MOGUĆNOSTI POBOLJŠANJA PLANUMA ŽELEZNIČKE PRUGE

IMPROVEMENT ALTERNATIVES FOR RAILWAY TRACK FORMATION

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1 UVOD

Kolosek treba razmatrati kao jedinstveni sistem. Svaki pojedini element tog sistema, počevši od šine i praga, preko zastora ili čvrste podloge (beton/asfalt), do zaštitnog sloja planuma, mora da obezbedi dugotrajnu stabilnost koloseka, zahtevajući pritom malo održavanja čak i pri velikim gustinama saobraćaja, povećanim brzinama i osovinskim opterećenjima.

Planum koloseka je površina na kojoj se gradi kolosek. Njegova glavna funkcija je da bude stabilna podloga za podzastorne i zastorne slojeve. On je veoma važna komponenta donjeg stroja, koja ima značajan uticaj na karakteristike i održavanje koloseka. Doprinosi elastičnosti oslanjanja gornjeg stroja i otuda elastičnom ugibu šine pod opterećenjem točka. Veličina krutosti planuma utiče na propadanje šine, praga i zastora, a takođe je uzrok nejednakog sleganja koloseka.

Slika 1 [5], [7], [10] pokazuje uobičajene termine za pojedine delove konstrukcije pruge.

Osnovni zahtevi za planum pruge jesu:

- ravnost i projektovani nagib gornje površine;
- izdržljivost na oštećenja;
- nosivost i sposobnost prenosa opterećenja od gornjeg stroja;
- stabilnost na zamrzavanje;
- filterska stabilnost.

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1 INTRODUCTION

The track has to be regarded as an inherent system. Each individual element of that system, beginning from rail and sleeper, via the ballast or solid bed (concrete/asphalt), down to the formation protection layer, must provide long-term track stability requiring low maintenance even at high train density, increasing running speeds and axle loads.

The track formation is the platform upon which the track superstructure is constructed. Its main function is to be a stable foundation for the subballast and ballast layers. It is a very important substructure component, which has a significant influence on track performance and maintenance. It contributes to the superstructure support resiliency and hence to the elastic deflection of the rail under wheel loading. The formation stiffness magnitude influences rail, sleeper and ballast deterioration and also is a source of track differential settlement.

Figure 1 [5], [7], [10] shows the usual terms of individual parts of railway structure.

The main requirements for track formation are:

- Evenness and designed slope of surface;
- Resistance to wear;
- Bearing and transmit the loading from the superstructure;
- Stability from freezing;
- Filter stability.

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Slika 1. Definisanje termina konstrukcije pruge
Figure 1. Definition of track structure terminology

Da bi planum ispunio te zahteve i služio kao stabilna osnova, moraju se izbeći sledeći oblici njegovog propadanja planuma moraju biti izbegnuti:

- prekomerna plastična deformacija;
- konsolidacija i veliki gubitak otpornosti na smicanje;
- ubrzani gubitak otpornosti na smicanje pod ponavljanim opterećenjem od točkova;
- značajna promena zapremine (bubrenja i skupljanja) od promene vlažnosti;
- omekšavanje usled zamrzavanja i odmrzavanja pri dejstvu mraza;
- osipanje planuma.

2 NOSIVOST PLANUMA

Odlučujuća veličina u međusobnoj povezanosti gornjeg i donjeg stroja pruge jeste sposobnost nosivosti planuma.

Nedovoljna nosivost planuma uglavnom je izazvana:

- lošom ili nedostajućom drenažom;
- sprečenim oticanjem vode s ramena zastorne prizme;
- udubljenjima u zaprljanom zastoru usled nedovoljnog čišćenja.

Uzroci nestabilnosti koloseka najčešće su baš deformacije planuma, a one se prepoznaju po sledećim vidnim znacima [8], [10]:

- stalna i ponovna pojavljivanja grešaka geometrije koloseka;
- blatnjava mesta na površini zastora izazvana prskanjem blata uvis za vreme prolaska vozova ("pumpanje");
- bočno istiskivanje razmekšalog podtla, najčešće kod preopterećenog glinovitog podtla;
- sleganje koloseka usled deformisanja planuma tla u vidu "džepova", "korita" ili "vreća" u kojima se skuplja voda;

To fulfill these requirements and to serve as a stable platform, the following formation failure modes must be avoided:

- Excessive plastic deformation;
- Consolidation settlement and massive shear failure;
- Progressive shear failure from repeated wheel loading;
- Significant volume change (swelling and shrinking) from moisture change;
- Frost and thaw softening;
- Formation attrition.

2 TRACK FORMATION BEARING CAPACITY

The decisive element in the connection between track superstructure and substructure is the bearing capacity of the track formation.

Insufficient bearing capacity of the formation is mostly caused by:

- Poor or lacking drainage;
- Prevented water flow off the ballast shoulders;
- Hollows in contaminated ballast due to insufficient cleaning.

The following phenomenons of formation deformations indicate the defects of the substructure [8], [10]:

- Permanent and recurrent irregularities of track geometry;
- Muddy spots due to subsoil material pumping up into ballast during train passing;
- Side squeezing out the wet soil (mostly clay);
- Track settlements due to formation deformation in forms of ballast pockets and troughs full of water;
- Raising the track due to substructure freezing;
- Shoulders settlements due to embankment shearing and shelling;
- Shoulders cracks as a result of embankment settlements;

- izdizanje koloseka od zamrzavanja u donjem stroju;
- sleganje bankina usled klizanja ili školjkanja nasipa;
- pukotine na bankinama kao posledica sleganja nasipa;

- masivno smicanje planuma za vreme velikih kiša.

Planum verovatno ima najveći uticaj na krutost oslanjanja koloseka, a njegov modul deformacije varira duž pruge. Modul deformacije planuma E_{v2} može se odrediti opitom statičkog pritiska pločom. S, obzirom na prirodu opterećenja vozom, merodavni je dinamički pritisak ploče, kada se određuje dinamički modul deformacije E_{din} . Pritom kratkovremensko udarno opterećenje nanosi se na planum, čime se on pobuđuje na prigušeno oscilovanje. Što su ugibi veći, pri čemu su i amplitude prigušenih sopstvenih oscilacija veće, to planum ima manju nosivost.

Kapacitet nosivosti planuma zavisi od:

- vlažnosti i suve gustine;
- plastičnog ponašanja;
- prirode veze napon-deformacija.

Pesak i šljunak zbijaju se vrlo lako i otuda imaju visoki kapacitet nosivosti. Kohezivna tla, kao što su prašina i glina, obično imaju vrlo nizak kapacitet nosivosti, što umnogome zavisi od sadržaja vode. Njihov kapacitet nosivosti je veći u uslovima isušenosti i očvršćavanja, a opada s povećanjem sadržaja vode, idući ka plastičnom stanju, sve do fluidnog.

Tabela 1 [5] pokazuje zahteve za pojedine slojeve donjeg stroja po modulima deformacije i zbijenosti za slučaj koloseka u zastoru i na čvrstoj podlozi, a za razne vrste pruga.

- Massive formation shearing during raining.

Track formation probable has the greatest influence on the superstructure support resiliency and its modulus of deformation varies along the track. Modulus of deformation E_{v2} can be derived from the plate static load bearing test. Taking the nature of train load into consideration, the modulus of dynamic deformation E_{din} is more competent. By the dynamic plate test an impact load for the short term is applied to the formation, which induced it to vibrate in damped oscillations. If the settlement and amplitude of the oscillation are high, the bearing capacity of the formation is low.

The formation bearing capacity depends on:

- moisture content and dry density,
- plastic behaviour,
- stress/strain relationship.

Sand and gravel consolidated easily and from that have the high bearing capacity. Coherent soils, like dust and clay, have the very low bearing capacity and it largely depends on water content. Their bearing capacity is higher in dry and hard conditions and falls with the water content increase, striving to plastic state, even to liquid.

Table 1 [5] shows the requirements to be met by the substructure layers for the modulus of deformation and consolidation in the case of ballasted or solid track, and different line types.

Tabela 1. Zahtevi za donji stroj
Table 1. Substructure requirements

Vrste pruge Line tipe V [km/h]			Planum Formation [MN/m ²]		Zaštitni sloj Protective layer				Zemljani planum Earth formation [MN/m ²]	
			E _{v2}	E _{din}	D _{Pr}	Dubina zamrzavanja Standard thickness [cm]			E _{v2}	E _{din}
						I	II	III		
Novoizgrađene New track	pruge velikih brzina HST (300)	u zastoru ballast	120	50	1,0	70	70	70	80	40
		u čvrstoj podlozi slab	120	50	1,0	40	40	40	60	35
	putnički saobraćaj passenger traffic (230)	u zastoru ballast	120	50	1,0	50	60	70	60	40
		u čvrstoj podlozi slab	120	50	1,0	40	40	40	60	35
	putnički saobraćaj passenger traffic (160) mešoviti saobraćaj mixed traffic (160) teretni saobraćaj freight traffic (120) lokalni saobraćaj commuter traffic (120)	u zastoru ballast	100	45	1,0	40	50	60	45	35

	lokalni saobraćaj commuter traffic (80) teretni saobraćaj freight traffic (50)	u zastoru ballast	80	40	1,0	30	40	50	45	30
Obnovljene Renewal track	pruge velikih brzina HST (300)	u zastoru ballast	120	50	1,0	70	70	70	80	40
		u čvrstoj podlozi slab	120	50	1,0	40	40	40	60	35
	putnički saobraćaj passenger traffic (230)	u zastoru ballast	80	40	1,0	30	40	50	45	30
		u čvrstoj podlozi slab	100	45	1,0	40	40	40	45	30
	putnički saobraćaj passenger traffic (160) mešoviti saobraćaj mixed traffic (160) teretni saobraćaj freight traffic (120) lokalni saobraćaj commuter traffic (120)	u zastoru ballast	50	35	1,0	20	25	30	30	25
	lokalni saobraćaj commuter traffic (80) teretni saobraćaj freight traffic (50)	u zastoru ballast	40	30	0,97	20	20	20	20	25

E_{v2} – statički modul deformacije/modulus of static deformation

E_{din} – dinamički modul deformacije/modulus of dynamic deformation

D_{Pr} – zbijenost po Proktoru/Proctor density

3 ZBIJENOST PLANUMA

Pri ispitivanju zbijenosti po Proktoru uzorak materijala iz planuma zbija se u normiranoj čeličnoj posudi tegom koji pada pod utvrđenim uslovima, pri raznim sadržajima vode. Proktorova kriva pokazuje do kojeg se dozvoljenog sadržaja vode propisana zbijenost može postići. Zbijenost po Proktoru odgovara zbijenosti (radu na zbijanju od oko 60 t/m^3), koja može biti postignuta na mestu izgradnje pruge sa uobičajenom opremom za zbijanje. Ona se može definisati putem stepena zbijenosti, koji predstavlja odnos izmerene zapreminske mase u suvom stanju zbijenog tla i maksimalne zapreminske mase pri optimalnoj vlažnosti dobijene Proktorovim opitom:

$$D_{Pr} = \gamma_d / \max \gamma \times 100 \quad [\%]$$

3 TRACK FORMATION CONSOLIDATION

Compression test is the famous Proctor test where the formation material sample is compressed under predetermined conditions in a calibrated receptacle with help of the drop weight, under five different water content at least. The Proctor curve shows which admissible water content the prescribed compression value can be reached. The Proctor density corresponds to a compression (work done of approx. 60 t/m^3) that may be reached on the track's site with the help of the usual compression devices. It can be defined by means of compaction ratio, as the relation between the volume weight in dry condition and in the most favourable water content:

4 ODVODNJAVANJE PLANUMA

Poznato je da voda u planumu negativno utiče na održavanje pravilne geometrije koloseka, pa treba nastojati da se njeno prisustvo smanji:

- čišćenjem zastora;
- održavanjem propisanog bočnog nagiba planuma;
- čišćenjem bočnih jarkova i drenaža;
- ako je potrebno, izradom kontrolnih i ventilacionih okana.

Postoje dva tipa odvodnjavanja: otvoreni i zatvoreni sistem odvodnjavanja.

Otvoreni sistem odvodnjavanja obično se sastoji od jarkova i kanala pored pruge u usecima, u koje se skuplja površinska voda. Širina jarkova u usecima obično je 0,4 m, a dubina ispod planuma 0,4 m. Širina kanala iznosi od 0,8 m do 1,6 m i dubina ispod planuma 0,2 m. Njihov podužni pad treba da je bar 0,3%, a najviše do 3%. U slučaju većeg ili manjeg podužnog pada, najbolje je koristiti prefabrikovane betonske kanale ili kanale zidane lomljenim kamenom, na peskovito-šljunkovitoj podlozi [8]. Prednost otvorenog sistema odvodnjavanja u odnosu na zatvoreni jeste to što je dostupniji i lakše se održava.

Zatvoreni sistem odvodnjavanja ugrađuje se tamo gde nivo podzemnih vode treba da se smanji (<1,5 m ispod gornje ivice šine), tlo oko pruge treba da se odvodnjava i filtrirana voda ili voda iz slojeva treba da se odvede. Kod zatvorenog sistema odvodnjavanja, za smanjenje nivoa podzemne vode koriste se porozne cevi, propusne sa svih strana. Delimično propusne cevi (samo s gornje strane) odvedu vodu koja se proceđuje bilo s površine, bilo iz slojeva konstrukcije. Podužni pad poroznih cevi mora da je bar 0,3%. One se polažu na najmanje 60 cm ispod planuma. Kanal za polaganje cevi mora biti ispunjen šljunkom. Okna za održavanje sistema za odvodnjavanje moraju da budu izrađena na 50–100 m, i ona se koriste za proveru i čišćenje cevi. Prednosti zatvorenog sistema odvodnjavanja nad otvorenim jesu u tome što je potreban manji minimalni pad i manji prostor, kao i to što ne zahteva reprofiliisanje i uklanjanje korova.

S dobro projektovanim sistemom za odvodnjavanje moguće je postići efikasno odvodnjavanje i u nekim slučajevima čak odustati od obnove planuma.

5 POBOLJŠANJE PLANUMA

U slučaju kada je planum slabe nosivosti ili male krutosti, što uzrokuje veće troškove održavanja pruge kao celine, nameće se potreba za poboljšanjem stanja planuma. Poboljšanje planuma je skupa mera. U ekonomskim razmatranjima za razdoblje od trideset pet godina, imajući u vidu povećane troškove održavanja ako se poboljšanje ne sprovodi, prednost ove mere pokazuje se već posle deset godina.

Poboljšanje planuma treba da ispuni sledeće zahteve:

- ujednačeni modul elastičnosti duž cele dužine pruge od najmanje 4,5 kN/m², optimalno 12 kN/m²;
- postepeni pad modula elastičnosti sa dubinom, inače nastaje pumpanje blata;

4 TRACK FORMATION DRAINAGE

It is well-known that water contained in the formation has an adverse effect on the correct track geometry. Therefore, the following measures are applied to reduce the water content in the formation:

- cleaning the ballast,
- maintain the formation cross fall,
- cleaning of side ditches and drainage,
- if necessary, building up the inspection and ventilation shafts.

There are two types of drainage facilities: open drainage facilities and enclosed drainage facilities.

Open drainage system usually consists of the ditches and canals in track sides at embankment cuts in which the surface water should be led away. The ditches width in cuts is usually 0.4m and the depth below the formation is of 0.4m. The channel width is from 0.8m to 1.6m and the depth below the formation is of 0.2m. Their longitudinal inclination should be at least 0.3% and at most 3%. If the longitudinal inclination is below or above these values, precast concrete canals in a fine gravel bed or a coarse pavement of broken stone on fine gravel have to be provided. The advantage of open drainage systems as compared to closed systems is that they are always easily accessible and easy to maintain.

Enclosed underground drainage facilities are installed where the groundwater level has to be lowered (<1.5m below TOR), the soil surrounding the track has to be drained and percolating or layer water has to be led away. If the groundwater level has to be lowered or the soil has to be drained, the porous pipes, permeable all around, are advisable. Partial-permeable, only on their top, pipes are used to lead away percolating and layer water. The longitudinal inclination of percolating water pipes should be at least 0.3%. They are laid at the depth below the formation of at least 60cm. The pipe ditch has to be filled with gravel. Inspection pits enable the pipes to be checked and cleaned and they are provided at distances of 50-100m. The advantage of enclosed drainage systems against open systems is that their minimum inclination and the required space is less and there is no need for reprofiling and weeding.

If the drainage system is correct designed, it is possible to attain effective track draining and in some cases it would not be necessary to renew the formation.

5 FORMATION IMPROVEMENT

In cases when the track formation is too weak or has too low stiffness, that resulting in high cost of track maintenance, may dictate the need to improve the formation conditions. The track formation improvement is the expensive measure. At economic consideration in thirty five years time period, with taking into account the maintenance costs, the advantage of the measure is obvious already after ten years.

Formation measures should meet the following requirements:

- constant modulus of elasticity along the entire track length of at least 4,5 kN/cm², optimum 12 kN/cm²,
- gradual decrease of the modulus of elasticity with depth, otherwise mud would be pumped up,

- stvaranje toplotne izolacione brane;
- sprečavanje stvaranja vodene pare i – ukoliko se ipak pojavi – odvođenje vode nastale njenom kondenzacijom,
- mali troškovi ugradnje;
- smanjenje poremećaja saobraćaja pri izgradnji;
- trajanost preko dvadeset godina.

Mogućnosti poboljšanja planuma navedene su u tabeli 2 [9]. Postoji šest opštih grupa. Kako je za većinu metoda potrebno iskustvo, često i specijalna oprema, preporučljivo je konsultovati se sa stručnjacima.

- create the heat insulation barrier,
- preventing from vapour seal, if happens, draining off condensation water,
- low installation costs,
- reduction operational hindrance during installation,
- life time of more than twenty years.

The formation improvement alternatives are listed in Table 2 [9]. There are six general groups. As for the majority of these methods the experience is needed, often special equipment, it is advisable to consult with specialists.

Tabela 2. Mogućnosti poboljšanja planuma
Table 2. Formation improvement alternatives

I Promene osobina planuma na terenu Altering formation properties in place A. Injektiranje Grouting <ol style="list-style-type: none"> 1. Penetracija Penetration 2. Zbijanje Compaction B. Injektiranje krečom pod pritiskom Lime slurry pressure injection C. Delovanje strujom Electrical treatment <ol style="list-style-type: none"> 1. Elektro-osmoza Electro-osmosis 2. Elektrohemijska stabilizacija Electrochemical stabilization
II Rekonstrukcija i zamena Reconstruction and replacement A. Zbijanje Compaction B. Zamena Replacement C. Stabilizacija dodacima Admixture stabilization <ol style="list-style-type: none"> 1. Cement Cement 2. Kreč Lime 3. Bitumen Bitumen
III Primena asfalt-betona Asphalt-concrete applications A. Na punoj dubini Full depth (replacing ballast and subballast) B. U zaštitnom sloju Underlayment (replacing subballast)
IV Stabilizacija klizišta Slip stabilization A. Odvodnjavanje Drainage B. Potporne konstrukcije Retaining structures C. Promena nagiba Slope change
V Ugradnja zaštitnog sloja Insertion of protective layer
VI Primena geosintetičkih proizvoda Geosintentic products implementation

5.1 Promena osobina planuma na terenu

5.1.1 Injektiranje

Injektiranjem se ubrizgava materijal u tlo kako bi se ono ojačalo, izmenilo ili kako bi se smanjila njegova propustljivost.

Injektiranje penetracijom ojačava tlo povezujući čestice tla, odnosno zatvaranjem šupljina smanjuje se propustljivost, ili oba. Za uspešno injektiranje penetracijom, tlo mora biti relativno propustljivo. Smanjenje propustljivosti peska i šljunka u trupu pruge može se postići injektiranjem cementnim malterom, glinenim muljem u vodi, peskom i letećim pepelom. Čestice ovih sredstava prevelike su da bi popunile šupljine u mulju i glini, ili pesku i šljunku s više od 10% mulja i gline. Zbog toga, ova metoda nije poželjna u tlu koje sadrži mulj i glinu. Hemijska sredstva (najčešće silikati) za injektiranje mogu prodrati u grubi mulj i u srednji do fini pesak. Sposobnost sredstva za injektiranje da proдре u tlo procenjuje se na osnovu ispitivanja njegove propustljivosti na terenu ili u laboratorijskim uslovima, kao i analizom veličine zrna. Prema [9] predlaže se da D_{15} tla treba da bude bar 25 puta D_{85} čestica injekcionog sredstva. Takođe, potrebna je procena poboljšanja čvrstoće planuma.

Injektiranjem zbijanjem se zbija i/ili potiskuje okolno tlo pritiskom grudvom injekcionog materijala. Injekciono sredstvo je veoma konzistentna mešavina cementa, peska, pepela, gline i vode, koja se putem cevi do željene dubine pumpa pod pritiskom 700 –4000 kPa. Ovaj postupak je neprikladan za ojačanje natopljenog vezanog tla koje je nestišljivo, jer se može istisnuti tlo pod pritiskom sredstva za injektiranje u dubljim šuplinama.

5.1.2 Injektiranje krečom pod pritiskom

Krečni mulj utiskuje se kroz cevi pod pritiskom od 340 do 1700 Mpa i prodire u naprsline, pukotine, te propusne slojeve. Nedostatak je slaba kontrola rasprostiranja sredstva i opasnost od loma tla i formiranja novih pukotina. Otuda je potrebno ispitivanje okolnog tla za procenu efektivnosti prodiranja sredstva, a laboratorijska ispitivanja za procenu poboljšanja osobina. Mogući neželjeni efekti su visok sadržaj vode, visok pritisak koji slabi tlo, kao i zagađenje vode krečom.

Opiti na železnici pokazuju da ovo poboljšanje traje relativno kratko pošto se pod opterećenjem od voza usitnjavaju glineno-krečne grudve [5].

5.1.3 Delovanje strujom

Efektivan način poboljšanja mekanog glinovitog tla jeste smanjenje sadržaja vode. Kako takvo tlo nije moguće slobodno odvodnjavati, mora biti izazvan tok vode ka drenaži. Prilikom izgradnje novih pruga, moguća je konsolidacija dugovremenskim opterećivanjem. Kod postojećih pruga, alternativa – iako skupa – jeste putem elektroosmoze. Električna struja prolazi kroz tlo između elektroda, pri čemu molekuli vode migriraju sa anode u okoline drenaže (katode), odakle se odvoде. Ova metoda je ekonomična za zasićena i normalno konsolidovana blata i gline s niskom koncentracijom

5.1 Altering formation properties in place

5.1.1 Grouting

By grouting a material is injecting into the soil to strengthen it, change it or to decrease its permeability.

Penetration grouting strengthens the soil by bonding the particles or decreases the permeability by sealing voids, or both. For the successful grouting the soil or rock must be relatively permeable. For reducing the sands and gravel permeability in track formation the injection with cement mortar, clay-water slurry, sand and fly ash can be used. The particles of these materials are too large to penetrate voids in silts and clays, or in sands and gravels with silt and clay components of more than 10%. So, penetration grouting is unsuitable for use with fine silts and clays. Chemical grouts (commonly silicates) can penetrate into coarse silts and medium to fine sands. In situ and laboratory permeability tests, as well as a grain size analysis, will judge the ability of grout to penetrate into soil. It is suggested [9] that D_{15} of the soil should be at least 25 times the D_{85} of the grout particles. Strength tests are needed to estimate the formation improvement.

Compaction grouting compacts and/or displaces surrounding soil by the pressure of grout material bulb. Compaction grout is a very stiff mixture of cement, sand, fly ash, clay and water, which is pumped by means of pipe to the desired depth at pressure of 700-4000 kPa. This treatment is not suitable for strengthening saturated cohesive soils which are incompressible, because the soil can be displaced by the grout pressure in shallow depths.

5.1.2 Lime slurry pressure injection

The lime slurry is pumped into the soil through pushed in pipes at pressure of 340 - 1700 kPa and penetrates through fissures, cracks or permeable seams. Disadvantages are little control over the lime distribution and danger of soil fracture and forming the new cracks. Therefore the surrounding soil investigation is needed to assess the effectiveness of slurry distribution and laboratory tests to evaluate the soil improvement. Possible adverse effects are high water content, high pressure which weakens the soil and water contamination by the lime.

Railway tests have shown that this improvement lasts for relatively short time as the clay-lime crumbs were crushed under the train loads [5].

5.1.3 Electrical treatment

An effective way to improve soft clayey soils is to reduce the water content. As such soils are not free draining, the flow into the drains must be inducted. For new track construction the soil strengthening by long term loading is possible. For existing track an alternative, although expensive, is through electro-osmosis. A direct electric current is passed through the soil between electrodes and the water molecules migrate from the anode into the drain surrounding (cathode), from where they are removed. This method is economical for saturated and normally consolidated silts and clays and

porne vode kao elektrolita.

Tipičan sistem elektrohemijske stabilizacije sastoji se od izbušenih gvozdених или aluminijskih cevi kao anoda ugrađenih na 1 do 5m od katoda. Kroz njih se u tlo ubacuje rastvor kalcijum-hlorida, natrijum-hlorida, magnezijum-hlorida или aluminiјum-hlorida, koji se kreće ka katodama, gde se voda skuplja i uklanja.

Ispitivanja na terenu su poželjna za proveru efektivnosti metode. Izbor tipa anode i elektrolitskog rastvora zahteva hemijsku analizu minerala gline. To je vrlo skupa metoda i koristi se tamo gde druge nisu izvodljive. Glavna prednost, kao i kada je u pitanju elektroosmoza, jeste to što se elektrode ugrađuju sa suprotnih strana koloseka i što se ne prekida se saobraćaj prugom.

5.2 Rekonstrukcija i zamena

5.2.1 Zbijanje

Zbijanje je proces zgušnjavanja tla mehaničkim presovanjem, na račun smanjenja zapremine šupljina ispunjenih vazduhom, pri čemu vlažnost ostaje nepromenjena. Sto posto zasićena tla se ne mogu zbijati, već konsolidovati, što se postiže postepenim potiskivanjem vode iz pora. Cilj zbijanja je poboljšanje svojstava planuma: povećanje čvrstoće i krutosti, a smanjenje stišljivosti, plastične deformacije pod učestalim opterećenjem, propustljivosti, bubrenja i skupljanja. Međutim, povećanje gustine je parametar koji se najčešće koristi za specifikaciju željene veličine zbijanja i određivanje stanja zbijenosti i podrazumeva poboljšanje ostalih pobrojanih parametara.

Data energija zbijanja ne proizvodi istu veličinu zbijanja i krutosti za svako tlo, što je na slici 2 pokazano za tri vrste tla. Za istu energiju, procenat zbijanja povećava

clays with low pore-water electrolyte concentration.

Typical electrochemical stabilization system consists of perforated iron or aluminium pipes as anodes installed about 1-5m away from the cathodes. A solution as calcium, potassium, magnesium or aluminium chloride is fed into the anodes entering the soil, and moves toward the cathodes, where water collects and removed.

In situ tests are desired to evaluate the effectiveness of the method. Selection of the anode type and electrolyte solution requires chemical analyses of the clay minerals. The method is very expensive and is to be used only where other are not feasible. The main advantage, as for electro-osmosis, is that the work can be done without disrupting the train operation, because the pairs of electrodes would be installed on opposite sides of the track.

5.2 Reconstruction and replacement

5.2.1 Compaction

Compaction is the process of soil densification by mechanical pressing and in that way reduction in volume of air voids, while the moisture content remains unchanged. The aim of compaction is to improve soil properties, such as: increasing strength and stiffness; decreasing compressibility, plastic strain under repeated load, permeability, and reducing swelling and shrinking. However, density is the most commonly used parameter for specifying the desired amount of compaction and for determining the state of compaction and implies an improvement in the other parameters.

A given compaction effort does not produce the same strength and stiffness for all soils, that is shown for the three soil types in Figure 2. For the same effort the

Slika 2. Uticaj vrste tla na promenu zbijanja i krutosti sa energijom zbijanja
Figure 2. Effect of soil type on variation of compaction and stiffness with compaction effort

se kako tlo postaje krupnije – slika 2a [9]. Za isti procenat zbijenosti, rezultujuća krutost se povećava, od gline, preko prašine, do peska – slika 2b [9]. Razlike su još veće za konstantnu energiju zbijanja. Ovo je važno uzeti u obzir prilikom određivanja potrebne energije zbijanja na terenu.

Zbijanje se najčešće radi pločama i valjcima (statični i vibracioni). Zbog njihove ograničene efektivne dubine zbijanja, neophodno je zbijanje u slojevima od 15 do 30 cm. Postoje i tehnike dubinskog zbijanja udarnim zbijanjem ili vibracionim zbijanjem vodenim mlazom.

5.2.2 Zamena

Ako se zasićena ili skoro zasićena tla dovoljno isušie, mogu se ukloniti i zameniti zbijanjem u slojevima. Ovo je izgleda izvodljivije za grubo granulirana ili prašinasta tla, nego za glinu koju je teško osušiti. Međutim, granulirana ili prašinasta tla neće biti zasićena ako nisu ispod nivoa podzemne vode, pa je potrebno odvodnjavanje terena za vreme njihovog uklanjanja i zamenje. Ako zbijanje nije izvodljivo, zasićena tla, posebno meke gline, potrebno je ukloniti i zameniti tlom koje ima vlažnost pogodnu za zbijanje.

Organska tla neprihvatljiva su za planum, te se moraju ukloniti i zameniti pogodnim tlom.

5.2.3 Stabilizacija dodacima

Kao dodatak iskopavanju i zameni sa zbijanjem tla, ili površinskom zbijanju, osobine tla se mogu poboljšati mešanjem s materijalima kao što su cement, kreč, bitumen i leteći pepeo.

Mešanje se najbolje izvodi specijalnom opremom za mešanje i usitnjavanje. Često se koristi konvencionalna oprema – drljače, buldožeri, grejderi, skreperi. Specijalne mašine iskopavaju sloj tla, prevoze ga u mešalice i rasprostiru promenjeno tlo sa zadnje strane bubnja mešalice u neprekidnom procesu. Mogući su zahtevi za povećanje ili smanjenje postojećeg sadržaja vode pre dodavanja aditiva, kako bi se postigli prihvatljivi rezultati.

Cement se može upotrebiti za stabilizaciju skoro svih vrsta tla, izuzev organskih, slanih ili sulfatnih materijala. Krupnozrni šljunak zahtevao bi više cementa, a teške gline otežavaju mešanje. Najpogodniji je široko građuiran pesak i šljunak. Uopšte, ova stabilizacija treba da se ograniči na tla s manje od 35% čestica koje prolaze kroz sito (0,075 mm) i imaju indeks plastičnosti manji od 30% [9].

Cementnom stabilizacijom postižu se sledeća poboljšanja osobina planuma:

- povećana čvrstoća, uključujući i zateznu;
- povećana krutost;
- povećana otpornost na uslove vlaženje–sušenje i zamrzavanje–otapanje;
- smanjenje propustljivosti, osim kod glina;
- smanjenje bubrenja u plastičnim glinama.

Količina potrebnog cementa menja se s tipom tla i zahtevanim osobinama, ali je obično između 5 i 15% od težine suvog tla.

percent compaction increases as the soil becomes more coarse-grained – Figure 2a). For the same percent compaction the resulting soil stiffness increases from clay to silt and sand - Figure 2 b). The contrast is greater for constant compaction effort. These are important considerations in determining the required compaction effort for a given application.

Compaction is most commonly done using surface rollers, static and vibratory. As the roller have the limited effective depth of compaction, it works in layers of 15-30cm. Deep compaction techniques, by dropping heavy weight or by inserting of vibration accompanied with water jets, are available.

5.2.2 Replacement

If saturated or nearly saturated soils can be dried sufficiently, they can be removed and replaced by compaction in layers. This would more likely be feasible for coarse-grained or silty soils than for clayey soils, which are much difficult to dry. However, coarse-grained or silty soils would probably not be saturated unless they were below the ground water table and dewatering of the site would be required during the soil excavation and replacement. If consolidation is unfeasible, the saturated soils, especially soft clays, would need to be removed and replaced with soil which has moisture suitable for compaction.

Organic soils are unacceptable as a track formation and must be replaced by an acceptable soil.

5.2.3 Admixture stabilization

As a supplement to excavation and replacement with compaction, or to surface compaction, soil properties can be improved by mixing in materials such as cement, lime, bitumen and fly ash.

Mixing is best performing by special mixing/pulverizing equipment. Conventional equipment is frequently used, like harrows, bulldozers, graders, scrapers. Some special machine excavates a soil layer, transports it to mixing drum and deposits the modified soil out the drum rear end in continuous process. Increasing or decreasing the existing moisture content may be required prior to adding the stabilizing material in order to achieve acceptable results.

Cement may be used to stabilize almost all soil except organic, salt or sulphate materials. Coarse gravel requires high cement content and heavy clays show mixing difficulties. Broadly-graded sands and gravels are best suited. Generally, this stabilization should be limited to soils with less than 35% passing the 0,075 mm sieve and a plasticity index of less than 30% [9].

Cement stabilization achieves the following formation performance improvements:

- Increases strength including tensile;
- Increases stiffness;
- Increases resistance to wet-dry and freeze-thaw condition;
- Lowers permeability, except for clay;
- Decreases swelling of plastic clays.

The amount of required cement will vary with the soil type and required properties, but falls within the range of 5-15% of dry weight of soil.

Cementom stabilizovana tla, postavljena preko tla s manjom krutošću zbog pojave horizontalnog napona zatezanja, mogu pući i izgubiti neke konstruktivne uloge.

Kreč se može upotrebiti za poboljšanje većine tla u planumu, koja sadrže neke frakcije minerala gline (min 7% od težine) i indeks plastičnosti veći od 10%. Dobro je poznato da glinovito tlo, pomešano s krečom, formira grudvastu strukturu, smanjujući bubrenje s vodom i povećavajući nosivost. Uobičajena je količina između 3 i 7% kreča od težine tretiranog tla.

Glavna prednost upotrebe kreča jeste to što daje trenutno i drastično poboljšanje obradljivosti glinovitog tla, tako da često obezbeđuje jedini način rada s mekim vlažnim glinovitim tlom, pre nego metoda iskopavanja i zamene takvog tla. Takođe, krečom tretirano tlo nije podložno pucanju kao cementirano. Međutim, kreč nije pogodan ako se zahteva nagli porast čvrstoće.

Kreč se ponekad upotrebljava u kombinaciji s drugim dodacima: sa cementom ili bitumenom da bi se poboljšala obradljivost tla i unapredilo mešanje i zbijanje, s letećim pepelom radi obezbeđenja komponenti minerala gline potrebnih za reaktivnost u čisto granularnom tlu.

Kreč se mešao u planume pruga s dugim šinskim tracima, posebno na krajevima mostova (prelazne zona), radi sprečavanja sleganja, ali na linijama s velikom gustinom saobraćaja nije pokazao dugotrajni efekat i postupak je ponavljan više puta [5].

Bitumen se koristi za vezivanje tla koje je uglavnom zrnasto sa ograničenim česticama ($<0,075$ mm), gde se svrstavaju i čist šljunak i pesak. Nije pogodan za vlažna tla, pošto dodavanje tečnog bitumenskog stabilizatora pogoršava karakteristike takvog tla, koje su potrebne za zbijanje. Mešavine tlo-bitumen prave se s razređenim asfaltom, emulzijom ili penom, radi unapređivanja procesa mešanja. Bitumen povećava čvrstoću tla i smanjuje njegovu propustljivost. Ako se previše bitumena doda, smanjuje se čvrstoća. Da bi se postigla vodootpornost, bitumenska emulzija može da se prska po površini zbijenog planuma i utiskuje u njega, tako da tanki bitumenski film sprečava prodiranje vode. Ovaj proces može da bude efikasan za obradu planuma koji omekšavaju u prisustvu vode, pa nivo podzemne vode mora da bude dovoljno nizak. U tom slučaju, razmekšavanje tla ne izaziva voda zarobljena ispod bitumena.

5.3 Primena asfalt-betona

Asfalt-beton je mešavina bitumena i drobljene stene. Preporučena mešavina za planum pruge jeste široko građuiran lomljeni kamen (maksimalne veličine zrna od 25 do 37 mm) s nešto više bitumena i sitnog agregata nego za kolovoze, i sa 1–3% šupljina.

Dva načina primene asfalt-betona u planumu pruge jesu: po celoj dubini zastorne prizme ili samo u donjem delu zastorne prizme.

Učinci asfalt-betona mogu se proceniti iz uloga zastora i planuma pruge.

Za zastor:

- veća vertikalna nosivost, ali manja podužna i bočna otpornost;
- elastičnost oslanjanja koloseka je smanjena, pošto asfalt-beton ima viši modul od zastora, ali

Cement stabilized soils over soils with a lower stiffness will develop horizontal incremental stress can crack under the train load and lose some of its structural benefits.

Lime may be used to treat most soils that have at least some clay fraction (min 7% by weight) and plasticity index which exceeds 10%. It is well-known that a clayey soil mixed with lime develops a crumbled structure that reduces the plasticity, reduces the swelling with water and increases strength. The required quantity of lime is directly related to clay content. A range of 3–7% by weight of lime will treat most soils.

The main advantage of using lime is that it produces immediate and dramatic improvements in the workability of clayey soil, often proving the only way to work with soft wet clayey soil other than excavating and replacing it. Also, lime-treated soils are not as susceptible to cracking as cement-treated. However, lime is unsuitable if the rapid increase in strength is required.

Lime is sometimes used in combination with other additives: with cement or bitumen to improve soil workability and promote mixing and compaction, with fly ash to provide the clay mineral component required for reactivity in clean granular soils.

Lime was mixed into CWR track formations, particularly at the ends of bridges (transition zones), to prevent the recurring settlement, but in heavy traffic lines show short-term effect and was repeated several times [5].

Bitumen is used to stabilize the soils that are mostly granular with limited plastic fines (less than 0.075mm), in which belong clear sands and gravels. It is unsuitable for the wet soils, because adding the liquid bitumen worsens its characteristics needed for compaction. Soil-bitumen mixtures are made with asphalt cutback, emulsion or foam to promote mixing with soil. Bitumen increases soil strength and decreases its permeability. If too much bitumen is added, strength will decrease. To achieve waterproofing, bitumen emulsion can be sprayed on the surface of the compacted formation and penetrate downward, so the thin bitumen film prevents water infiltration. This process may be effective for the railway formations that soften in the presence of water, so the groundwater level must be low enough. In that case the softening is unlikely due to water trapped beneath the bitumen.

5.3 Asphalt-concrete application

Asphalt-concrete is a mixture of bitumen and crushed stone. The recommended mixture for track formation use is broadly-graded crushed stone (maximum grain size of 25–37mm) with slightly more bitumen and aggregate fines than in highway, and with 1–3% air voids.

Two ways of using asphalt-concrete in the track substructure are: either in full-depth ballast bed or in ballast bottom. In both cases the crib and shoulder of the ballast remain.

The effectiveness of the asphalt-concrete design can be evaluated from the ballast and formation functions.

For the ballast:

- Increased vertical bearing, but decreased lateral and longitudinal resistance;

elastičnost pruža donji stroj;

- efikasno odvodi atmosfersku vodu;
- podbijanje nije moguće u primeni asfalt-betona celom dubinom, pa je podešavanje vertikalne geometrije otežano;
- za istu debljinu zastora, asfalt-beton smanjuje naprezanje donjih slojeva, sve dok ostaje neoštećen, što znači da pucanje mora biti sprečeno pravilnim projektovanjem;
- obezbeđena je izolacija za zaštitu od mraza;
- ne podstiče rast vegetacije;
- obezbeđeni su apsorpcija buke i smanjenje vibracija;
- rekonstrukcija koloseka je mnogo teža i skuplja.

Za planum:

- na smanjenje naprezanja može se uticati pravilnim projektovanjem;
- zaštita od mraza može da se smanji ako je debljina sloja asfalt-betona manja od debljine zastora, zbog boljeg rasprostiranja opterećenja;
- sprečeno je međusobno prodiranje čestica zastora i planuma;
- sprečeno je „pumpanje“ finih čestica nagore iz drugih slojeva donjeg stroja;
- sprečeno je habanje planuma zastorom;
- obezbeđeno je odvođenje površinske vode.

Bolje je sloj asfalt-betona postaviti na zaštitni drenažni sloj, nego direktno na planum, jer on predstavlja dobru osnovu za razastiranje i zbijanje asfalt-betona.

Ukratko, da bi projekat sa asfalt-betonom u punoj visini zastora bio prihvatljiv, mora da ispuni dva uslova:

1. smanjenje elastičnosti oslanjanja koloseka i smanjenje poprečne i podužne stabilnosti mora biti u prihvatljivim granicama;
2. potreba za podešavanje geometrije i za rekonstrukciju mora se isključiti.

Zahtevana debljina asfalt-betona zavisi od osovinskog opterećenja, gustine saobraćaja i krutosti planuma. Tipični projekti u SAD koriste od 10 do 20 cm debeo sloj asfalt-betona samo u donjem delu zastorne prizme sa 12,5 do 25 cm tucanika do osnove praga. Primena asfalt-betona u SAD, u najviše slučajeva, jeste prilikom rehabilitacije kratkih deonica koloseka kao što su ukrštaji, skretnice, prilazi mostu, tunnelske podloge i ukrštaji s putevima u nivou i ta mesta su često problematična za održavanje [9].

5.4 Stabilizacija klizišta

Stabilizacija deonica koloseka s potencijalnim klizištem je bitna jer klizišta narušavaju planum pruge. Poremećaji mogu biti grupisani na sledećim mestima: kosine useka; kosine nasipa; podloga nasipa; planum pruge.

Poremećaj ili kretanje *kosina useka*, formiranih za vreme izgradnje pruge, mogu prouzrokovati pomeranje i u planumu pruge i prekid saobraćaja, nanosima zemlje i stena na prugu. Problem stabilnosti obično nastaje od vode unutar njih, delovanjem pritiska i smanjenjem otpornosti na smicanje. Rešenja uključuju jednu mogućnost ili više sledećih mogućnosti: skrenuti vodu koja dolazi odozgo, što je moguće više; postaviti

– Track resiliency is reduced because asphalt-concrete has a higher modulus than ballast, but most of the resiliency gives the formation;

- Effectively shed water coming onto the track;
- Tamping is not possible with asphalt-concrete in full-depth ballast and track vertical geometry will be difficult;
- For a given ballast thickness, asphalt-concrete will reduce stress on bottom layers as long as it remains undamaged that means the cracking must be prevented by proper design;
- Frost protection will be provided;
- Vegetation growth will not be promoted;
- Noise absorption and vibration attenuation will be affected;
- Track renewal will be much more difficult and expensive.

For the formation:

- On the stress reduction can be influenced by proper design;
- Frost protection could be less with the asphalt-concrete if the layer depth is less than the ballast depth, because of the better load spreading;
- Interpenetration of ballast and formation grains will be eliminated;
- "Pumping up" of fines from the other substructure layers will be prevented;
- Formation attrition by ballast is eliminated;
- Water shedding is provided.

A granular drainage layer beneath the asphalt-concrete, rather than directly on the formation, might be desirable, because it also provides a good bed for placing and compacting the asphalt.

In summary, two conditions must be met for the asphalt-concrete in full-depth ballast design to be viable:

- Track resiliency reduction and the lateral and longitudinal stability reduction must be within acceptable limits;
- The need for geometry adjustment and renewal must be eliminated.

The required thickness of the asphalt-concrete layer depends on the axle loads, the traffic amount and the formation stiffness. Typical designs in USA have used thickness of 10-20cm in ballast bottom with 12.5-25cm of ballast to the sleeper bottom. The majority of asphalt-concrete application at USA railway lines have been for rehabilitation short track sections such as turnouts, crossings, bridge approaches, tunnel floors and level crossings, because these are maintenance problematic areas [9].

5.4 Slip stabilization

The stabilization of track sections with potential slip failures is essential, because they will affect track formation. The failure location may be grouped as: cut slopes, embankment slopes, embankment foundation and track formation.

Failure or movement of *cut slopes*, formed by track building, can cause movement of the track formation and interrupt traffic by depositing earth and rock on the track. The stability problem usually arises from water within the slope exerting pressure and decreasing the shearing resistance. The solutions include one or more of the

drenaže unutar kosine; ublažiti kosinu; dodati ankere ili potporne konstrukcije. Useci u ekspanzivnim glinama mogu izazvati poteškoće zbog rasterećenja pri uklanjaju zemlje, u kombinaciji sa izlaganjem ciklusima vlaženja i sušenja. Tada je potrebna zaštita od promene vlažnosti ili ublaženje kosina.

Poremećaj unutar postojećeg *nasipa* obično je rezultat prodiranja vode usled jakih padavina i poplava, koje smanjuju nosivost tla na smicanje i povećavaju težinu. Zaštita od velikih padavina je odvodnjavanje nasipa. Tamo gde se očekuje poplava, kosine mogu biti ublažene ili se prave berme da obezbede odgovarajući faktor sigurnosti od poremećaja. Alternativno, može biti potrebno ojačanje dodavanjem potpornih zaštitnih konstrukcija. Erozija postojećih kosina nasipa takođe smanjuje njihovu sigurnost, pa je poželjna preventivna zaštita.

Poremećaj podloge nasipa češći je kod novih pruga, jer konsolidacija tla s vremenom pod težinom nasipa povećava njegovu otpornost. Međutim, povećane padavine i poplave mogu oslabiti osnovu nasipa i kasnije, pa će ublaženje kosina i ugradnja bermi takođe smanjiti ove potencijalne poremećajne sile.

Najkritičnija moguća situacija postoji kada je nasip na padini. Pomeranje nasipa može da se desi klizanjem nizbrdo po površinama kroz nasip ili kroz tlo unutar padine, s pretpostavkom da su stepenasti zaseci bili korišćeni da zadrže nasip na padini. To pomeranje može nekada početi odmah nakon izgradnje pruge, a verovatnije kao rezultat promena u uslovima površinskog ili podzemnog odvodnjavanja. Ovaj problem mora da se reši pre nego što se poremećaj desi – obezbeđenjem pravilnog odvodnjavanja.

5.5 Ugradnja zaštitnog sloja

Ako planum ne ispunjava postavljene zahteve, potreban je zaštitni sloj odgovarajuće debljine od šljunkovito-peskovitog materijala određene granulacije. U suprotnom, takvo stanje planuma vodilo bi većim troškovima održavanja geometrije koloseka, smanjenju veka trajanja cele pruge, smanjenju brzina vozova i tako dalje.

Zaštitni sloj ugrađuje se sa sledećim zadacima:

- nosivi sloj (raspodelom opterećenja na veću površinu, štiti donji stroj od prevelikog naprezanja);
- zaštitni sloj od smrzavanja (efektom toplotne izolacije, štiti tlo ispod planuma, osetljivo na mraz);
- filtrirajući i razdvajajući sloj (sprečavanjem mešanja zastora s donjim strojem, kao i sprečavanjem migracije finih čestica u zastor);
- izravnavajući sloj (ako je kolosek oslonjen neujednačeno i neogovarajućeg bočnog nagiba);
- pokrivajući sloj (sa smanjenom vodopropustljivošću štiti tlo osetljivo na vodu od površinskih voda);
- sloj za sprečavanje habanja planuma od strane zastora;
- sloj za ublažavanje vibracija od vozila, koloseka i zemljanog trupa.

Zaštitni sloj treba da ima sledeće karakteristike:

- uglavnom vodonepropustan ili vodopropustan u određenim granicama, tako da najveći deo vode oteče po planumu;

following possibilities: divert water coming from above to the extent possible, install drains within the slope, flatten the slope, add anchors or retaining structures. Cuts in expansive clays can give difficulties, because of unloading from soil removal combined with exposure to wetting and drying cycles. Protection from moisture change or slope flattening may be required.

Failure within existing *embankments* usually results from water infiltration by heavy rainfall or flooding, which reduces the soil shear strength and increases its weight. Drainage of the embankment protects from the heavy rainfall. In areas where flooding is expected, the slopes have to be flattened or have berms to provide an adequate safety factor against failure. Alternatively, strengthening through the additional of retaining structures may be necessary. Erosion of existing embankment slopes will also decrease their safety factor and slope preventive protection must be provided.

Failure of the embankment foundation is more usually with new track construction, since consolidation of the soil under the embankment weight will increase the foundation strength over time. However, increasing rainfall or flooding could weaken the foundation strength at a later time, so the flattened slopes and berms will reduce this potential force of failure as well.

The most critical situation exists when the embankment is on the side of a hill. Embankment movement could occur downhill along embankment surfaces or through the soil within hill, assuming that benches are used to key the embankment into the hill. This movement may begin after track construction, but probably as a result of changes in surface or subsurface drainage conditions. This problem must be corrected before failure occurs by providing proper drainage.

5.5 Insertion of protective layer

If the track formation does not satisfy the stated requirements, the protective layer of appropriate thickness made of gravel-sand material definite grading is needed. Otherwise, such formation state would lead to high costs of track geometry maintenance, decrease of track life cycle, reduction the train speeds and so on.

The formation protective layer is inserted to fulfil the following functions:

- Supporting layer (by load distribution effect protects the subsoil from too high stress);
- Frost protective layer (by its thermal insulating effect protects frost sensitive soils bellow the formation);
- Filtering and separating layer (by preventing the ballast from mixing in with substructure and fines from rising into the ballast);
- Equalizing layer (if track is supported unevenly and with unsuitable cross fall);
- Covering layer (with low water permeability protects soils sensitive to water from surface water);
- Attrition prevention layer (against ballast attrition);
- Vibration attenuation layer (from vehicle, track and subsoil).

Protective layer would have the following characteristics:

- Mostly impermeable to water or permeable to such extend that the majority of the water runs off the formation;

- filterski stabilan prema donjem stroju ili tlu, inače mu se poveća debljina za 10cm ili se doda geotekstil;
- elastičnost (modul elastičnosti), što ujednačenje od zastora ka donjem stroju;
- pri debljini preko 30cm, ugrađuje se i zbija u dva sloja;
- trajan na abraziju i drobljenje.

Geometrijski zahtevi za zaštitni sloj, odnosno planum:

- minimalne debljine 20 cm;
- bočni nagib najmanje 1:25–1:20 ili 4–5% s tolerancijom od 0,5%;
- ne sme da odstupa više od ± 2 cm od projektovanog položaja;
- mora biti ravan u podužnom pravcu (≤ 2 cm na osnovici dužine 4 m), ne sme da ima ulegnuća i kolotrage, odnosno debljina zastora treba da je konstantna;
- na nasipima se izvodi do ivice kosine, a u usecima do sistema za podužno odvodnjavanje.

Slika 3 [10] poredi raspodelu naprezanja na planum kod koloseka sa zaštitnim slojem i bez njega.

Slika 3. Raspodela naprezanja na planum sa zaštitnim slojem i bez njega
Figure 3. Pressure distribution on formation with and without protective layer

Slika pokazuje da je pritisak na planum bez zaštitnog sloja mnogo veći i postavljaju se visoki zahtevi za nosivost tla. Čestice tla se penju i prljaju zastor, ugao rasprostiranja pritiska se smanjuje i pritisak na donji stroj se povećava. Usled zaprljanosti zastora, opada trajnost efekta podbijanja, pa ono mora češće da se sprovodi. U slučaju sa zaštitnim slojem, voda će putem njega biti odvođena i neće kvasiti donji stroj. Povećana debljina sprečava štete od zamrzavanja. Zaštitni sloj kao filter sprečava penjanje finih čestica tla. Trajnost podbijanja je velika, zastor se ređe čisti..

5.5.1 Dimenzionisanje zaštitnog sloja kao nosećeg

Da bi zaštitni sloj služio kao konstruktivni materijal, mora da ima dovoljno veliki modul elastičnosti i stabilnu akumulaciju plastičnih deformacija pod ponavljanim opterećenjem točkova. Debljina zaštitnog sloja mora se birati tako da postigne zahtevanu nosivost planuma. Kod tla osetljivog na mraz, treba ugraditi sloj za zaštitu od mraza.

Tabela 3 daje pregled zahteva za zaštitni sloj planuma i pokazuje kako ih odrediti [5].

- Filter stable against substructure or subsoil, otherwise should be thicker by 10cm or a geotextile should be inserted;

- Elasticity (modulus of elasticity) as uniform as possible from the ballast to the subsoil;
- Thicker than 30cm, have to be laid and compacted in two layers;
- Durable against attrition and crumble.

The following geometrical requirements have to be met by the protective layer, i.e. formation:

- Minimum thickness to be inserted is 20cm;
- Cross inclination of at least 1:25 – 1:20 or 4-5% with a tolerance of 0.5%;
- Must not deviate by more than ± 2 cm from the design position;
- Must be plane in longitudinal direction (≤ 2 cm on the basis of 4m), without any troughs or traffic traces, in other words must be of uniform thickness;
- On embankments must be up to edge of the slope and in cuts up to longitudinal drainage system.

Figure 3 [10] compares the pressure distribution on formation by the track with and without protective layer.

The figure shows that the pressure on the formation without protective layer is much higher and this makes high demands on the bearing capacity of the soil. Soil fines coming up contaminate the ballast, the pressure propagation angle is reduced and the pressure on the subsoil increases. As the ballast is contaminated, the durability of tamping decreases and the cleaning has to be performed more frequently. In the case with protective layer the water is led away through it and cannot soak into the subsoil. The increased thickness prevents frost damage. The protective layer as a filter prevents soil fines from rising. The tamping durability is high, ballast cleaning becomes less frequently.

5.5.1 Protective layer dimensioning as the bearing layer

To serve like constructive material, the formation protective layer have to be of high enough modulus of elasticity and the stable plastic deformation accumulation under the repeated wheels load. The thickness is chosen in such way as to achieve the required bearing capacity of the formation. By the soil sensitive to frost, a frost protective layer has to be inserted.

Table 3 gives a summary of the requirements for the formation protective layer and shows how to prove its suitability [5].

Tabela 3. Zahtevi za zaštitni sloj planuma
Table 3. Track formation requiremants

osobine properties	zahtevi requirements	ispitivanje test / assessment
nosivost bearing capacity	zbijenost/density nosivost/bearing capacity elastičnost/elasticity	Proktorov opit/Proctor test opit pritiska pločom/plate load test opit sa padanjem tereta/ light hammer elastična deformacija/ elastic deformation
sleganje settlement	zbijenost/density minimizirana veličina šupljina/ minimized pore space bez habanja/no wear	Proktorov opit/Proctor test $n_a < 15\%$ dupli Proktorov opit/ double Proctor test
otpornost na mraz resistance to frost	mali udeo zrna/small portion of grains $d < 0,063\text{mm}$ ($< 5\%$) dobro odvodnjavanje/good drainage prekid kapilarnog penjanja/ capillary breaking	kriva granulometrijskog sastava/ grading curve
filtersko dejstvo filtering effect	filterska pravila/filter rules bez prenosa finih čestica/ no fines transportation	granulometrijski sastav/ grain distribution filterska pravila/filter rules
elastičnost elasticity	što veći procenat zrna kvarcnog peska/ highest possible portion of quartz sand	merenje ugiba praga/ measurement of the sleeper settlement

Prema [5] preporučuje se sledeći kriterijum za modul deformacije i zbijenost zaštitnog sloja po Proktoru:

- za nove pruge: $E_{v2} \geq 120 \text{ MN/m}^2$ $D_{Pr} \geq 1.03$
- za postojeće pruge: $E_{v2} \geq 80 \text{ MN/m}^2$ $D_{Pr} \geq 0.97$

Dozvoljeno naprezanje na zaštitni sloj, odnosno donji stroj, σ_{dozv} može se izraziti empirijskom formulom prema Klompu [5]:

$$\sigma_{dozv} = 0,006 E_{din} / (1 + 0,7 \log N) \quad [\text{MN/m}^2]$$

gde je:

E_{din} $[\text{MN/m}^2]$ – dinamički modul elastičnosti zaštitnog sloja odnosno donjeg stroja,

N – broj prelazaka opterećenja za vreme kritičnog perioda (kod tla osetljivog na vodu i mraz to su periodi kiša i otapanja).

Kod poznatog modula deformacije E_{v2} , dinamički modul deformacije nevezanog tla može se uzeti kao: $E_{din} = 1,2 - 2,5 E_{v2}$.

Tabela 4 [5] pokazuje orjentacione koeficijente posteljice, dinamički modul elastičnosti i dozvoljena naprezanja na pritisak zaštitnog sloja za različita tla, zavisno od broja ponavljanja opterećenja, kada je zastor debljine 30cm i modula deformacije 150 MN/m^2 .

Nosivost se ocenjuje statičkim modulom deformacije E_{v2} , koji se određuje opitom pločom i dinamičkim modulom deformacije E_{din} , koji se određuje opitom s padajućim teretom. Otuda, da bi se debljina zaštitnog sloja odredila, moraju biti poznati sledeći moduli deformacije: modul deformacije planuma tla E_{v1} , sopstveni modul deformacije zaštitnog sloja E_{v2} , te modul deformacije planuma pruge E_{pl} . Sopstveni modul deformacije zaštitnog sloja kod adekvatne raspodele zrna i zbijenosti zaštitnog sloja može da se usvoji od 150

According to [5] the following criterion for modulus of deformation and Proctor's density is recommended:

- For the new tracks: $E_{v2} \geq 120 \text{ MN/m}^2$ $D_{Pr} \geq 1.03$
- For the existing tracks: $E_{v2} \geq 80 \text{ MN/m}^2$ $D_{Pr} \geq 0.97$

The admissible pressure σ_{adm} on formation protective layer, i. e. subsoil can be empirically determined according Klompp's formula [5]:

where are:

E_{din} $[\text{MN/m}^2]$ – modulus of dynamic elasticity of formation protective layer, i. e. subsoil

N – number of load alternations during the critical period (rain and thaw periods for soils sensitive to water and frost)

When the modulus of deformation E_{v2} is known, the modulus of dynamic elasticity of incoherent soils may be assumed as: $E_{din} = 1,2 - 2,5 E_{v2}$.

Table 4 shows the approximate bed coefficient, modulus of dynamic elasticity and admissible compressive strain of different soils depending on the number of load repetitions for the ballast thickness of 30cm and the modulus of elasticity of 150 MN/m^2 .

The bearing capacity is assessed by modulus of static deformation E_{v2} which is determined in plate load test, and modulus of dynamic deformation E_{vd} which determined in drop hammer test. From there, to determine the thickness of the formation protective layer, the following modules of deformation should be known: the modulus of deformation of the earth formation E_{v1} , the modulus of natural deformation of the protective layer E_{v2} , and the modulus of deformation of the formation E_f . The modulus of natural deformation of the protective

do 200 MN/m². Modul deformacije planuma tla zavisi od sadržaja vode tla. Nosivost planuma tla je za vreme otapanja u proleće najmanja i tada veliki značaj ima ugrađeni sistem odvodnjavanja. Minimalna vrednost modula deformacije planuma tla može vrlo teško merno da se odredi, te se radi s proračunskim vrednostima. U tabeli 5 date su orijentacione vrednosti zavisne od materijala tla i hidroloških uslova [5].

layer by proper grain distribution and density may be assumed as 150 - 200 MN/m². The modulus of deformation of the earth formation depends on the water content. The bearing capacity is lowest during the thaw in spring, and then the drainage system becomes enormously important. The minimum modulus of deformation of the earth formation is very hard to determine by measures and, therefore, calculated values are applied. In Table 5 the approximate values, depending on the type of soil and hydrological cases, are given [5].

Tabela 4. Koeficijenti posteljice, dinamički modul elastičnosti i dozvoljena napreznja na pritisak zaštitnog sloja za različita tla, zavisno od broja ponavljanja opterećenja
Table 4. Bed coefficient, modulus of dynamic elasticity and admissible compressive strain of different soils depending on the number of load repetitions

Klasifikacija tla/ Soil classification	c [N/cm ²]	E _{din} = 1,2 - 2,5 E _{v2}	σ _{adm} [N/cm ²]	
			N=10 ⁶	N=10 ⁷
loše/bad	3	10	1,2	1
	4	20	2,4	2
srednje/medium	7	50	5,8	5,1
dobro/good	9	80	9,6	8,1
	11	100	10,2	10

Tabela 5. Orientacione vrednosti modula deformacije planuma tla zavisno od materijala tla i hidroloških uslova
Table 5. Approximate modulus of deformation of the earth formation depending on type of soil and hydrological cases

vrsta tla type of soil	dodatni zahtevi za udeo zrna/additional requirement grain share d < 0,1mm	moduli deformacije/ modulus of deformation E _{v1} [MN/m ²] Hidrološki slučajevi/hydrological cases		
		1	2	3
muljevit ili glinoviti šljunak/ silty or clayey gravel	10-20%	60	30	20
muljevit ili glinoviti pesak/ silty or clayey sand	10-20%	50	25	20
jako muljevit ili glinoviti šljunak odn. pesak/ highly silty or clayey gravel e.i. sand	20-30%	40	20	15
	>30%	30	15	10
mulj ili glina/ silt or clay	lako plastični slightly plastic	25	15	10
	srednje plastični medium plastic	25	15	10
	jako plastični very plastic	20	15	10

Hidrološki slučajevi/Hydrological cases:

- 1 – nema dodatnog natapanja, nenačet planum / no additional soaking, integer formation
- 2 – povremeno natapanje, loše oticanje vode / occasional soaking, bad water drainage
- 3 – stalno natapanje, bez oticanja vode / permanent soaking, no water drainage

Pri izrazito maloj nosivosti planuma tla, kada je E_{v1} < 10 MN/m², najbolje je sprovesti zamenu tla. Debljina zaštitnog sloja planuma pruge može se dimenzionisati zavisno od predviđene brzine na pruži i nosivosti (modula deformacije) planuma tla, prema dijagramu na slici 4 [5].

When the bearing capacity of the earth formation is very low, when it is E_{v1} < 10 MN/m², it is advisable to replace the soil. According to Figure 4 [5], the thickness of the track formation protective layer can be dimensioned depending on target line speed and the bearing capacity (modulus of deformation) of the earth formation.

Slika 4. Dimenzionisanje debljine zaštitnog sloja planuma pruge
Figure 4. Dimensioning the thickness of track formation protective layer

Prema standardima nemačkih železnica [6], s poznatom vrednošću modula deformacije planuma tla E_{v1} i zahtevanog modula deformacije zaštitnog sloja E_{v2} , putem dijagrama na slici 5, može se odrediti minimalna debljina zaštitnog sloja.

Furthermore, according to DB standards [6], with known value of the modulus of deformation of the earth formation E_{v1} and required value of modulus of deformation of the protective layer E_{v2} , with help of the diagrams in the Figure 5, the minimum protective layer thickness can be determined.

Slika 5. Određivanje minimalne debljine zaštitnog sloja iz poznatog E_{v1} i zahtevanog E_{v2}
Figure 5. Determination the minimum protective layer thickness from known E_{v1} and required E_{v2}

ORE komitet D117 [1], na osnovu velikih serija merenja i proračuna, dao je traženu ukupnu debljinu, koja se sastoji od 25 cm zastora i jednog ili više međuslojeva ispod njega. Na slici 6 prikazane su krive koje se koriste na raznim železnicama (DB, SNCF, SBB), na osnovu CBR indeksa. Slika takođe ukazuje i na razne načine klasifikacije tla, kao što je putem CBR indeksa, modula elastičnosti i prema UIC preporuci 719R.

ORE Committee D117 [1], on the basis of the major series of measures and calculations, gives the desired total depth consisting of a 25cm ballast layer and one or more intermediate layers below it. In the Figure 6, the curves used by various railways (DB, SNCF, SBB) based on the CBR (California Bearing Ratio) index, are plotted. Figure 6 also indicates the various scales for classification of soils, such as CBR, modulus of deformation, and according to UIC leaflet 719R.

Slika 6. Podaci iz ORE D117
Figure 6. Data from ORE D117

Još jedan način određivanja preporučene debljine zaštitnog sloja zajedno sa zastorom, zavisno od koeficijenta posteljice zastora c i geometrije pragova, dat je u tabeli 6 [5].

One more way of determination the recommended thickness of the protective layer together with ballast bed related to the coefficient of ballast c and the sleeper geometry is given in the Table 6 [5].

Tabela 6. Debljina zaštitnog sloja + zastor zavisno od koeficijenta posteljice zastora c i geometrije pragova
Table 6. Thickness of protective layer+ballast related to the coefficient of ballast c and the sleeper geometry

pragovi sleepers		osovinsko opterećenje axle load [kN]	200		250		300	
dužina length	razmak spacing	c [kN/cm ³]	50	100	50	100	50	100
240	55	debljina (zastor+zaštitni sloj) thickness (ballast+protective layer) [cm]	60	30	80	45	100	65
260	55	debljina (zastor+zaštitni sloj) thickness(ballast+protective layer) [cm]	45	30	65	35	80	50

Linija prosejavanja materijala zaštitnog sloja planuma pruge prikazana je na slici 7 [5]. Šrafirano područje je dozvoljeno područje prosejavanja prema DB propisima. Za izradu planuma u slučaju tla osetljivih na vodu, njegov zaštitni sloj treba da je od vodonepropusne mešavine zrna KG1, koja ima najveći modul deformacije od 250 MN/m².

The usual grain mixture applied for formation protective layer is represented in Figure 7 [5]. In the shaded surface have to be the scatter of admissible grading curves according to DB regulations. For the formation construction in the case of water sensitive soils, its protective layer would consist of the water impermeable grain mixture KG1, which has the highest modulus of deformation of 250 MN/m².

MEŠAVINA KG 1/GRAIN MIX KG 1
područje optimalne granulometrijske krive/optimum grain size range

Slika 7. Mešavina za zaštitni sloj planuma pruge
Figure 7. Grain mixture for formation protective layer

5.5.2 Uloga odvodnjavanja i filterska stabilnost zaštitnog sloja

Materijal zaštitnog sloja treba da bude takvog sastava zrna i zbijenosti da spreči migracije i prodiranje čestica tla u zastor, dok voda može da prolazi (razdvajajuća uloga zaštitnog sloja). To će se ostvariti kada stepen neujednačenosti zrna zaštitnog sloja bude preko 15 i kad filtersko pravilo po Tercagiju (slika 8 [5]) bude ispunjeno poznatim odnosom:

$$D_{15} \leq 4 \times d_{85}$$

Time je krupnoća zrna kao filtera ograničena s gornje strane i sprečena je kontaktna erozija. Ako ovaj uslov ne može da se ispuni, mogu se primeniti geosintetici kao razdvajajući, filtrirajući i odvodnjavajući element.

Osim uobičajenog odvodnjavanja, kod železničkih linija u zonama vodozaštite, u okviru posebnog projekta, primenjuju se i prostirke za zaptivanje u zaštitnom sloju planuma.

Pri tome, zaštitni sloj kao filter mora da ima vodopropustljivost veću od planuma. Brzina protoka ne sme biti toliko velika da čestice budu isprane, i to je filterska stabilnost (filterska uloga zaštitnog sloja), što je zadovoljeno ako je:

$$D_{15} \geq 4 \times d_{15}$$

To znači da prečnik zrna zastora D_{15} mora biti veći od četvorostrukog prečnika zrna zaštitnog sloja d_{15} i da linija prosejavanja seče liniju AB (pogledati sliku 8). Ovim odnosom krupnoća zrna zaštitnog sloja je ograničena s donje strane, čime je obezbeđeno da je tlo ispod zaštićeno i efikasno odvodnjavano.

U slučaju da ovaj uslov nije ispunjen, može se koristiti dvoslojna zastorna prizma: gornji sloj krupniji - da odgovara zastoru a donji sitniji - da odgovara planumu (obično pesak), ali odnos ta dva sloja mora da

5.5.2 Protective layer drainage and filter stability roles

The protective layer material has to be of such grain mixture and density to prevent the soil fines migration and penetration in the ballast, while the water can pass through (separating effect of protective layer). This is achieved by the grains irregularity degree of $U = d_{60}/d_{10} \geq 15$ and by fulfilled the filter role of Terzaghi (Figure 8 [5]), with the known relation:

This limits the filter grain upwards and by this way the contact erosion is avoided. If this cannot be met, geosynthetic acting as a separating, filtering and draining element may be used.

By railway lines in water-protected zones, except the usual drainage system, the water-block mats would be inserted in the formation protective layer within the separate design.

Furthermore, the protective layer as a filter must to have permeability to water better than formation. The flow rate must not be so high that soil particles are rinsed out and this is hydraulic filter stability (filtering effect of protective layer), which is fulfilled if:

This means that the grain size of ballast D_{15} must be larger than the fourfold grain size of formation protective layer d_{15} and the grading curve intersects the AB line (see Figure 8). The lower size of protective layer is limited by this relation and this guaranteed that the soil below is protected and drained effectively.

If this requirement may not be fulfilled, the two-layered protective layer can be used: on top coarse-grained to suit the ballast bed and on bottom fine-grained (usually sand) to suit formation, but the

zadovolji filtersko pravilo po Tercagiju. Pri tome, početna granulacija mora da ostane stabilna kroz vreme.

relationship between these two layers must fulfil the Terzaghi's rule. In addition, the initial grain sizes should be stable in time.

Slika 8. Filtersko pravilo po Tercagiju za zaštitni sloj planuma pruge
Figure 8. Filter role of Terzaghi for formation protective layer

5.5.3 Dimenzionisanje zaštitnog sloja za zaštitu od zamrzavanja

Problem zamrzavanja-odmrzavanja-omekšavanja tla ispod pruge dovodi do značajnih i neujednačenih vertikalnih pomeranja koloseka i ubrzava njegovo propadanje. Otuda, ako je tlo osetljivo na zamrzavanje, treba sprovesti dimenzionisanje zaštitnog sloja za sigurnost tla od mraza. Pritom treba razlikovati potpunu i delimičnu sigurnost od mraza. Delimična sigurnost znači da je pri jakim zimama dozvoljeno ograničeno prodiranje mraza u tlo. Potpuna sigurnost od mraza propisana je za novoizgrađene pruge, pruge za velike brzine i pruge s kolosekom na čvrstoj podlozi. Za sve ostale pruge dozvoljava se delimična sigurnost od mraza.

Osetljivost na mraz zavisi od:

- indeksa zamrzavanja kao zbiru proizvoda dana s mrazom i temperature zamrzavanja tokom jednog perioda zamrzavanja;

- stepena neujednačenosti oblika zrna $U=d_{60}/d_{10}$,
- kapilarnosti tla (kapilarnog penjanja vode).

Razlikuju se tri klase osetljivosti tla na zamrzavanje (dijagram na slici 9 [5]):

F1 – neosetljivo na zamrzavanje;

F2 – mala do srednja osetljivost tla na zamrzavanje;

F3 – vrlo osetljivo na zamrzavanje.

5.5.3 Protective layer dimensioning as the frost protection

The freeze-thaw-softening track subsoil problem leads to the significant and differential vertical displacements of track and accelerates its deterioration. So, if the soil is frost sensitive, the protective layer must be dimensioned to the frost safety. There is a distinction between full and partial frost safety. Partial frost safety means that a limited frost penetration in the soil is admitted in severe winters. Full frost safety is prescribed for new lines, high-speed lines and ballastless tracks. For all other types of lines the partial frost safety is admissible.

The sensitivity to frost depends on:

- frost index as the sum of the products of frost days and the frost temperature within a frost period,
- degree of irregularity,
- soil capillarity.

There are three classes of sensitivity to frost (Figure 9 [5]):

F1 – no sensitivity to frost

F2 – low to medium sensitivity to frost (silty and clayey gravel and sand, depending on their degree of irregularity and the share of fines with $d \leq 0.063\text{mm}$ in percents in weight)

F3 – high sensitivity to frost

Malu, srednju do visoku osetljivost na zamrzavanje imaju muljevit i glinovit šljunak i pesak, zavisno od indeksa neujednačenosti U i procenta udela u težini finih čestica sa $d \leq 0,063\text{mm}$, prema slici 9.

Low, medium to high sensitivity to frost has silty and clayey gravel and sand, depending on their degree of irregularity and the share of fines with $d \leq 0,063\text{mm}$ in percents in weight according to Figure 9.

Slika 9. Klase osetljivosti tla na zamrzavanje
Figure 9. Classes of sensitivity to frost

Planum osetljiv na mraz takođe može da se zaštiti ugradnjom termoizolacionog sloja (toplotne brane). Za to su pogodni noseći slojevi od lakog betona gustoće oko 600 kg/m^3 debljine između 16 i 20 cm i ploče od tvrde penaste plastike gustoće $\geq 30 \text{ kg/m}^3$ debljine 5 do 10 cm sa slojem peska debljine oko 10 cm odozgo za zaštitu od proboja zrnima zastora, zavisno od konstrukcije koloseka i klimatskih uslova. Ta mera se može sprovesti u okviru čišćenja zastora specijalnim mašinama za čišćenje ili saniranje planuma. Kada se ove ploče kombinuju s geotekstilom, smanjuje se buka do 5 dB i prenos vibracija u donji stroj za 20 do 45%.

Kada zastor leži preko čvrste (betonske ili stenske) podloge, mora se predvideti međusloj za apsorpciju udara (npr. elastična podzastorna prostirka), kako bi se ublažilo njegovo sitnjenje pod točkovima šinskih vozila.

PVC folije debljine 2 mm mogu biti korisne kada je planum već raskvašen i jako zbijen, posebno pri dubokim zastornim vrećama.

5.6 Ugradnja geosintetičkih materijala

Geosintetički materijali treba da doprinose smanjenju naprezanja i deformacija i poboljšanju nosivosti i trajnosti zaštitnog sloja planuma. Oni se obično ugrađuju između tla i zaštitnog sloja ili sloja za zaštitu planuma od mraza, polažu se na zbijeni i isplanirani planum i pokrivaju zaštitnim materijalom. Oni treba da ispunjavaju mehaničke i hidrauličke zahteve i treba da spreče pumpanje finih čestica tla nagore.

Geosintetičke materijale treba primenjivati ako:

- filterska stabilnost ne postoji između tla i zaštitnog sloja;
- odvodnjavanje bočnim nagibom planuma tla nije dovoljno;

Formation sensitive to frost may also be protected by the insertion of thermal insulating layers (barriers). Supporting layers of foam concrete with density of about 600 kg/m^3 of thickness between 16-20cm and plastic foam slabs with density of $\geq 30 \text{ kg/m}^3$ of thickness between 5-10cm and protective sand layer on it of at least 10cm against crashing by the ballast, depending on the track structure and climatic conditions, are suitable for this. These works may be carried out during formation cleaning or improvement measures. When these frost protective layers are combined with geotextiles the noise level is decreased by least of 5dB and vibration transfer in substructure by 20-45%.

When the ballast lies on solid (concrete or rock) layers, shock-absorbing layers such as elastic mats against crushing the ballast grains under the train wheels, have to be provided.

PVC foils of thickness of 2mm can be useful, when the formation is already soaking and strongly consolidated, especially with dip ballast troughs.

5.6 Geosintetic products implementation

Geosintetics contribute to a reduction of stress and deformation, so as to improve and maintain the bearing capacity of formation protective layer. They are usually inserted between the subsoil and the formation or frost protective layer, on the compacted and regulated formation and covered by the protective materials. They have to fulfil the mechanical and hydraulic requirements and to prevent soil fines being pumped up.

Geosintetics should be applied if:

- filter stability between subsoil and protective layer do not exists,
- water drainage by cross fall of the earth formation

- postoje mesta sa smanjenom nosivošću planuma tla;
- treba poboljšati dugovremensko ponašanje donjeg stroja na jako opterećenim prugama.

Vrste geosintetika i njihove funkcije jesu:

- geotekstili: razdvajanje, filtracija, prenos, ojačanje;
- geomembrane: izolacija, razdvajanje, ojačanje;
- georešetke: ojačanje;
- geomreže: prenos;
- geosaće: ojačanje;
- vezani (kombinovani) materijali.

Geosintetički materijali se uglavnom proizvode od poliestera, polipropilena ili polietilena.

U tabeli 7 skupljeni su zahtevi za geosintetičke materijale prema tehničkim uslovima isporuke na DB [5].

is not sufficient,

- there are areas with low bearing capacity in the earth formation,
- long-term behaviour of substructure on high-density lines has to be improved.

The types of geosynthetics and their functions are:

- Geotextiles: separation, filtration, transmission, reinforcement;
- Geomembranes: isolation, separation, reinforcement;
- Geogrids: reinforcement;
- Geonets: transmission;
- Geowebs: reinforcement;
- Geocomposites: combinations.

Geosynthetics are mainly of polyester, polypropylene or polyethylene.

Table 7 gives a summary of the requirements to be met by geosynthetics according to the technical terms of delivery of the DB [5].

Tabela 7. Zahtevi za geosintetike
Table 7. Requirements for geosynthetics

zahtevi requirements	masa mass [g/m ²]	najveća sila zatezanja maximum tensile force [kN/m]	najveća rastegljivost maximum elongation under tensile stress [%]	vodopropustljivost permeability to water [m/s]		sila proboja plunger puncture force [kN]
				k _v	k _h	
filter filter	100 - 250			≥ 10 ⁻³		≥ 1,0
razdvojno-filterski sloj zašt.sloja planuma pruge separating-filtering layer of the track formation protective layer	≥ 300	≥ 16	≥ 30 ≤ 40	≥ 10 ⁻³	≥ 10 ⁻³	≥ 2,0
razdvojno-filterski sloj planuma tla separating-filtering layer of earth formation	≥ 400 ≥ 200	≥ 16 ≥ 40	≤ 85 ≤ 25	≥ 10 ⁻³		≥ 2,0
ojačanje u zaštitnim slojevima reinforcement of formation protective layers		≥ 10	≤ 20			

Geotekstili se proizvode od mehanički, termički ili hemijski zbijanih izvlačenih vlakana. Oni su obično pleteni, tkani ili netkani, u obliku prostirki. Mogu da budu pleteni ili nepleteni. Geotekstil ima više mogućnosti za mesto ugradnje: između zastora i planuma, između zaštitnog sloja i podtla, između zastora i zaštitnog sloja, između novog i starog sloja zastora.

Jedna od glavnih primena geotekstila u koloseku jeste ispunjenje nekih od funkcija zaštitnog sloja, bilo da ga zamenjuje, bilo da ga dopunjuje. U tu svrhu, on treba prvo da izdrži napone pri rukovanju i ugradnji i sile kojima je izložen tokom eksploatacije, uključujući probode čestica zastora, istezanje da bi se prilagodio nepravilnostima terena, kao i da se odupre pokretima tla.

Geotekstili se obično umeću u kontaktnoj zoni, između zaštitnog sloja i podtla, kao razdvojni, filtrirajući i

Geotextiles are manufactured from mechanically, thermally or chemically compacted extruded fibers, which are usually needled, woven or no-woven, in the form of sheets. Geotextiles have the following alternatives for the installation place: between ballast and formation, between protective layer and subsoil, between ballast and protective layer, between the new and existing ballast layer.

One of the primary applications of geotextiles in track is to fulfil some of the functions of protective layer, either in place of or to assist it. For this purpose it will first withstand the handling and installation and the forces encountered in service, including puncturing by ballast grains, stretching to conform to the surface irregularities and to resist soil movements.

Geotextiles are usually inserted in contact area

odvodnjavajući element, ali ojačanje na zatezanje ima ograničenja. Što je manja nosivost tla, sve teži geotekstil treba da bude. Ispitivanja pokazuju da vlaknasti tkan geotekstil zadržava svoje dobre osobine i da na SNCF-u uveliko uspešno primenjuju teške geotekstile. Takođe, pokazalo se da termički ojačani geotekstili potpuno zaptivaju, delujući kao vodonepropusna membrana.

Vibracije od vozova moraju se uzeti u razmatranje kada se projektuje kolosečna noseća konstrukcija. Kritične vibracije nastale u geosintetičkim materijalima u srednjefrekventnom području jesu oko 40 Hz [5]. Jačina na zamor geotekstila i veza s tlom (smanjenje koeficijenta trenja) mogu biti izloženi nepovoljnom uticaju vibracija, posebno pri većim brzinama vozova.

Ugradnja geotekstila je mehanizovana u okviru postupaka obnove planuma i vrlo je ekonomična, jer smanjuje troškove održavanja i obnove koloseka, a štete od zamrzavanja tla se izbegavaju. Pri tome bi trebalo da je geotekstil bar 300 mm ispod dna praga da bi se izbeglo oštećenje pri podbijanju, kao i poremećaji od čišćenja zastora. Građevinska mehanizacija ne sme da se vozi preko geotekstila. Treba obezbediti glatku površinu na koju se polaže, bez oštih objekata i izloženost ultraljubičastom zračenju treba da je što je moguće kraća. Treba izbegavati duple slojeve geotekstila zbog mogućnosti da se razviju ravni klizanja između njih. Naposletku, potrebno je obezbediti adekvatan sistem odvodnjavanja.

Geotekstili su često lakši za ugradnju od drugih metoda poboljšanja planuma, pa njihova upotreba može rezultirati smanjenjem početnih troškova. Istovremeno, geotekstili imaju ograničenu trajnost poboljšanja koja pružaju, pa se moraju periodično menjati, što je težak posao koji može prevazići dobit od njihove lake ugradnje. Dalje, geotekstili ne mogu ispuniti sve funkcije zaštitnog sloja, pa je potrebno pažljivo razmotriti sve aspekte da bi se donela odluka o najekonomičnijem rešenju [9].

Geomembrane su nepropusni, savitljivi plastični slojevi debljine od oko 0,15 mm do najviše 3 mm, bez otvora, od neoprena, polivinil-hlorida, hlorisanog polietilena ili drugih plastika. Radi ojačanja na zatezanje, vezuju sa mrežu od najlona ili poliestera, a površina im se ohrapavljuje da bi se povećao otpor smicanja s tlom. Osnovna funkcija im je sprečavanje prodiranja vode odozgo i vlage koja dolazi iz tla odozdo, kao i zadržavanje proticanja podzemne vode. Otuda je proces spajanja ivica – bilo na gradilištu ili tokom proizvodnje – kritičan, pa mnoge membrane propuštaju na šavovima. Geomembrane postavljaju se na planum, između dva sloja peska debljine najmanje 50 do 100 mm, koji ih štiti od probijanja; one ne smeju doći u kontakt sa zastorom.

Ozbiljan problem javio bi se ako je suvišna voda zarobljena ispod membrane, što može nastati od ponavljano opterećenja kod zasićenih tla ili kretanjem podzemne vode nagore. Tada bi ta voda morala da se odvede.

Membrane obezbeđuju i razdvajanje čestica tla. Zbog svoje čvrstoće na zatezanje imaju i izvesnu ulogu ojačanja, ali to nije njihova zahtevana funkcija.

Alternativni metod za proizvodnju vodonepropusnih barijera jeste prskanje bitumenom ili polimerom, ili noseće površine (obično nepleteni geotekstil), ili sloja peska na planumu. Da bi se sprečila mesta curenja, poželjan je zaštitni sloj peska preko bitumena. Površina

between protective layer and subsoil as separation, filtering and draining element, but for tensile reinforcement has limitations. The lower the soil bearing capacity, the heavier used geotextile. Experiments have shown that needled filament geotextiles maintain their good properties and the SNCF have successfully used heavier types for a long time. Also, they show that thermally bonded geotextiles got clogged and act as a water-proof membrane.

The vibrations from trains must be taken into consideration when design the track supporting structure reinforced by geotextiles. Critical vibration occurs in it at about medium frequencies of 40 Hz [5]. The geotextile fatigue strength and the interface between geotextile and soil (reduced friction coefficient) may be adversely influenced by vibrations, especially at higher running speeds.

Geotextiles are inserted by machines during formation renewal and are very economical, as reduce maintenance and renewal costs and prevent the occurrence of frost damage. In addition, the depth of geotextiles installation would be at least 300mm below the bottom of the sleepers to avoid damage during tamping and deteriorating from ballast cleaning. Construction equipment should not drive over the geotextiles. Smooth surface on which to lay it, without sharp objects, should be prepared and the exposure time to ultraviolet radiation as short as possible. Double layers of geotextiles should be avoided because of the possibility of slip planes between them. Finally, an adequate drainage system should be established.

Geotextiles are often easier to install from other improvement measures, so their use may result in a lower initial costs. On the other hand, geotextiles have a limited duration of improvement and have to be replaced periodically, which is a difficult work which may offset the benefits of their ease installation. Further, it cannot fulfil all functions of protective layer, so the careful decision is required for the most economical solution [9].

Geomembranes are impermeable, flexible plastic sheets in thickness from 0.15mm to at least 3mm without holes, made from neoprene, polyvinyl chloride, polyethylene or other plastics. For higher strength they are bonded to nylon or polyester mesh, and for increased shearing resistance with soil their surface is roughened. The main applications are to prevent infiltration of water from the surface, to block water coming from the soil below and to interrupt the flow of ground water. So, the edges connecting, either at the situ or during fabrication is considered critical as the many of them leaking at borders. The membrane is placed at formation, between two sand layers of at least 50-100mm, which protected them from puncturing as they must not come in contact with ballast particles.

Severe problem will occur if excess water is trapped beneath the membrane, that result from repeated loading by saturated soils or upward flow of ground water. Then, that water must be drained away.

Membranes also provide the soil separation. Although they have tensile strength and therefore certain reinforcement function, this is not its demanded function.

An alternative method for producing water impermeable barrier is by spraying bitumen or polymer, either the supporting surface (usually no-woven geotextil) or sand layer on formation. To avoid the leakage points, a protective sand layer over bitumen is advisable. The

mora biti pravilno oblikovana za oticanje vode pre prskanja, da se ne bi stvarali vodeni džepovi iznad premaza. Nepovoljan efekat je zarobljena voda ispod premaza.

Georešetke nastaju razvlačenjem sintetičkog materijala ili spajanjem niti u nizove molekula polimera s velikom jačinom i krutošću. One se utiskuju u mešavinu čestica unutar zaštitnog sloja i deluju na rasprostiranje opterećenja i smanjenje naprezanja. Na taj način, one premošćavaju područja pruge male nosivosti i povećaju njenu zateznu nosivost u svojoj ravni kada su deformacije tla zatežuće. Dimenzije okaca mreže su između $1,67 \times d_{80}$ i 40 mm.

Geomreže čine kanali sa strujanjem, koji se sastoje od šupljeg plastičnog jezgra obmotanog geotekstilom. Voda iz tla prolazi kroz geotekstil i protiče duž šupljeg jezgra, tako da geomreža ima funkciju prenosne drenaže. Geomreže moraju da budu dovoljno nosive da izdrže protok kroz kanale pod pritiskom tla.

Geosaće čine plastične ćelije otvorene i ka gore i ka dole, ispunjene zrnastim tlom. Svojom čvrstoćom na istezanje, formiraju ojačan sloj tla koji nosi opterećenje.

Vezani materijali su kombinovani razni geosintetički materijali, tako da se istovremeno postiže više efekata. Na primer, za ojačanje je najbolje polagati georešetku sa geotekstilom, čime se obezbeđuje održavanje nosivosti i rastavljanje filtersko delovanje pri promenljivim hidrološkim zahtevima. Pri upotrebi ovakvog geosintetičkog materijala s višestrukim dejstvom, može se smanjiti debljina sloja za zaštitu od mraza za 10 cm.

6 ZAKLJUČAK

Glavna funkcija planuma pruge jeste da obezbedi stabilnu podlogu konstrukciji koloseka. Da bi to ispunio, oblici propadanja se moraju izbeći i planum pruge – kao prvi sloj ispod gornjeg stroja pruge – mora da se unapredi. Savremena praksa projektovanja pruga i planiranja održavanja zanemaruju tu činjenicu. Često se odluke donose na osnovu iskustva. Prilika da se napravi greška postoji zbog velike različitosti uslova na terenu i promena u saobraćajnim zahtevima kroz vreme.

Iz ovog pregleda mogućnosti unapređivanja planuma pruge, može se zaključiti da je odluka o primenjenoj metodi rezultat jednog procesa. Prvo, mora se odrediti uzrok problema u koloseku pravilnim istraživanjem planuma – na terenu i pomoću laboratorijskih opita i analiza. Moguće funkcije i primenljivost postojećih mogućnosti treba proceniti. To je ključni korak i predstavlja izazov za građevinskog inženjera stručnjaka za železnicu, zbog nedostatka uvida u trenutno stanje u toj oblasti. Posle toga, treba sprovesti uporednu ekonomsku analizu tih mogućnosti. Za najbolju metodu, pošto obično prethodna iskustva na istoj deonici koloseka ne postoje, preporučuje se da se sprovedu opiti na terenu. Po snimanju karakteristika pruge, u dovoljno dugom periodu, rezultate treba proceniti. Veoma je korisno dokumentovati rezultate izabrane metode poboljšanja planuma pruge za buduću primenljivu preporuku.

Potrebu poznavanja stanja planuma pruge i mogućnosti sprovođenja postupaka poboljšanja trebalo bi da prepoznaju i Železnice Srbije, jer će bez toga trend porasta troškova održavanja i obnove pruga biti sve očigledniji.

surface must be first properly shaped for shedding water before spraying, to avoid developing water-pockets above coating. The adverse effect again is of water trapping beneath the coating.

Geogrids originate from strands stretched to align the long-chain polymer molecules for high strength and stiffness. The grids interlock with the grain mixture within the protective layer to create the load-distributing and tension-reducing effects. So, they bridge areas of poor bearing capacity and in general increase tensile reinforcement in their plane when the soil strains are extensional. The mesh size is between $1,67 \times d_{80}$ and 40mm.

Geonets are flat flow channels consisting of a hollow plastic core wrapped with a geotextile. Water from the soil will pass through the geotextile and flow along the hollow core and perform its function as a transmission drain. Geonet must be strong enough to maintain its flow channel under pressure from the soil.

Geowebbs are plastic cells with open top and bottom, filled with granular soil. Through their tensile strength they form a load bearing reinforced soil layer.

Geocomposites are combinations of different geosynthetics, attaining at the same time more effects. For example, for reinforcement application it is best to lay the geogrids bonded to a geotextile to provide better reinforcement capability and separating filter effect under the changeable hydraulic requirements. By using such geosynthetic materials with multipurpose effect, the frost protective layer may be reduced by 10cm.

6 CONCLUSION

The main track formation function is to provide a stable platform for the track structure. To do this, the failure modes must be avoided and the track formation as the first layer under the track superstructure must be improved. The current practice of railway track design and maintenance planning ignore this fact. Usually, the decisions have been made on the empirical bases. The opportunity for error exists because of the large variety of field conditions and the changes in track service demands over the time.

From this review of track formation improvement possibilities, it can be decided that the decision about the applied method is the result of a process. First, the cause of the track problem is determined by proper investigations of formation in field and with help of laboratory tests and analysis. Possible functions and the applicability of existing improvement alternatives may be evaluated. This is the key step and presents a challenge to the railway track engineer, because of the lack of state-of-the-art in that field. Afterwards, comparative economic analysis of these alternatives should be carried out. For the best alternatives, as usually the prior experiences at the same track section lack, it is recommended to conduct the field trials. After monitoring the track performance for a sufficient time, the results should be accessed. It is very useful to document the results of the selected improvement alternatives of track formation for the future applicable recommendation.

The need for considering conditions of track formation and its improvement alternatives may be also recognized at Serbian Railways, because in contrary the increasing trend of track maintenance and renewal costs would be more evident.