# Comparison of two approaches to soil strength classifications

**Tomislav Poršinsky, Mario Sraka, Igor Stankić**

***Abstract – Nactrak***

*The paper presents a comparison of two approaches to describing vehicle trafficability of cohesive soils. The first approach is based on soil consistency and Atterberg index indicators. The second approach is based on the cone penetrometer measurement and on the vane shear test, as well as on the EcoWood classification of soil strength.*

*The research was carried out in the lowland region of pedunculate oak forests in the Sava River basin. Three cut-blocks of different moisture and forest soil strength were selected, in which timber was extracted by a forwarder. Measurements and sampling were carried out on undisturbed soil.*

*Research results have shown that both approaches to describing vehicle trafficability of cohesive soils describe the soil strength of forest wilderness in a similar way and provide a good basis for developing a trafficability evaluation system, as a future task of forest engineering.*

*The soil cone index and shear strength values calculated in this research do not concur with the classes of EcoWood soil strength classification and indicate that the limits and ranges of these parameters are questionable. The problem of defining the threshold values of soil strength parameters covered by this research will be the subject of future investigations.*

*Keywords: soil strength classification, shear strength, cone index, consistency index, liquidity index*

## 1. Introduction – *Uvod*

Ecoefficient mechanization of forest operations involves 1) efficiency of machine operations and 2) minimization of site impacts by machines used for timber harvesting (Owende et al. 2002).

On wet harvesting sites with deep soils (gleys or peats), timber extraction is sometimes impossible due to low soil bearing capacity (Fig. 1) and increased machine sinkage, which impede mobility; hence, machine productivity is diminished (Horvat & Poršinsky 2001, Tiernan et al. 2003). Effective management of machine mobility, control of site disturbance, and moderation of potential soil damage due to wood harvesting and extraction machinery traffic requires characterization of the effects of the soil-machine interaction. This interaction should take into account the influence of machine variables on a range of forest terrains that may be encountered (Nugent et al. 2003).

One aim is to understand the behaviour of the vehicle–soil interaction and to provide threshold values to improve vehicle mobility and restrict the possible damages to an acceptable level. Mechanical behaviour of soil depends on its water content. One

**Figure 1** Vehicle mobility? – ***Slika 1.*** *Kretnost vozila?*

strategy to limit soil disturbances is to avoid traffic whenever the water content approaches the limit of liquidity, or even exceeds it (Heinimann 2000). Soil strength >480 kPa is another strategy, which separates trafficable from non-trafficable forest terrains (Eichrodt 2003). Therefore, the following questions arise in planning timber harvests: 1) is it possible to analyze and spatially describe soil mechanical properties, especially water content and soil bearing capacity?, 2) which areas are trafficable at harvesting time?, and 3) how does one visualize the results in maps that will assist planners and machine operators? (Eichrodt & Heinimann 2002).

## 2. Problem and scope of research – *Problem i cilj istraživanja*

The main objective of a terrain classification in forestry is the division of the terrain into units, which have the same or at least a similar degree of difficulty from the point of view of forest operations (Löffler 1979). There have been numerous attempts to develop a comprehensive terrain classification system for forest operations based on three influencing factors (terrain slope, ground roughness and soil strength), but due to the development of machinery, data processing and the society, older classification systems always seem to contain some deficiencies (Saarilahti 2002B).

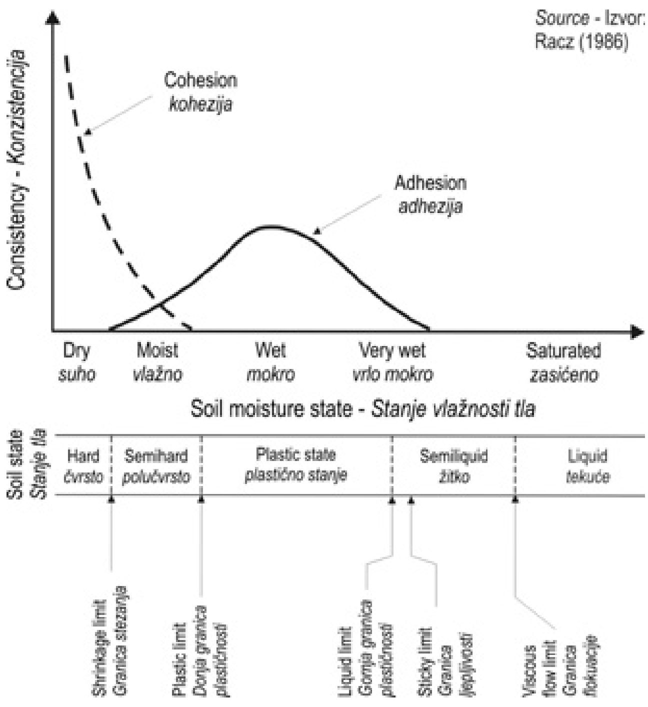


**Figure 2** Different states of soil consistency

***Slika 2.*** *Različita stanja konzistencije tla*

In terramechanics (it deals with soil response to physical stress), various classification systems have been devised to evaluate soil suitability for engineering purposes. Therefore, different soil mechanics theories have been applied to modelling wheel-soil, machine-terrain and transport-environment interactions. The main problem is the dependence of soil strength on the soil type and moisture (weather conditions).

The scope of this paper is the comparison of two different approaches to soil strength classification.

The first approach involves soil consistency, which is defined as: 1) the resistance of a material to deformation or rupture, 2) the degree of cohesion or adhesion of the soil mass (Hunt 1986). Consistency is used to describe the strength of cohesive soil at various soil moisture levels and degrees of cementation.

In 1911, the Swedish soil physicist Atterberg developed a classification system and method, by which states of consistency could be determined. The method is based on the determination of soil water content [calculated as: (mass of water)/(dry mass of soil)] at distinct transitions between different states of soil consistency. Transitions are defined as the liquid limit, plastic limit and shrinkage limit. The values for these limits are dependent on various soil parameters, e.g., particle size, specific surface area of particles capable of water uptake, and hence its particle size distribution.

Shrinkage limit is the moisture content at which no more volume change occurs upon drying.

Plastic limit is the constant defined as the lowest moisture content and expressed as percentage of the weight of the oven dried soil at which the soil can be rolled into threads 3 mm in diameter without being broken into pieces, also the moisture content of a solid at which a soil changes from the plastic state to the semisolid state.

Liquid limit is determined in a standardized Casagrande dish. The soil in the dish is divided by a cutting knife into 2 parts, and the whole dish falls on a pad from a height of 1 cm. If both parts along the cut are reconnected at a length of 12.5 mm after 25 blows, the soil's moisture content is at its liquid limit. Depending on their liquid limit, soils may be further specified as soils showing the following plasticity: low (<35 %), medium (35–50 %), high (50–70 %), very high (70–90 %) and extremely high (>90 %).

A soil with a moisture content above its liquid limit exhibits soil particles that begin to stick together (sticky limit).

Atterberg's limits are used to derive indices, e.g., index of plasticity and index of consistency, and obtain the basic index information about the soil used to estimate its strength and settlement characteristics. It is the primary form of classification for cohesive soils.

Plasticity index ($I_P = \theta_L - \theta_P$) is the numerical difference between the liquid and the plastic limit of a soil. The relation between the plasticity index and moisture content at the liquid limit is expressed in the Casagrande plasticity diagram (Fig. 3). A high plasticity index indicates low shear strength.

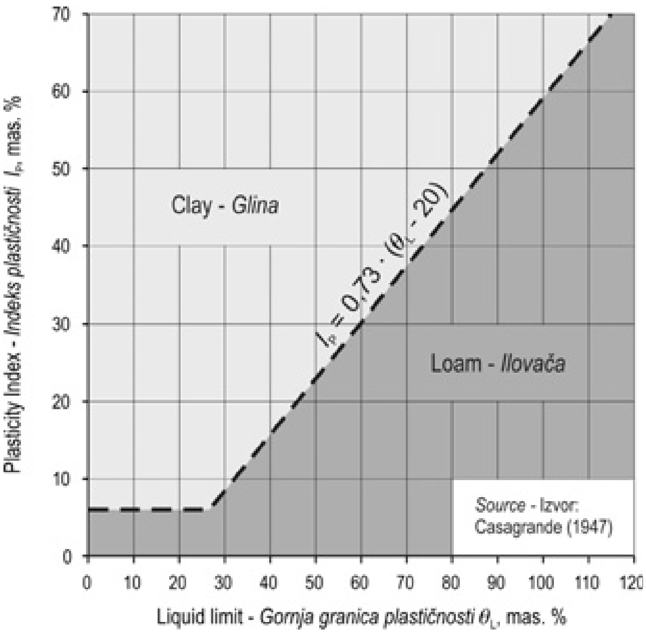


**Figure 3** Casagrande plasticity diagram

***Slika 3.*** *Casagrandeov dijagram plastičnosti*

Consistency index ($I_C$) is the most common way of expressing the consistency of cohesive soils $I_C = [(\theta_L - \theta_{V0}) \div I_P]$. Depending on its value, the following consistencies are distinguished: solid to hard (≥1), stiff to soft (0–1), slurry to liquid (≤0).

Liquidity index ($I_L$), defined as the difference between the plastic limit and the initial water content divided by the plasticity index, is useful for clarifying the meaning of the natural water content ($\theta_{V0}$) of the soil. $I_L = [(\theta_{V0} - \theta_P) \div I_P]$ Depending on the liquidity limit, soils are: solid ($I_L < 0$), plastic ($0 < I_L < 1$) or liquid ($I_L > 1$).

Consistency and liquidity indices are believed by many authors to reflect more usefully the properties of cohesive soils than the generally used plastic and liquid limits.

The second research approach involves *in situ* testing methods – the vane shear and cone penetrometer tests, the commonly used methods for predicting trafficability of soils and off-road mobility of vehicles (Poršinsky & Horvat 2005, Saarilahti 2002A, Shoop 1993).

Cone penetrometer measurement (penetration curve) is the force required to press the 30° circular cone through a specified increment of soil depth (ASAE S313). In practice, the widely used parameter is the cone index, which was originally defined as the average penetration resistance for the top 150 mm of soil (ASAE EP 542). While the penetration techniques mentioned above relate to vehicle sinkage and motion resistance, the measurement of the soil shear strength provides information more indicative of their tractive performance. The vane shear test is commonly used to estimate the undrained shear strength of soft to firm cohesive soils (Fig. 4).

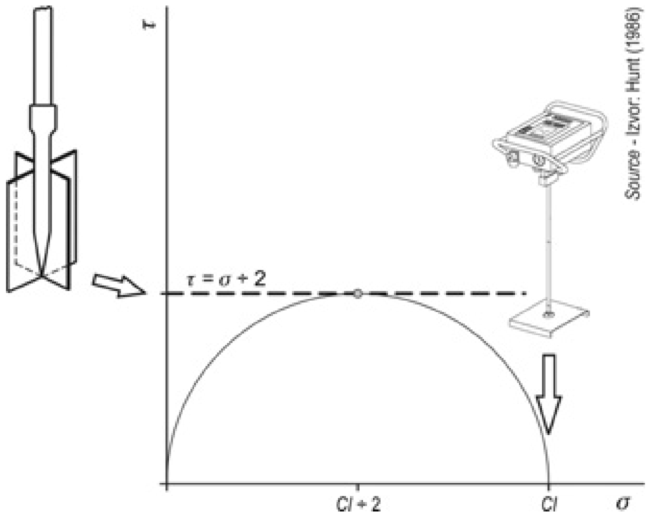


**Figure 4** Undrained shear strength

***Slika 4.*** *Nedrenirani pokus brzoga smicanja*

Shear strength and cone index depend on various factors, including soil texture, organic matter content, bulk density and, most importantly, soil moisture content (Saarilahti 2002B).

Cone index (*CI*), shear strength ($\tau$) and deformation modulus (*E* value) are the parameters used in the soil strength classification (Table 2) developed under the EcoWood Operations Protocol for eco-efficient wood harvesting on sensitive sites (Ward & Lyons 2000, Owende et al. 2002, Ward & Owende 2003). Each of these parameters can be measured quite readily in the field using portable equipment. The soil is classified into a strength category based on the »least common denominator«, i.e., the parameter value that falls into the lowest strength category.

Soil strength determines the bearing capacity and traction capacity of soil, and thereby soil trafficability. In forest operations, the soil bearing capacity

**Table 1** EcoWood soil strength classification
***Tablica 1.*** *Raščlamba razreda čvstoće tla prema projektu EcoWood*

| Soil strength *Čvrstoća (nosivost) tla* | | Soil strength parameters – *Parametri čvrstoće tla** | | | Allowed soil bearing capacity *Dopušteno opterećenje tla* |
|---|---|---|---|---|---|
| Classes *Razredi* | Soil strength descriptions *Opis čvrstoće tla* | Cone Index *Konusni indeks* | Module E *Modul elastičnosti* | Shear strength *Otpor tla na smicanje* | |
| | | *CI*, kPa | *E*, MPa | $\tau$, kPa | *NGP*, kPa |
| 1 | Strong soil – *Čvrsto tlo* | > 500 | > 60 | > 60 | > 80 |
| 2 | Average soil – *Osrednje čvrsto tlo* | 300–500 | 20–60 | 20–60 | 60–80 |
| 3 | Soft soil – *Meko tlo* | < 300 | < 20 | < 20 | 40–60 |

* maximum value in the top 300 mm of the soil profile – *najveće vrijednosti u površinskom sloju tla dubine do 30 cm*

is usually considered as the maximum allowable wheel contact pressure. The actual wheel pressure, however, is difficult to assess, because the true contact area depends on the tyre and soil properties (Saarilahti 2002A). In the EcoWood soil strength classification, the estimation of allowed bearing capacities (contact pressure of vehicles) is based on nominal ground pressure equations (Mellgren 1980).

$$NGP = \frac{G}{r \cdot b} \text{ (for wheeled vehicles)}$$

$$NGP = \frac{G}{b \cdot (1{,}25 \cdot r + L)} \text{ (for tracked vehicles)}$$

In these equations, *NGP* is the nominal ground pressure (kPa), *G* – wheel or axle load (kN), *r* – unloaded wheel radius (m), *b* – tyre or track width (m) and *L* – centre-to-centre distance between bogie wheels covered by semitrack (m).

## 3. Sites and methods – *Mjesto i metode*

Comparison of the two approaches to soil strength classification was tested in the region of lowland pedunculate oak forests in the Sava River basin. Three cut-blocks (sites) of forest soil were selected, of different moisture and strength, in which timber is extracted by forwarders (Fig. 5). Measurements and sampling were carried out on undisturbed soil. Soil features of investigated cut-blocks are presented in Table 2.

Thirty penetrometer, vane shear and moisture readings were taken per each research site. Moisture and shear strength were measured at three depths: 0, 15 and 30 cm.

Penetration resistance (cone index) measurements were made with an Eijkelkamp Penetrologger (electronic recording penetrometer) using a 2 cm$^2$ base area 30° angle cone tip. Measurements were taken to 80 cm depth in 1 cm increments.


**Figure 5** Research sites – ***Slika 5.*** *Mjesta istraživanja*

**Table 2** Soil features of investigated cut-blocks – ***Tablica 2.*** *Svojstva tla istraživanih sječina*

| | Research sites (cut-blocks) – *Mjesta istraživanja (sječine)* | | |
|---|---|---|---|
| | A | B | C |
| Forest Office – *Šumarija* | Novoselec | Remetinec | Lipovljani |
| Management Unit – *Gospodarska jedinica* | Žutica | Obreški Lug | Josip Kozarac |
| Subcompartment – *Odsjek* | 44b | 24b | 14a |
| Soil type – *Vrsta tla* | gleysol amphigleyic – *amfiglej* | planosol – *pseudoglej* | planosol – *pseudoglej* |
| Grain size distribution – *Granulometrijski sastav** | clay – *glina* | loam – *ilovača* | clay – *glina* |
| Sand – *Pijesak*, % | 34.1 | 38.5 | 28.8 |
| Silt – *Prah*, % | 31.9 | 43.9 | 40.3 |
| Clay – *Glina*, % | 34.0 | 17.6 | 30.9 |
| Soil water-air properties – *Vodno-zračna svojstva tla** | | | |
| Bulk density – *Volumna gustoća tla*, g/cm$^3$ | 1.10 ± 0.06 | 1.01 ± 0.08 | 1.11 ± 0.10 |
| Solid density – *Gustoća čvrste faze tla*, g/cm$^3$ | 2.60 ± 0.06 | 2.57 ± 0.06 | 2.57 ± 0.03 |
| Soil porosity – *Poroznost tla*, vol. % | 57.5 ± 2.5 | 60.5 ± 2.5 | 56.7 ± 3.8 |
| Saturation capacity – *Kapacitet tla za vodu*, vol. % | 51.0 ± 3.5 | 46.7 ± 2.5 | 46.5 ± 5.6 |
| Air capacity – *Kapacitet tla za zrak*, vol. % | 6.5 ± 2.7 | 13.8 ± 1.7 | 10.3 ± 4.4 |

* values at soil depth of 15 cm – *vrijednosti na dubini tla od 15 cm*

A GEONOR H-60 field shear vane borer was used to obtain the peak undrained strength of the soil. The height and diameter of the used four-bladed vane were 32 mm and 16 mm, respectively, in compliance with the 2:1 ratio. The measurement range of the instrument was from 0 to 260 kPa.

Soil moisture was measured with a ThetaProbe ML2 moisture meter. ThetaProbe is designed to measure volumetric soil water content using the Frequency Domain Reflectrometry technique.

In addition, five undisturbed (100 cm$^3$ sample cores for determination of water-air properties) and disturbed (consistency limits and grain size distribution) soil samples per each research site were taken at a depth of 15 cm for laboratory analyses. Standard soil procedures were used in laboratory analyses (Anon. 1971).

## 4. Research results – *Rezultati istraživanja*

Physical–mechanical properties of undisturbed soil of the studied subcompartments are presented in terms of soil penetration resistance measured by the penetrometer and soil shear strength measured by the vane borer.

Values of these parameters describe the soil strength conditions that prevailed in cut-blocks during the research period. The measured values were strongly influenced by water circulation dynamics in the soils of the studied cut-blocks (Fig. 6).

The wide range of the cone penetration resistance values in dependence on soil depth (penetration resistance) and shear strength of particular cut-blocks are a consequence of forest soil non-homogeneity due to its layered structure, but also of different soil moisture per profile depth, which is especially noticeable in planosol of research site C (Fig. 6).

Full water saturation of the whole soil profile at site A and the upper part of soil profile at site C caused lower values of the entire penetration resistance curve, indicating fully and partially restricted strength of the substratum of these two cut-blocks, respectively. Values of the entire penetration resistance curve for site B indicate very high effective strength of water-unsaturated planosol. Since the effective moisture at sites A and C is mainly between soil water capacity and its total pore content, it seems logical that the resistance to cone penetration values are lower compared to site B, where moisture is below the plastic limit. The cone indices for research sites were 0.426 MPa (A), 2.000 MPa (B) and 0.744 MPa (C), respectively.

Shear strength of surface soil layers, in all the three research cut-blocks, assumed median values below 50 kPa as a consequence of increased moisture of the humus-accumulative horizons of sites A and C, and increased humus content of this shallow and dry layer of site B. Soil shear strength values go up with increasing soil depth; the high effective soil strength of site B exceeds the upper limit of vane borer measuring potentials (260 kPa).

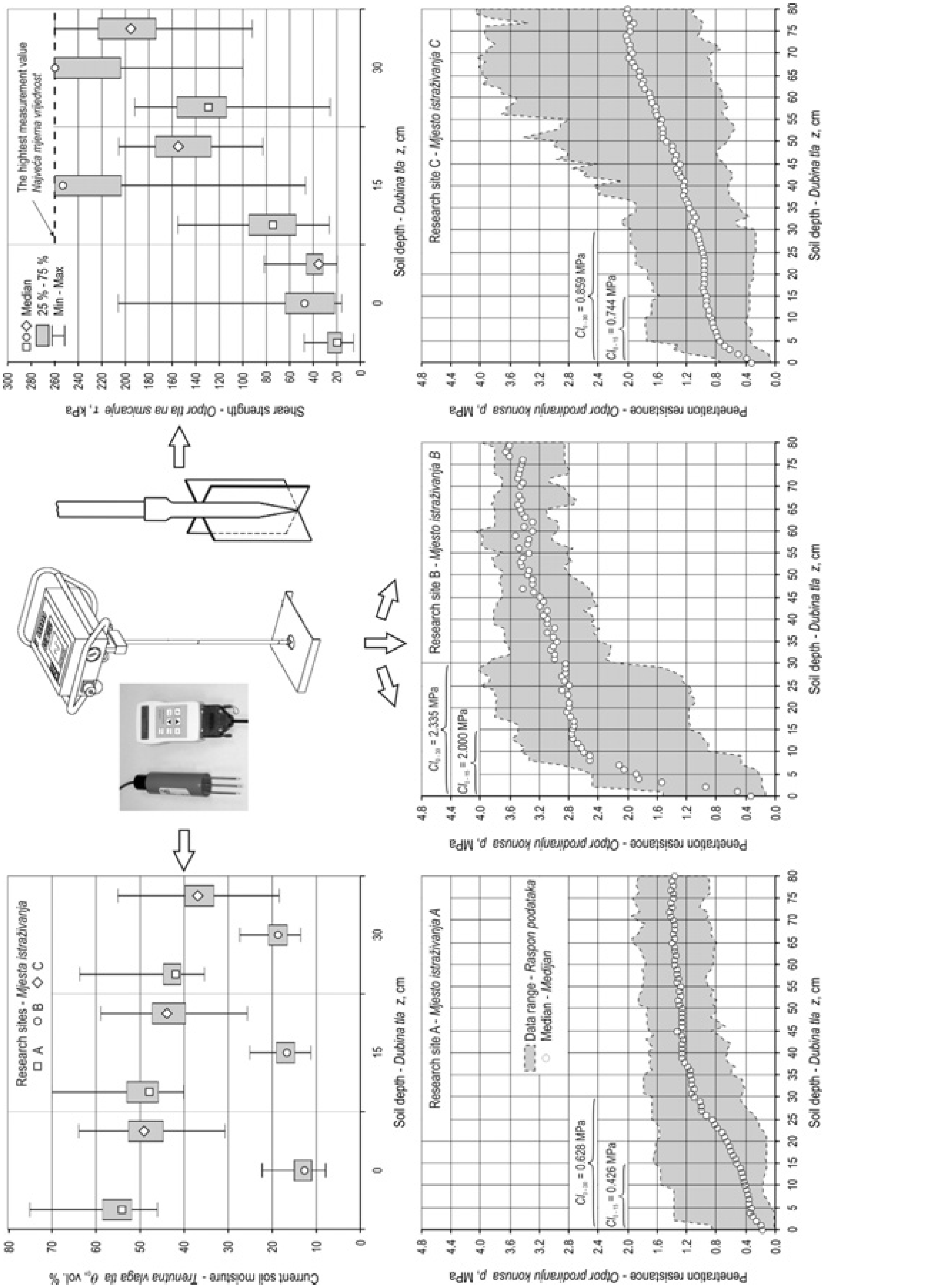


**Figure 6** – Results of current moisture, shear strenght and penetration resistance of soil

***Slika 6.*** *Rezultati trenutne vlage, posmične čvrstoće i prodirne značajke tla*

Cone index and shear strength values of soil measured in this research do not concur with the classes of EcoWood soil strength classification and indicate that the limits and ranges of these parameters are questionable (Table 1).

The soil strength state and the sensitivity of cut-block wilderness at the time of research are also demonstrated through the parameters of soil consistency. For this purpose, plastic and liquid limits were determined by laboratory procedures from disturbed soil samples (Fig. 7). Figure 7A shows the range of plastic limit values while the liquid limit was determined using the Casagrande diagram (Fig. 7B), from which the liquid limit was calculated mathematically.

It can be seen from the results given in Fig. 7 that the plastic limit and plasticity index increase with an increase of clay and silt particles in soil (sites A and C). Compared to these sites, the texturally lighter eluvial horizon of site B influenced the lowest values of both plastic and liquid limits.

Based on the determined plastic and liquid limits (Fig. 7) and the measured effective soil moisture (Fig. 6), the other consistency parameters were also calculated: plasticity index, consistency index, liquidity index (Fig. 8). To calculate these consistency parameters, the weight in weight values of plasticity limits were expressed as volume in volume values by using soil bulk density.

Summary of the results of soil consistency index indicators that are directly influenced by effective moisture points to the following conclusions: at site B – planosol is in a strong consistency state and suitable for vehicle mobility, at site C – planosol is of plastic consistency restrainedly suitable for vehicle mobility, while at site A – amphigley is of liquid consistency and unsuitable for any vehicle traffic.

According to Racz (1986), a narrow moisture range between the water retention capacity of soil and its plastic limit is more favourable for soil strength. The same author reports that from the aspect of soil consistency, the texturally most suitable soils for vehicle mobility are loamy soils with approximately equal values of their water retention capacity and plastic limit. Investigating forwarder mobility on soils of restricted strength, Seixas and McDonald (1997) point to the environmental benefit of wood extraction in the conditions where effective moisture does not exceed the value corresponding to the plastic limit.

Indices of soil consistency and plasticity limits provide useful information about the potentials of vehicle mobility (and also of soil tillage), and their value, according to Hillel (1980), is confirmed by the fact that they have been used for over 70 years in geomechanical and pedological laboratories all over the world.

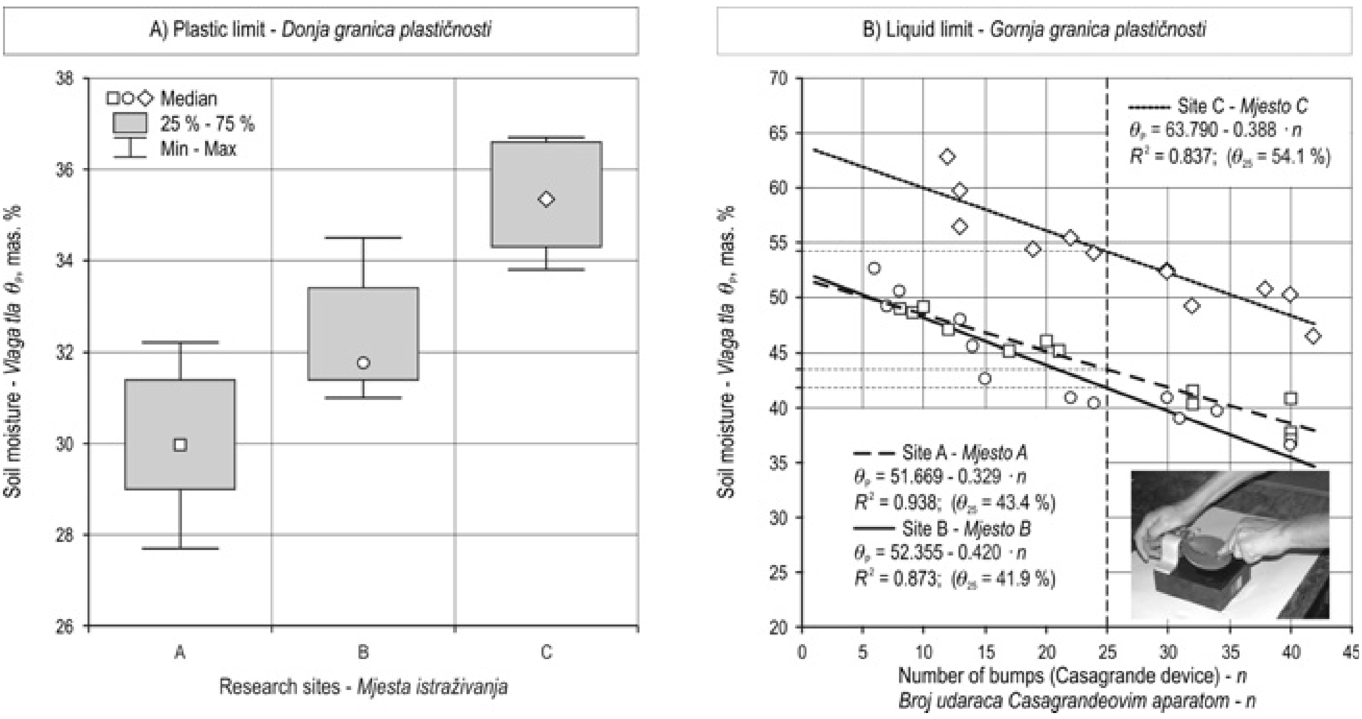


**Figure 7** Plastic and liquid limits – ***Slika 7.*** *Donja i gornja granica plastičnosti*

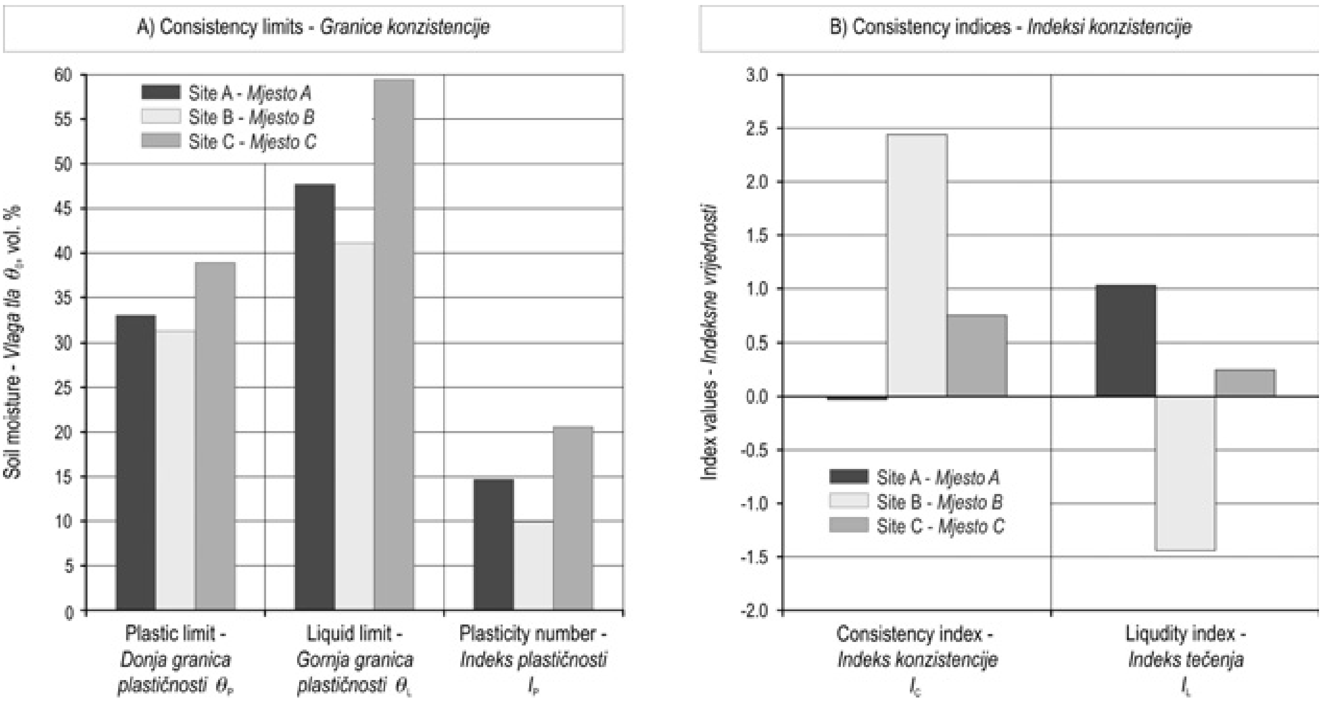


**Figure 8** Consistency limits and indices – ***Slika 8.*** *Granice i indeksi konzistencije*

## 5. Conclusions – *Zaključci*

This paper presents a comparison of two approaches to describing the vehicle trafficability of cohesive soils. The first approach is based on soil consistency and Atterberg's index indicators. The second approach is based of the cone penetrometer measurement and on the vane shear test, as well as on the Ecowood classification of soil strength.

Research results have confirmed that both approaches to describing trafficability of research cohesive soils (clay and loam) the conditions of forest wilderness trafficability describe in a similar way and provide a good basis for the development of a trafficability evaluation system, as a future task of forest engineering.

The soil cone index and shear strength values calculated in this research do not concur with the classes of EcoWood soil strength classification and indicate that the limits and ranges of these parameters are questionable. The problem of defining the threshold values of soil strength parameters covered by this research will be the subject of future investigations.

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## *Sažetak*

# Usporedba dvaju pristupa razredbi nosivosti tla

*U radu je provedena usporedba dvaju pristupa opisu uvjeta prohodnosti koherentnih tala kretanju vozila. Prvi je pristup zasnovan na konzistenciji tla i Atterbergovim indeksnim pokazateljima. Drugi je pristup zasnovan na izmjeri konusnoga indeksa tla penetrometrom i posmične čvrstoće tla krilnom sondom te raščlambi Ecowoodove razredbe nosivosti tla.*

*Istraživanje je provedeno u području nizinskih lužnjakovih šuma porječja rijeke Save. Odabrane su tri sječine, različite vlažnosti i uvjeta nosivosti šumskoga tla, u kojima se drvo privlačilo forvarderom. Mjerenja i uzimanje uzoraka provedena su na neizgaženom tlu.*

*Rezultati istraživanja potvrdili su da oba pristupa opisa prohodnosti koherentnih tala kretanju vozila slično opisuju uvjete nosivosti šumskoga bespuća te predstavljaju dobru osnovu za razvoj sustava procjene kretnosti vozila, što je i budućnosna zadaća šumarskoga inženjerstva.*

*Izmjerene vrijednosti konusnoga indeksa i posmične čvrstoće tla u ovom istraživanju ne odgovaraju razredima Ecowoodove razredbe nosivosti tla te upućuju na upitnost granica i raspona vrijednosti navedenih parametara. Problem određivanja graničnih vrijednosti parametara nosivosti tla obuhvaćenih ovim istraživanjem zadatak je budućih istraživanja.*

*Ključne riječi: razredba nosivosti tla, posmična čvrstoća, konusni indeks, indeksi konzistencije i tečenja tla*

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