Use of Penetration Methods for Evaluation of Ground Bearing Capacity

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Abstract

Reliable off-road trafficability assessment hinges on in-situ penetration testing that captures depth-dependent soil strength across moisture states and translates it into operational pass/fail decisions. We present a field-deployable workflow centred on cone (static) and dynamic penetration methods. In the static branch, Cone Penetration Tests (CPT) advance a conical probe at a constant 20 mm s^{-1}*, logging cone resistance (*$q_{(c)}$*) and sleeve friction (*$f_{(s)}$*) continuously or at 10–20 cm intervals; in the dynamic branch, DPL/DPM/DPH/DPSH tests derive specific dynamic resistance from standardized hammer blows with friction corrections at 1 m steps. From penetration records we compute Cone Index (CI) and Remoulding Index (RI) and derive the Rating Cone Index (RCI = CI·RI) for dry, moist, wet conditions, anchored to laboratory-verified USCS classes. We compile RCI look-ups for dominant soils (e.g., SM: 119 → 72 → 25 for dry→moist→wet) and demonstrate the operational rule by comparing RCI with Vehicle Cone Index (*VCI_1*,* VCI_{50}*): at the Živanice site (USCS SM, moist ≈ 51 %),* $RCI_2 \approx 72$*, thus vehicle classes with VCI ≤ 72 are passable, whereas higher-demand classes are not. Penetration methods deliver continuous or quasi-continuous strength profiles, outperforming point sampling for heterogeneity detection, but show reduced reliability in gravelly/stony and organic horizons and in impermeable clays exhibiting a "rubber effect," and are sensitive to moisture stratification. The workflow (CPT/DPT → CI, RI → RCI → RCI ≥ VCI decision) supports rapid, reproducible trafficability mapping and provides clear guidance on when to pair penetration testing with core drilling or auxiliary geotechnical probes.*

Keywords: *Penetration Tests, Cone Index, Remolding Index, Rating Cone Index, Off-road vehicle, Unified Soil Classification*

1. Introduction

The professional evaluation of the territory's passability by off-road vehicles is one of the key analyses for the military-geographical assessment of the territory during military operations and the assessment of the territory for the crisis operation staffs during the deployment of integrated rescue teams in the preparatory period and during crisis situations.

When modelling the influence of the area of interest on the movement of mobile equipment, it is necessary to base the analysis on the synthetic effect of individual terrain components on the behaviour of a specific vehicle. The main terrain elements that are evaluated include: terrain relief gradients, micro-relief shapes and surface topography (roughness), vegetation, water, roads, settlements, meteorological factors, etc. A number of professional studies are focused on evaluating the individual elements mentioned, or on a synthetic evaluation of the influence of the terrain as a whole [1-23]. The scientific study builds on previous research [24-29]. The influence of these elements on the terrain passability must be calculated synthetically, because all these factors are related to each other. Also, the influence of soils on the passability of vehicles depends on the slopes of the terrain and also on the meteorological situation, especially on precipitation and water content in the soil. For field identification and classification, soils may be grouped into five principal types (see also [18]): gravel, sand, silt, clay, and organic matter.

The presented study is the result of many years of research aimed at determining the movement possibilities of selected military vehicles on various types of soil found in the territory of the Czech Republic.

2. Objectives

The paper aims to design and validate a practical, reproducible workflow for evaluating terrain trafficability from in-situ penetrometric measurements and soil classification, so that off-road vehicles (military and emergency response) can be reliably assessed for passage under varying soil moisture conditions. The workflow integrates (i) field measurements of the Cone Index (CI) and Remoulding Index (RI), (ii) laboratory grain-size analyses and transformation to the Unified Soil Classification System (USCS), (iii) derivation of Rating Cone Index (RCI) for dry, moist, and wet states, and (iv) comparison with Vehicle Cone Index (VCI) classes to yield an operational pass/fail decision.

The study's primary objective is to develop and demonstrate an end-to-end, field-deployable methodology that quantifies soil bearing capacity and translates CI/RI → RCI by USCS soil classes, then maps RCI to VCI to decide vehicle passability for representative Czech soils and meteorological states.

To achieve the research objective, four research questions Q1-Q4 were formulated:

- Q1 on soil and moisture: How suitable/unsuitable are combined CI and RI (RCI) measurements for determining soil bearing capacity in the main USCS classes and hydrological conditions?
- Q2 on decision reliability: Is the RCI vs. VCI criterion reliable for determining passability for different vehicle categories in single

(VCI1) and repeated (VCI50) traffic?

- Q3 on sensitivity to site representativeness: How do soil types in synthetic maps agree/disagree with laboratory-verified data at measurement sites, and how does any agreement/disagreement affect the interpretation of RCI?
- Q4 on the limits of the method. Under what geological/pedological conditions (e.g., gravelly/stony soils, organic soils, uneven moisture profiles) do penetrometric methods become suitable/unsuitable, and what influences this?

The research objectives defined in Chapter 1 will be considered fulfilled if the following results are achieved:

a) consistent RCI tables will be compiled for the dominant USCS classes and moisture conditions,
b) the correct decision on compliance/non-compliance with VCI requirements in given locations (e.g., Živanice, SM) will be demonstrated,
c) an operational protocol will be compiled that experts can apply with standard equipment (E-960 kit) and minimal follow-up processing to inform the planning of military and rescue vehicle movements.

2. Materials and methods

The research methods are focused on rapid assessment of terrain passability for off-road mobility planning. Therefore, the solution procedure requires soils suitable for cone penetration or dynamic penetration testing, i.e., coarse, gravelly, or very rocky substrates; organic soils and heterogeneous moisture profiles may reduce accuracy or feasibility. In such conditions, the authors sought to recommend when to change the type of test (cone vs. dynamic) and when to supplement penetrometry with core drilling or other geotechnical probes to ensure representative parameters.

The methodology for the determination of the passability of the soils was based on standard penetrometric procedures:

d) Selection of sites to be measured that represent the main soil species, using as the main criterion the ratio of the relative areas of occurrence of the soil species to the total area of the study area, using synthetic soil maps 1 : 200 000 – see Fig. 1;
e) Determination of the measurement period in relation to the water content of the soil (dry, moist, wet periods);
f) Actual measurements of Cone Index (CI), Remoulding Index (RI) and determination of Rating Cone Index (RCI) – see Fig. 2 left;
g) Soil sampling from 0-15, 15-30, 30-45 cm deep layers to determine soil grain size distribution – see Fig. 2 right;
h) Laboratory pedological tests to verify soil types according to the Unified Soil Classification System (USCS) methodology;
i) Calculation of Vehicle Cone Index (VCI) values from specified vehicle engineering parameters;
j) Determination of soil passability based on analysis of RCI and VCI values.

In determining soil passability, we relied on the standard USCS system of categorizing soils based on the grain size – see Fig. 3

The Unified Soil Classification System (USCS) is a prerequisite for the analysis of terrain passability by off-road Vehicles. Soils are made up of a combination of particles of different sizes. Grain diameters can be determined using special sieves (dry sieve analysis) or wet mechanical analysis. For this purpose, it was also necessary to transform the soil categories used in the Czech Republic to the USCS system. For this purpose, we used the results of laboratory tests of soil grain size.

Based on the grain size curves and the determination of soil species categories at predetermined locations, the measured CI, RI, and RCI values were assigned to specific soil species.

Based on the transformation relationships, values for RCI under different meteorological conditions (for dry, moist and wet soils) were further derived – see Fig. 4.

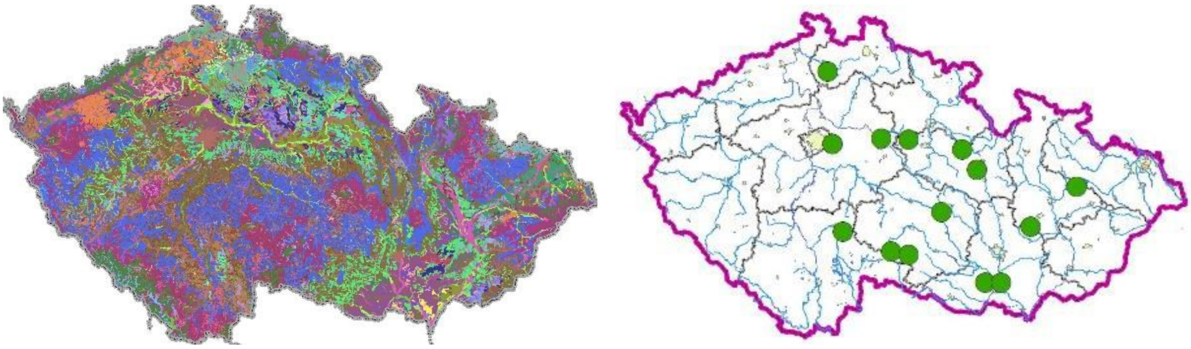
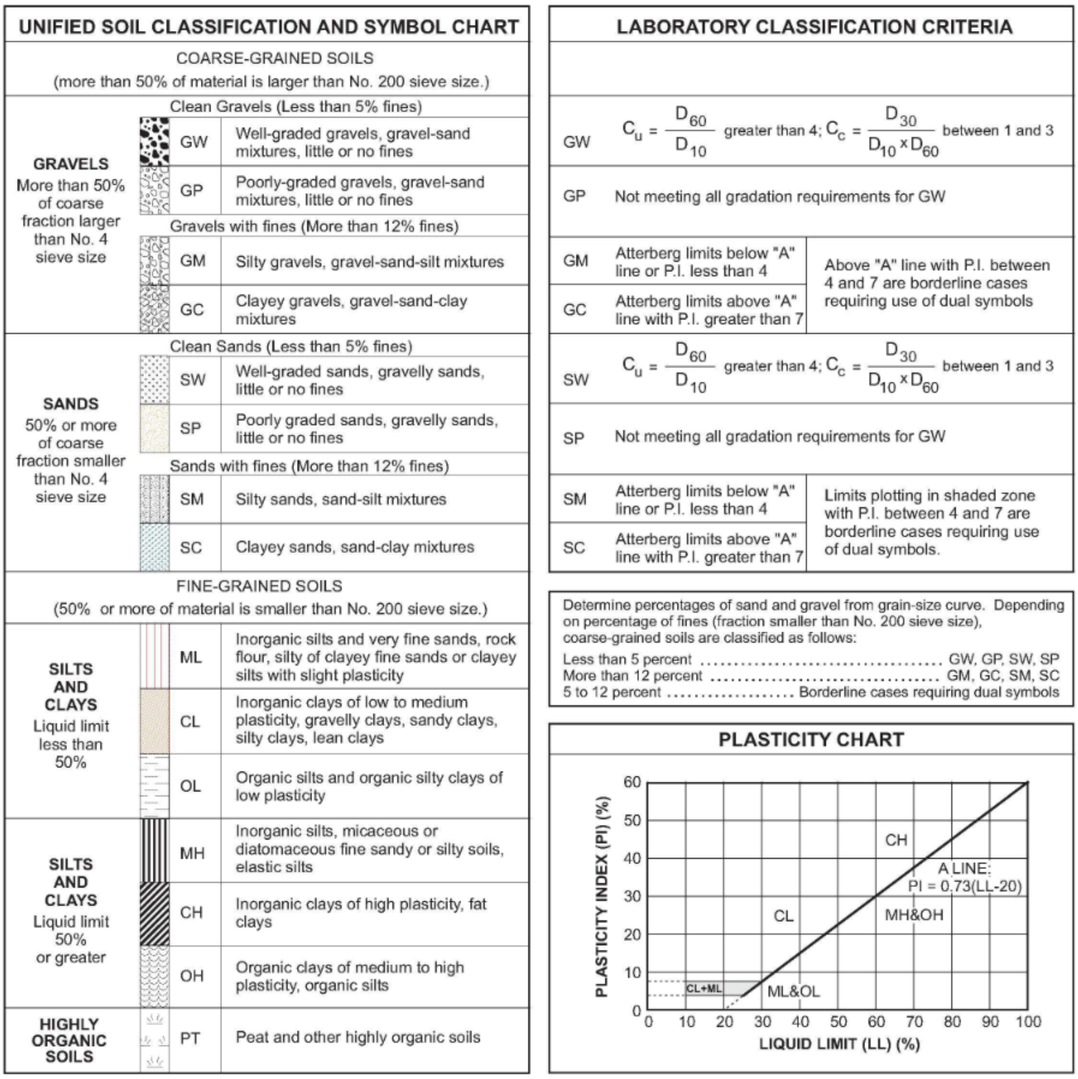


Fig. 1. Soil types and the locations of measurement.

Fig. 2. Penetrometry and soil sampling in dry (left) and wet (right) seasons.



UNIFIED SOIL CLASSIFICATION AND SYMBOL CHART

COARSE-GRAINED SOILS
(more than 50% of material is larger than No. 200 sieve size.)

GRAVELS More than 50% of coarse fraction larger than No. 4 sieve size	Clean Gravels (Less than 5% fines)	
	GW	Well-graded gravels, gravel-sand mixtures, little or no fines
	GP	Poorly-graded gravels, gravel-sand mixtures, little or no fines
	Gravels with fines (More than 12% fines)	
	GM	Silty gravels, gravel-sand-silt mixtures
	GC	Clayey gravels, gravel-sand-clay mixtures
SANDS 50% or more of coarse fraction smaller than No. 4 sieve size	Clean Sands (Less than 5% fines)	
	SW	Well-graded sands, gravelly sands, little or no fines
	SP	Poorly graded sands, gravelly sands, little or no fines
	Sands with fines (More than 12% fines)	
	SM	Silty sands, sand-silt mixtures
	SC	Clayey sands, sand-clay mixtures

FINE-GRAINED SOILS
(50% or more of material is smaller than No. 200 sieve size.)

SILTS AND CLAYS Liquid limit less than 50%	ML	Inorganic silts and very fine sands, rock flour, silty of clayey fine sands or clayey silts with slight plasticity
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
	OL	Organic silts and organic silty clays of low plasticity
SILTS AND CLAYS Liquid limit 50% or greater	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
	CH	Inorganic clays of high plasticity, fat clays
	OH	Organic clays of medium to high plasticity, organic silts
HIGHLY ORGANIC SOILS	PT	Peat and other highly organic soils

LABORATORY CLASSIFICATION CRITERIA

GW	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}}{D_{10} \times D_{60}}$ between 1 and 3	
GP	Not meeting all gradation requirements for GW	
GM	Atterberg limits below "A" line or P.I. less than 4	Above "A" line with P.I. between 4 and 7 are borderline cases requiring use of dual symbols
GC	Atterberg limits above "A" line with P.I. greater than 7	
SW	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{D_{30}}{D_{10} \times D_{60}}$ between 1 and 3	
SP	Not meeting all gradation requirements for GW	
SM	Atterberg limits below "A" line or P.I. less than 4	Limits plotting in shaded zone with P.I. between 4 and 7 are borderline cases requiring use of dual symbols.
SC	Atterberg limits above "A" line with P.I. greater than 7	

Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows:

Less than 5 percent	GW, GP, SW, SP
More than 12 percent	GM, GC, SM, SC
5 to 12 percent	Borderline cases requiring dual symbols

PLASTICITY CHART

Fig. 3. USCS soil categories.

3. Results

The classification of soil types in the Czech Republic has long been based on the percentage content of fine-grain fraction (grains smaller than one hundredth of a millimeter) – see Table 1.

Tab. 1. Soil types in the Czech Republic.

Soil category	Percentage of clay [%]
sandy soil	< 10
loamy sand	10 - 20
sandy loam	20 – 30
loamy	30 – 45
clayey loam	45 – 60
clayey	60 – 75
clay	> 75

The following soil types and their percentage distribution in the Czech Republic were determined by soil grain size analysis:

Tab. 2. Soil types and their percentage distribution in the Czech Republic.

Soil category	Percentage of occurrence [%]
light soils (sandy to loam sandy)	19
medium heavy soils (sandy loam to loam)	59
heavy soils (clayey loam to clay)	17
heavily gravelly to stony	5

The determination of the bearing capacity of the soils was subject to verification that the soil type determined from the 1 : 200 000 synthetic soil map corresponded to the actual soil type at the site based on soil laboratory grain size tests. These tests were carried out in the pedological laboratory of Mendel University, Brno. The result of these tests for the Zivanice site (see locality in Fig. 4) is shown in Fig. 5.

Fig. 4. Test site Zivanice (loamy sand soil type).

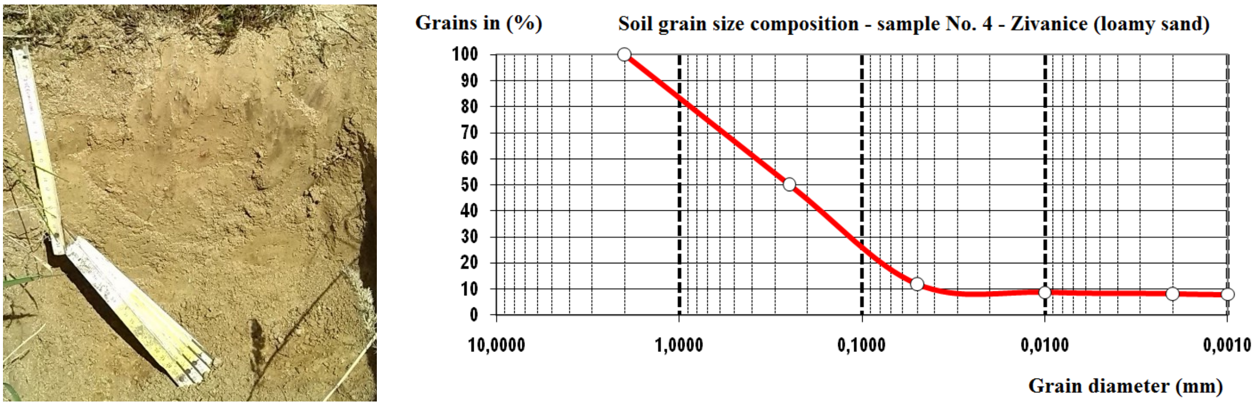


Fig. 5. Percentage of soil grain size in locality 4 (Zivanice).

On the basis of grain size measurements, the Czech soil type classification was transformed into the Unified Soil Classification System (USCS) – see Table 3.

Tab. 3. Transformation of the soil type classification of the Czech Republic into the USCS classification.

Czech classification	USCS classification
gravel soil	GW, GP, GM, GC
sandy soil	SW, SP
loamy sand	SM
sandy loam	SC
loamy soil	ML
clayey loam	CL
clayey + clay	CH
organic loam	OL
organic dust, micaceous	MH
organic clay	OH
peat	PT

Subsequently, CI, RI, RCI values were determined for the Zivanice site using the standardized E-960 penetrometer kit.

RCI_n – (Rating Cone Index) is a coefficient of individual groups of soils for three categories of weather conditions (see also Table 4):

- RCI_1 – the coefficient of soils for the dry period,
- RCI_2 – the coefficient of soils for the humid period,
- RCI_3 – the coefficient of soils for the wet period.

$$RCI = CI \cdot RI \tag{1}$$

where is

CI – cone index measured by penetrometer;

RI – remoulding index measured by remoulding set,

VCI_1, VCI_{50} (Vehicle Cone Index) – parameters of a vehicle [17]:

VCI_1 – average concretion of soil for the first passage,

VCI_{50} – average concretion of soil after the 50th passage.

Tab. 4. Values of RCI_n.

Soil type	**Specification**	**Values of RCI_n**		
		RCI_1	RCI_2	RCI_3
GW	Well-graded grits, mixtures of grit and sand with a little amount of fine fraction	163	123	83
GP	Badly graded grits or mixtures of grit and sand with a little amount of fine fraction (or none)	160	120	81
GM	Muddy grit, mixtures of grit – sand - mud	120	76	32
GC	Clayey grit, mixtures of grit – sand - clay	130	91	52
SW	Well-graded sands, gravels with a low level of (or without) fine fraction	155	116	78
SP	Badly graded sands, gravels with a low level of (or without) fine fraction	145	109	73
SM	Muddy sands, mixtures of sand and mud	119	72	25
SC	Clayey sands, mixtures of clay and sand	126	86	46
ML	Inorganic mud and very fine sands and stony dust, muddy or clayey fine sands or clayey mud with moderate plasticity.	118	69	20
CL	Inorganic clays with low to moderate plasticity, gritty clay, muddy clay, lean clay	123	81	40
OL	Organic mud and organic muddy clays, muddy clays with low plasticity	11	57	3
MH	Inorganic mud, micaceous or diatomeous fine sands or muddy soils, elastic silts	114	61	8
CH	Inorganic clays with high plasticity, fat clays	136	99	62
OH	Organic clays with medium to high plasticity, organic silts	107	54	1

Since the soil moisture value of 51% (moist soil) was measured, it can be concluded that the RCI_2 value for the site Zivanice and soil type loamy sand (SM) - see grain size in Fig. 5 is approximately equal to 72. This value is then compared with the *VCI* index – see Table 5 of the specific class of off-road vehicles. If the *RCI* values are greater than the corresponding VCI_1 (for one vehicle of the given category to pass) or VCI_{50} (for 50 vehicles to pass on the same track), the vehicle(s) will pass the location; otherwise, they will not.

Tab. 5. Values of VCI_n.

Category	Travel Range		Vehicles
	VCI_1	VCI_{50}	
1	1–12	1–29	Lightweight vehicle category with low contact pressure (less than 0.907 kg per cm^2)
2	12–21	30–49	An engineering and high-speed tractor with relatively wide tracks and low contact pressures.
3	21–26	50–59	Tractors with average contact pressures, tanks with relatively low contact pressures, and some towed vehicles with very low contact pressures
4	26–30	60–69	Most medium tanks, high-touch tractors, and four-wheel drive trucks and low-touch towed vehicles
5	31–35	70–79	Most of the trucks are four-wheel drive, a large number of towed vehicles and heavy tanks
6	35–44	80–99	A large number of all-wheel drive vehicles and rear-wheel drive trucks and towed vehicles designed primarily for use on the road
7	>45	>100	Rear-wheel drive vehicles designed for off-road work, especially in wet soils

Findings Relative to Objectives and Research Questions

Regarding Q1 concerning soil classes and moisture suitability (RCI behavior), the results in the RCI table (Table 4) show that moisture conditions strongly influence bearing capacity within USCS classes. For most soils, there is a monotonic decrease from RCI_1 to RCI_2 to RCI_3 (e.g., SM: 119→72→25; CH: 136→99→62). The exception is OL, where RCI_2 is greater than RCI_1, which likely reflects the measurement context and the influence of organic structure. This anomaly is consistent with the limitations for organic horizons and should be considered conditionally valid. Overall, RCI captures the interaction between soil and moisture as intended and supports the suitability of CI·RI-derived indices for class-based classification.

When evaluating the results for Q2 for the decision credibility of the rule $RCI \geq VCI$, it was found that in the Živanice location (USCS: SM; humidity ~51%), the derived value $RCI_2 \approx 72$ (in Table 4) provides a specific reference value for compliance/non-compliance. When using VCI bands (T5), the one-time passage condition (VCI_1) is met for vehicles with $VCI_1 \leq 72$. For repeated operation (VCI_{50}), categories with $VCI_{50} \leq 72$ are passable, while classes with $VCI_{50} > 72$ are not. In practice, categories with $VCI_{50} \approx 60–69$ (category 4) are passable, while classes around $VCI_{50} \approx 70–79$ (category 5) are borderline and sensitive to small changes in humidity. Higher VCI_{50} (category ≥6) are not passable under the observed humid conditions. This confirms the practical usefulness of the rule and emphasizes the dependence of the scenario on threshold values.

The representativeness of mapped vs. laboratory soil classes, i.e., Q3, was verified by laboratory grain size curves (Fig. 5) and consistently converted to USCS: SM (Table 3). This agreement supports the use of synthetic soil maps for site targeting and preliminary classification, provided that laboratory checks are carried out on site before the final tabulation of the RCI. More frequent sampling from multiple sites will reduce the error rate when converting the map to USCS.

When determining the limits of the penetrometer method (Q4), it was found that these methods are dependent on local conditions. Reliability decreases in gravelly to stony and organic soils, while in impermeable clays and heterogeneous moisture, thin weak layers may obscure the results. In such terrain, it is recommended to give preference to CPT for fine to mixed soils; in coarser and heterogeneous conditions, DPT in combination with core drilling for lithological control is more suitable. Large torque corrections are considered unreliable. These measures ensure that the "pass/fail" results are defensible even under problematic conditions.

The authors documented the limitations of the method (coarse/rocky and organic soils, heterogeneous moisture) using a complete workflow (CI, RI to RCI according to USCS; comparison with VCI; decision on compliance/non-compliance) at a real location and under actual moisture conditions. These findings as a whole meet the primary objective and at the same time motivate expansion to other locations and seasons in order to generalize the decision-making range around critical VCI bands.

4. Discussion

4.1 Deep Penetration Methods for Engineering Geological and Geotechnical Purposes

Building on the conceptual framework and data needs outlined in Chapters 2 and 3 (site context, target parameters, and decision criteria), this chapter details the in-situ deep penetration methods used to characterize subsurface conditions at the depth resolution required for the subsequent interpretations. Penetration tests determine selected physical–mechanical soil properties and delineate layer boundaries by recording penetration resistance while a rod with a conical tip advances into the ground. Two families are commonly applied: cone (static) penetration and dynamic penetration. In practice, the selection between them follows the grain-size distribution and expected stiffness: cone penetration is generally better suited to fine-grained soils (clays, silts, fine sands), whereas dynamic penetration performs robustly in coarse-grained soils (sandy gravels, heterogeneous fills).

Compared with coring and purely laboratory testing, penetration methods offer continuous (or quasi-continuous) profiling over the full investigation depth, thereby improving representativeness of the derived stiffness/strength trends. Drilling remains essential for lithological confirmation and sampling, yet typically only a subset of the recovered core is tested in the lab; penetration testing complements this by capturing in-situ variability between sample points.

Cone Penetration Test (CPT)

The Cone Penetration Test advances the probe at a constant rate (20 mm s^{-1}), measuring the static resistance mobilized at the cone tip and along the sleeve. Instrumentation may be electrical (strain gauges) for continuous logging or mechanical (dynamometers/manometers) for interval readings (e.g., every 10–20 cm). The total recorded resistance, q_t, consists of the cone resistance ($q_{(c)}$) and local sleeve (shaft) friction ($f_{(s)}$); depending on equipment, both are reported either continuously or at fixed depths.

Strengths and use cases. CPT provides a high-resolution profile of strength and deformability, enabling:

- Recognition of interfaces where stiffness contrasts are pronounced;
- Detection and thickness estimation of weak or unsuitable horizons (soft clays, collapsible deposits);
- Screening for weathered or altered zones within otherwise competent strata;
- Verification of embankment homogeneity;
- Identification of probable slip surfaces where the probe can penetrate soft/structured materials.

Through established correlations, CPT can support derivation of practical parameters for preliminary design and screening—e.g., consistency, relative density/compaction, oedometer/deformation moduli, and shear strength surrogates (effective friction angle, total cohesion). Typical applications include pile design (driven/bored), assessment of liquefaction susceptibility in saturated loose soils under dynamic loading, and evaluation of preconsolidation or collapse potential.

Operational note. Maintaining the constant push rate (20 mm s^{-1}) is critical for data comparability (as referenced in Chapter 3's parameter requirements). Where continuous electronics are unavailable, interval readings at 20 cm provide sufficient vertical resolution for the interpretations formulated in Chapter 3.

Dynamic Penetration Test (DPT)

The Dynamic Penetration Test advances the rod by hammer blows dropped from a fixed height; the response is recorded as the number of blows required to achieve a set penetration increment (typically 10 or 20 cm). Owing to simplicity and cost-efficiency, DPT is widely used for reconnaissance and for coarse or variable soils where static pushing is impractical. A rod fitted with a special cone (diameter larger than the rod) is driven by a hammer falling from a constant height. Common classes are: DPL (Light) – 10 kg hammer**,** DPM (Medium) – 30 kg hammer**,** DPH (Heavy) – 50 kg hammer**,** DPSH (Very Heavy) – 63 kg hammer**.**

Impact rates of 20–60 blows min^{-1} are typical; ~30 bpm yields stable results. The specific dynamic penetration resistance $q_{(dym)}$ is calculated (e.g., by the Dutch formula) from: hammer weight (kN), drop height (m), blow count per 10/20 cm, cone cross-section (m^2), penetration depth (m), and the system weight (cone, rods, anvil, basket; kN). Because shaft friction biases blow counts with depth, the raw N is corrected using measured torque (e.g., every 1 m): the estimated blows required to overcome friction are removed from the gross count. From the corrected N (for 10 cm), a relative compaction index can be inferred.

The deformation modulus for a layer is commonly estimated as $E \approx \alpha \cdot q_{(dym)}$, with α reflecting material state: ≈ 1 (saturated sands), 2 (slightly moist sands), 3–5 (silts/clays), 3.8–5 (clayey gravels), 5.3–9 (sandy gravels). These ranges are consistent with the material groupings introduced in Chapter 2 and supply the stiffness inputs requested in Chapter 3.

Strengths and limits. DPT is valued for low cost, robustness, and versatility, and is widely applied for verifying soil and fill compaction. Its principal limitation is lower vertical precision in identifying thin weak layers because energy is averaged over the cone's advance and adjacent materials. In some geological settings – e.g. fine impermeable Neogene/Paleogene clays manifesting a pronounced "rubber effect"—results may be non-diagnostic or overly conservative. In such cases, as anticipated in Chapter 3's workflow, DPT should be paired with core drilling and/or complementary tests to confirm lithology and mitigate interpretive ambiguity.

4.2 GIS Implementation and Data Processing

All field measurements (CI, RI) and laboratory measurements of grain size have strong potential to be integrated into a geospatial workflow designed for reproducibility and rapid decision support. Point observations (CI/RI in the range of 0–15–30–45 cm) were stored, including metadata, location data and QC flags. They were then linked to laboratory grain size records and transformed into USCS classes to pair RCI according to standardized soil categories. For each observation, $RCI_{1/2/3}$ = f(CI·RI, USCS, moisture condition) was calculated for processing using map algebra.

To derive continuous RCI surfaces, raster layers (grids) were generated for each depth (0–15, 15–30, 30–45 cm) separately for dry, moist, and wet soils using interpolation (IDW) for operational transparency and kriging for error estimation. VCI thresholds for representative vehicle classes were generated as raster layers of categorical data. A binary "pass/fail" layer (RCI ≥ VCI ⇒ pass) was then created by comparing individual cells, from which a multi-class suitability map was compiled (e.g., impassable/borderline/passable with caution/passable). All steps were scripted to ensure repeatability and enable quick repetition for different moisture scenarios.

To visualize the results, the final layers were published via OGC services (WMS/WFS/WCS) and vector tiles. The map concept pays attention to visual hierarchy: (i) RCI as a color scale with quantile intervals, (ii) discrete color shades to express "meets/does not meet," and (iii) USCS as categorical fills with consistent symbolism.

The results obtained enable the compilation of several map products in a GIS environment, which will allow different user groups to easily and quickly read, analyze, and interpret the findings and the topological information between them, for example

- RCI map (dry/damp/wet) – surfaces with regard to depth, revealing spatial variability in bearing capacity,
- USCS classification map with laboratory-verified classes facilitating the interpretation of RCI trends,
- synthetic suitability map by vehicle category (VCI_1/VCI_{50}),
- scenario viewer – user interface with moisture state switching,
- uncertainty maps (standard interpolation errors and sensitivity bands).

The integration of penetration methodology into GIS provides a number of methodological advantages. It is possible to trace the genealogy of data from the probe to the map, model across locations and seasons, and visualize the results in analytical and synthetic thematic maps. This approach clearly shows the dependence on the scenario (dry vs. moist vs. wet) and reveals spatial heterogeneity that one-off assessments cannot capture. The authors are also aware of the limitations of the chosen solution. Gravelly/stony soils, organic horizons, or clays with a rubber effect are visualized as zones of low reliability (through symbols of uncertainty and "masking" layers), leading to targeted drilling or alternative testing.

To disseminate information, OGC web services and vector tiles provide geovisualization on devices with limited bandwidth. The map design follows a cartographic hierarchy: the base terrain (hill shading/DEM) is muted, success/failure and suitability layers are prominent, USCS boundaries are thin, and uncertainty is overprinted as hatched or alpha-blended polygons. Products assembled in this way can support route selection, convoy spacing, and planning for emergencies or for defining mobility corridors.

5. Conclusions

Penetration measurements are based on the measurement of the resistance of the soil to penetration by a specially designed penetrometer needle. The relationship between the magnitude of the resistance and the degree of soil compaction is well reproducible in most arable soils, but measurements are conditionally suitable or even problematic in most forest soils. The method is less suitable for soils with gravel and for soils with uneven soil moisture in the soil profile. It cannot practically be used on stony soils or on organic soils.

Factors affecting penetrometric measurements include:

1 soil type (soil grain size)
2 soil texture (crumbly – prismatic – foliated...)
3 physical conditions (soil lightness is demonstrated by a higher dry bulk density and reduced porosity. Influence of fissures, macropores after fauna)
4 soil humus content
5 soil moisture (dry – moist – wet...)
6 soil type (application of pedogenetic processes – illimerisation, podzolisation, charring, etc.)
7 soil skeleton and nature of the soil-forming substrate
8 winter freezing of the soil and gradual thawing in spring
9 groundwater and groundwater level fluctuations.

The results achieved clearly answer the research questions formulated in Chapter 2. RCI reflects changes in capacity caused by moisture across USCS classes with minor anomalies specific to individual classes (Q1). The RCI ≥ VCI rule provides usable pass/fail results and reveals the threshold sensitivity under wet conditions at SM in Živanice (Q2). The soil type map classification conversion (Czech to USCS) was locally verified by laboratory data (Q3). Finally, the discussed material and methodological limitations define when it is necessary to change the test type or add core sampling, thereby limiting operational use (Q4).

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