; d) 2D spektrogram šipa s primenjenim filterom

Figure 10. Reflectograms and 2D spectrograms of a pile with larger defects in the middle of the pile: a) pile reflectogram without applied filter, b) pile reflectogram with applied filter, c) 2D pile spectrogram without applied filter, d) 2D pile spectrogram with applied filter

4 ISPITIVANJE INTEGRITETA ŠIPOVA TESTOM INTEGRITETA ŠIPA SA SONDAMA (CSL)

Test integriteta šipa sa sondama (CSL) zasniva se na propagaciji talasa, primenom sondi s razdvojenim transmiterom i risiverom. Ovim testom se interaktivno i simultano, između instaliranih cevi u šipu, detaljno može ispitati integritet šipa celom dužinom po svim poprečnim presecima [6]. Ispitivanje integriteta sprovodi se kod svih tipova armiranobetonskih bušenih šipova. Metodologija ispitivanja integriteta šipa sa sondama (CSL) definisana je standardom ASTM D6760 [2]. Centar za puteve i geotehniku Instituta IMS poseduje licenciranu opremu za test integriteta šipa sa sondama američke firme *Pile Dynamics*. Korišćenjem ove opreme moguće je sprovesti analizu ultrazvučnih profila u vremenskom domenu (TDA), ali i dodatnu tomografsku analizu integriteta šipa (CSLT). Oprema poseduje integrisane softverske module za: procesiranje, skaliranje, korekciju i filtriranje signala. CHAMP-Q oprema [14] za test integriteta šipa sa sondama (CSL), američke firme *Pile Dynamics*, sastoji se iz: metra s tegom za preliminarnu proveru dužine i nezapušenosti instaliranih cevi, sondi - transmitera (generišu ultrazvučni signal nominalne frekvencije 45 kHz), sondi - risivera (nominalne frekvencije 45 kHz), četiri seta kablova za povezivanje četiri sonde, tripoda za kablove sa senzorima za analizu pozicije sondi u cevima, hardverskog sistema za akviziciju, memorisanje, procesiranje i vizuelizaciju podataka i softvera CHA-S, CHA-W i PDI-Tomo. Konverzija AD signala sprovodi se primenom 12-bitnog konvertera (frekvencija semplovanja je od 500 kHz do 2 MHz). Na slici 11 prikazana je CHAMP-Q oprema za ispitivanje integriteta šipova testom integriteta šipa sa sondama (CSL) američke firme *Pile Dynamics*.

4 PILE INTEGRITY TESTING USING CROSSHOLE SONIC LOGGING (CSL)

Crosshole Sonic Logging (CSL) is based on wave propagation using separate transmitter and receiver sensor. With this test, the integrity of the pile can be thoroughly examined interactively and simultaneously, between the installed pipes in the pile, along entire length and across all cross sections [6]. Integrity testing is performed on all types of bored reinforced concrete piles. The testing methodology of CSL is defined by ASTM D6760 [2]. The *Centre for Roads and Geotechnics of the IMS Institute* possesses the licensed CSL equipment manufactured by the US *Pile Dynamics* company. Using this equipment, it is possible to perform ultrasonic time domain analysis (TDA), as well as additional Crosshole Sonic Logging Tomography (CSLT). The equipment has integrated software modules for: signal processing, scaling, correction and filtering. The CHAMP-Q equipment [14] for CSL, of the U.S. *Pile Dynamics* company, consists of: a meter with a weight for preliminary checking of the length and possibility of installed pipes, probes - transmitters (generating ultrasonic signal of 45kHz nominal frequency), probes - receivers (nominal frequencies 45kHz), 4 sets of cables for connecting 4 probes, tripods for cables with sensors for analyzing the position of probes in the pipes, hardware system for acquisition, storage, processing and visualization of data and software CHA-S, CHA-W and PDI-Tomo. AD signal conversion is conducted using the 12-bit converter (sampling frequency is from 500kHz to 2MHz). Figure 11 shows the CHAMP-Q equipment for CSL by the U.S. *Pile Dynamics* company.

Slika 11. CHAMP-Q oprema za ispitivanje integriteta šipova testom integriteta šipa sa sondama (CSL) američke firme Pile Dynamics [14]

Figure 11. CHAMP-Q CSL equipment of the U.S. company Pile Dynamics [14]

Pravilno sprovođenje testa integriteta šipa sa sondama (CSL) zahteva prethodnu pripremu cevi u koje se spuštaju sonde za ispitivanje. Ove cevi se ugrađuju u telo šipa, a naknadno se mogu injektirati nakon sprovedenog ispitivanja. Na slici 12 prikazane su čelične cevi spojene i zavarene za unutrašnju stranu armaturnog koša šipa i krajevi cevi koji vire nakon betoniranja.

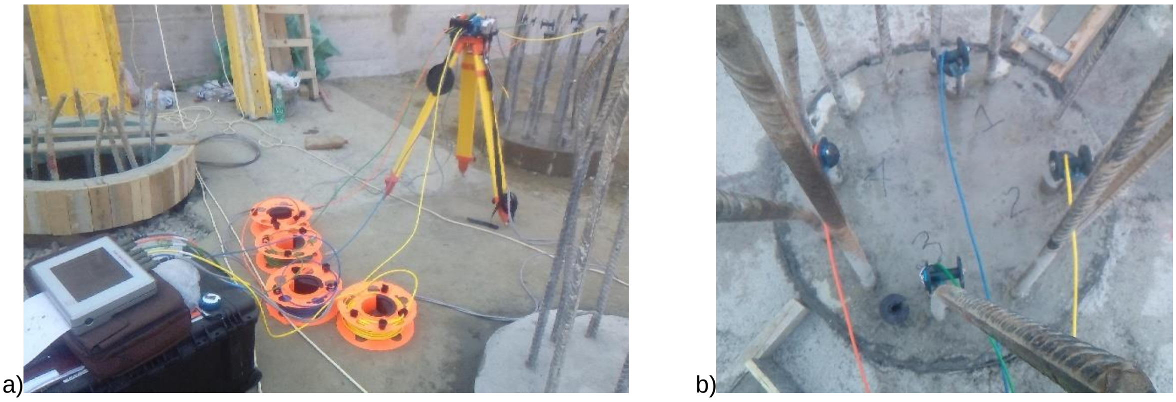
A proper procedure of CSL requires the preliminary preparation of pipes into which test probes are lowered. These tubes are embedded in the body of the pile and they can be subsequently injected after testing. Figure 12 shows the steel pipes connected and welded to the inside of the pile reinforcement cage and the ends of the pipes protruding after concreting.

Slika 12. a) i b) čelične cevi spojene i zavarene za unutrašnju stranu armaturnog koša šipa; c) krajevi cevi koji vire nakon betoniranja

Figure 12. a) and b) steel pipes joined and welded to the inside of the pile reinforcement cage, c) pipes ends protruding after concreting

Na slici 13 prikazani su: tripod za kablove sa senzorima, uređaj za akviziciju, memorisanje, procesiranje i vizuelizaciju podataka i povezane i postavljene sonde u cevima. Sonde na svojim krajevima imaju tegove, tako da je ukupna dužina sondi i tegova nešto veća od 30 cm. U tom smislu, da bi se adekvatno sprovela analiza integriteta glave šipa, potrebno je ispustiti cevi dovoljno izvan glave šipa, kako bi se i sonde izvukle izvan glave šipa, a ostale u cevima. Budući da prilikom krajcovanja glave šipa vrlo često nastupi oštećenje cevi za ispitivanje integriteta šipa sa sondama (CSL), to je gotovo nemoguće sprovesti adekvatnu analizu integriteta glave šipa.

Figure 13 shows: tripod for sensor cables, acquisition, storage, processing and data visualization device and connected and placed probes in tubes. The probes have weights at their ends, so the total length of the probes and weights is a little over 30 cm. In this sense, in order to adequately carry out the analysis of the integrity of the pile head, it is necessary to make the pipes sufficiently protrude outside the pile head to allow the probes to be pulled out of the pile head and remain in the pipes. Since during the trimming of the pile head the pipe for CSL is very often damaged, it is almost impossible to perform an adequate analysis of the integrity of the pile head.



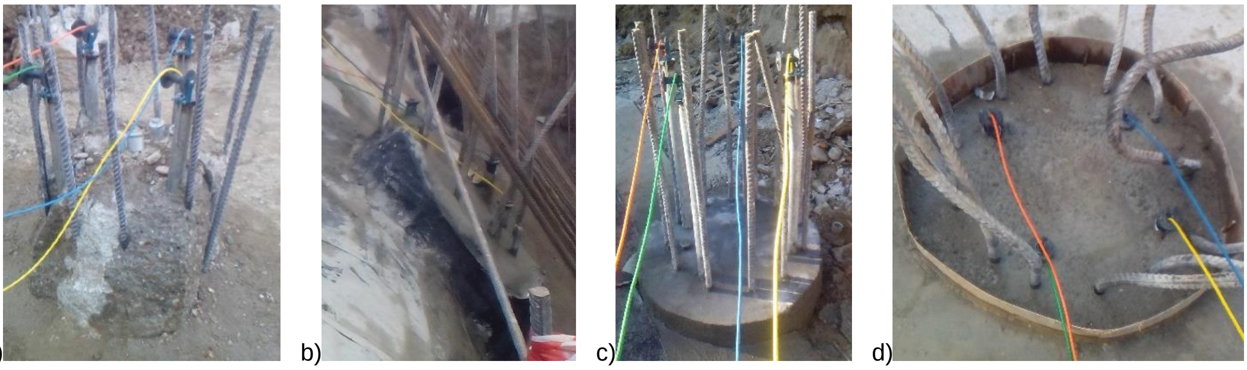
Slika 13. a) tripod za kablove sa senzorima, uređaj za akviziciju, memorisanje, procesiranje i vizuelizaciju podataka povezan sa sondama; b) povezane i postavljene sonde u cevima

Figure 13. a) tripod for sensor cables, device for acquisition, storage, processing and visualization of data connected to probes, b) probes connected and placed in pipes

Na slici 14 prikazani su specifični slučajevi pozicija i dužina cevi izvan glave šipa: cevi su adekvatne dužine, čak je i beton nedovoljno okrajcovan, što je povoljno u smislu ispitivanja integriteta glave šipa, cevi nisu adekvatne dužine i krajevi cevi se završavaju na različitim visinama, cevi su adekvatne dužine, glava šipa je dobro okrajcovana i naknadno obrađena (najpovoljnija situacija) i krajevi cevi se završavaju u ravni glave šipa, što je nepovoljno, jer se sonde ne mogu izvući kompletno, pa se samim tim ne može sprovesti adekvatna analiza integriteta glave šipa.

Figure 14 shows specific cases of positions and lengths of pipes outside the pile head: the pipes are adequate in length, even the concrete is insufficiently trimmed, which is advantageous in terms of testing the integrity of the pile head, the pipes are inadequate in length and the ends of the pipes end at different heights, the pipes are of adequate length, the head of the pile is well-trimmed and finished (the most favourable situation) and the ends of the pipe end flush with the pile head, which is unfavourable, since the probes cannot be pulled out completely, and thus, it is impossible to carry out an adequate analysis of pile head integrity.

a) b) c) d)



Slika 14. Specifični slučajevi pozicija i dužina cevi izvan glave šipa: a) cevi su adekvatne dužine, čak je i beton nedovoljno okrajcovan, što je povoljno u smislu ispitivanja integriteta glave šipa; b) cevi nisu adekvatne dužine i krajevi cevi se završavaju na različitim visinama; c) cevi su adekvatne dužine, glava šipa je dobro okrajcovana i naknadno obrađena (najpovoljnija situacija); d) krajevi cevi se završavaju u ravni glave šipa, što je nepovoljno, jer se sonde ne mogu izvući kompletno, pa se samim tim ne može sprovesti adekvatna analiza integriteta glave šipa

Figure 14. Specific cases of positions and lengths of pipes outside the pile head: a) the pipes are adequate in length, even the concrete is insufficiently trimmed, which is advantageous in terms of testing the integrity of the pile head, b) the pipes are not adequate in length and the ends of the pipes end at different heights, c) the pipes are of adequate length, the head of the pile is well-trimmed and finished (the most favourable situation), d) the ends of the pipe end flush with the pile head, which is unfavourable, since the probes cannot be pulled out completely, and thus, it is impossible to carry out an adequate analysis of pile head integrity.

Transmiterom se emituju talasi kroz telo šipa, a s obzirom na to što su transverzalni talasi znatno sporiji, od interesa za ispitivanje su samo longitudinalni talasi, koji su dosta brži i nose u sebi informaciju o stanju šipa. Merenje se zasniva, zapravo, na analizi promene: vremena (FAT) ili brzine propagacije talasa od transmitera do risivera, a za poznato rastojanje između cevi po dubini šipa i količine relativne energije po dubini šipa. Signali primljeni risiverom sempluju se i beleže kao promene amplitude u funkciji vremena, a zatim procesiraju po dužini ispitanog šipa. Dobijeni podaci koriste se za potvrdu kvaliteta betona i za identifikaciju zona lošeg kvaliteta. Kompletna obrada (procesiranje) signala sprovodi se primenom teorije i obrade signala, pri čemu se zapis signala prikazuje u digitalizovanom formatu, a sam signal prikazuje u vremenskom domenu. Merenje se sprovodi za vertikalni interval od 2 cm do 5 cm. Kriterijumi za analizu oštećenja šipa definisani su prema [13]:

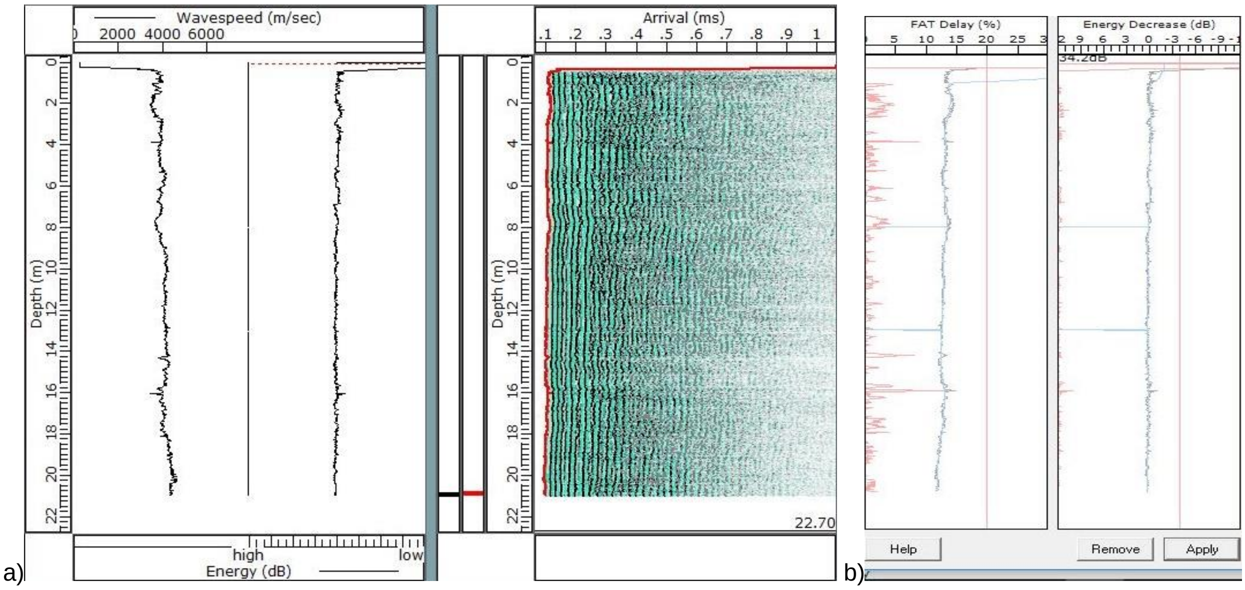
- zadovoljavajuće (G), (odlično): povećanje FAT od 0 do 10% (mada se može tolerisati i do 15%) i/ili redukcija energije < 6 db (mada se može tolerisati i do 7.5 db);
- odstupanje (Q), (devijantno): povećanje FAT od 11% do 20% i/ili redukcija energije od 6 db do 9 db;
- prslina/pukotina (P/F), (lošije): povećanje FAT od 21% do 30% i/ili redukcija energije od 9 db do 12 db;
- defekat (P/D), (defekat/diskontinuitet): povećanje FAT > 31% i/ili redukcija energije > 12 db.

S obzirom na to što se ispitivanje integriteta šipova, testom integriteta šipa sa sondama (CSL), sprovodi s četiri sonde, simultano se u šest pravaca dobijaju ultrazvučni profili. Na slikama 15, 16 i 17, za jedan pravac, prikazani su ultrazvučni profili integralnog šipa (bez defekata), šipa s diskontinuitetom u domenu baze i defektnog šipa - dijagrami promena: brzina propagacije talasa, relativne energije, vremena dolaska signala

Transmitters emit waves through the body of the pile, and since transversal waves are considerably slower, only longitudinal waves, which are much faster and carry information about the state of the pile, are interesting for testing. In fact, the measurement is based on an analysis of variation: of time (FAT) or the wave propagation speed from the transmitter to the receiver, for the known distance between the pipes along the depth of the pile and the quantity of relative energy along the depth of the pile. The signals received by the receiver are sampled and recorded as variation in amplitude as a function of time and then processed along the length of the test pile. The data obtained are used to confirm the quality of concrete and identify poor quality zones. Complete signal processing is performed by applying theory and signal processing, whereby the signal record is displayed in a digitized format and the signal itself is displayed in the time domain. The measurement is carried out for a vertical interval of 2cm to 5cm. Criteria for pile damage analysis are defined according to [13]:

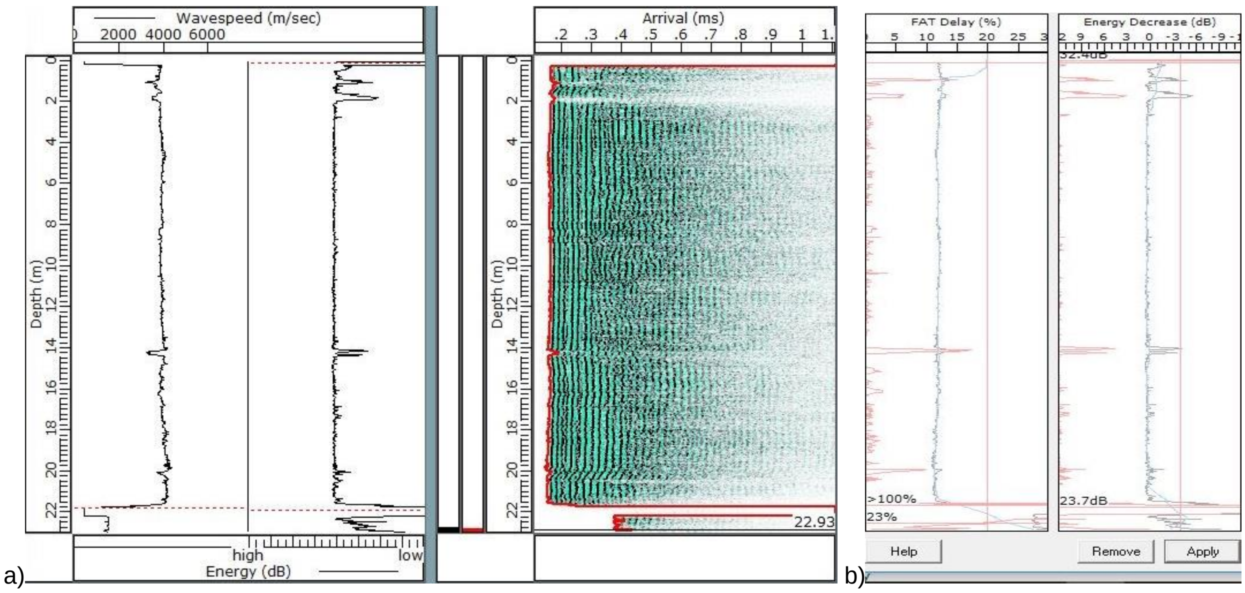
- satisfactory (G) (good): increase of FAT from 0 to 10% (even though up to 15% can be tolerated) and/or energy reduction < 6db (even though up to 7.5db can be tolerated),
- deviation (Q) (questionable): increase of FAT from 11% to 20% and/or energy reduction from 6db to 9db,
- flaw (P/F) (poor/flaw): increase of FAT from 21% to 30% and/or energy reduction 9db to 12db,
- defect (P/D) (poor/defect): increase of FAT > 31% and/or energy reduction > 12db.

Since the pile integrity test, CSL, is performed with 4 probes, ultrasonic profiles are obtained simultaneously in 6 directions. For one direction, Figures 15, 16 and 17, show ultrasonic profiles of an integral pile (without defects), a pile with discontinuity at the toe and a defective pile – variation diagrams: of wave propagation



Slika 15. Ultrazvučni profili integralnog šipa (bez defekata): a) dijagrami promena brzina propagacije talasa, relativne energije i vremena dolaska signala (FAT); b) dijagrami povećanja vremena dolaska signala (FAT) i redukcije relativne energije duž stabla šipa

Figure 15. Ultrasonic profiles of an integral pile (without defects): a) diagrams of variations in wave propagation velocities, relative energy and signal first arrival time (FAT), b) diagrams of increase of time of signal first arrival time (FAT) and reduction of relative energy along the pile shaft



Slika 16. Ultrazvučni profili šipa s diskontinuitetom u domenu baze: a) dijagrami promena brzina propagacije talasa, relativne energije i vremena dolaska signala (FAT); b) dijagrami povećanja vremena dolaska signala (FAT) i redukcije relativne energije duž stabla šipa

Figure 16. Ultrasonic profiles of a pile with a discontinuity at the toe: a) diagrams of variations in wave propagation velocities, relative energy and signal first arrival time (FAT), b) diagrams of increase of time of signal first arrival time (FAT) and reduction of relative energy along the pile shaft

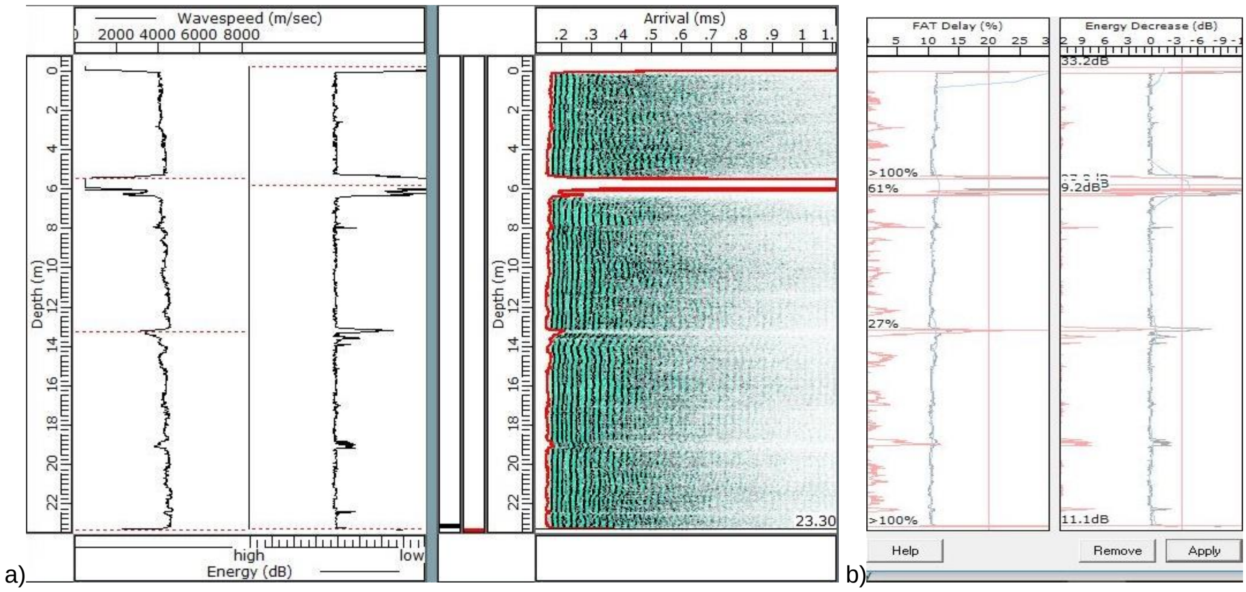
(FAT), povećanja vremena dolaska signala (FAT) i redukcije relativne energije duž stabla šipa, respektivno. U konkretnom slučaju, kod integralnog šipa, analizom ultrazvučnih profila za sve pravce (nisu svi prikazani, s obzirom na obimnost ispitivanja), može se konstatovati

velocity, relative energy, first arrival time (FAT) increases in first arrival time (FAT) and reductions in relative energy along the pile shaft, respectively. In the specific case of the integral pile by analyzing the ultrasonic profiles for all directions (not all of them are shown, da je šip u pogledu integriteta zadovoljavajućeg kvaliteta. Kod integralnog šipa (bez defekata) nije bilo moguće detaljno snimiti bazu šipa, jer su određene cevi bile zapušene, dok su kod šipa s diskontinuitetom u domenu baze, za sve pravce, konstatovana povećanja FAT i redukcija energije.

U slučaju defektnog šipa, za sve pravce, konstatovana su značajnija povećanja FAT i redukcija energije na određenom intervalu dužine šipa. Snimanje je još dva puta ponovljeno i dobijeni su gotovo identični rezultati.

given the scope of the test), it can be concluded that the pile has satisfactory quality in terms of integrity. In the case of the integral pile (without defects) it was impossible to record the pile toe in detail because certain pipes were obstructed, while in the case of piles with a discontinuity at the toe, for all directions, FAT increases and energy reductions were observed.

In the case of defective pile, for all directions, significant increases in FAT and energy reduction of certain pile length interval were observed. Recording was repeated two times more and almost identical results were obtained.

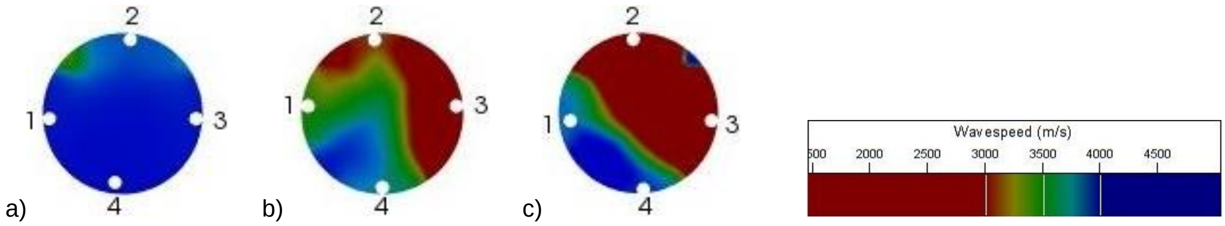


Slika 17. Ultrazvučni profili defektnog šipa: a) dijagrami promena brzina propagacije talasa, relativne energije i vremena dolaska signala (FAT); b) dijagrami povećanja vremena dolaska signala (FAT) i redukcije relativne energije duž stabla šipa

Figure 17. Ultrasonic profiles of a defective pile: a) diagrams of variations in wave propagation velocities, relative energy and signal first arrival time (FAT), b) diagrams of increase of time of signal first arrival time (FAT) and reduction of relative energy along the pile shaft

Na osnovu sprovedenih ispitivanja i prikazanih ultrazvučnih profila integralnog šipa (bez defekata), šipa s diskontinuitetom u domenu baze i defektnog šipa, primenom softvera PDI-Tomo za tomografiju, dodatno su analizirane identifikovane karakteristične zone promena povećanja i smanjenja brzina propagacije talasa u betonu. Ove zone prikazane su primenom izopovrši, čije boje odgovaraju brzinama propagacije talasa u betonu. Na slici 18 prikazani su poprečni preseci za integralni šip (bez defekata), šip sa diskontinuitetom u domenu baze i defektni šip, kod kojih se najviše identifikuju povećanja FAT i redukcije energije, a prikazane su takođe i odgovarajuće proračunate efektivne površine ovih poprečnih preseka šipova. Efektivna površina poprečnog preseka proračunata je kao odgovarajući procenat površine poprečnog preseka šipa, kod kojeg je brzina propagacije talasa u betonu veća od 3600 m/s.

Using PDI-Tomo tomography software, the identified characteristic zones of variation of increase and decrease of wave propagation velocity in concrete were additionally analyzed based on the performed tests and presented ultrasonic profiles of an integral pile (without defects), pile with a discontinuity at the toe and defective pile. These zones are shown using isosurface, the colours which correspond to the wave propagation rates in concrete. Figure 18 shows the cross sections for the integral pile (without defects), the pile with the discontinuity at the toe, and the defective pile, where FAT increases and energy reductions are mostly identified. In addition, the corresponding calculated effective surfaces of these pile cross sections are shown as well. The effective cross-sectional area was calculated as the corresponding percentage of the pile cross-sectional area where the wave propagation velocity in concrete is higher than 3600m/s



Slika 18. Poprečni preseci kod kojih se najviše identifikuju povećanja FAT i redukcije energije, a takođe prikazane su i odgovarajuće proračunate efektivne površine ovih poprečnih preseka šipova: a) integralni šip (bez defekata) - efektivna površina je 95%; b) šip s diskontinuitetom u domenu baze - efektivna površina je 52%, c) defektni šip - efektivna površina je 31%

Figure 18. Cross-sections where FAT increases and energy reductions are identified the most, and corresponding calculated effective surfaces of these cross-sections of piles are also shown: a) integral pile (without defects) - effective surface is 95%, b) pile with discontinuity at the toe - effective area is 52%, c) defective pile - effective area is 31%

5 ZAVRŠNE NAPOMENE I ZAKLJUČCI

Ispitivanje integriteta šipova metodološki se može prikazati u nekoliko faza: priprema ispitivanja, *in-situ* ispitivanje šipova na gradilištu, analiza i odlučivanje tokom ispitivanja, analiza, interpretacija i prezentacija rezultata ispitivanja, dodatne numeričke analize integriteta, donošenje odluke o integralnom stanju šipa i pisanje izveštaja o integritetu šipa. S obzirom na troškove ispitivanja, najčešće se za ispitivanje integriteta šipova koristi test integriteta šipa sa senzorom (SIT). Međutim, u zavisnosti od stepena važnosti objekta, pa i pouzdanost rešenja na raspolaganju je ispitivanje integriteta šipova testom integriteta šipa sa sondama (CSL). U praksi, za gotovo sve šipove objekata, primenjuje se test integriteta šipa sa senzorom (SIT), s obzirom na efikasnost i brzinu ispitivanja, ali se često i zanemaruje to da je ovo indirektna metoda. Istraživanjem su pokazani karakteristični modeli reflektograma, na osnovu kojih se lako mogu doneti odluke o stanju integriteta šipa. Međutim, veoma često se u praksi pojavljuju diskutabilne situacije u kojima nije moguće odmah dati odgovor o stanju integriteta šipa, pa je preporuka da se koriste dodatne metode koje se zasnivaju na talasnoj teoriji, kompatibilizaciji signala i numeričkim analizama.

Kada je u pitanju veliki broj šipova objekta, pouzdanije je napraviti plan ispitivanja pre izgradnje šipova. Kvalitetnim planom ispitivanja, mogu se definisati probni (testni) šipovi na kojima će se sprovesti testovi integriteta šipa sa sondama (CSL) i uticati na korekciju tehnologije izgradnje i/ili dispozicije i/ili broja šipova. Naknadno se svi radni (eksploatacioni) šipovi mogu ispitati testom integriteta šipa sa senzorom (SIT). Najveći problem pojavljuje se kada se svi šipovi objekta izgrade, pa se nakon toga zahteva sprovođenje ispitivanja integriteta šipova, jer se stvara ograničen prostor za korekcije – kako na konstruktivnom nivou, tako i na nivou dinamičkog plana izgradnje objekta. U velikom broju slučajeva, kada naručioci ispitivanja interpretiraju rezultate ispitivanja prikazane u izveštajima, kriterijumi integriteta i nosivosti šipova razmatraju se nezavisno. Takođe, vrlo često se jedan kriterijum favorizuje ili se potpuno isključuje drugi kriterijum. Jedino i inženjerski ispravno rešenje jeste da se oba kriterijuma poštuju i da se uvažavaju uslovi pod kojima se ispunjavaju ovi kriterijumi. Sve to, pored

5 CLOSING REMARKS AND CONCLUSIONS

Pile integrity testing can be methodologically presented in several stages: test preparation, *in-situ* pile testing at the construction site, analysis and decision-making during testing, analysis, interpretation and presentation of test results, additional numerical integrity analysis, decision on the integral condition of a pile and pile integrity report writing. Given the cost of testing, SIT is the most commonly used pile integrity test. However, CSL pile integrity test is also available depending on the degree of importance of the structure and even the reliability of the solution. In practice, SIT is applied for almost all structural piles given the efficiency and speed of testing, but it is often neglected that it is an indirect method. The research has shown characteristic models of reflectograms on the basis of which it is possible to make decisions on the state of pile integrity. However, there are often debatable situations in practice where it is impossible to immediately provide an answer concerning the pile integrity state, so it is recommended to use additional methods based on wave theory, signal matching, and numerical analyses.

When there is a large number of piles in a structure, it is more reliable to make a test plan before building the piles. A quality test plan can define the test piles on which CSL will be conducted and the construction technology and/or the arrangement and/or number of piles can be corrected. Subsequently, all working (service) piles can be tested with SIT. The biggest problem arises when all the piles of a structure are built, and then subsequently the pile integrity test is applied. In that case the space for corrections is limited, both in terms of the structural level and the dynamical construction plan of the structure. In many cases the integrity and load-bearing criteria of piles are considered independently when test results presented in the reports are interpreted by the contracting party. In addition, very often one criterion is favoured or another criterion is completely excluded. The only correct engineering solution is that both criteria are observed and the conditions under which these criteria are met are considered. All this, in addition to knowledge and experience, requires continuous improvement in this multidisciplinary pile testing problem which goes beyond the usual domains of construction and geotechnical practice.

znanja i iskustva, zahteva i kontinualno usavršavanje iz ove multidisciplinarne problematike ispitivanja šipova, koje pravazilazi uobičajene domene građevinske i geotehničke prakse.

ZAHVALNICA

Ovaj rad je deo istraživanja u okviru projekta TR 36014, koje finansira Ministarstvo prosvete, nauke i tehnološkog razvoja Republike Srbije.

ACKNOWLEDGEMENT

This paper is a part of the research within the project TR 36014 supported by the *Ministry of education, science and technological development of the Republic of Serbia.*

6 LITERATURA
REFERENCES

[1] ASTM D5882, Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations, ASTM International, West Conshohocken, USA, 2016.

[2] ASTM D6760, Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing, ASTM International, West Conshohocken, USA, 2016.

[3] Berisavljević D., Šušić N.: *Basis of Pile Integrity Testing with Few Case Histories*, Building Materials and Structures, Vol. 55, No. 1, 2012, pp. 55–64.

[4] Chan F., Tsang S.: *Quality Assurance of Concrete Foundation Elements Using an Ultrasonic Evaluation Technique*, Insight – Non-Destructive Testing and Condition Monitoring, Vol. 48, No. 6, 2006, pp. 360–367.

[5] Cui D., Yan W., Wang X., Lu L.: Towards Intelligent Interpretation of Low Strain Pile Integrity Testing Results Using Machine Learning Techniques, Sensors, Vol. 17, No. 11, 2017, pp. 1–15.

[6] Ćosić M., Božić-Tomić K., Šušić N.: *Pile Integrity and Load Testing: Methodology and Classification*, Building Materials and Structures, Vol. 62, No. 1, 2019, pp. 43–68.

[7] Ćosić M., Folić B., Folić R.: *Developing a Methodology for the Integrated Numerical Evaluation and Performance Assessment of Soil – Pile – Pier*, The 13th International Science Conference VSU, Sofia, Bulgaria, 2013, pp. II-236–244.

[8] Ćosić M., Folić B., Folić R.: *Numerical Simulation of the Pile Integrity Test on Defected Piles*, Acta Geotechnica Slovenica, Vol. 11, No. 2, 2014, pp. 5–19.

[9] Ding X., Liu H., Liu J., Chen Y.: *Wave Propagation in a Pipe Pile for Low-Strain Integrity Testing*, Journal of Engineering Mechanics, Vol. 137, No. 9, 2011, pp. 598–609.

[10] Hilber H., Hughes T., Taylor R.: *Improved Numerical Dissipation for Time Integration Algorithms in Structural Dynamics*, Earthquake Engineering and Structural Dynamics, Vol. 5, No. 3, 1977, pp. 283–292.

[11] Holeyman A.: *Technology of Pile Dynamic Testing*, Application of Stress-Wave Theory to Piles, F. Barends ed., Balkema, 1992, pp. 195–215.

[12] https://www.pile.com/download/brochure/english-pit-w.pdf

[13] https://www.pile.com/download/sample-specifications/csl.pdf

[14] http://www.pile.com/wp-content/uploads/2019/06/PDI-CHAMP-Q-Brochure.pdf

[15] https://www.profound.nl/downloads/Profound_SIT_series_leaflet_uk.pdf

[16] Li D., Zhang L., Tang W.: *Reliability Evaluation of Cross-Hole Sonic Logging for Bored Pile Integrity*, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 131, No. 9, 2005, pp. 1130–1138.

[17] Liang L., Rausche F.: *Quality Assessment Procedure and Classifications of Cast-In-Place Shaft using Low Strain Dynamic Test*, 36th Annual Conference on Deep Foundations, Deep Foundations Institute, Boston, USA, 2011, pp. 553–562.

[18] Middendorp P.: *Thirty Years of Experience With the Wave Equation Solution Based on the Method of Characteristics*, 7th International Conference on the Application of Stress Wave Theory to Piles, Kuala Lumpur, Malaysia, 2004.

[19] Ni S., Isenhower W., Huang Y.: Continuous Wavelet Transform Technique for Low-Strain Integrity Testing of Deep Drilled Shafts, Journal of GeoEngineering, Vol. 7, No. 3, 2012, pp. 97–105.

[20] Promputthangkoon P., Swasdi S., Kuasakul T.: *Interpretation of Pile Integrity Test Results Obtained from Model Concrete Piles Having Two Defect Locations*, International Journal of GEOMATE, Vol. 15, No. 47, 2018, pp.132–138.

[21] Rausche F., Likins G., Hussein M.: *Formalized Procedure for Quality Assessment of Cast-In-Place Shafts Using Sonic Pulse Echo Methods*, Transportation Research Record No. 1447; Design and Construction of Auger Cast Piles and Other Foundation Issues, Washington, USA, 1994, pp. 30–38.

[22] Rausche F., Ren-Kung S., Likins G.: *Comparison of Pulse Echo and Transient Response Pile Integrity Test Methods*, Transportation Research Board Annual Meeting, Washington, USA, 1991, pp. 21–27.

[23] Richart F., Hall J., Woods, R.: *Vibrations of Soils and Foundations*, Prentice Hall, New Jersey, USA, 1970.

[24] Voitus van Hamme G., Jansz J., Bomer H., Arentsen D.: *Hydroblok and Improved Pile Driving Analysis*, De Ingenieur, No 8, Vol 86, 1974, pp 345–353.
[25] White B., Nagy M., Allin R.: *Comparing Cross-Hole Sonic Logging and Low-Strain Integrity Testing Results*, 8th International Conference on the Application of Stress-Wave Theory to Piles, Lisbon, Portugal, 2008, pp. 471–476.
[26] Xu J., Shen Z., Ren Q.: *Simulation Analysis of Low Strain Dynamic Testing of Pile with Inhomogeneous Elastic Modulus*, Journal of Measurements in Engineering, Vol. 5, No. 3, 2017, pp. 152–160.
[27] Ya-lun C.: Statistical Analysis with Business and Economic Applications, Holt, Rinehart and Winston, USA, 1975.
[28] Zhang L., Wu Y., Wei M.: *Detection of Defective Piles Using Analysis Tools*, Electronic Journal of Geotechnical Engineering, Vol. 20, No. 14, 2015, pp. 6073–6082.
[29] Zheng C., Kouretzis G., Ding X., Liu H., Poulos H.: *Three-Dimensional Effects in Low-Strain Integrity Testing of Piles: Analytical Solution*, Canadian Geotechnical Journal, Vol. 53, No. 2, 2017, pp. 225–235.
[30] Zheng C., Liu H., Ding X., Kouretzis G., Sheng D.: *Three-Dimensional Effects in Low-Strain Integrity Testing of Large Diameter Pipe Piles*, Journal of Engineering Mechanics, Vol. 142, No. 9, 2016.

REZIME

ISPITIVANJE INTEGRITETA ŠIPOVA: TESTIRANJE I ANALIZA REZULTATA

Mladen ĆOSIĆ
Kristina BOŽIĆ-TOMIĆ
Nenad ŠUŠIĆ

U radu su prikazani karakteristični primeri ispitivanja integriteta šipova sa analizom rezultata, pri čemu se metodologija ispitivanja oslanja na postojeće ASTM standarde, ali i na metodologiju ispitivanja prikazanu u naučnom radu „Ispitivanje integriteta i nosivosti šipova: metodologija i klasifikacija", koji je publikovan u ovom časopisu. Ispitivanja šipova sprovedena su primenom licenciranih oprema za test integriteta šipa sa senzorom (SIT) i test integriteta šipa sa sondama (CSL). Ispitivanjima su prikazane korektne i problematične situacije, koje se pojavljuju prilikom analize integriteta šipova. Ukazano je na aspekte primene talasne teorije, ali i na procesiranja signala i numeričke analize. Takođe, posebno je skrenuta pažnja na potrebu izrade plana ispitivanja integriteta šipova kod objekata s velikim brojem šipova.

Ključne reči: šip, ispitivanje, integritet, reflektogram, SIT, ultrazvučni profil, CSL

SUMMARY

PILE INTEGRITY TESTING: TESTING AND RESULTS ANALYSIS

Mladen COSIC
Kristina BOZIC-TOMIC
Nenad SUSIC

The paper presents typical examples of pile integrity testing and the results analysis, whereby the testing methodology relies on existing ASTM standards, as well as on the testing methodology presented in the scientific paper *Pile Integrity and Load Testing: Methodology and Classification*, published in this journal. The pile tests were conducted using licensed equipment for Sonic Integrity Test (SIT) and Crosshole Sonic Logging (CSL). The tests have shown the correct and problematic situations that arise when analyzing pile integrity. Some aspects of the wave theory implementation, but also of signal processing and numerical analysis have been indicated. Also, the need to develop a plan for testing the integrity of piles in structures with a large number of piles has been emphasized.

Key words: pile, testing, integrity, reflectogram, SIT, ultrasonic profile, CSL