ISPITIVANJE INTEGRITETA I NOSIVOSTI ŠIPOVA: METODOLOGIJA I KLASIFIKACIJA

PILE INTEGRITY AND LOAD TESTING: METHODOLOGY AND CLASSIFICATION

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PREGLEDNI RAD
REVIEW PAPER
UDK:624.154.046.2
doi:10.5937/GRMK1901043C

1 UVOD

Fundiranje objekata na šipovima deo je kompleksne geotehničke problematike koja se u poslednjih nekoliko decenija intenzivno razvija u saradanji s drugim naučnim disciplinama na poljima: laboratorijskih analiza tla, ispitivanja tla putem *in-situ* testova, kao i numeričkim analizama, projektovanja prema propisima, tehnologiji izvođenja i slično. S obzirom na to što stepen nepouzdanosti parametara u geotehnici može biti znatno visok, u poređenju na, na primer, sa stepenom nepouzdanosti parametara kod konstrukcija, a imajući u vidu i to da broj ovih parametara kojima se modelira konstitutivni model ponašanja tla može biti znatan, može se pojaviti situacija vidnijeg odstupanja ponašanja projektovanog matematičkog modela u odnosu na izvedeno projektno rešenje šipova. Efekti ovih odstupanja iskazuju se u formi značajnijih sleganja konstrukcija i gubitka geotehničke nosivosti, odnosno sloma u tlu, pa i kolapsa konstrukcija. U tom smislu, da bi se maksimalno eliminisala razlika između ponašanja projektnog matematičkog modela i izvedenog projektnog rešenja šipova, razvijen je niz metoda ispitivanja šipova na mestu izgradnje objekta. Ekspanzija softversko-hardverskog inženjerstva, u poslednje dve decenije, omogućila je uvođenje multidisciplinarnog pristupa u analizi stanja šipova, gde se, u najvećem broju slučajeva, sprovode ispitivanja integriteta i nosivosti šipova. Gotovo svi testovi za ispitivanje integriteta i nosivosti šipova jesu *in-situ* elektronski instrumentalizovani, tako da se u *real time* ili naknadnim

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1 INTRODUCTION

Pile foundations for structures is a part of a complex geotechnical issue, which has been developed over the past few decades in cooperation with other scientific disciplines in the fields of: laboratory soil analysis, soil investigations via in-situ tests, numerical analysis, planning according to regulations, execution technology, and the like. Given that the unreliability level of the parameters in geotechnics may be quite high, compared to, for example, the level of unreliability in the case of constructions, and also that the number of these parameters which are used for modelling the constitutive model of soil behaviour can be significant, all of it may lead to a situation of considerable deviation in behaviour of mathematical model design from the executed pile solution design. The effects of these deviations are expressed in the form of quite significant construction settlement and geotechnical load capacity loss, i.e. soil failure, and even constructions collapse. Thus, a number of methods for pile testing at the construction site has been developed with the aim to maximally eliminate the difference between the behaviour of mathematical model design and executed pile design solution. The expansion of software-hardware engineering, in the last two decaes, has facilitated the introduction of multidisciplinary approach to pile condition analysis, out of which, in most cases, pile integrity and load tests are conducted. Almost all pile integrity and load tests are in-situ electronically instrumentalised, so the results relevant for

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procesiranjem podataka dobijaju rezultati od interesa za građevinsku praksu. Procedure sprovođenja testova integriteta i nosivosti šipova definisane su standardima, u kojima su prikazani elementi, kriterijumi i tokovi ispitivanja. Jedni od najdetaljnijih i najpouzdanijih standarda jesu američki ASTM standardi, gde postoje jasno definisane procedure, pravila i sistem kvaliteta ispitivanja. Ispitivanja integriteta šipova prema američkim standardima definisana su putem: ASTM D7949 [5], ASTM D5882 [6], ASTM D6760 [7], dok su ispitivanja nosivosti šipova definisana putem: ASTM D7383 [1], ASTM D1143 [2], ASTM D3689 [3], ASTM D3966 [4], ASTM D4945 [8], ASTM D8169 [9]. Takođe, evropski standard EN 1997-1:2004 [20], u određenom obimu, ima definisanu regulativu ispitivanja šipova, s tim što se ovi propisi umnogome odnose na međunarodne ISO standarde.

U modernom građevinarstvu, procedura izgradnje objekta fundiranog na šipovima sprovodi se u nekoliko koraka, pri čemu ispitivanje integriteta i nosivosti šipova predstavlja jednako bitnu kariku u kompletnom procesu. Na slici 1 prikazan je dijagram toka metodologije:

– ispitivanja tla (laboratorijska ispitivanja tla i *in-situ* ispitivanja tla, geotehnički elaborat),

– projektovanje objekta (projektno-tehnička dokumentacija),

– izgradnja objekta (projekat tehnologije gradnje objekta, izgradnja konstrukcije, dokument o tehnologiji izgradnje šipova, izgradnja šipova),

– ispitivanje konstrukcije (dokument o tehnologiji ispitivanja konstrukcije, izveštaj ispitivanja konstrukcije),

– ispitivanje šipova (dokument o tehnologiji ispitivanja šipova, izveštaj ispitivanja šipova).

Svaka faza, od ispitivanja tla, preko projektovanja i izgradnje, pa sve do ispitivanja konstrukcije i šipova, usmerena je procedurama definisanim u standardima o: ispitivanju tla, projektovanju objekata, izgradnji objekata, ispitivanju konstrukcija i ispitivanju šipova.

Postojeći inostrani standardi definišu smernice za ispitivanje šipova, međutim, postoje određeni elementi koje je potrebno dodatno unaprediti. U tom smislu, u ovom radu prikazani su neki segmenti unapređivanja postojećih standarda i sopstvene definicije određenih ključnih elemenata, koji su, između ostalog, razmatrani u istraživanjima [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [23], [24], [25], [26], [27], [28], [29]. Značajan doprinos u izučavanju i poboljšanju ispitivanja šipova prikazan je u radu [22], čije je izučavanje dodatno doprinelo razumevanju ove kompleksne problematike. Unapređivanje segmenata postojećih standarda ogleda se u: detaljnijem razjašnjenju pojedinih faza ispitivanja, te redukciji i selekciji metoda i postupaka ispitivanja u okviru jednog testa, a s obzirom na to što u postojećim standardima ispitivanja šipova postoji veći broj opcija ispitivanja koje se najčešće i ne koriste, prikazani su ključni elementi ispitivanja integriteta i nosivosti šipova, bez dodatnih (nepotrebnih) opcija koje, u najvećoj meri, zbunjuju investitora i nadzora prilikom samog sprovođenja ispitivanja šipova.

the practice of civil engineering are obtained in real time or through additional data processing. The procedures for conducting pile integrity and load tests are defined by standards, which describe elements, criteria, and testing processes. Among the most detailed and reliable standards are the USA ASTM standards, which have clearly defined procedures, rules, and quality test system. According to the USA standards, pile integrity tests are defined through: ASTM D7949 [5], ASTM D5882 [6], ASTM D6760 [7], whereas pile load tests are defined through: ASTM D7383 [1], ASTM D1143 [2], ASTM D3689 [3], ASTM D3966 [4], ASTM D4945 [8], ASTM D8169 [9]. In addition, European standard EN 1997-1:2004 [20] has a defined pile testing regulations to a certain extent, but they mostly refer to international ISO standards.

In modern civil engineering the procedure of building an object founded on piles is conducted in several steps, and in which case the pile integrity and load testing makes an equally important component in the whole process. The figure 1 shows a methodology flowchart:

– geotehnical investigation (laboratory soil testing and in-situ soil testing, geotechnical study),

– building design (technical-design documentation),

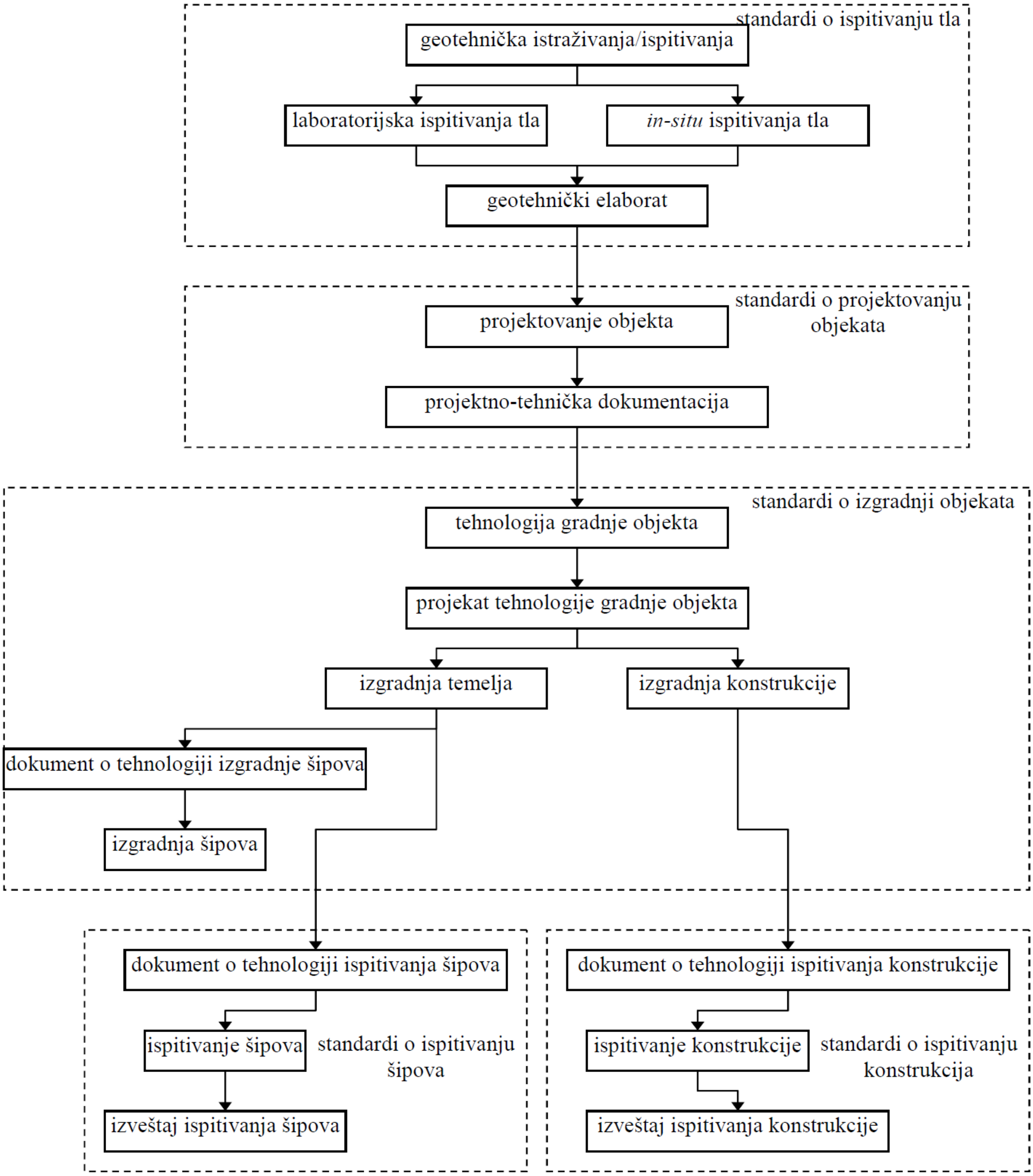
– building construction (construction technology project, building construction, document regarding the pile construction technology, pile construction),

– structural testing (document regarding the structural testing technology, structural testing report),

– pile testing (document regarding the pile testing technology, pile testing report).

Each phase, from soil testing, through designing and constructing, all the way to the structural and pile testing, is guided by the procedures defined in the standards of: geotehnical investigation, building design, building construction, structural testing and pile testing.

The existing foreign standards define the guidelines for pile testing, although there are certain elements, which need further improvement. In that regard, this paper presents certain segments of the improvement of the existing standards and our own definitions of certain key elements, which, among other things, have been examined in the testing [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [23], [24], [25], [26], [27], [28], [29]. A significant contribution to the study and pile testing improvement has been presented in the paper [22], and the study of which has further contributed to the understanding of this complex issue. The improvement of segments of the existing standards reflects in: a detailed explanation of individual testing phases, reduction and selection of testing methods and steps within one test, since in the existing pile testing standards there is a larger number of testing options which are not even used ordinarily. The key elements of pile integrity and load testing have been presented, without the additional options which, mostly, confuse the investor and supervisor during the pile testing conduction.



Slika 1. Dijagram toka metodologije: ispitivanja tla, projektovanja objekta, izgradnje objekta, ispitivanja konstrukcije i ispitivanja šipova

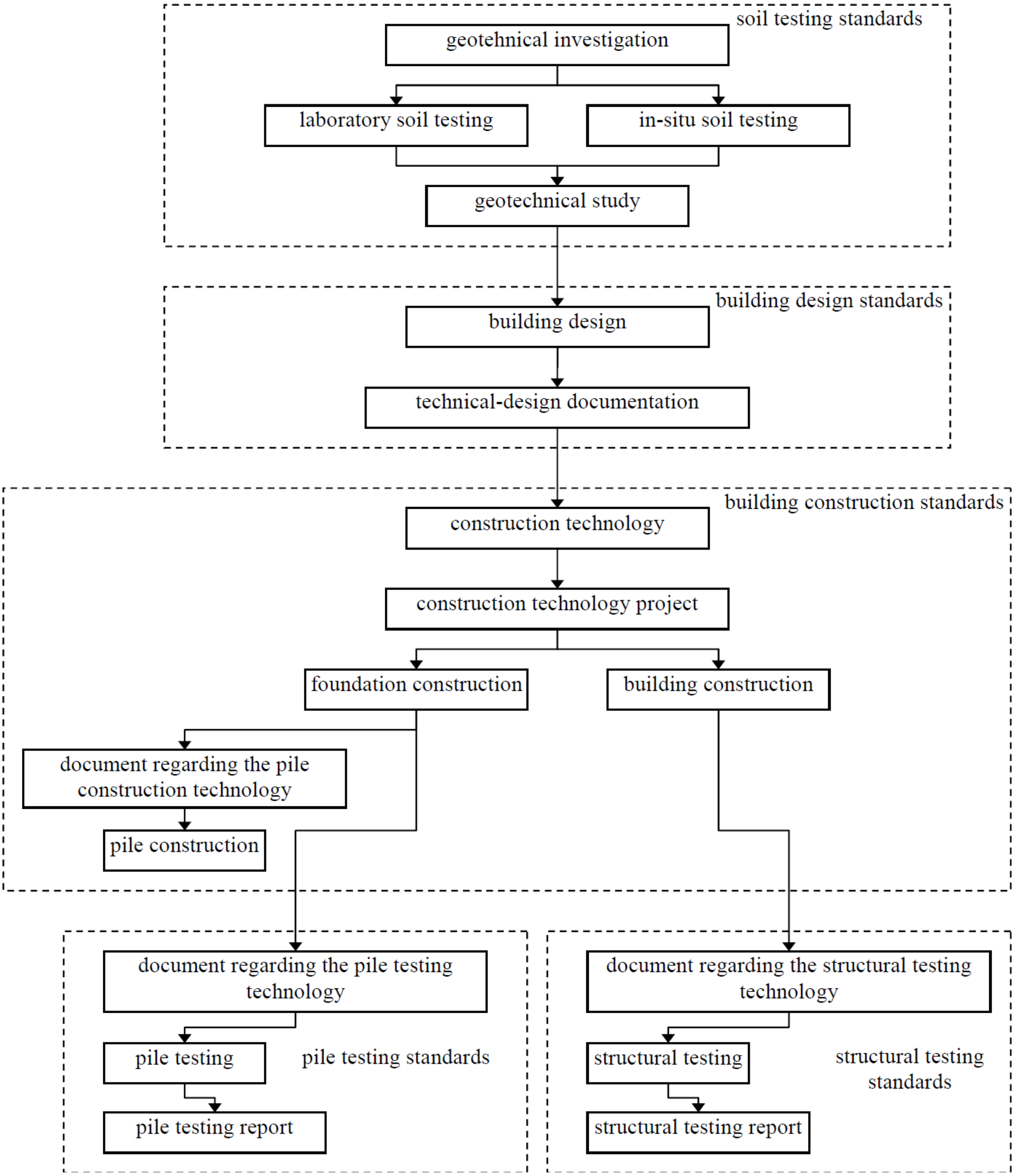


Figure 1. Methodology flowchart: soil testing, building design, building construction, structural testing, and pile testing

2 ISPITIVANJE INTEGRITETA ŠIPOVA

S obzirom na to što je razvijen veći broj testova ispitivanja integriteta šipova, ovde je prikazana sprovedena klasifikacija na:

2 PILE INTEGRITY TESTING

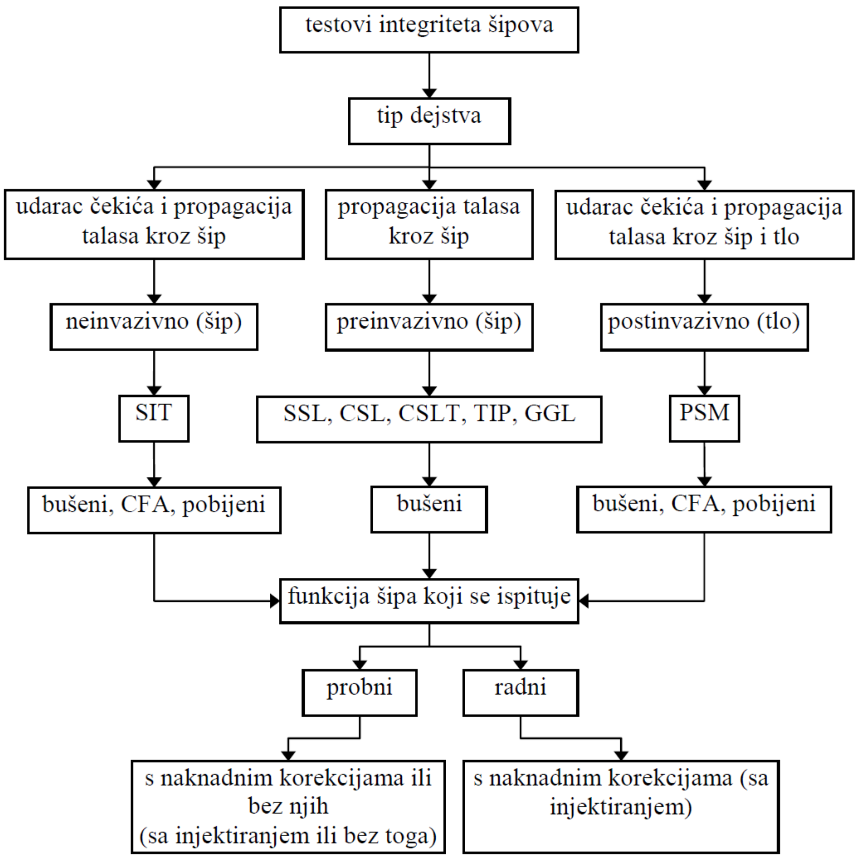
Since a larger number of pile integrity tests has been developed, the conducted classification is presented as the following:

– test integriteta šipa sa senzorom (SIT),
– test integriteta šipa sa jednom sondom (SSL),
– test integriteta šipa sa dve ili više sondi (CSL),
– test integriteta šipa sa 3D tomografskim prikazom (CSLT),
– test termalnog integriteta šipa (TIP),
– gama-gama test integriteta šipa (GGL),
– paralelna seizmička metoda (PSM).

Testovi integriteta šipova sprovode se kod: bušenih šipova izgrađenih tehnologijom bušenja i vađenja tla na površinu terena, šipova izgrađenih tehnologijom nevibriranja, odnosno bušenjem bez vađenja tla na površinu terena (CFA) i šipova izgrađenih tehnologijom pobijanja. Tipovi integriteta koji se ispituju ovim testovima klasifikovani su u nekoliko grupa: stvarna dužina šipa, promena porečnog preseka duž omotača šipa, pojava diskontinuiteta (prslina) duž omotača šipa, analiza defekata duž omotača šipa, analiza brzine propagacije talasa kroz šip, analiza gustine ili poroznosti betona i analiza temperature hidratacije cementa. U zavisnosti od samog pristupa šipu, ispitivanje integriteta može se sprovesti: preko glave šipa (neinvazivni test SIT), kroz instalirane cevi u šipu (preinvazivna priprema testa SSL, CSL, CSLT, TIP, GGL) i preko glave šipa i kroz instaliranu cev u tlu (neinvazivni test šipa, ali postinvazivna priprema tla PSM). Na slici 2 prikazan je dijagram toka opšte klasifikacije tipova testova integriteta šipova.

– SIT - *Sonic Integrity Test*,
– SSL - *Singlehole Sonic Logging*,
– CSL - *Crosshole Sonic Logging*,
– CSLT - *Crosshole Sonic Logging Tomography*,
– TIP - *Thermal Integrity Profiler*,
– GGL - *Gamma-Gamma Logging*,
– PSM - *Parallel Seismic Method*.

Pile integrity tests are carried out in the case of: bored piles built through the technology of drilling and extracting soil out onto the surface of the field, pile built through a non-vibration technology, i.e. by continuous flight auger (CFA), and the pile built through the driving technology. The integrity types examined in these tests are classified into several groups: the actual pile length, changes in the cross-section along the pile shell, the occurrence of discontinuity (cracks) along the pile shell, the analysis of the defects along the pile shell, the analysis of the velocity of the wave propagation through the pile, concrete density or porosity analysis, and the cement hydration temperature analysis. Depending on the available access to the pile, the integrity testing can be conducted: through the pile head (a non-invasive test SIT), through the tubes installed in the pile (a pre-invasive test preparation SSL, CSL, CSLT, TIP, GGL) and through the pile head and via the tube installed in the ground (non-invasive pile test, yet a post-invasive ground preparation PSM). Figure 2 shows a flowchart of the general pile integrity test types classification.



Slika 2. Dijagram toka opšte klasifikacije tipova testova integriteta šipova

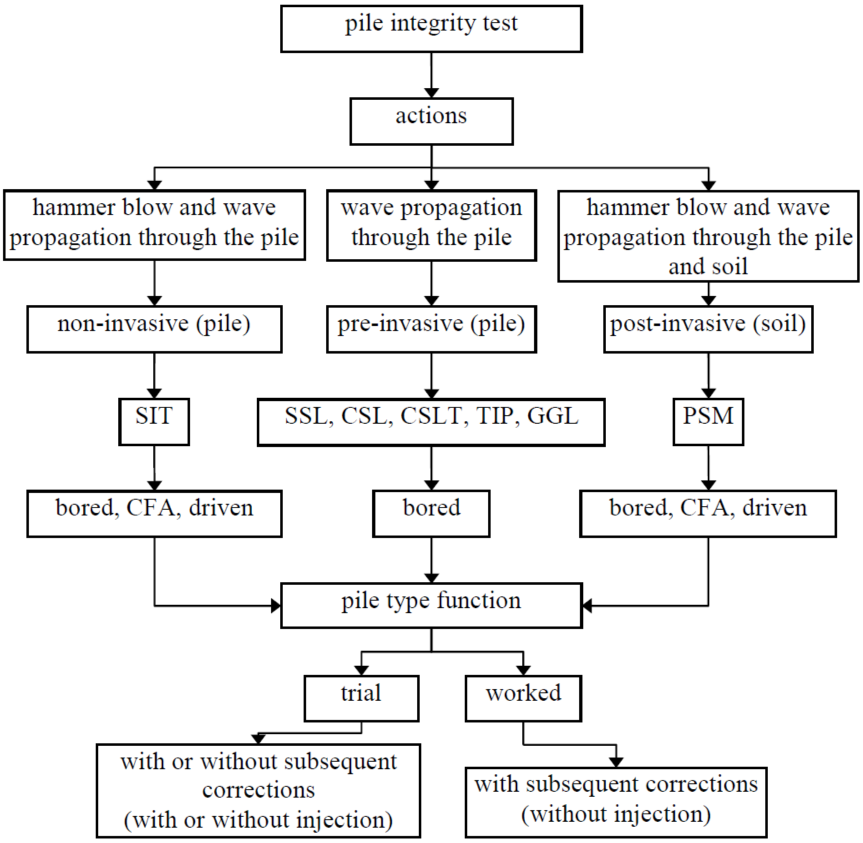


Figure 2. Flowchart of the general pile integrity test types classification

Test integriteta šipa sa senzorom (SIT ili PIT) u praksi se zove i test eha zvuka (SET) ili test eha šipa (PET), a pripada grupi niskodilatacionih testova (LST) [6]. Test integriteta šipa sa senzorom (SIT) zasniva se na teoriji propagacije talasa kroz šip, s ciljem utvrđivanja defekata/diskontinuiteta i dužine šipa. Ovaj test realizuje se na principu indukovanja, propagacije, refleksije, refrakcije i recepcije talasa u šipu. Indukcija talasa inicira se putem spoljašnjeg dejstva, udarom čekića, tako da je spoljašnji transmitovani signal, u opštem slučaju, impulsnog karaktera. Propagacija talasa kroz šip sprovodi se nakon iniciranja talasa, od glave do baze šipa i suprotno. Efekat refleksije javlja se na mestu kontakta dva različita medijuma, u konkretnom slučaju, na mestu baze šipa i tla, gde talas propagira ka glavi šipa. Refrakcija talasa jeste efekat prelamanja talasa na kontaktu dva medijuma, kao što je kontakt baze i omotača šipa s tlom. Bazni uslov, koji treba da je ispunjen kako bi se mogao efikasno razmatrati integritet šipa ovim testom, jeste da dužina talasa, koji se inicira, bude veća od prečnika šipa, tako da se propagacija talasa u šipu može razmatrati primenom jednodimenzionalne teorije rasprostiranja talasa u čvrstom medijumu. Zapis promene brzine propagacije talasa u vremenu, mereno na mestu glave šipa, prikazuje se putem reflektograma. Generalno razmatrajući, promene na reflektogramu javljaju se usled promene u bazi šipa, promene u prečniku duž omotača šipa, delimičnom inkluzijom tla u domen šipa, prslinama (većim, značajnijim), varijacijom kvaliteta materijala šipa, varijacijom slojeva tla i uticajem armaturnog čelika u šipu (jako

Sonic Integrity Test (SIT) or Pile Integrity Test (PIT), is also commonly known as Sonic Echo Test (SET) or Pile Echo Test (PET), and it is one of the Low Strain Tests (LST) [6]. SIT is based on the theory of wave propagation through the pile with the aim of determining defects/discontinuities and the length of the pile. This test is carried out on the principle of induction, propagation, reflection, refraction, and reception of the waves in the pile. The wave induction is initiated via the outside action, by a hammer hit, so the external transmitted signal is of impulse type, in general. Wave propagation through the pile is conducted after the wave induction, from the pile head to its base and vice versa. The reflection effect occurs where two different mediums come into contact, in this case, on the spot of pile base and the ground, where the wave propagates towards the pile head. Wave refraction is the effect of wave fraction on the point of contact between the two mediums, such as the contact between the pile base and shell with the ground. The basic condition, which needs to be fulfilled, so as to efficiently examine the pile integrity via this test, is that the length of the wave, which is initiated, is bigger than the pile diameter, so that the wave propagation in the pile can be examined through the application of the one-dimensional theory of wave propagation in a solid medium. The record of the wave propagation velocity in the period of time, measured on the pile head point, is presented via reflectogram. In general, the changes on the reflectogram occur due to the change in the pile base, the change in the diameter along the pile shaft, partial inclusion of the ground in the pile domain, cracks armirani šip). Test integriteta šipa sa senzorom (SIT) zasniva se na: dinamici kretanja krutog tela, talasnoj teoriji, metodi karakteristika, teoriji elastičnosti, dinamici konstrukcija, interakciji konstrukcija-tlo i teoriji i obradi signala. Prema dinamici kretanja krutog tela, razmatra se apliciranje spoljašnjeg dejstva udarom idealno krutog tela (čekića) o glavu šipa. Prema talasnoj teoriji, razmatraju se aspekti propagacije talasa kroz šip i tlo. Prema metodi karakteristika, razmatraju se aspekti kretanja odlazećih i dolazećih talasa sa identifikacijom defekata i diskontinuiteta u šipu. Prema teoriji elastičnosti, uzima se u obzir to što je konstitutivni model ponašanja šipa i tla linearno-elastičan. Prema dinamici konstrukcija, razmatraju se oscilacije šipa u interakciji sa tlom u vremenskom domenu. Prema interakciji konstrukcija-tlo, razmatra se spregnut problem statičke i dinamičke interakcije i reakcije dva medijuma (šip i tlo), bitno različitih fizičko-mehaničkih karakteristika. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala, s ciljem dobijanja odgovarajućih konačnih rezultata, primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o stanju integriteta šipa. Oprema za sprovođenje testa integriteta šipa sa senzorom (SIT) sastoji se iz: klasičnog mehaničkog čekića ili mehaničkog čekića povezanog električnim kablom za merenje karakteristika indukovanog signala, čije vreme trajanja ne sme biti duže od 1ms i ne sme prouzrokovati defekat šipa (za šipove prečnika manjeg od 1m koriste se čekići težine 0.5kg, 1.5kg i 3.5kg, a za šipove prečnika većeg od 1m koriste se čekići težine 1.5kg, 3.5kg i 6kg), senzora (akcelerometra) za prijem signala (opsega akceleracija minimalno 50g, rezonantne frekvencije minimalno 30kHz i tačnosti minimalno 5%) i uređaja za akviziciju, memorisanje, obradu i vizuelizaciju podataka. Test integriteta šipa sa senzorom (SIT) sprovodi se u nekoliko koraka: analiziraju se svi relevantni podaci u pasošu šipa i geotehničkom elaboratu, setuje se oprema, podaci i parametri za šip koji se ispituje, aplicira se udarac čekića u zoni centra ose šipa, na prethodno pripremljenu površinu glave šipa se postavi senzor (akcelerometar), pri čemu treba da je udaljenost pozicije senzora od mesta aplikacije udarca maksimalno 300mm, postupak se ponavlja nekoliko puta (minimalno 3 puta), a ukoliko se pokaže potrebnim koriguju se parametri skaliranja i filtriranja (za šipove prečnika većeg od 500mm primenjuju se 4 merenja - u 2 ortogonalna-radijalna pravca), konstruiše se reprezentativni reflektogram za prosečne vrednosti (3 reflektograma) i naknadno se sprovodi obrada podataka dobijenih reflektograma.

Test integriteta šipa sa sondama (CSL) pripada grupi niskodilatacionih testova (LST), pri čemu postoje varijantna rešenja s jednom sondom ili većim brojem sondi [7]. Test integriteta šipa ili test eha zvuka s jednom sondom (SSL ili SHUT) sprovodi se radi analize defekata/diskontinuiteta u šipu, a zasniva se na propagaciji talasa primenom sonde u kojoj su smešteni transmiter i risiver. Talasi se emituju putem transmitera, propagiraju kroz vodu, zid cevi, šip, reflektuju na mestima kontakta s tlom i prihvataju risiverom. S

(bigger, more significant), pile material quality variation, soil layers' variation, and the influence of the reinforcing steel in the pile (high reinforced pile). SIT is based on: rigid-body dynamics, wave theory, method of characteristics, theory of elasticity, dynamics of structures, soil-structure interaction (SSI), and theory and signal processing. According to the rigid-body dynamics, the application of an external action through a hit from an ideally rigid-body (hammer) onto the pile head is considered. According to the wave theory, the aspects of wave propagation through the pile and the soil are considered. According to the method of characteristics, the propagation aspects of downward and upward waves with the identification of defects and discontinuities in the pile are considered. According to the theory of elasticity, we take into account the fact that the constitutive models of the pile and soil are linear-elastic. According to the dynamics of structures, the pile oscillations during the interaction with the soil within the time domain are considered. According to soil-structure interaction, the coupled problem of static and dynamic interaction and reaction of two mediums (pile and soil), with significantly different physical-mechanical properties are considered. According to the theory and signal processing, signal digitalisation and processing are considered with the aim of acquiring corresponding final results, practically applicable in civil engineering, and with the help of which the decisions regarding the pile integrity conditions are reached. SIT equipment consists of: a conventional mechanic hammer or a mechanic hammer connected to an electric cable for measuring induced signal characteristics, whose period must not be longer than 1ms and must not cause a defect in the pile (for piles of less than 1m in diameter, hammers weighing 0.5kg, 1.5kg and 3.5kg are used, and for piles bigger than 1m in diameter, hammers weighing 1.5kg, 3.5kg and 6kg are used), sensor (accelerometer) for signal reception (of minimum acceleration range 50g, minimum resonance frequencies 30kHz and minimum accuracy 5%), and data acquisition, storage, processing, and visualisation equipment. SIT is conducted in a few steps: all the relevant data in the pile's passport and geotechnical study are analyzed, the equipment, data, and parameters are set for the pile being tested, hammer hit is applied in the pile axis centre zone, a sensor (accelerometer) is placed onto the previously prepared pile head surface, while the sensor position should not be more than 300mm away from the hit application point, the process is repeated several times (minimum of 3), and, if it turns out to be necessary, the scaling and filtering parameters are adjusted (4 measurements are applied for the piles bigger than 500mm in diameter - in 2 orthogonal radial directions), a representational reflectogram for average values (3 reflectograms) is produced, and data processing from acquired reflectograms is additionally conducted.

Crosshole Sonic Logging (CSL) belongs to the group of low strain tests (LST), while there are variant solutions with one or a number of probes [7]. Singlehole Sonic Logging (SSL) or Singlehole Ultrasonic Test (SHUT) is conducted with the aim of analyzing defects/discontinuities in the pile, and it is based on the wave propagation by implementation of a probe which contains a transmitter and a receiver. The waves are emitted via the transmitter, they propagate through the obzirom na to što se transmiter spušta/podiže vertikalno naniže/naviše duž šipa, kontinualno se prati signal koji se dobija putem risivera. U tom smislu, ovaj test najviše se koristi za direktnu analizu defekata u poprečnom preseku, pa se integracijom odgovora dobija kompletnija slika o stanju šipa. Primena testa eha zvuka, s jednom sondom (SSL), najzastupljenija je kod šipova manjeg prečnika ili kod šipova kod kojih se, usled odgovarajućih ograničenja za ispitivanje, može koristiti mala zona poprečnog preseka. Test integriteta šipa ili test eha zvuka s dve sonde ili više sondi (CSL ili CHUT), slično testu integriteta šipa s jednom sondom (SSL), zasniva se na propagaciji talasa primenom sondi, međutim, s razdvojenim transmiterom i risiverom. U jednu cev postavlja se transmiter, a u drugu risiver, tako da se postepenim spuštanjem/podizanjem transmitera i risivera vertikalno naniže/naviše prati stanje šipa po poprečnim presecima duž omotača šipa. Integracijom dobijenih analiza duž šipa, dobija se kompletna slika o mogućim defektima/diskontinuitetima, pri čemu se mogu detektovati i manji defekti, prsline (veće, značajnije), šupljine, intruzija sa vodom/tlom i betonska gnezda. Najveći broj defekata identifikuje se u okolini cevi, međutim, za veće prečnike šipova može se koristiti veći broj cevi za sprovođenje testa. Na taj način, dobija se kvalitetnija slika stanja integriteta šipa. 2D ili 3D tomografija integriteta šipa (CSLT) jeste dodatno unapređena verzija testa integriteta šipa s dve sonde ili više sondi (CSL). Prilikom ovog testa, beleže se emitovani signali pod različitim uglovima i pravcima, a ne samo direktno horizontalno između transmitera i risivera, tako da se naknadnim procesiranjem i rekonstrukcijom dobija 2D i 3D prikaz stanja u šipu, pri čemu se vizuelno volumenski mogu jasno uočiti i izdvojiti defekti/diskontinuiteti kao nezavisne celine. Takođe, ovi defekti i kompletan šip mogu se prikazati u 4D. Test integriteta šipa sa sondama (CSL) zasniva se na: talasnoj teoriji, teoriji elastičnosti i teoriji i obradi signala. Prema talasnoj teoriji, razmatraju se aspekti propagacije talasa kroz šip, vodu i cevi. Prema teoriji elastičnosti, uzima se u obzir to što je konstitutivni model ponašanja šipa linearno-elastičan. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala, s ciljem dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o stanju integriteta šipa. Oprema za sprovođenje testa integriteta šipa sa sondama (CSL) sastoji se iz: metra s tegom za preliminarnu proveru dužine i nezapušenosti instaliranih cevi, transmitera (generiše ultrazvučni signal frekvencije od 30kHz do 100kHz), risivera (frekvencije do 50kHz), kablova za povezivanje transmitera i risivera sa uređajem za akviziciju podataka, tripoda za kablove sa senzorima za pozicioniranje sondi i uređaja za akviziciju, memorisanje, obradu i vizuelizaciju podataka. Test integriteta šipa sa sondama (CSL) sprovodi se u nekoliko koraka: analiziraju se svi relevantni podaci u pasošu šipa i geotehničkom elaboratu, definiše se orijentacija cevi u šipu, u odnosu na poziciju ostalih šipova i naglavnu ili temeljnu ploču, cevi se ispune vodom pre betoniranja šipa ili sat vremena nakon toga, setuju se oprema, podaci i parametri za šip koji se ispituje, u cev se paralelno spuštaju/podižu transmiter i risiver, a za SSL test transmiter pa risiver, mada su zajedno povezani istim kablom, transmiter i risiver se spuštaju približno do 50mm od kraja cevi, a zatim

water, wall, tubes, pile, are reflected on the points of contact with the soil, and picked up by the receiver. Since the transmitter is lowered/lifted vertically downwards/upwards along the pile, the signal, picked up through the receiver, is continuously being monitored. In that respect, this test is mostly used for a direct analysis of the defects in the cross-section, and the response integration gives a more complete image of the pile condition. Singlehole Sonic Logging (SSL) application is the most frequent in the case of piles of a smaller diameter or in the case of the piles in which, as a result of corresponding testing limitations, a small zone of the cross-section can be used. Crosshole Sonic Logging (CSL) or Crosshole Ultrasonic Test (CHUT), similarly to SSL, is based on wave propagation by probes implementation, though with a separate transmitter and a receiver. Transmitter is placed in one tube, and receiver in the other, so that through the gradual lowering/lifting of the transmitter and the receiver vertically downwards/upwards we can record the pile condition on the cross-sections along the pile shaft. Integration of the obtained analyses along the pile, gives a complete image of the possible defects/discontinuities, also allowing for detection of the smaller defects, cracks (larger, more significant), cavities, water/soil intrusion, and honeycombs in the concrete texture. The largest number of defects is identified in the tube adjacent area, while a larger number of tubes to perform the tests are used for larger pile diameters. Thus, a higher quality image of the pile condition is obtained. A 2D or 3D Crosshole Sonic Logging Tomography (CSLT) is an additionally improved version of the CSL. In this test, signals emitted under different angles and directions are recorded, not only directly horizontally between the transmitter and the receiver, hence, the subsequent processing and reconstruction gives 2D and 3D pictures of the condition in the pile, whereby the defects/discontinuities can clearly be visually, in full volume, spotted as independent units. Also, the defects and the whole pile can be represented in 4D. CSL is based on: wave theory, theory of elasticity, and theory and signal processing. According to the wave theory, the aspects of wave propagation through the pile, water, and tubes are considered. According to the theory of elasticity, we take into account that the constitutive model of the pile is linear-elastic. According to the theory and signal processing, signal digitalisation and processing are considered with the aim of acquiring corresponding final results, practically applicable in civil engineering, and with the help of which the decisions regarding the pile integrity conditions are reached. CSL equipment consists of: a meter with a weight for a preliminary check of the length and the potential blockages in the installed tubes, a transmitter (it generates an ultrasonic signal of 30kHz to 100kHz in frequency), a receiver (up to 50kHz frequency), cables for connecting the transmitter and the receiver with the data acquisition equipment, a tripod for cables with sensors for probes positioning, and data acquisition, storage, processing, and visualisation equipment. CSL is conducted in several steps: all the relevant data in the pile's passport and geotechnical study are analyzed. The tube orientation within the pile is defined in relation to the position of the other piles and the pile cap or the base foundation plate. The tubes are filled with water before or an hour after pouring concrete. The započinje proces snimanja signala uz postepeno (polako) podizanje transmitera i risivera, kada se ispitivanje sprovodi u cilju 2D ili 3D tomografskog prikaza integriteta šipa (CSLT), preporuka je da vertikalna visinska razlika između transmitera i risivera bude do 300mm (najviše do 500mm), konstruišu se adekvatni dijagrami, odnosno ultrazvučni profili i naknadno se sprovodi obrada podataka dobijenih ispitivanjem.

Test termalnog integriteta šipa (TIP) pripada grupi niskodilatacionih testova (LST) i zasniva se na analizi temperature hidratacije cementa radi identifikacije defekata/diskontinuiteta kod bušenih i nekih tipova CFA šipova [5]. Karakteristike ovog testa jesu to što se mogu analizirati kompletni poprečni preseci duž šipa i indicirati zone betona viših i nižih kvaliteta, a mogu se otkriti i veoma mali defekti/diskontinuiteti u šipu. Varijantna rešenja ovog testa integriteta su: s jednom sondom, dve sonde ili više sondi i kablovima s termalnim senzorima. Test termalnog integriteta šipa (TIP) zasniva se na: termodinamičkoj teoriji, teoriji elastičnosti i teoriji i obradi signala. Prema termodinamičkoj teoriji, razmatraju se aspekti provođenja toplote kroz šip. Prema teoriji elastičnosti, uzima se u obzir to što je konstitutivni model ponašanja šipa linearno-elastičan. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala, s ciljem dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o stanju integriteta šipa. Oprema za sprovođenje testa termalnog integriteta šipa (TIP) sastoji se iz: metra s tegom za preliminarnu proveru dužine i nezapušenosti instaliranih cevi (ukoliko se koristi sistem sa cevima), sonde (4 ortogonalno postavljena senzora po jednoj sondi, ukoliko se koristi sistem sa cevima), kablova s termalnim senzorima (ukoliko se koristi sistem sa senzorima), kablova za povezivanje sonde ili kablova i senzora sa uređajem za akviziciju podataka, tripoda za kablove sa senzorima za pozicioniranje sondi i uređaja za akviziciju (frekvencija semplovanja signala minimalno 1Hz), memorisanje, obradu i vizuelizaciju podataka. Test termalnog integriteta šipa (TIP) s cevima sprovodi se u nekoliko koraka: analiziraju se svi relevantni podaci u pasošu šipa i geotehničkom elaboratu, definiše se orijentacija cevi u šipu, u odnosu na poziciju ostalih šipova i naglavnu ili temeljnu ploču, setuje se oprema, podaci i parametri za šip koji se ispituje, u cev se spušta sonda do 10cm od kraja (dna) cevi, a zatim započinje očitavanje uz postepeno (polako) podizanje, konstruiše se dijagram promene temperature duž šipa i naknadno se sprovodi obrada podataka dobijenih ispitivanjem. Test termalnog integriteta šipa (TIP) s kablovima i termalnim senzorima sprovodi se u nekoliko koraka: analiziraju se svi relevantni podaci u pasošu šipa i geotehničkom elaboratu, prethodno instalirani kablovi i senzori povezuju se sa uređajem za akviziciju podataka, setuju se oprema, podaci i parametri za šip koji se ispituje, senzorima se detektuje promena toplote hidratacije cementa, konstruiše se dijagram promene temperature duž šipa i naknadno se sprovodi obrada podataka dobijenih ispitivanjem.

equipment, data, and parameters are set for the pile being tested. The transmitter and the receiver are lowered/lifted in the tube in parallel with each other. For SSL the transmitter goes first and then the receiver. Although they are connected via the same cable, the transmitter and the receiver are lowered down approximately to the last 50mm of the tube, and then begins the signal recording process with gradual (slow) transmitter and receiver lifting, when the examination is conducted for the purposes of 2D or 3D CSLT. It is recommended that the vertical difference in height beween the transmitter and the receiver is up to 300mm (maximum 500mm). Adequate diagrams are constructed, i.e. the ultrasonic profile, and the data acquired through testing are additionally processed.

Thermal Integrity Profiler (TIP) belongs to the group of low strain tests (LST) and it is based on the cement hydration temperature analysis, with the aim of identifying the defects/discontinuities in bored and some types of CFA piles [5]. This test is characterised by the possibility of analysing the whole cross-sections along the pile and indicating zones of high and low-quality concrete, as well as detecting even the very small defects/discontinuities in the pile. The variant solutions of this integrity test are with: one probe, two or more probes and cables with thermal sensors. TIP is based on: thermodynamic theory, theory of elasticity, and theory and signal processing. According to thermodynamic theory, the aspects of heat conduction through the pile are considered. According to the theory of elasticity, we take into account that the constitutive model of the pile is linear-elastic. According to the theory and signal processing, signal digitalisation and processing are considered with the aim of acquiring corresponding final results, practically applicable in civil engineering, and with the help of which the decisions regarding the pile integrity conditions are reached. TIP equipment consists of: a meter with a weight for a preliminary check of the length and the potential blockages in the installed tubes (if the system with tubes is used), probes (4 orthogonally oriented sensors per probe, if the system with tubes is used), cables with thermal sensors (if system with sensors is used), cables for connecting the probe or cables and sensors with data acquisition device, a tripod for cables with sensors for probes positioning, and data acquisition (signal sampling frequency of minimum 1Hz), storage, processing, and visualisation equipment. TIP with tubes is conducted in several steps: all the relevant data in the pile's passport and geotechnical study are analyzed, we define the tube orientation within the pile, relative to the position of the other piles and the pile cap or the base foundation plate. The equipment, data, and parameters are set for the pile being tested, a probe is lowered inside the tube down to 10 cm from the tube's end (bottom), and then the reading process begins with gradual (slow) lifting, a diagram of the temperature change along the pile is constructed, and the data acquired through testing are additionally processed. TIP with cables and thermal sensors is conducted in several steps: all the relevant data in the pile's passport and geotechnical study are analyzed, the previously installed cables and sensors are connected to the data acquisition device, the equipment, data, and parameters are set for the pile being tested, the change in the cement hydration heat is

Gama-gama test integriteta šipa (GGL) pripada grupi niskodilatacionih testova (LST) i zasniva se na emitovanju i propagaciji gama zraka kroz šip, analizirajući gustinu ili poroznost betona i identifikujući defekte/diskontinuitete [21]. Ovaj test sprovodi se tako što se kroz instalirane cevi (potpuno suve) vertikalno naniže/naviše spušta/podiže integrisana sonda transmiter-risiver ili nezavisne sonde transmiter i risiver. Na osnovu etalonske vrednosti gustine betona, za svaki korak merenja, utvrđuje se odstupanje i konstruiše dijagram s prikazom zona visokih gustina, zona niskih gustina i tranzicione zone. Gama-gama test integriteta šipa (GGL) zasniva se na: talasnoj teoriji, teoriji elastičnosti i teoriji i obradi signala. Prema talasnoj teoriji, razmatraju se aspekti propagacije gama zraka kroz šip i cevi. Prema teoriji elastičnosti, uzima se u obzir to što je konstitutivni model ponašanja šipa linearno-elastičan. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala, s u ciljem dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o stanju integriteta šipa. Oprema za sprovođenje gama-gama testa integriteta šipa (GGL) sastoji se iz: metra s tegom za preliminarnu proveru dužine i nezapušenosti instaliranih cevi, transmitera (izvor emitovanja gama zraka treba da je cezijum 137), risivera (detektor gama zraka treba da se zasniva na principu rada *Geiger-Mueller*-ovog brojača), kablova za povezivanje transmitera i risivera sa uređajem za akviziciju podataka, tripoda za kablove sa senzorima za pozicioniranje sondi i uređaja za akviziciju, memorisanje, obradu i vizuelizaciju podataka. Gama-gama test integriteta šipa (GGL) sprovodi se u nekoliko koraka: analiziraju se svi relevantni podaci u pasošu šipa i geotehničkom elaboratu, definiše se orijentacija cevi u šipu, u odnosu na poziciju ostalih šipova i naglavnu ili temeljnu ploču, setuju se oprema, podaci i parametri za šip koji se ispituje, u cev se spuštaju/podižu transmiter i risiver (transmiter je s donje, a risiver s gornje strane, pri čemu radijus detekcije gama zraka treba da je od minimalno 7.5cm do maksimalno 12cm) - ispitivanje s jednom cevi, transmiter i risiver se spuštaju do 15cm od kraja (dna) cevi, a zatim započinje proces očitavanja uz postepeno (polako) podizanje transmitera i risivera (interval očitavanja treba da je maksimalno 4cm, uz minimalnih 200 očitavanja za ceo šip) - ispitivanje s dve cevi ili više cevi, konstruišu se adekvatni dijagrami s prikazom zona visokih gustina, zona niskih gustina i tranzicione zone i naknadno se sprovodi obrada podataka dobijenih ispitivanjem.

Paralelna seizmička metoda (PSM) pripada grupi niskodilatacionih testova (LST), a ovim postupkom se indirektnim putem, propagacijom talasa kroz šip i tlo, utvrđuje postojanje defekata/diskontinuiteta u šipu, a takođe određuje se njegova dužina. Ovaj test je posebno koristan za određivanje dužine postojećih šipova objekata. Aplikacijom spoljašnjeg dejstva po glavi ili bočnoj strani glave šipa, stvaraju se vibracije koje se prenose kroz šip i tlo, gde se primenom risivera beleže signali u digitalnom formatu, koji se naknadno obrađuju.

detected through the sensors, a diagram of the temperature change along the pile is constructed, and the data acquired through testing are additionally processed.

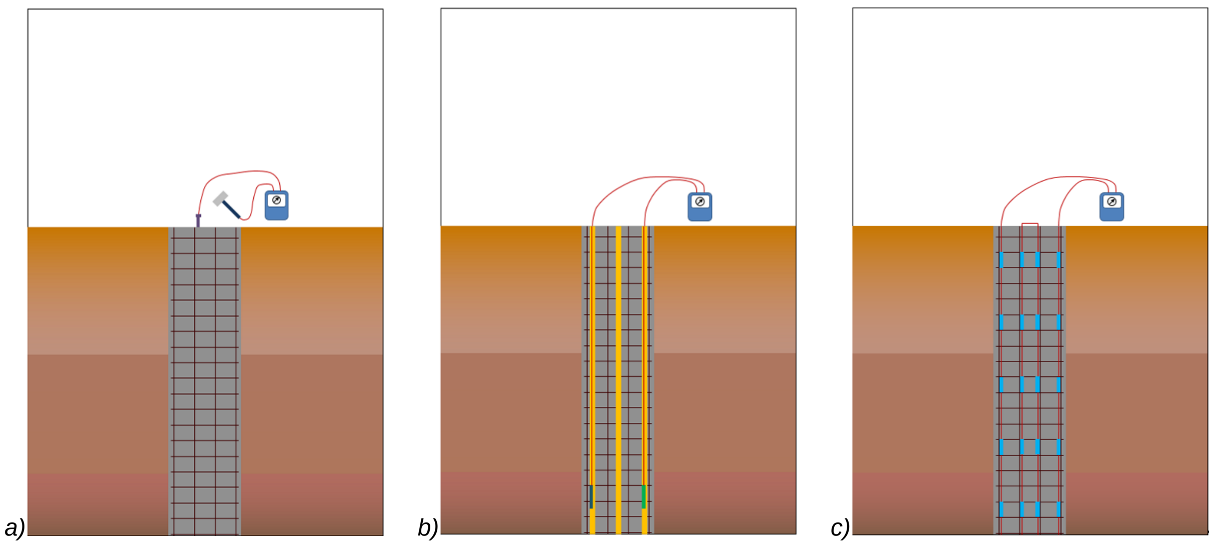
Gamma-Gamma Logging (GGL), belongs to the group of low strain tests (LST) and it is based on the emission and propagation of gamma rays through the pile, thus analysing the concrete density or porosity and identifying the defects/discontinuities [21]. This test is performed by lowering/lifting an integrated transmitter-receiver probe or independent transmitter and receiver probes vertically downward/upward through the installed tubes (completely dry). Based on the standard value of concrete density, for each step of the measuring, deviation is determined, and a diagram showing high density zones, low density zones and transition zones is constructed. GGL is based on: wave theory, theory of elasticity, theory and signal processing. According to the wave theory, we consider the aspects of the gamma ray propagation through the pile and tubes. According to the theory of elasticity, we take into account that the constitutive model of the pile is linear-elastic. According to the theory and signal processing, we consider signal digitalisation and processing with the aim of acquiring corresponding final results, practically applicable in civil engineering, and with the help of which the decisions regarding the pile integrity conditions are reached. GGL equipment consists of: a meter with a weight for a preliminary check of the length and the potential blockages in the installed tubes, a transmitter (gamma ray source should be caesium 137), a receiver (gamma ray detector should be based on the operation principle of the *Geiger-Mueller* counter), cables for connecting the transmitter and the receiver with the data acquisition device, a tripod for cables with sensors for probes positioning, and data acquisition, storage, processing, and visualisation equipment. GGL is conducted in several steps: all the relevant data in the pile's passport and geotechnical study are analyzed, then the tube orientation within the pile relative to the position of the other piles and the pile cap or the base foundation plate is defined, the equipment, data, and parameters are set for the pile being tested, the transmitter and the receiver are lowered/lifted within the tube (the transmitter is on the bottom side and the receiver on the top side, whereas the gamma ray detection radius should range between the minimum of 7.5cm to the maximum of 12cm) - the testing with one tube, the transmitter and the receiver are lowered down to 15cm from the tube's end (bottom), and then the reading process begins with gradual (slow) transmitter and receiver lifting (the reading interval should be up to the maximum of 4 cm, with a minimum of 200 readings for the whole pile) - the testing with two or more tubes, a diagram of the high density zones, low-density zones and transition zones is constructed, and the data acquired through testing are additionally processed.

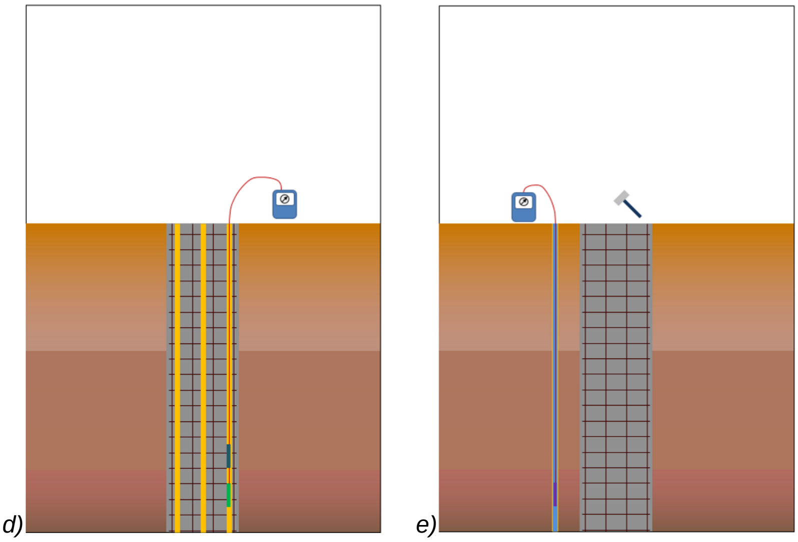
Parallel Seismic Method (PSM) belongs to the group of low strain tests (LST), and through this procedure, by wave propagation through the pile and the soil, we indirectly establish the existence of defects/discontinuities in the pile, as well as determine its length. This test is particularly useful for determining the depth of the existing piles. Application of an external action on the pile's head or its lateral side produces vibrations which are transmitted through the pile and the soil, Analizom serije zabeleženih signala, utvrđuju se stvarna dužina šipa i eventualno postojanje defekata/dis-kontinuiteta. Paralelna seizmička metoda (PSM) zasniva se na: talasnoj teoriji, teoriji elastičnosti i teoriji i obradi signala. Prema talasnoj teoriji, razmatraju se aspekti propagacije talasa kroz šip, tlo, cev i vodu. Prema teoriji elastičnosti, uzima se u obzir to što je konstitutivni model ponašanja šipa linearno-elastičan. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala u cilju dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o stanju integriteta šipa. Oprema za sprovođenje paralelne seizmičke metode (PSM) sastoji se iz: klasičnog mehaničkog čekića ili mehaničkog čekića povezanog električnim kablom za merenje karakteristika indukovanog signala, čije vreme trajanja ne sme biti duže od 1ms i ne sme prouzrokovati defekat šipa, sonde (hidrofona) za prijem signala (longitudinalnih i transverzalnih talasa) na svakih 10cm do 50cm duž šipa (frekvencija semplovanja minimalno 50kHz), čelične cevi i uređaja za akviziciju, memorisanje, obradu i vizuelizaciju podataka. Paralelna seizmička metoda (PSM) sprovodi se u nekoliko koraka: analiziraju se svi relevantni podaci u pasošu šipa i geotehničkom elaboratu, cev se utiskuje u tlo, a zatim ispuni vodom, setuju se oprema, podaci i parametri za šip koji se ispituje, u cev se spušta/podiže sonda (hidrofon) do kraja cevi, uz kontinualno snimanje signala i aplikaciju udarca čekićem, postupak se ponavlja nekoliko puta (minimalno 3 puta), a ukoliko se pokaže potrebnim koriguju se parametri skaliranja i filtriranja, konstruišu se reprezentativni signali u vremenskom domenu i nak-nadno se sprovodi obrada podataka dobijenih signala.

Na slici 3 dati su opšti šematski prikazi: a) testa integriteta šipa sa senzorom (SIT), b) testa integriteta šipa sa dve ili više sondi (CSL), c) testa termalnog integriteta šipa sa kablovima i termalnim senzorima (TIP), d) gama-gama testa integriteta šipa (GGL), e) testa integriteta šipa paralelnom seizmičkom metodom (PSM).

where the receiver records the signals in digital format, which are additionally processed. Through the analysis of the recorded signals we establish the actual length of the pile as well as the potential existence of any defects/discontinuities. PSM is based on: wave theory, theory of elasticity, theory and signal processing. According to the wave theory, the aspects of wave propagation through the pile, soil, tube and water are considered. According to the theory of elasticity, we take into account that the constitutive model of the pile is linear-elastic. According to the theory and signal processing, we consider signal digitalisation and processing with the aim of acquiring corresponding final results, practically applicable in civil engineering, and with the help of which the decisions regarding the pile integrity conditions are reached. PSM equipment consists of: a conventional mechanic hammer or a mechanic hammer connected to an electric cable for measuring induced signal characteristics, whose period must not be longer than 1ms and must not cause a defect in the pile, a probe (hydrophone) for signal reception (longitudinal and transverse waves) at every 10cm to 50cm along the pile (sampling frequency of minimum 50kHz), a steel tube, and data acquisition, storage, processing, and visualisation equipment. PSM is conducted in a few steps: all the relevant data in the pile's passport and geotechnical study are analysed, the tube is pressed into the ground, then filled with water, the equipment, data, and parameters are set for the pile being tested, a probe (hydrophone) is lowered/lifted inside the tube to the tube's end, while continuously recording the signal and applying the hammer hits, the procedure is repeated several times (at least 3 times), and if turns out to be necessary, the parameters of scaling and filtering are adjusted, representative signals are constructed in time domain, and the acquired signal data are subsequently processed.

Figure 3 gives a general scheme of: a) SIT, b) CSL, c) TIP with cables and thermal sensors, d) GGL, e) PSM.





Slika 3. Opšti šematski prikazi: a) testa integriteta šipa sa senzorom (SIT), b) testa integriteta šipa sa dve sonde ili više sondi (CSL), c) testa termalnog integriteta šipa sa kablovima i termalnim senzorima (TIP), d) gama-gama testa integriteta šipa (GGL), e) testa integriteta šipa paralelnom seizmičkom metodom (PSM)

Figure 3. The general scheme of: a) SIT, b) CSL, c) TIP with cables and thermal sensors, d) GGL, e) PSM

3 ISPITIVANJE NOSIVOSTI ŠIPOVA

S obzirom na to što je razvijen veći broj testova nosivosti šipova, ovde je prikazana sprovedena klasifikacija na:

- statički test opterećenja šipa (SLT),
- dinamički test opterećenja šipa (DLT),
- dinamički test opterećenja šipa pri pobijanju (PDT),
- hibridnamički test opterećenja šipa (HLT),
- statnamički test opterećenja šipa (SNLT),
- bidirekcioni statički test opterećenja šipa (BDSLT),
- test aksijalnog zatezanja šipa (ATT),
- test horizontalnog opterećenja šipa (LLT).

Tipovi nosivosti koje se ispituju ovim testovima klasifikovani su u tri grupe: aksijalni pritisak (kod svih testova ovog tipa SLT, DLT, PDT, HLT, SNLT aksijalna nosivost utvrđuje se opterećenjem šipa vertikalno naniže silom pritiska, dok se kod BDSLT šip opterećuje vertikalno naniže i vertikalno naviše silom pritiska), aksijalno zatezanje (aksijalna nosivost ATT utvrđuje se opterećenjem šipa vertikalno naviše silom zatezanja) i horizontalno dejstvo savijanjem (horizontalna nosivost LLT utvrđuje se opterećenjem šipa u horizontalnom pravcu silom pritiska). U zavisnosti od formulisanog programa ispitivanja šipa, funkcija šipa može biti: probni ili testni šip (šip se izlaže opterećenju do dostizanja graničnog stanja nosivosti - destruktivni test nosivosti (DT) ili eventualno nedestruktivni test nosivosti (NDT)) i radni ili eksploatacioni šip (šip se izlaže opterećenju do dostizanja projektne nosivosti, a čija je uloga da dokaže nivo projektne nosivosti šipa i ponašanje šipa pri nivou projektne nosivosti - nedestruktivni test nosivosti (NDT)). Spoljašnje dejstvo - opterećenje, gotovo kod svih šipova, aplicira se na glavu šipa, a sam karakter dejstva može biti sledeći: statičko (SLT, BDSLT, ATT, LLT), dinamičko (DLT, PDT, HLT) i prelazna kategorija statičko-dinamičko (SNLT). Spoljašnje dejstvo može biti

3 PILE LOAD TESTING

Since a larger number of pile load tests has been developed, the conducted classification is presented as the following:

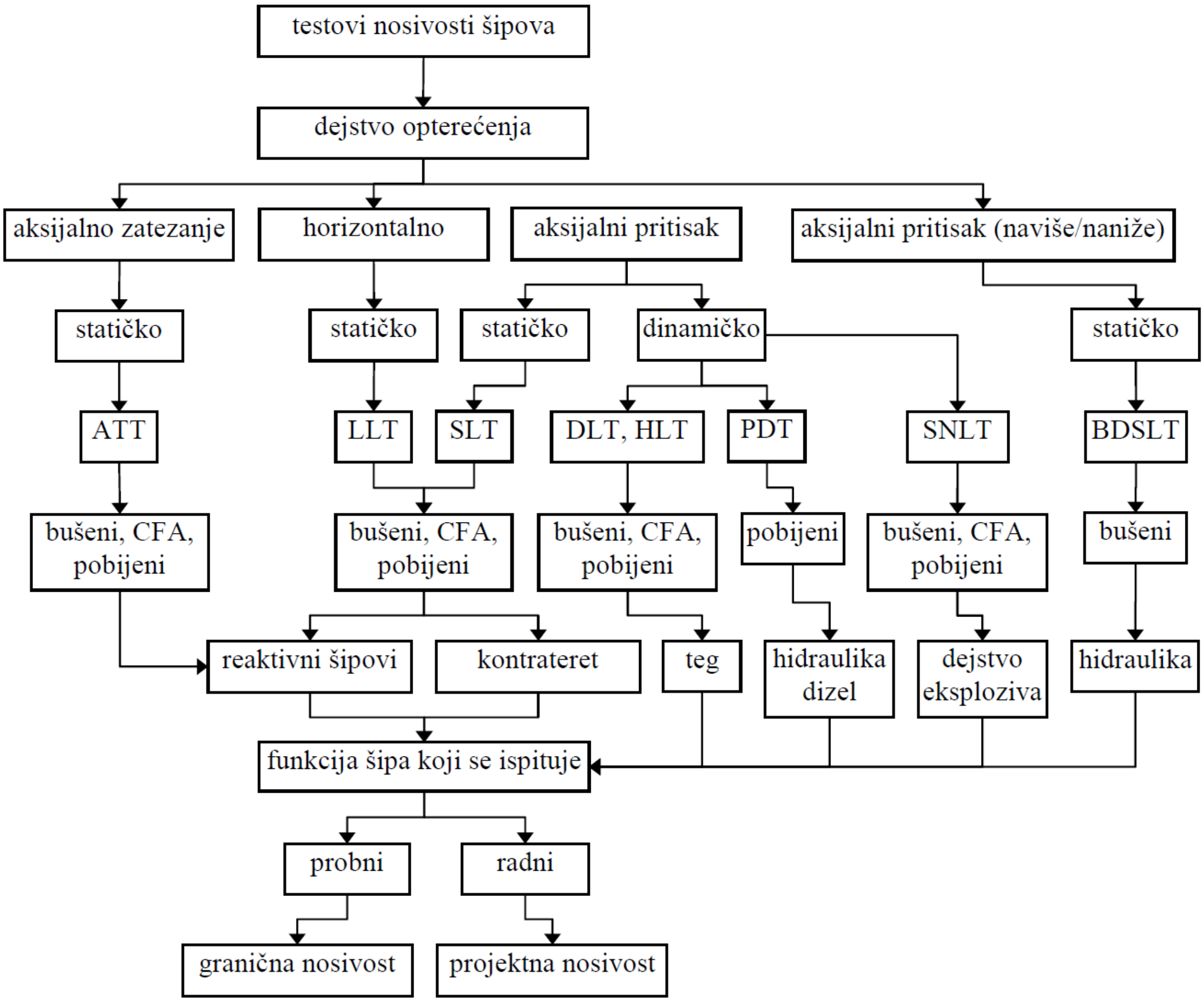
- SLT - *Static Load Test*,
- DLT - *Dynamic Load Test*,
- PDT - *Pile Driving Test*,
- HLT - *Hybridnamic Load Test*,
- SNLT - *Statnamic Load Test*,
- BDSLT - *Bi-Directional Static Load Test*,
- ATT - *Axial Tension Test*,
- LLT - *Lateral Load Test*.

Capacity types examined through these tests are classified into three groups: axial pressure (in case of all the tests of this type SLT, DLT, PDT, HLT, SNLT the axial load carrying capacity is determined by loading the pile vertically downwards by the force of pressure, while in the BDSLT case the pile is loaded vertically downwards and vertically upwards by the force of pressure), axial tension (axial load carrying capacity ATT is determined by loading the pile vertically upwards by the tension force), and the lateral bending effect (lateral load capacity LLT is determined by loading the pile in the horizontal direction by force of pressure). Depending on the formulated pile testing programme, the function of the pile can be: experimental or test pile (the pile is being loaded until the load capacity limit is reached by destructive testing (DT) or possibly non-destructive testing (NDT)), and working or exploitation pile (the pile is being loaded until the design load is reached, which has the role to prove the level of pile design load and the pile behaviour under the design load by non-destructive testing (NDT)). The external action - the load, in the case of almost all piles, is applied onto the head of the pile, and the type of the action can be: static (SLT, BDSLT, ATT, LLT), dynamic (DLT, PDT, HLT) and a transition static-dynamic category (SNLT). The external effect can proizvod: sopstvene težine kontratereta kod testova aksijalne nosivosti - sila pritiska šipova (SLT), reakcije od reaktivnih šipova kod testova aksijalne nosivosti - sila pritiska ili zatezanja šipova (SLT, ATT), reakcije pritiska u (približnom) nivou baze šipa (BDSLT), reakcije od kontratereta kod horizontalnog dejstva (LLT), reakcije od reaktivnih šipova kod horizontalnog dejstva (LLT), sile udara tega koji pada sa određene visine vertikalno naniže (DLT, PDT, HLT), sile od dejstva eksplozije i odbijanja tega vertikalno naviše (SNLT) i kontinualnih vibracija (PDT). Na slici 4 prikazan je dijagram toka opšte klasifikacije tipova testova nosivosti šipova.

Statički test opterećenja šipa (SLT) pripada grupi najpouzdanijih visokodilatacionih testova (HST) za utvrđivanje nosivosti šipova, ali, u pogledu pripreme i toka ispitivanja, ovo je najzahtevniji test [2]. Generalno razmatrajući, postoje dve varijante prema kojima se ovaj test može izvoditi: test s kontrateretom i test s reaktivnim šipovima. U prvom slučaju, pre sprovođenja testa, potrebno je dopremiti i geometrijski pravilno složiti kontrateret koji, u zavisnosti od nosivosti šipa, može biti

be a product of: the counter-load's own weight in the case of axial load tests - the pile pressure force (SLT), the reaction of reaction piles' in the case of axial load tests - the pile pressure or tension force (SLT, ATT), pressure reaction in the pile base (approximate) level (BDSLT), the counter-load's reaction in the case of lateral action (LLT), the reaction of piles in the case of lateral action (LLT), impact force of the weight falling from the certain height vertically downwards (DLT, PDT, HLT), the explosion force and the weight rebounding vertically upwards (SNLT), and continuous vibrations (PDT). Figure 4 shows a flowchart of the general pile load test types classification.

Static Load Test (SLT) belongs to the group of the most reliable high strain tests (HST) for determining pile load capacity, but, in terms of preparation and process, this is also the most demanding test [2]. Generally speaking, there are two variant ways in which this test can be performed: the test with a counter-load and the test with reaction piles. In the first case, prior to conducting the test, the counter-load, which can weigh



Slika 4. Dijagram toka opšte klasifikacije tipova testova nosivosti šipova

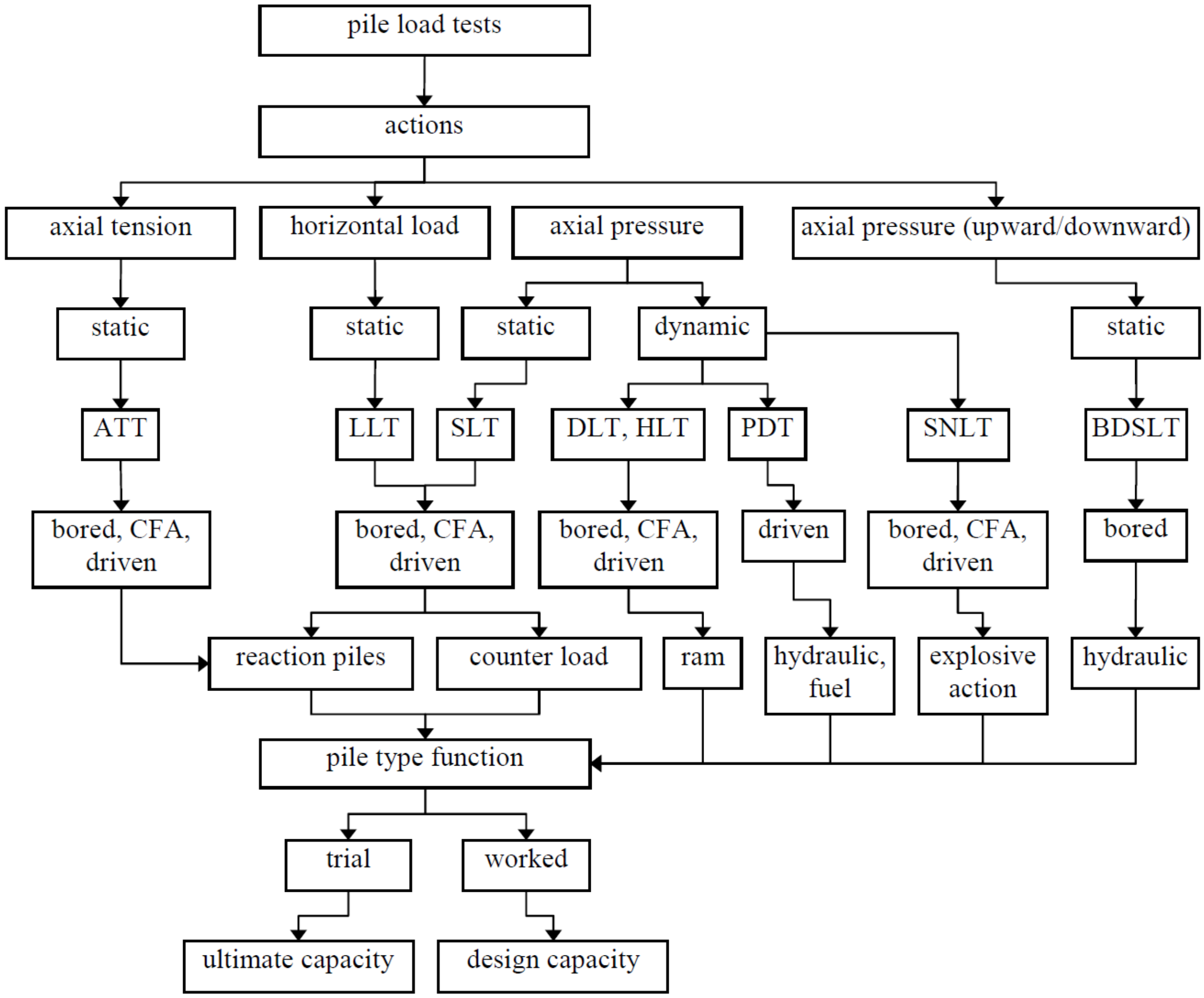


Figure 4. Flowchart of the general pile load test types classification

biti težine od nekoliko stotina do nekoliko hiljada tona. U drugom slučaju, koriste se reaktivni šipovi, koji su u toku ispitivanja opterećeni na zatezanje. Na glavu šipa postavlja se hidraulična presa preko koje se, pod inkrementalnim priraštajem pritiska ulja, istiskuje klip. Usled istiskivanja klipa i suprostavljanja težine kontratereta ili sila reaktivnih šipova, ispitivani šip se utiskuje u tlo. Primenom komparatera, prati se sleganje glave šipa. Takođe, primenom geodetskih uređaja, prati se sleganje šipa preko mernih letvi, tako da se komparacijom i naknadnom korekcijom merenja komparaterima utvrđuju krajnje vrednosti rezultata sleganja. Na osnovu sprovedenog testa, uspostavlja se relacija opterećenje-sleganje putem krive probnog opterećenja, a zatim se određuje nosivost šipa nekom od matematičkih metoda. Statički test opterećenja šipa (SLT) može se sprovoditi primenom dva varijantna rešenja: test s kontrateretom (dejstvo pritiska se realizuje usled odupiranja prese o dejstvo sopstvene težine kontratereta) i test s reaktivnim šipovima (dejstvo pritiska se realizuje usled odupiranja prese o poprečnu čeličnu gredu/traverzu koja je povezana s reaktivnim šipovima). Pod terminom ispitivanje nosivosti šipa,

between a few hundred and a few thousand tons, depending on the pile load capacity, needs to be delivered and arranged into regular geometric shapes. In the second case, we use reaction piles, which sustain tension force through the course of testing. A hydraulic press is placed on the pile head, and the piston is pressed out through it, under the incremental increase in the pressure of the oil. As a consequence of piston ejection and the opposing weight of the counter-load or the reaction piles' forces, the pile is pressed into the ground. Pile head settlement is tracked via comparators. Also, through the use of geodetic instruments we can track the pile settlement by means of measuring battens, so that by comparing and subsequently correcting the measurements, the comparators can determine the final values of settlement results. On the basis of the conducted test, load-to-settlement relation is established by means of trial-load curve, and then the pile load capacity is determined through one of the mathematical methods.

SLT can be conducted through implementation of two variant solutions: the test with a counter-load (the pressure effect is realised as a consequence of the podrazumeva se utvrđivanje intenziteta reaktivnih sila šipa u kumulativnoj formi (po omotaču i bazi). Statičkim testom opterećenja šipa (SLT) utvrđuje se aksijalna vertikalna nosivost šipa (bazom i omotačem) na statičku silu pritiska (vertikalno naniže), a koja se aplicira na glavu šipa, pri čemu postoje dve opcije: da se šip ispituje na opterećenje pritiskom do dostizanja granične nosivosti (probni šip), a koja je prethodno određena u funkciji faktorisane vrednosti zahtevane projektne nosivosti (faktor sigurnosti jeste od 2 do 3) ili da se šip ispituje na opterećenje pritiskom do dostizanja projektne nosivosti (radni šip), a koja je prethodno određena u funkciji faktorisane vrednosti zahtevane projektne nosivosti i čija je uloga samo da dokaže nivo projektne nosivosti šipa i ponašanje šipa pri nivou projektne nosivosti (faktor sigurnosti minimalno 1.1).

Statički test opterećenja šipa (SLT) zasniva se na: nelinearnoj teoriji, interakciji konstrukcija-tlo i teoriji i obradi signala. Prema nelinearnoj teoriji, uzima se u obzir to što je konstitutivni model ponašanja šipa i tla nelinearno-plastičan. Prema interakciji konstrukcija-tlo, razmatraju se spregnut problem statičke interakcije i reakcije dva medijuma (šip i tlo), bitno različitih fizičko-mehaničkih karakteristika. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala, s ciljem dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o nosivosti šipa. Potiskivanjem klipa iz cilindra prese, na glavu šipa, aplicira se sila čiji se intenzitet inkrementalno povećava i smanjuje putem: ciklusa samo jednog opterećenja i jednog rasterećenja ili većeg broja ciklusa opterećenja i rasterećenja, koji mogu biti različitih maksimalnih intenziteta. Za probni šip opterećenje aplicira se inkrementalno do maksimalne sile definisane programom ispitivanja, a koja treba da je jednaka 200% vrednosti projektne nosivosti šipa. Za radni šip opterećenje se aplicira inkrementalno do maksimalne sile definisane programom ispitivanja, koja treba da je jednaka faktorisanoj vrednosti projektne nosivosti šipa. Vrednost inkrementa opterećenja treba da je jednaka 25% vrednosti ukupnog opterećenja. Nakon potpunog apliciranja opterećenja, sprovodi se potpuno raterećenje. Naredni ciklus opterećenja može se, takođe, sprovoditi do maksimalne sile definisane programom ispitivanja. Vrednost svakog inkrementa aplicirane sile treba održavati na konstantnoj vrednosti, uz postizanje uslova da sleganje bude manje od 0.25mm za vreme od 1 sata, ali ne duže od 2 sata. Vrednost aplicirane sile koja odgovara projektnoj nosivosti šipa i maksimalnoj sili definisanoj programom ispitivanja treba održavati na konstantnoj vrednosti, uz postizanje uslova da sleganje bude manje od 0.25mm za vreme od 2 sata, ali ne duže od 4 sata. Nakon sprovedenog statičkog testa opterećenja šipa (SLT), obrađuju se podaci merenja i konstruiše finalna kriva opterećenje-sleganje, a zatim se određuje granična nosivost šipa.

press resistance to the counter-load's own weight) and the test with reaction piles (the pressure effect is realised as a consequence of the press resistance to the steel crossbeam/transverse beam which is connected to the reaction piles). The term pile load testing stands for determining the intensity of pile reaction forces in a cumulative form (via the shaft and the base). SLT determines the axial vertical load carrying capacity (by the base and the shaft) on the static pressure force (vertically downwards), and which is applied to the pile head, with two options: to test the pile by applying pressure until the limit carrying capacity is reached (test pile), and which has been previously established in the factorised value function of the required design load (the safety factor is between 2 and 3), or to test the pile by applying pressure until the design load is reached (working pile), which has been previously established in the factorised value function of the required design load and with the sole role of demonstrating the level of the pile design load and the pile behaviour while under the design load (safety factor minimum 1.1). SLT is based on: non-linear theory, soil-structure interaction, and theory and signal processing. According to the non-linear theory, we take into account the fact that the constitutive models of the pile and soil are non-linear-plastic. According to soil-structure interaction, the coupled problem of static interaction and reaction of two mediums (pile and soil), with significantly different physical-mechanical properties are considered. According to the theory and signal processing, signal digitalisation and processing with the aim of acquiring corresponding final results are considered. They are practically applicable in civil engineering, and with their help the decisions regarding the pile load capacity conditions are reached. A force is applied through pushing the piston from the press cylinder, to the pile head, whose intensity incrementally increases and decreases through the cycle of a single loading and a single unloading or a higher number of loading and unloading cycles, which can have different maximum intensities. In the case of a trial pile, the load is applied incrementally to the maximum force defined in the research programme, and which should be equal to 200% of the pile design load value. In the case of a working pile, the load is applied incrementally to the maximum force defined in the research programme, and which should be equal to the factorised value of the pile design load. The load increment value should be equal to 25% of the total load value. After a complete load application, complete unloading is carried out. The next loading cycle can also be carried out to the maximum force defined by the research program. The value of each increment of the applied force should be kept at a constant value, while achieving the conditions for subsidence to be less than 0.25mm during a 1 hour period, but no longer than 2 hours. The applied force value corresponding to the pile design load and the maximum force defined in the research program should be kept at a constant value, while achieving the conditions for subsidence to be less than 0.25mm during a 2 hour period, but no longer than 4 hours. After conducting the SLT the measurement data are processed and the final load-settlement curve is constructed, and then the ultimate load of the pile is determined.

Dinamički test opterećenja šipa (DLT) pripada grupi visokodilatacionih testova (HST) za utvrđivanje nosivosti šipova, pa je, s obzirom na vreme pripreme i toka ispitivanja, ovo dosta brži test u poređenju sa SLT [8]. Postoji nekoliko varijanti ovog testa, ali se ovde razmatraju: test opterećenja šipa pri udaru tega, test opterećenja šipa pri pobijanju i kombinovani testovi opterećenja šipa sa dinamičkim dejstvom. Dinamički test opterećenja šipa (DLT) zasniva se na utvrđivanju statičke nosivosti šipa pri dinamičkom dejstvu. Generalno razmatrajući, postoje dve varijante prema kojima se može ovaj test sprovoditi: test sa sopstvenim sistemom za podizanje tega i test sa pomoćnim sistemom za podizanje tega na određenu visinu. Zajedničko za obe ove varijante jeste to što se teg izlaže slobodnom padu sa određene visine i tako, usled udara tega o glavu šipa, izazove dinamičko dejstvo u šipu. U prvom slučaju, u okviru opreme za dinamičko ispitivanje, postoji sistem kojim se teg podiže na određenu visinu i tu zaustavlja kočnicama s varijantama: sa opremom samo povezanom za glavu šipa i opremom koja se oslanja na okolno tlo (za veće težine tega). U drugom slučaju, koriste se autodizalica, kran ili neko drugo slično vozilo kojim se teg podiže na određenu visinu, zadržava, te tako dozvoljava se njegovo slobodno padanje.

Dinamički test opterećenja šipa pri pobijanju (PDT) zasniva se na analizi nosivosti i monitoringu ponašanja šipa prilikom pobijanja. U odnosu na dinamički test opterećenja šipa (DLT), gde se koristi posebna oprema za ispitivanje nosivosti šipa, ovaj test se zasniva na korišćenju mašina za pobijanje šipova kao spoljašnjeg dinamičkog dejstva. Generalno razmatrajući, postoje dve varijante prema kojima se može ovaj test izvoditi: test s mašinom za pobijanje šipa pod udarcima tega (cikličan proces) i test s mašinom za pobijanje šipa vibracijama (kontinualan proces). Prednost dinamičkog testa pri pobijanju šipa (PDT), u odnosu na dinamički test šipa (DLT), jeste to što se kontinualno, u fazama pobijanja šipa kroz tlo, može pratiti i određivati sila reakcije u bazi i po omotaču. Takođe, mogu se pratiti i drugi efekti, kao što su provera integriteta šipa (npr. velike prsline, oštećenja, lom šipa).

Hibridnamički test opterećenja šipa (HLT) naziva se i brzi test opterećenja šipa (RLT), a u osnovi koristi princip dinamičkog testa opterećenja šipa (DLT), s tim što su eliminisani efekti naknadnih udara spoljašnjeg dejstva. Na taj način, naponsko stanje postaje sličnije naponskom stanju pri statičkom testu opterećenja šipa (SLT). U slučaju ovog testa postoje tri opcije za eliminisanje naknadnih udara: test s hibridnamičkim jastukom, test s hidrauličnim kočionim mehanizmom i test s kombinovanim sistemom (hibridnamički jastuk i hidraulični kočioni mehanizam). Zahvaljujući razvijenom hibridnamičkom jastuku, vreme apliciranja kinetičke energije, od spoljašnjeg dejstva (tega), na glavu šipa je znatnije produženo, nego što je to slučaj kod dinamičkog testa opterećenja šipa (DLT). Hibridnamički jastuk je oblika saća i sastoji se iz čeličnih ploča, ćelija ispunjenih vazduhom i elastomera koji ima svojstvo gume. Ovako konstruisan hibridnamički jastuk sprečava dodatno stvaranje naknadnih udara pri odbijanju tega od glave šipa, budući da ovo stvara dodatan negativan efekat u toku ispitivanja. U drugom slučaju ovaj test se sprovodi

Dynamic Load Test (DLT) belongs to the group of high strain tests (HST) for determining the pile load capacity, so, considering the amount of time that the preparation and the process take, this is a much faster test compared to the SLT [8]. There are several variants of this test, but the ones considered here are: pile load test in the case of weight (ram) impact, pile load test in the case of pile driving, and combined pile load tests with a dynamic effect. DLT is based on determining the static pile load capacity in the case of a dynamic effect. Generally speaking, there are two variant ways in which this test can be performed: a test with its own system for lifting the weight (ram), and a test with an auxiliary system for lifting the weight (ram) to a certain height. What these two variants have in common is that the weight is exposed to a free fall from a certain height, and thus, due to the impact on the pile head, it causes a dynamic effect in the pile. In the first case, as a part of the dynamic testing equipment, there is a system by which the weight is lifted to a certain height and then stopped there by brakes with variants: with the equipment only connected to the pile head, and the equipment that leans on the surrounding ground (for larger weights). In the second case, we use a crane, auto crane, or a similar vehicle, which helps lift the weight to a certain height, keep it, and then allowing its free fall.

Pile Driving Test (PDT) is based on load capacity analysis and pile behaviour monitoring while it is driven into the ground. Compared to the DLT, where special equipment is used for pile load capacity testing, this test is based on the use of driving machines as an external dynamic effect. Generally speaking, there are two variant ways in which this test can be performed: a test with a machine for pile driving under a weight impacts (cyclic process), and a test with a machine for pile driving through vibrations (continuous process). The advantage of the PDT over the DLT is that, in the stages of driving the pile into the soil, it is possible to continuously monitor and determine the reaction force in the base and the shaft. Also, other effects can be monitored, such as pile integrity checks (large cracks, damage, breakage).

Hybridnamic Load Test (HLT) is also called the Rapid Load Test (RLT), and basically uses the DLT principle, but eliminates the additional effects of an external effect impacts. Thus, the stress-state becomes more similar to the stress-state during to the SLT. In the case of this test, there are three options for eliminating the additional impacts: the hybridinamic cushion test, the hydraulic brake mechanism test, and a combined system test (hybridinamic cushion and hydraulic brake mechanism). Thanks to the developed hybridinamic cushion, the kinetic energy application time, from the external effect (the weight), onto the pile head is considerably extended compared to the DLT. The hybridinamic cushion has a honeycomb shape and consists of steel plates, air-filled cells and elastomer with rubber properties. A hybridinamic cushion structured in this way prevents additional impacts as the weight rebounds after hitting the pile head, since this would create an additional negative effect during the testing. In the second case, this test is conducted by allowing the external action (weight) impact and its rebounding after hitting the pile head, and then stopping it by means of the hydraulic braking mechanism, so as to prevent the tako što se nakon udara spoljašnjeg dejstva (tega) i njegovog odbijanja od glave šipa, on zadržava hidrauličnim kočionim mehanizmom, tako da se ne dozvoljavaju naknadni udari pri odbijanju tega od glave šipa.

Statnamički test opterećenja šipa (SNLT) u osnovi koristi princip dinamičkog testa opterećenja šipa (DLT), s tim što su eliminisani efekti naknadnih udara spoljašnjeg dejstva, međutim, ovo dejstvo kojim se deluje na glavu šipa realizuje se eksplozivnim dejstvom goriva [1]. Generalno razmatrajući, postoje dve varijante prema kojima se ovaj test može izvoditi: test kod koga se teg eksplozivnim dejstvom podiže vertikalno naviše, a zatim slobodno pada na šljunak (ili sličan materijal), koji se nalazi između glave šipa i tega, kao i test kod koga se teg eksplozivnim dejstvom podiže vertikalno naviše, a zatim hidrauličnim kočionim mehanizmom zaustavlja na određenoj visini, ne dozvoljavajući mu da slobodno padne. Primenom šljunka ili hidrauličnim kočionim mehanizmom, ublažava se efekat dinamičkog dejstva naknadnih udaraca koji bi se ralizovali odbijanjem tega od glave šipa, dok se šip pod dejstvom sile potiska pomera vertikalno naniže. Reaktivna sila koja se aplicira na glavu šipa, usled eksplozivnog dejstva pri podizanju tega vertikalno naviše, veća je nekoliko desetina do stotina puta od sopstvene težine tega. Dinamički testovi opterećenja šipa zasnivaju se na: dinamici kretanja krutog tela, talasnoj teoriji, metodi karakteristika, nelinearnoj teoriji, dinamici konstrukcija, interakciji konstrukcija-tlo i teoriji i obradi signala. Prema dinamici kretanja krutog tela, razmatra se apliciranje spoljašnjeg dejstva udarom idealno krutog tela (tega) o glavu šipa. Prema talasnoj teoriji, razmatraju se aspekti propagacije talasa kroz šip i tlo. Prema metodi karakteristika, razmatraju se aspekti kretanja odlazećih i dolazećih talasa u šipu. Prema nelinearnoj teoriji, uzima se u obzir to što je konstitutivni model ponašanja šipa i tla nelinearno-plastičan. Prema dinamici konstrukcija, razmatraju se oscilacije šipa u interakciji s tlom u vremenskom domenu. Prema interakciji konstrukcija - tlo, razmatraju se spregnut problem statičke i dinamičke interakcije i reakcije dva medijuma (šip i tlo), bitno različitih fizičko-mehaničkih karakteristika. Prema teoriji i obradi signala, razmatraju se digitalizacija, procesiranje i kompatibilizacija (*signal matching*) signala, s ciljem dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o nosivosti šipa. Dinamički testovi opterećenja šipa sprovode se u nekoliko koraka: analiziraju se svi relevantni podaci u pasošu šipa i geotehničkom elaboratu, setuje se oprema, podaci i parametri za šip koji se ispituje, ukoliko se test sprovodi s tegom, teg se podiže na odgovarajuću visinu, a ukoliko se sprovodi pobijanjem ili vibracijama, kontinualno se prati stanje sile reakcije. Ukoliko se test sprovodi s eksplozivom, preduzimaju se sve prethodne mere bezbednosti i instalacije punjenja eksploziva, postupak se ponavlja nekoliko puta (maksimalno 10 puta ukupno i maksimalno 2 puta za jednu istu visinu). Za sve DLT testove analiziraju se: količina unete kinetičke energije, nivo napona zatezanja, nivo napona pritiska, apsolutne maksimalne vrednosti akceleracija, maksimalne vrednosti elasto-plastičnih deformacija, pojava negativnih vrednosti u dolazećem signalu sile u šipu i slično. Ako se pokaže potrebnim koriguju se parametri koji su korišćeni

additional impacts as the weight rebounds after hitting the pile head.

Statnamic Load Test (SNLT) basically uses the principle of the DLT, but it eliminates the additional effects of the external action impacts, however, this action that the head of the pile sustains is realized by the explosive action of the fuel [1]. Generally speaking, there are two variant ways in which this test can be performed: a test where a weight is lifted by an explosive action vertically upwards, and then falls freely on gravel (or a similar material) placed between the pile head and the weight, and a test where a weight is lifted by an explosive action vertically upwards, and then stopped at a certain height by a hydraulic braking mechanism, not allowing it to fall freely. The gravel or hydraulic braking mechanism mitigates the dynamic action effect of the additional impacts, which would be realised by the weight rebounding after hitting the pile head, while the pile under the thrust force moves vertically downwards. The reaction force applied to the pile head, as a consequence of the explosive action when the weight is lifted vertically upwards, is tens or hundreds of times larger than the weight's own weight. All DLT tests are based on: rigid-body dynamics, wave theory, method of characteristics, non-linear theory, dynamics of structures, soil-structure interaction and theory and signal processing. According to the rigid-body dynamics, we consider the application of an external action through an impact from an ideally rigid body (weight) onto the pile head. According to the wave theory, the aspects of wave propagation through the pile and the soil are considered. According to the method of characteristics, the propagation aspects of downward and upward waves in the pile are considered. According to the non-linear theory, we take into account the fact that the constitutive models of the pile and soil are non-linear-plastic. According to the dynamics of structures, the pile oscillations during the interaction with the soil within the time domain are considered. According to soil-structure interaction, the coupled problem of static and dynamic interaction and reactions of two mediums (pile and soil) with significantly different physical-mechanical properties are considered. According to the theory and signal processing, signal digitalisation, processing and signal matchnig are considered with the aim of acquiring corresponding final results, practically applicable in civil engineering, and with the help of which the decisions regarding the pile load capacity conditions are reached. Dynamic load tests are carried out in several steps: all the relevant data in the pile's passport and geotechnical study are analysed, the equipment, data, and parameters are set for the pile being tested, if the test is carried out with a weight, the weight is raised to the appropriate height, and if it is carried out by driving the pile or through vibrations, the state of the reaction force is continuously being monitored. If the test is carried out with an explosive, we take all preceding safety measures and explosive loading installations, the procedure is repeated several times (maximum of 10 times in total and maximum of 2 times for the same height). For all DLT tests we analyse: the amount of kinetic energy input, the tension level, the pressure level, absolute maximum acceleration values, maximum elastoplastic deformation values, the occurrence of negative values in the upward force signal in the pile, and the like. If necessary, the pri inicijalnom setovanju, radi dobijanja što tačnijih rezultata ispitivanja, konstruiše se reprezentativni dijagram sila dobijenih proračunom akceleracija i dilatacija i naknadno se sprovodi obrada podataka dobijenih ispitivanja u cilju utvrđivanja nosivosti šipa. Proračun nosivosti šipa sprovodi se primenom indirektnih metoda, koje se zasnivaju na iterativnoj kompatibilizaciji numeričkog nelinearnog histerezisnog modela interakcije šip-tlo prema *in-situ* merenom signalu dinamičkog testa, tako što se eliminiše dinamička komponenta nosivosti šipa, a zadržava statička komponenta nosivosti šipa.

Bidirekcioni statički test opterećenja šipa (BDSLT) jeste test novije generacije, koji ne zahteva angažovanje kontratereta ili reaktivnih šipova, a pripada grupi visokodilatacionih testova (HST) [9]. Specifičnost ovog testa jeste to što se glavni deo opreme za ispitivanje testa (*Osterberg*-ova ćelija) ugrađuje u telo bušenih šipova, pa se ovakvi šipovi ne mogu dalje koristiti u eksploataciji kao primarni noseći elementi dubokog fundiranja. Bidirekcioni statički test opterećenja šipa (BDSLT) zasniva se na: nelinearnoj teoriji, interakciji konstrukcija-tlo i teoriji i obradi signala. Prema nelinearnoj teoriji, uzima se u obzir to što je konstitutivni model ponašanja šipa i tla nelinearno-plastičan. Prema interakciji konstrukcija-tlo, razmatraju se spregnut problem statičke interakcije i reakcije dva medijuma (šip i tlo), bitno različitih fizičko-mehaničkih karakteristika. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala, s ciljem dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o nosivosti šipa. Postupak pripreme i sprovođenja testa odvija se u nekoliko koraka: za formirani armaturni koš zavaruju se dve kružne čelične ploče, između kojih se postavlja/ju *Osterberg*-ova/e ćelija/e do kojih se dovode creva za hidrauliku i ekstenziometri, ugrađuje se armaturni koš i izliva betonska mešavina, nakon očvršćavanja betona pristupa se sprovođenju testa, pod dejstvom hidrauličnog pritiska dolazi do loma u betonu na mestu gde su postavljene *Osterberg*-ove ćelije, šip se potiskuje vertikalno naviše, a zatim naniže, dok se primenom instrumenata prate pritisak u *Osterberg*-ovoj ćeliji i deformacije (sleganje/izdizanje) šipa. Potiskivanjem klipa iz cilindra prese (*Osterberg*-ove ćelije), aplicira se sila po poprečnom preseku u nivou baze (nešto iznad baze), čiji se intenzitet inkrementalno povećava i smanjuje putem: ciklusa samo jednog opterećenja i jednog rasterećenja ili većeg broja ciklusa opterećenja i rasterećenja, koji mogu biti različitih maksimalnih intenziteta.

Test aksijalnog zatezanja šipa (ATT) pripada grupi visokodilatacionih testova (HST) za utvrđivanje nosivosti šipova, koji se sprovodi primenom reaktivnih šipova izloženih dejstvu aksijalnog pritiska, dok je šip koji se ispituje, izložen dejstvu aksijalne sile zatezanja [3]. Test aksijalnog zatezanja šipa (ATT) može se sprovoditi primenom dva varijantna rešenja: test s presom postavljenom na glavnu čeličnu gredu/traverzu iznad šipa koji se ispituje (dejstvom sile pritiska, vertikalno naviše, podižu se poprečne čelične gredice, pri čemu se ispitni šip izlaže sili zatezanja preko ankera ugrađenih u njemu, a povezanih s poprečnim čeličnim gredicama),

parameters used in the initial setup are corrected, in order to obtain the most accurate results of the test, a representative diagram of the forces obtained through the acceleration and strain calculations are constructed, and the data acquired through testing are additionally processed with the aim of determining the pile load capacity. The pile load capacity calculation is conducted by using indirect methods, which are based on the iterative compatibilisation of the numerical non-linear hysteresis model of the soil-structure interaction according to the in-situ measured signal of the dynamic test, by eliminating the dynamic component of the pile load capacity and retaining the static component of the pile load capacity.

Bi-Directional Static Load Test (BDSLT) is a new generation test that does not require the use of counter-load or reaction piles, and belongs to a group of high strain test (HST) [9]. What's specific about this test is that the main piece of the test examination equipment (*Osterberg* cell) is incorporated into the body of bored piles, so these piles can no longer be used in exploitation as the primary deep foundation supporting elements. BDSLT is based on: non-linear theory, soil-structure interaction, and theory and signal processing. According to the non-linear theory, we take into account the fact that the constitutive models of the pile and soil are non-linear-plastic. According to soil-structure interaction, account the fact that the constitutive models of the pile and soil are non-linear-plastic. According to soil-structure interaction, the coupled problem of static interaction and reactions of two mediums (pile and soil) with significantly different physical-mechanical properties are considered. According to the theory and signal processing, signal digitalisation and processing with the aim of acquiring corresponding final results are considered. They are practically applicable in civil engineering, and with their help the decisions regarding the pile load capacity conditions are reached. The process of preparing and conducting the test is done in several steps. Two circular steel plates are welded onto the formed reinforcement cage, while also placing *Osterberg* cell(s), which are connected to hydraulic hoses and extensometers. Between the two plates, the reinforcement cage is installed and the concrete mix poured in. After concrete curing the test is conducted. The concrete breaks at the spots where the *Osterberg* cells have been placed under hydraulic pressure. The pile is pushed vertically upwards and then downwards, while the pressure in the *Osterberg* cell and pile deformations (subsidence/lifting) are monitored through the instruments. By pressing the piston from the press cylinder (*Osterberg* cell), force is applied on the cross-section at the base level (somewhat above the base), and the intensity of which incrementally increases and decreases through: a single loading and single unloading cycle or a larger number of loading and unloading cycles, which can have different maximum intensities.

Axial Tension Test (ATT) belongs to the group of high strain tests (HST) for determining the pile load capacity, which is carried out through the use of reaction piles exposed to axial pressure, while the pile being examined is exposed to the axial tension force [3]. ATT can be carried out through the use of two variant solutions: a test with a press placed on the main steel beam/transverse beam above the pile being tested (the kao i test s presama postavljenim na glave reaktivnih šipova ispod glavne čelične grede/traverze (dejstvom sile pritiska, vertikalno naviše, podiže se glavna čelična greda/traverza, pri čemu se ispitni šip izlaže sili zatezanja preko ankera ugrađenih u njemu, a povezanih s poprečnim čeličnim gredicama koje su oslonjene na glavnu čeličnu gredu/traverzu). Potiskivanjem klipa iz cilindra prese, podižu se anker nosači i aksijalno zateže šip koji se ispituje, pri čemu se intenzitet sile inkrementalno povećava i smanjuje putem: ciklusa samo jednog opterećenja i jednog rasterećenja ili većeg broja ciklusa opterećenja i rasterećenja, koji mogu biti različitih maksimalnih intenziteta. Test aksijalnog zatezanja šipa (ATT) zasniva se na: nelinearnoj teoriji, interakciji konstrukcija-tlo i teoriji i obradi signala. Prema nelinearnoj teoriji, uzima se u obzir to što je konstitutivni model ponašanja šipa i tla nelinearno-plastičan. Prema interakciji konstrukcija-tlo, razmatraju se spregnut problem statičke interakcije i reakcije dva medijuma (šip i tlo), bitno različitih fizičko-mehaničkih karakteristika. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala, s ciljem dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o nosivosti šipa.

Test horizontalnog opterećenja šipa (LLT) pripada grupi visokodilatacionih testova (HST) za utvrđivanje nosivosti šipova, koji se, u najvećem broju slučajeva, sprovodi primenom kontratereta koji predstavlja oslonac za horizontalno dejstvo na šip koji se ispituje ili primenom reaktivnih šipova, koji preuzimaju ulogu oslonca za horizontalno dejstvo [4]. Ovim testom, između ostalog, mogu se utvrditi vrednosti: koeficijenta horizontalne rekacije tla, napona pritiska i zatezanja (od savijanja) u šipu i horizontalnog pomeranja glave šipa. Test horizontalnog opterećenja šipa (LLT) može se sprovoditi primenom dva varijantna rešenja: test s kontrateretom (dejstvo horizontalnog opterećenja realizuje se usled horizontalnog odupiranja prese o dejstvo sopstvene težine kontratereta) i test s reaktivnim šipovima (dejstvo horizontalnog opterećenja realizuje se usled horizontalnog odupiranja prese o reaktivne šipove). Test horizontalnog opterećenja šipa (LLT) zasniva se na: nelinearnoj teoriji, interakciji konstrukcija-tlo i teoriji i obradi signala. Prema nelinearnoj teoriji, uzima se u obzir to što je konstitutivni model ponašanja šipa i tla nelinearno-plastičan. Prema interakciji konstrukcija-tlo, razmatraju se spregnut problem statičke interakcije i reakcije dva medijuma (šip i tlo), bitno različitih fizičko-mehaničkih karakteristika. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala, s ciljem dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o nosivosti šipa. Potiskivanjem klipa iz cilindra prese, na bočnu stranu glave šipa, aplicira se sila čiji se intenzitet inkrementalno povećava i smanjuje putem: ciklusa samo jednog opterećenja i jednog rasterećenja ili većeg broja ciklusa opterećenja i rasterećenja, koji mogu biti različitih maksimalnih intenziteta. Za probni šip opterećenje se aplicira inkrementalno do maksimalne sile definisane programom ispitivanja, koja treba da je jednaka 200% vrednosti projektne horizontalne nosivosti šipa. Za radni

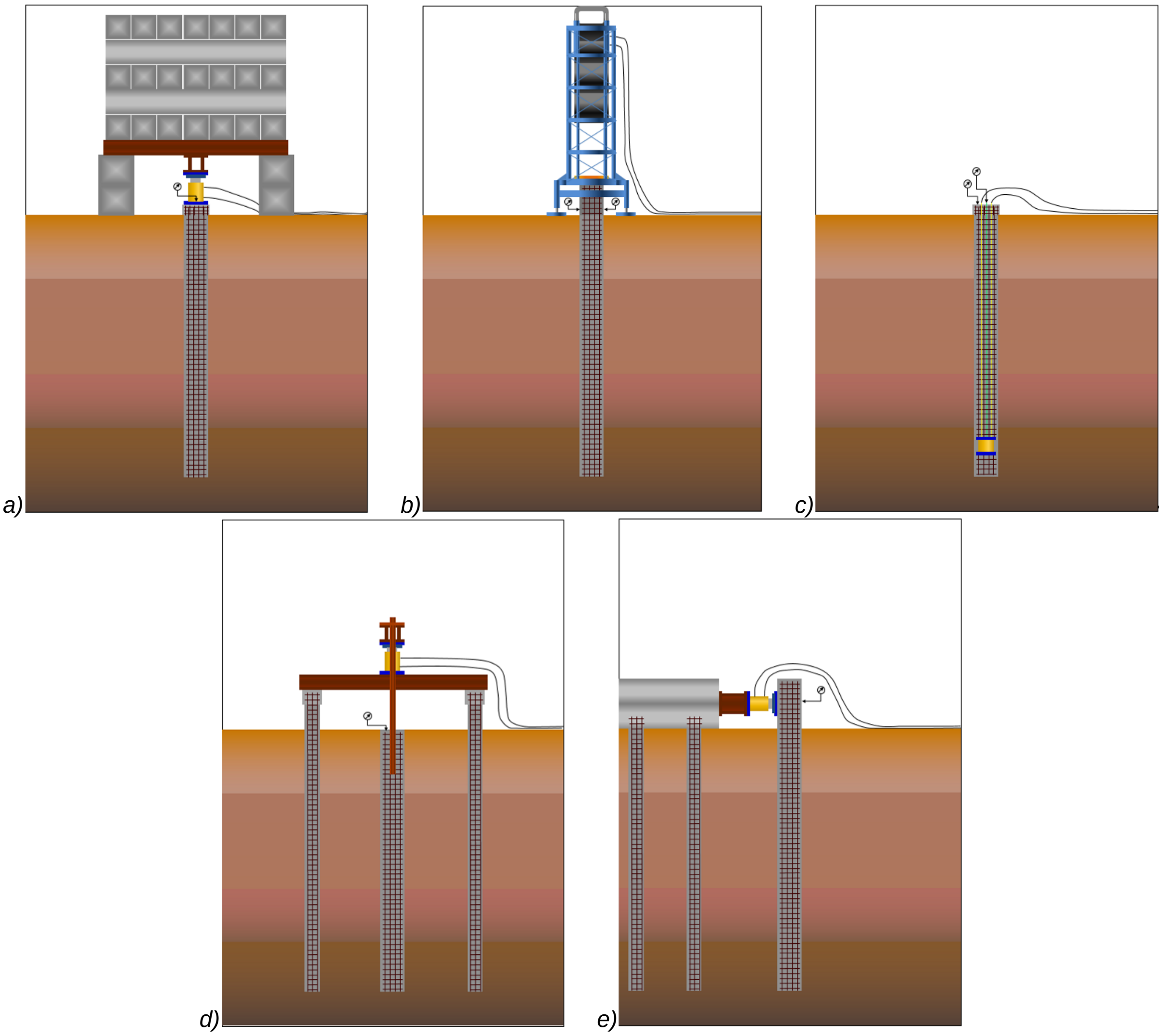
force of pressure, vertically upwards, lifts the steel cross bars, while the test pile is exposed to the tension force via the built-in anchors, which are connected to the steel cross bars), and a test with presses placed on the reaction piles' heads below the main steel beam/transverse beam (the force of the pressure, vertically upwards, lifts the main steel beam/transverse beam, while the test pile is exposed to the tension force via the built-in anchors, which are connected to the steel cross bars that are supported by the main steel beam/transverse beam). Pressing the piston from the press cylinder lifts the pile anchor beams and puts the pile being examined under the axial tension, with the force intensity incrementally increasing and decreasing through: a single loading and single unloading cycle or a larger number of loading and unloading cycles, which can have different maximum intensities. ATT is based on: non-linear theory, soil-structure interaction, and theory and signal processing. According to the non-linear theory, we take into account the fact that the constitutive models of the pile and soil are non-linear-plastic. According to soil-structure interaction, we consider the coupled problem of static interaction and reactions of two mediums (pile and soil), with significantly different physical-mechanical properties. According to the theory and signal processing, we consider signal digitalisation and processing with the aim of acquiring corresponding final results, practically applicable in civil engineering, and with the help of which the decisions regarding the pile load capacity conditions are reached.

Lateral Load Test (LLT) belongs to the group of high strain tests (HST) for determining the pile load capacity, which, in most cases, is carried out through the use of a counter-load, which is a support for the horizontal action that the tested pile sustains, or through the use of reaction piles, which take over the role of support for the horizontal action [4]. This test can determine, among other things, the values of: coefficient of horizontal subgrade reaction, stress pressure and stress tension in the pile and pile head horizontal displacement. LLT can be carried out using two variant solutions: the test with a counter-load (the lateral load effect is realised as a consequence of the lateral press resistance to the counter-load's own weight) and the test with reaction piles (the lateral load effect is realised as a consequence of the lateral press resistance to the reaction piles). LLT is based on: non-linear theory, soil-structure interaction, and theory and signal processing. According to the non-linear theory, we take into account the fact that the constitutive models of the pile and soil are non-linear-plastic. According to soil-structure interaction, we consider the coupled problem of static interaction and reactions of two mediums (pile and soil), with significantly different physical-mechanical properties. According to the theory and signal processing, we consider signal digitalisation and processing with the aim of acquiring corresponding final results, practically applicable in civil engineering, and with the help of which the decisions regarding the pile load capacity conditions are reached. By pushing the piston from the press cylinder, to the pile head lateral side, with the force intensity incrementally increasing and decreasing through: a single loading and single unloading cycle or a larger number of loading and unloading cycles, which can have different maximum intensities. In the case of šip opterećenje se aplicira inkrementalno do maksimalne sile definisane programom ispitivanja, koja treba da je jednaka faktorisanoj vrednosti projektne horizontalne nosivosti šipa. Ukoliko se razmatra konstruktivna granična nosivost, tada se ona određuje iz uslova granične nosivosti šipa na uticaje momenta savijanja. Ukoliko se razmatra geotehnička granična nosivost, tada se ona određuje iz uslova granične horizontalne otpornosti tla. Vrednost inkrementa opterećenja treba da je jednaka 25% vrednosti ukupnog opterećenja.

Na slici 5 dati su opšti šematski prikazi: a) statičkog testa opterećenja šipa (SLT) s kontrateretom, b) dinamičkog testa opterećenja šipa (DLT), c) bidirekcionog statičkog testa opterećenja šipa (BDSLT), d) testa aksijalnog zatezanja šipa (ATT) s presom postavljenom na glavnu čeličnu gredu/traverzu iznad šipa koji se ispituje, e) testa horizontalnog opterećenja šipa (LLT) s reaktivnim šipovima.

trial piles, the load is applied incrementally to the maximum force defined by the test programme, which should be equal to 200% of the pile lateral design load value. In the case of working piles, the load is applied incrementally to the maximum force defined by the test program, which should be equal to the factorised value of the pile lateral design load. If the constructive ultimate bearing capacity is considered, then it is determined from the pile ultimate bearing capacity conditions to the bending moment influence. If the geotechnical ultimate bearing capacity is considered, then it is determined from the conditions of the ultimate lateral soil resistance. The load increment value should be equal to 25% of the total load value.

Figure 5 gives a general scheme of: a) SLT with a counter-load, b) DLT, c) BDSLT, d) ATT with a press set onto the main steel beam/transverse beam above the pile being examined, e) LLT with reaction piles.



Slika 5. Opšti šematski prikazi: a) statičkog testa opterećenja šipa (SLT) sa kontrateretom, b) dinamičkog testa opterećenja šipa (DLT), c) bidirekcionog statičkog testa opterećenja šipa (BDSLT), d) testa aksijalnog zatezanja šipa (ATT) sa presom postavljenom na glavnu čeličnu gredu/traverzu iznad šipa koji se ispituje, e) testa horizontalnog opterećenja šipa (LLT) sa reaktivnim šipovima

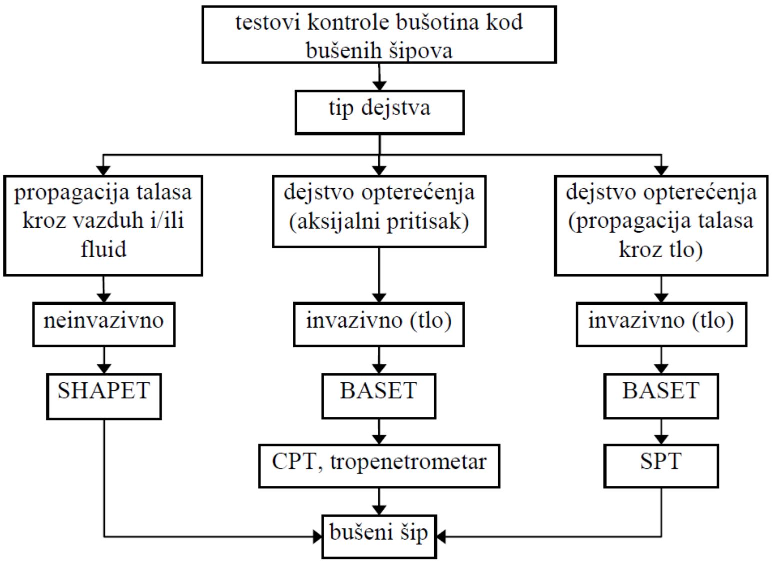
Figure 5. The general scheme of: a) SLT with a counter-load, b) DLT, c) BDSLT, d) ATT with a press set onto the main steel beam/transverse beam above the pile being examined, e) LLT with reaction piles

4 KONTROLA BUŠOTINE KOD BUŠENIH ŠIPOVA

Tipovi testova kontrole bušotina kod bušenih šipova mogu se podeliti u dve grupe: test evaluacije geometrijskih karakteristika bušotine kod bušenog šipa (SHAPET) i test evaluacije geomehaničkih karakteristika baze bušotine kod bušenog šipa (BASET). Tipovi evaluacija bušotina kod bušenih šipova, koji se utvrđuju ovim testovima, klasifikovani su u nekoliko grupa: stvarna dužina bušotine, inklinacija bušotine, promena oblika poprečnog preseka bušotine i analiza geomehaničkih karakteristika baze bušotine. Opšta metodologija ispitivanja bušotina zasniva se na: ispitivanju prilikom formiranja bušotine (neinvazivni test monitoringa bušenja) i ispitivanju nakon formirane bušotine (invazivni test tla). Na slici 6 prikazan je dijagram toka opšte klasifikacije tipova testova i kontrole bušotina kod bušenih šipova.

4 CONTROL OF BORED PILE SHAFTS

Shaft control test types in the case of bored piles can be divided into two groups: the Shaft Profile Evaluation Test (SHAPET) and the Base Evaluation Test (BASET). Shaft evaluation types in the case of bored piles, which are determined by these tests, are classified into several groups: the actual shaft length, shaft inclination, changes in the shaft cross-section shape and shaft base (geomechanical properties) analysis. The general shaft testing methodology is based on: testing during the shaft drilling (non-invasive drilling monitoring test) and testing after the drilling has been completed (invasive soil test). Figure 6 shows a flowchart of the general classification of shaft test and control types in the case of bored piles.



Slika 6. Dijagram toka opšte klasifikacije tipova testova kontrole bušotina kod bušenih šipova

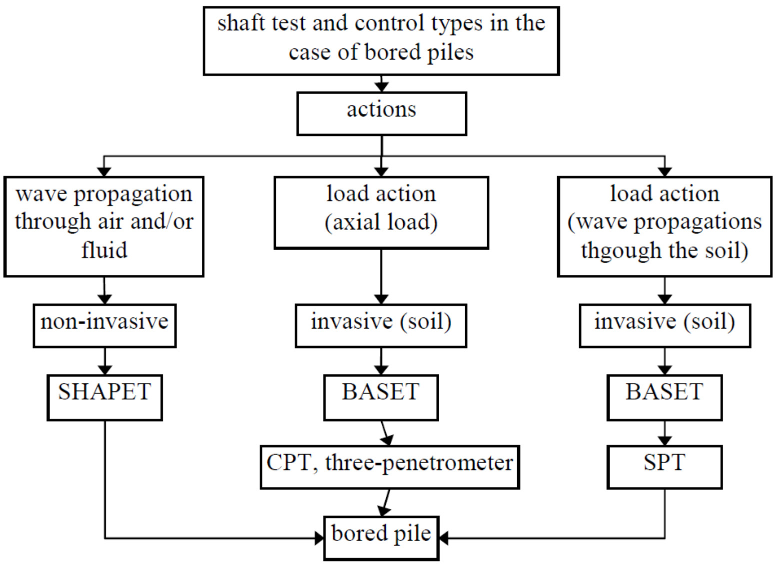


Figure 6. Flowchart of the general classification of shaft test and control types in the case of bored piles

Test evaluacije geometrijskih karakteristika bušotine kod bušenog šipa (SHAPET) zasniva se na GPS praćenju signala prilikom bušenja ili naknadnom kontrolom bušotine kod bušenih šipova, radi evaluacije devijacije vertikalnosti i dužine bušotine. Takođe, ovim testom, ultrazvučnom metodom, spuštajući sonde kontinualno naniže, utvrđuje se promena geometrijskog oblika bušotine kod bušenih šipova [30]. Ovaj test zasniva se na: talasnoj teoriji i teoriji i obradi signala. Prema talasnoj teoriji, razmatraju se aspekti propagacije talasa kroz vazduh i fluid. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala, s ciljem dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o evaluaciji geometrijskih karakteristika bušotine kod bušenog šipa. Test evaluacije geometrijskih karakteristika bušotine kod bušenog šipa (SHAPET) sprovodi se u nekoliko koraka: analiziraju se svi relevantni podaci u geotehničkom elaboratu, ukoliko se ispitivanje sprovodi na bušotini za bušeni šip koja tek treba da se izgradi bušenjem tla, tada se senzor za monitoring inklinacije i dubine bušotine i digitalni merač dubine bušotine pričvršćuju za nosač alata mašine kojim se buši tlo i kojim se oprema spušta do baze bušotine (naknadno, nakon izgradnje bušotine, sprovodi se 2D i/ili 3D skeniranje oblika bušotine ultrazvučnim sondama, koje se instaliraju na mašinu za bušenje tla ili drugi pomoćni sistem, kojim se oprema spušta do baze bušotine), ukoliko se ispitivanje sprovodi na formiranoj bušotini za bušeni šip, tada se senzor za monitoring inklinacije i dubine bušotine i digitalni merač dubine bušotine pričvršćuju za nosač alata mašine kojim se buši tlo ili za pomoćni sistem (tripod) kojim se oprema spušta do baze bušotine (naknadno se sprovodi 2D i/ili 3D skeniranje oblika bušotine ultrazvučnim sondama, koje se instaliraju na mašinu za bušenje tla ili drugi pomoćni sistem, kojim se oprema spušta do baze bušotine), setuju se oprema, podaci i parametri za bušotinu (bušenog šipa) koja se ispituje, konstruišu se adekvatni dijagrami kojima se prikazuju: stvarne dužine (dubine), inklinacije, devijacije vertikalnosti/horizontalnosti i promena oblika poprečnog preseka bušotine inkrementalno po dubini i naknadno se sprovodi obrada podataka dobijenih ispitivanjem.

Test evaluacije geomehaničkih karakteristika baze bušotine kod bušenog šipa (BASET) zasniva se na primeni geomehaničkih *in-situ* metoda radi evaluacije karakteristika tla u bazi bušotine. Ovaj test može se sprovoditi primenom postojećih ili unapređenih (sofisticiranijih) geomenhaničkih *in-situ* testova: test statičke penetracije (CPT), test standardne penetracije (SPT) ili test statičke penetracije sa integrisanim tropenetrometrom (simultano tropenetrometarsko ispitivanje). Test evaluacije geomehaničkih karakteristika baze bušotine kod bušenog šipa (BASET) zasniva se na: dinamici kretanja krutog tela, talasnoj teoriji, nelinearnoj teoriji, mehanici tla, dinamici tla i teoriji i obradi signala. Prema dinamici kretanja krutog tela, razmatra se apliciranje spoljašnjeg dejstva udarom idealno krutog tela (tega) o cev koja se pobija u tlo. Prema talasnoj teoriji, razmatraju se aspekti propagacije talasa kroz tlo. Prema nelinearnoj teoriji, uzima se u obzir to što je konstitutivni model ponašanja tla nelinearno-plastičan. Prema mehanici tla, razmatraju se 3D naponska stanja u tlu (u bazi bušotine). Prema dinamici tla, razmatraju se vibracije u

Shaft Profile Evaluation Test (SHAPET) is based on GPS signal tracking during drilling or the subsequent shaft control in the case of bored piles, with the aim of evaluating the deviation in verticality and the shaft length. Also, this test, through an ultrasonic method, by lowering the probes continuously downwards, determines the change in the shaft's geometric shape in the case of bored piles [30]. This test is based on: wave theory, and theory and signal processing. According to the wave theory, bored piles [30]. This test is based on: wave theory, and theory and signal processing. According to the wave theory, the aspects of wave propagation through the air and fluid are considered. According to the theory and signal processing, signal digitalisation and processing with the aim of acquiring corresponding final results are considered. They are practically applicable in civil engineering, and help in reaching decisions about the shaft profile evaluation in the case of bored piles. SHAPET is carried out in several steps: all the relevant data in the geotechnical study are analyzed, if the testing should be performed on a shaft for a bored pile which has yet to be built by drilling the soil, then the sensor for monitoring the inclination and shaft depth, and a digital shaft depth gauge are attached to the tool holder of the machine that drills the ground and lowers the equipment to the base of the shaft (subsequently, after the shaft has been constructed, we conduct 2D and/or 3D scanning of the shaft shape by ultrasonic probes, which are installed on the soil drilling machine or another auxiliary system, used for lowering the equipment to the base of the shaft), if the test is carried out on a formed drilled pile shaft, then the sensor for monitoring the inclination and shaft depth and a digital shaft depth gauge are attached to the tool holder of the machine that drills the ground or to an auxiliary system (tripod) used for lowering the equipment to the shaft base (subsequently, we conduct 2D and/or 3D scanning of the shaft shape by ultrasonic probes, which are installed on the soil drilling machine or another auxiliary system, used for lowering the equipment to the base of the shaft), the equipment, data, and parameters are set for the (bored pile) shaft being tested, adequate diagrams are constructed to show: the actual lengths (depths), inclinations, verticality/horizontality deviations, and the shaft cross-section shape changes, incrementally in depth, and we subsequently process the testing obtained data.

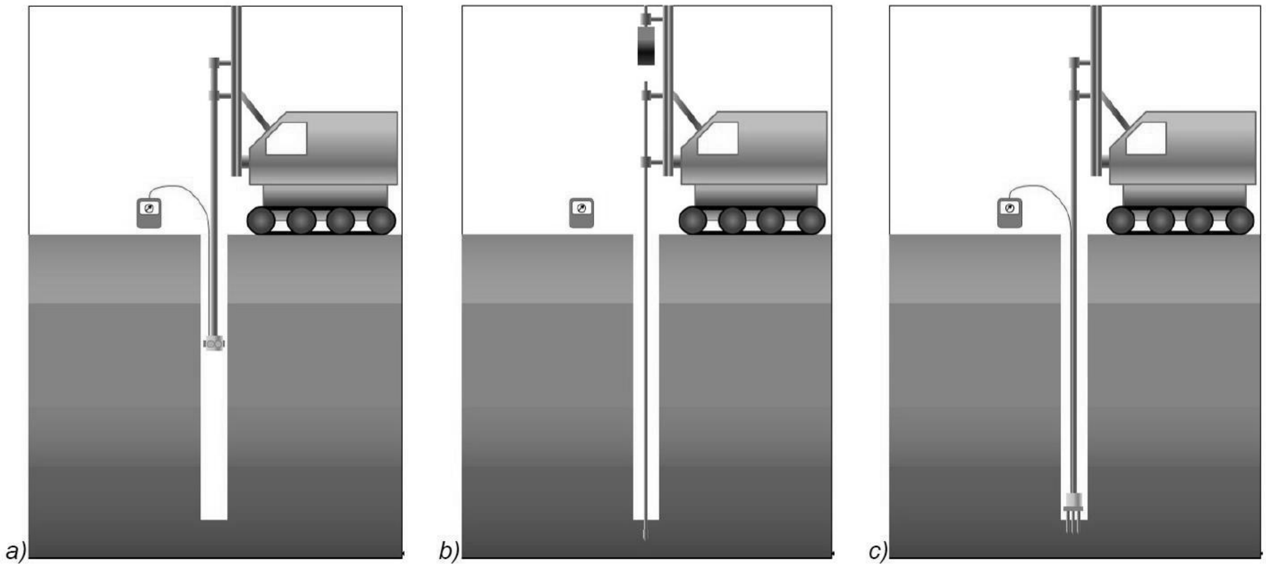
Base Evaluation Test (BASET) is based on the use of geomechanical in-situ methods with the aim of evaluating soil properties in the shaft base. This test can be carried out using the existing or improved (more sophisticated) geomechanical in-situ tests: *Cone Penetration Test* (CPT), *Standard Penetration Test* (SPT) or static penetration test with an integrated three-penetrometer (simultaneous three-penetrometric testing). BASET is based on: the rigid-body dynamics, wave theory, non-linear theory, soil mechanics, soil dynamics, and theory and signal processing. According to the rigid-body dynamics, we consider the application of an external action through an ideally rigid body (weight) impact on the tube that is being driven into the soil. According to the wave theory, we consider the aspects of wave propagation through the soil. According to the non-linear theory, we take into account the fact that the constitutive model of soil is non-linear-plastic.

tlu u vremenskom domenu i aspekti prigušenja. Prema teoriji i obradi signala, razmatraju se digitalizacija i procesiranje signala, s ciljem dobijanja odgovarajućih konačnih rezultata primenljivih u građevinskoj inženjerskoj praksi, pomoću kojih se donose odluke o evaluaciji geomehaničkih karakteristika baze bušotine kod bušenog šipa. Test statičke penetracije (CPT) i test standardne penetracije (SPT) sprovode se prema odgovarajućim standardima. Test integrisanim tropenetrometrom sprovodi se slično testu CPT, s tim što se tri penetrometra simultano utiskuju u bazu bušotine šipa.

Na slici 7 dati su opšti šematski prikazi: a) testa evaluacije geometrijskih karakteristika bušotine kod bušenog šipa (SHAPET) - evaluacija promene oblika poprečnog preseka bušotine, b) testa evaluacije geomehaničkih karakteristika baze bušotine kod bušenog šipa (BASET) - test standardne penetracije (SPT) baze, c) testa evaluacije geomehaničkih karakteristika baze bušotine kod bušenog šipa (BASET) - integrisani tropenetrometar.

According to the soil mechanics, 3D soil stress conditions are considered (in the shaft base). According to the soil dynamics, we consider soil vibrations in the time domain and the absorption aspects. According to the theory and signal processing, we consider signal digitalisation and processing with the aim of acquiring corresponding final results, practically applicable in civil engineering, and which will help in reaching decisions about the base evaluation in the case of bored piles. CPT and SPT are conducted according to corresponding standards. The integrated three-penetrometer test is performed similarly to the CPT test, while there are three penetrometers which are simultaneously pressed into the base.

Figure 7 gives a general scheme of: a) SHAPET - the evaluation of the shaft cross-section shape change, b) BASET - SPT of the base, c) BASET - integrated three-penetrometer.



Slika 7. Opšti šematski prikazi: a) testa evaluacije geometrijskih karakteristika bušotine kod bušenog šipa (SHAPET) - evaluacija promene oblika poprečnog preseka bušotine, b) testa evaluacije geomehaničkih karakteristika baze bušotine kod bušenog šipa (BASET) - test standardne penetracije (SPT) baze, c) testa evaluacije geomehaničkih karakteristika baze bušotine kod bušenog šipa (BASET) - integrisani tropenetrometar

Figure 7. The general scheme of: a) SHAPET - the evaluation of the shaft cross-section shape change, b) BASET - SPT of the base, c) BASET - integrated three-penetrometer

5 ZAKLJUČAK

Metodologija ispitivanja integriteta i nosivosti šipova definisana je procedurama propisanim u standardima o ispitivanjima šipova. Unapređivanje segmenata postojećih standarda odgleda se u sledećem: detaljnijem razjašnjenju pojedinih faza ispitivanja, redukciji i selekciji metoda i postupaka ispitivanja u okviru jednog testa, s obzirom na to što u postojećim standardima ispitivanja šipova postoji veći broj opcija ispitivanja koja se najčešće i ne koriste, prikazani su ključni elementi ispitivanja integriteta i nosivosti šipova, bez dodatnih (nepotrebnih) opcija koje umnogogme zbunjuju investitora i nadzora prilikom samog sprovođenja ispitivanja šipova. S obzirom na iskustvo autora u ispitivanju integriteta i

5 CONCLUSIONS

The pile integrity and load testing methodology is defined by the procedures prescribed in the pile testing standards. The improvement of segments of the existing standards is reflected in: a more detailed clarification of the individual testing phases, the reduction and selection of the testing methods and procedures within a single test, since there is a larger number of testing options that are not used ordinarily in the existing testing standards, we present the key elements of pile integrity and load testing, without additional (unnecessary) options which, mostly confuse investors and supervision during the actual pile testing conduction. Considering our own experience in pile integrity and load testing, acquired nosivosti šipova, na nekoliko stotina, pa i hiljada ispitivanja, u ovom radu prikazane su metodologije ispitivanja koje su se najbolje i pokazale u praksi, i čiji je stepen pouzdanosti, s vremenom, dodatno usavršavan. Definisane su metode koje se koriste u analizi, obradi i interpretaciji podataka, što nije prikazano u izvornim standardima ispitivanja šipova.

Problematika ispitivanja integriteta i novosti šipova multidisciplinarnog je karaktera, jer zahteva integraciju znanja i iskustva iz oblasti: građevinarstva, geologije, geotehnike, analize i obrade signala, softverskog i hardverskog inženjerstva, tako da se konstantno javlja potreba za usklađivanjem gotovo svih aspekata ispitivanja. Posebno je osetljiva problematika u vezi s teorijom i obradom signala i hardverskim i softverskim inženerstvom, jer se moderne informacione tehnologije stalno unapređuju. U tom smislu, pred inženjere građevinarstva i geotehnike stalno se nameće pitanje usavršavanja iz ove oblasti, pri čemu, jednu od polaznih osnova informativno-edukativnog karaktera, može predstavljati i ovaj rad, u kom su, pored standardizovanih procedura ispitivanja šipova, definisana i usklađena iskustva i znanja autora iz većeg broja različitih metoda ispitivanja šipova.

through several hundred, and even thousands of tests, this paper presents the testing methodologies that have stood out in practice, and whose degree of reliability, has been further enhanced through time. The methods used in data analysis, processing and interpretation are defined, and this hasn't been presented in the original pile testing standards.

The problem of pile integrity and load testing is multidisciplinary in nature, since it requires the integration of knowledge and experience in the fields of civil engineering, geology, geotechnics, signal analysis and processing, software and hardware engineering, so there is a constant need for harmonisation of almost all testing aspects. The issues of theory and signal processing, and hardware and software engineering are particularly sensitive, because of the constant improvements in modern information technologies. In this regard, the civil and geotechnical engineers are constantly faced with the question of improvement in this field, where this paper can be one of the informative and educational starting points, and in which, beside the standardised pile testing procedures, we have defined and matched personal experiences and knowledge from a number of different pile testing methods.

ZAHVALNICA

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

ACKNOWLEDGEMENTS

The work reported in this paper is a part of the investigation within the research project TR 36014 supported by the *Ministry of Education, Science and Technological Development of Serbia*.

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REZIME

ISPITIVANJE INTEGRITETA I NOSIVOSTI ŠIPOVA: METODOLOGIJA I KLASIFIKACIJA

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U radu su prikazane metodologija i klasifikacija ispitivanja integriteta i nosivosti šipova, u saglasnosti sa važećim inostranim standardima, ali i sa sopstvenim definisanim segmentima unapređivanja standarda i sopstvenim definicijama određenih ključnih elemenata. Klasifikacija je sprovedena po tipovima testova u kojima su jasno definisani: tok ispitivanja šipova, metode analize i obrade rezultata ispitivanja. Pored osnovne podele testova ispitivanja šipova na testove integriteta i testove nosivosti, dodatno je definisana i grupa testova kontrole bušotine kod bušenih šipova, s obzirom na to što je za pravilno formiranje bušotine, kada je reč o bušenim šipovima, neophodno prethodno ispuniti određene kvalitativno-kvantitativne kriterijume. Ovako prikazane metodologija i klasifikacija ispitivanja integriteta i nosivosti šipova prvenstveno služe za edukativne svrhe inženjera građevine i geotehnike koji se bave ovom problematikom, da dodatno donese novine na ovom polju ispitivanja i da dodatno pojasne sve elemente ispitivanja, budući da se u praksi vrlo često susreću protivrečna mišljenja i nesuglasice oko detalja ispitivanja.

Ključne reči: šip, ispitivanje, standardi, klasifikacija, integritet, nosivost

APSTRACT

PILE INTEGRITY AND LOAD TESTING: METHODOLOGY AND CLASSIFICATION

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The paper presents the methodology and classification of pile integrity and load testing, in compliance with current foreign standards, as well as our own defined segments of standard improvement and our own definitions of certain key elements. The classification has been conducted according to the test types which clearly define the pile testing process, analysis methods, and test results processing. Beside the basic division of pile testing to integrity tests and load tests, there is also an additionally defined group of shaft control tests in the case of bored piles, since for the proper shaft formation, when it comes to bored piles, certain qualitative-quantitative criteria must be fulfilled beforehand. Presented in this way, the methodology and classification of pile integrity and load tests serves, primarily, an educational purpose for civil and geotechnics engineers who deal with this issue, to additionally introduce innovations in this field of testing and clarify all the elements of the testing since contradictory opinions and disagreements regarding the testing details are quite common in practice.

Key words: pile, testing, standards, classification, integrity, load