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Reliability Analysis of the GEOSL2000 Soil Passability Prediction Model and its Implications for Military Use

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Abstract

The objective of this study was to validate a geoprocess model devised to predict soil passability based on in-situ measurements of soil bearing capacity. The bearing capacity of the soils was gauged using a conical penetrometer, and the measured values were juxtaposed with the Vehicle Coin Index (VCI) value for typical vehicles deployed in the Czech Armed Forces. Field measurements were conducted across nine distinct locations over a span of several years. The measured values were compared with the modelled passability, which was in line with the actual meteorological conditions on the individual days of measurement. The results clearly indicate that the model, created for the needs of the Army of the Czech Republic, exhibits significant inaccuracies. In most instances, it considerably overestimates the real situation. The primary recommendation of the research is the implementation of major modifications or the development of a new geoprocess model.

KEY WORDS: *soils, passability, modeling, CCM, VCI, GIS, reliability*

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1. Introduction

Soils have a major impact in the evaluation of terrain passability by military equipment [1]. For this reason, the issue of soil passability assessment is given a lot of attention across different armies. Within the evaluation of soil passability, attention is focused mainly on the grain size composition of soils and on soil properties reflecting the way individual soil types are formed [2, 3] and on the actual method of measuring passability. Penetrometric measurement is currently used as the key method for determining soil passability [4, 5, 6]. Determination of soil passability using penetrometric measurements is usually based on procedures established and used by the U.S. Army [7, 8].

The measuring principle is based on the measurement of soil penetration resistance against the penetration of the metal tip of the penetrometer by gradual pushing into the soil. The amount of soil resistance is directly proportional to the degree of soil compaction, soil composition and soil moisture. On the scale, the resistance values in the critical layers (depths) of 0, 6, 12 and 18 inches (approx. 0, 15, 30 and 45 cm) are read. From the measurements taken at one location, the arithmetic mean is used to calculate the value of penetration resistance for individual depths and the value of the cone index (CI) for individual depths of the critical layer. The use of the critical layer value depends on the type of vehicle chassis, its weight, the type of soil and the monitored number of passes. The second step is to determine the RI (remolding index) for fine-grained soils that are subject to deformation under load and the resulting changes in volume and consistency. To determine the formation index, a soil sample is taken from the critical layer for the vehicle using a piston sampler. To calculate the actual passability depending on the type of vehicle and its weight, it is necessary to calculate the RCI (rating cone index). The actual determination of the passability of the monitored locality is based on the comparison of the values of the RCI index with the cone index of the vehicle VCI (vehicle cone index). The calculated VCI values are permanently valid for the vehicle unless there is a change in the tactical and technical parameters affecting the calculation. Although this procedure for determining soil passability is time-consuming both in the measurement and data processing phases, it is more reliable than other methods due to the fact that soil passability assessment is assessed for specific vehicles.

This was also proven by independent measurements carried out by the Department of Engineering Technologies of the University of Defence [9, 10]. This procedure for determining soil passability is also commonly used in a number of foreign scientific papers dealing with soil passability [11, 12, 13]. Due to its reliability and its widespread use in other research work, it was used to determine reference values of patency within this work.

Contemporary methodologies, primarily aimed at predicting soil passability, leverage digital geographic soil data, remote sensing imagery, meteorological data (with particular emphasis on soil moisture and precipitation), and the application of Geographic Information System (GIS) tools [14, 15, 16, 17]. The genesis of these methodologies coincides with the advent of GIS technology and its application in the geographical security of military forces.

One such methodology is a model developed by the Geographical Service of the Army of the Czech Republic towards the end of the 20th century, known as GOESL2000. This model utilizes the Special-Purpose Soil Database (SPSD), created in the late 1990s, as a data source for assessing the impact of soil passability. The database is a digital adaptation of the Soil Map of the Czech Republic, scaled at 1:200,000. It encompasses information on the dominant component of the soil type and soil-forming substrate, along with associated characteristics of the grain size composition for individual soil areas. However, the database's scope is confined to the territory of the Czech Republic.

For the evaluation of soil passability, it is feasible to categorize soil areas into four groups based on expert opinion [18]:

- passable soils (GO);
- soils with limited pasability under difficult meteorological conditions (SLOW GO);
- soils impassable under difficult meteorological conditions (SLOW/NO GO);
- impassable soils throughout the year (NO GO).

Difficul meteorological conditions are delineated based on the season and the cumulative precipitation over a span of three consecutive days within the observed period. During the summer months (May through September), these conditions are characterized by precipitation totals exceeding 60 mm (70 mm in certain contexts). However, the specific circumstances under which the 70 mm threshold applies remain unclear due to the lack of available documentation. Consequently, a threshold of 60 mm was adopted for summer conditions.

In contrast, the winter period (October through April) designates challenging meteorological conditions as those with total precipitation surpassing 40 mm [19].

The primary objective of the research was to validate the outcomes of soil passability modeling derived from the GEOSL2000 process. Furthermore, it aimed to ascertain the reliability of soil passability predictions for the principal soil groups, utilizing field measurements procured through a penetrometer.

2. Selection of localities, implementation of control measurements and preparation of meteorological data

A total of nine localities within Moravia, each characterized by distinct soil classifications, were selected for the measurements. The selection process was conducted in collaboration with pedologists, and was informed by extensive practical experience accumulated through the analysis of soil probes and field testing of equipment feasibility.

The selection was strategically designed to enable the completion of measurements across all localities within a single day. Simultaneously, the chosen localities represented a diverse range of soil areas, encompassing various soil types found within the Czech Republic (Figure 1). The classification of soil at the measurement sites, as per the SPSD, along with the control sample procured during the initial measurement, is presented in Table 1.

Table 1.
Classification of soils at the measurement site according to database and soil control probe

	SPSD		Soil probe	
Locality	Soil type	Grain	Soil type	Grain
Záhlinice A	Phaeozems	Clay loam	Fluvisols	Sandy loam
Záhlinice B	Phaeozems	Clay loam	Gleysols	Loamy
Chropyně	Fluvisols	Clay loam	Fluvisols	Clay loam
Troubky	Fluvisols	Clay loam	Fluvisols	Loamy
Tovačov	Phaeozems	Loamy clay	Phaeozems	Loamy
Štětovice	Peat	N/A	Histosols	Loamy
Olšany	Phaeozems	Loamy	Phaeozems	Clay loam
Křtiny	Cambisols	Loamy	Gleysols	Clay loam
Ochoz	Cambisols	Sandy loam	Stagnosols	Loamy

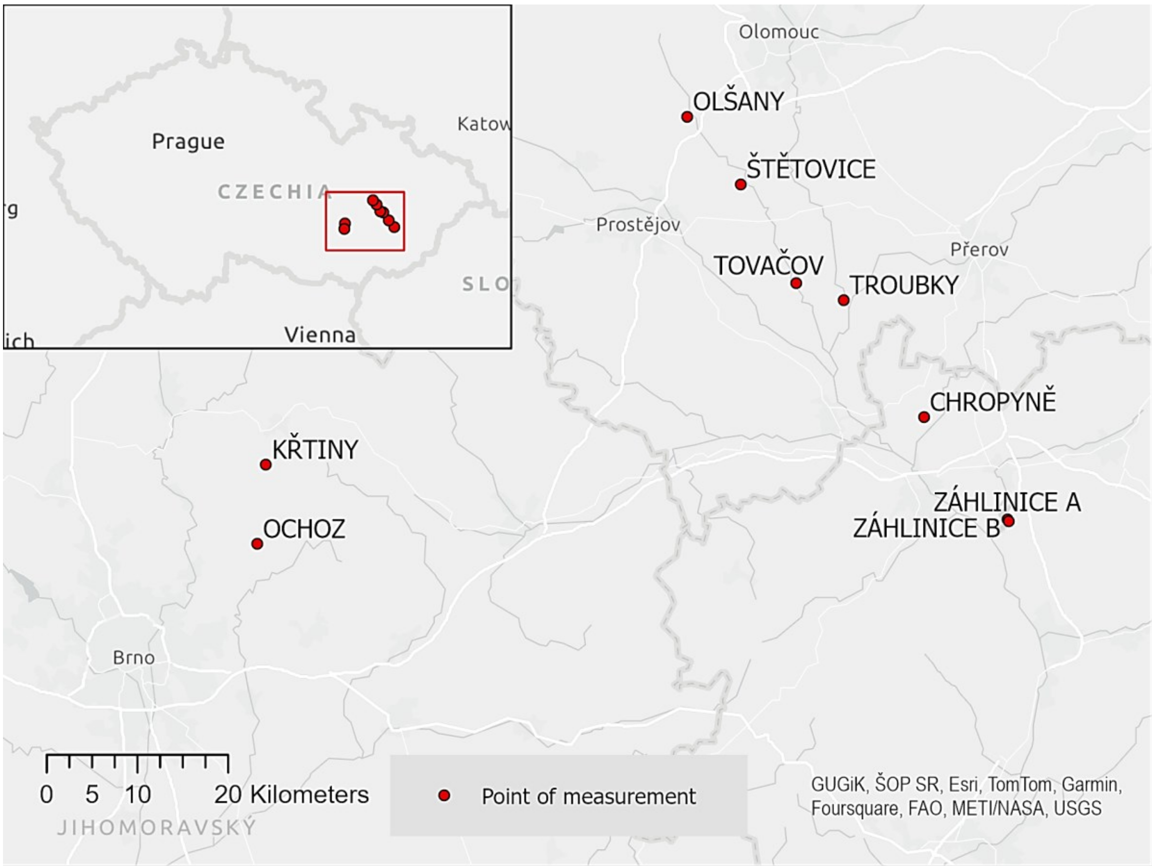

Fig. 1. Localization of measurement points in Moravia.

Systematic, repeated measurements of soil bearing capacity were conducted across various locations utilizing the E-960 soil passability measurement apparatus. The measurement process spanned from December 2014 to September 2016. A total of fourteen measurements were executed at disparate intervals, predominantly during the more humid part of the year. Of these fourteen measurements, three were conducted during the summer season (May through September), while the remaining eleven measurements were carried out during the winter period (October through April). The classification of the periods into summer or winter was determined based on the methodology delineated in the documentation for the GEOSL2000 model [19].

The relatively fewer measurements during the summer can be attributed to the prevailing weather conditions, which rendered the soils dry, firm, and passable. Owing to the overall shift in the weather pattern in the Czech Republic [20], the climatic conditions in the area of interest deviated from the average climatic values during the measurement period. Predominantly, it was a drier period characterized by below-average precipitation, above-average temperatures, and a longer sunshine duration than is typical for an average year. This anomaly also influenced the measured values of load capacity.

This atypical weather pattern can be substantiated by comparing long-term and current (as of the date of measurement) average temperatures and precipitation totals. Data from the meteorological station of the Czech Hydrometeorological Institute (CHMI) Brno-Turany, situated in proximity to some of the locations, were utilized for this demonstration.

Figures 2-4 provide a comparative analysis of the 2015 data against the 30-year average spanning from 1981 to 2010. During the summer months of 2015, the average monthly air temperatures were observed to be higher, deviating from the long-term averages by up to 5 °C (Figure 2). The most significant temperature extremes were recorded in August, which, in conjunction with the precipitation deficit, influenced the passability of soils. The majority of the soils were notably dry and highly passable throughout the autumn season. In terms of precipitation totals in 2015, they were predominantly below average in most months, often amounting to half of the long-term average (Figure 3). In instances where precipitation reached or even surpassed normal values (notably in the month of August), it typically occurred over fewer days. The majority of the precipitation during these periods was in the form of torrential rains, which resulted in surface runoff. A smaller number of days with precipitation of at least one millimetre can be as restrictive as the total amount of precipitation. The final significant meteorological phenomenon impacting soil moisture, and consequently the bearing capacity of soils, is the duration of sunshine. A comparison of the number of clear days and the duration of sunshine in 2015 with the long-term average (Figure 4) reveals an increase in values. This increase, coupled with higher temperatures and lower precipitation, results in the overall drying of soils, thereby enhancing the bearing capacity of soils.

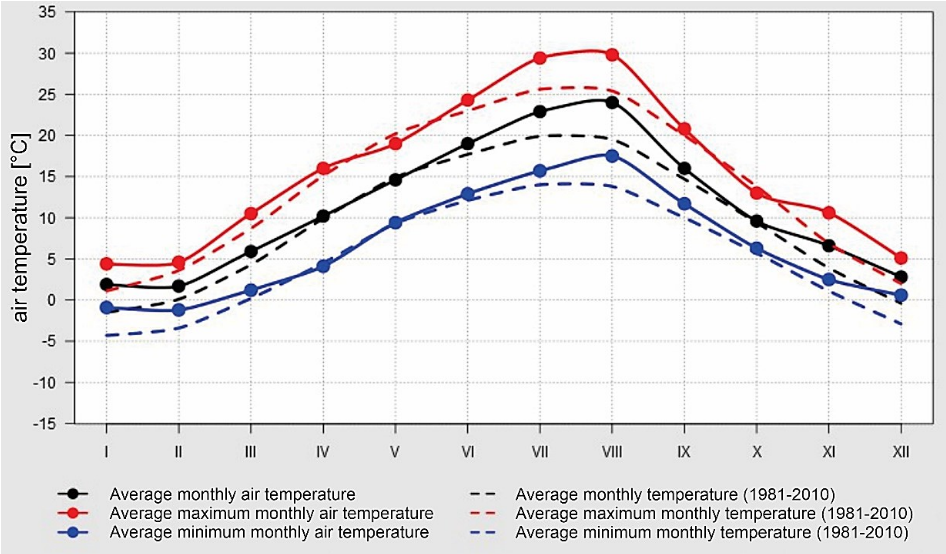

Fig. 2. Course of average monthly, average monthly maximum and minimum air temperature in 2015 compared to the long-term average 1981-2010 [21].

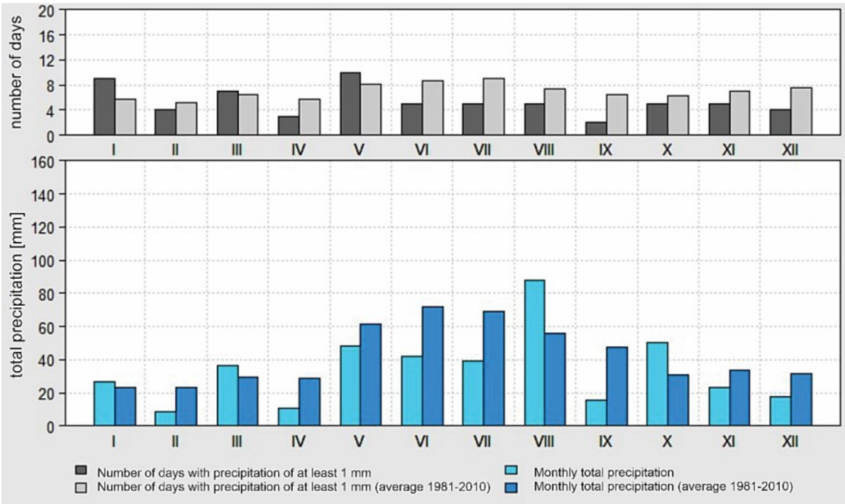

Fig. 3. Course of monthly precipitation and monthly number of days with precipitation of at least 1 mm in 2015 compared to the long-term average 1981-2010 [21].

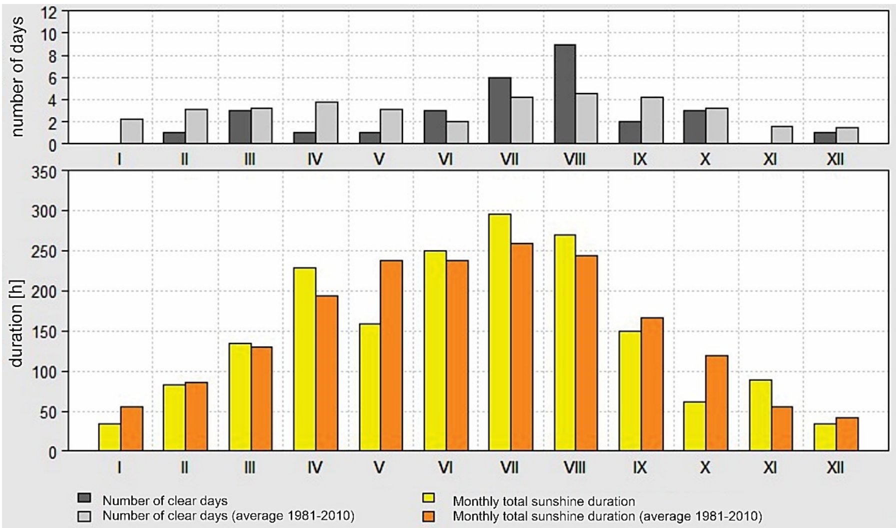

Fig. 4. Course of monthly totals of solar irradiance and monthly number of clear days in 2015 compared to the long-term average 1981-2010 [21].

The observed meteorological phenomena in 2016 did not exhibit significant alterations. The sole distinction was the higher precipitation recorded in some months of the first half of the year. Both temperatures and sunshine duration throughout the year surpassed long-term averages. Graphs representing these trends for 2016 can be accessed on the CHMI website [21].
Subsequent to the measurements, the bearing capacity of soils was calculated using the Rating Cone Index (RCI), which was then compared with the Vehicle Cone Index (VCI) value. The latter was determined for the basic types of vehicles deployed in the Czech Armed Forces. The measured passability was simplified to three fundamental categories: GO, SLOW GO, and NO GO. This categorization facilitated a comparison with the results derived from the GEOSL2000 continuity model. The actual passability, thus obtained at individual locations, was juxtaposed with the outputs of the analytical model GEOSL2000. The model incorporated real precipitation totals for individual locations and measurement dates in its calculations. This comparative analysis served to validate the reliability and accuracy of the GEOSL2000 model in predicting soil passability.
To facilitate a comparison between the soil passability model, as per the GEOSL2000 methodology, and the actual measured values, it is imperative to ascertain the passability of soils at the measurement sites. The analysis reveals that the majority of the sites are situated in areas with soils that pose difficulties for passability under deteriorated meteorological conditions. Two of the sites are located in areas where soils are passable without any restrictions, while one site is in an area where soils are impassable, irrespective of weather conditions (Table 2). It is important to note that the results of the soil passability analysis, as per this methodology, do not take into account the type of vehicle.
In three instances, the measurement sites are in close proximity (80 to 250 m) to the interface with passable soil areas (Olšany, Štětovice, Tovačov). Consequently, if the course of the interface is inaccurately drawn, it could lead to an erroneous classification of passability. For the purpose of this comparison, it is assumed that the course of the interface is accurately drawn.

Table 2.
Throughput of sites according to SPSD under favourable and unfavourable conditions according to the GEOSL2000

Locality / METEO conditions	Záhlinice A	Záhlinice B	Chropyně	Troubky	Tovačov	Štětovice	Olšany	Křtiny	Ochoz
Favourable	GO	GO	GO	GO	GO	NO	GO	GO	GO
Difficult	SLOW	SLOW	SLOW	SLOW	SLOW	NO	SLOW	GO	GO

To compare the passability measurements at individual locations with the values derived from the analysis according to the GEOSL2000 methodology, it is essential to ascertain whether the meteorological conditions were favourable or difficult at the respective measurement dates. This involves determining the amount of precipitation for the three days preceding the day of measurement and discerning whether it is a summer or winter season. Given that the average distance between the penetrometric measurement sites and the nearest rain gauge is approximately 5.7 km [14], it is not suitable to determine the precipitation total based on values obtained from the nearest rain gauge stations. Consequently, combined precipitation estimates were employed. These estimates amalgamate information from meteorological radars, calibrated in accordance with the precise values obtained at the locations of individual rain gauge stations. In the Czech Republic, such data have been generated by the Czech Hydrometeorological Institute since 2003. The resultant data, currently calculated for a 1 × 1 km network at five-minute intervals, can be regarded as the most accurate information on precipitation total in the Czech Republic, notwithstanding the potential error rate of the calculation [22].

3. Verify the reliability of the GEOSL2000 model

Based on the derived area estimates of precipitation, the cumulative precipitation for the three days preceding the day of measurement was computed for each date and location, in accordance with the GEOSL2000 methodology for evaluating soil passability. The computations reveal that the maximum three-day precipitation totals were recorded during the measurements conducted in February, March, and September 2016. However, in all instances, the values did not exceed the thresholds established for the categorization of difficult conditions. The peak values of three-day totals during these periods ranged between 10 and 15 mm at certain locations, while in all other cases, they were less than 10 mm. Consequently, it can be asserted that the meteorological conditions can be classified as favourable on all measurement dates. In terms of the impact of soils, all sites should be navigable without any issues, with the exception of the Štětovice site, which is predicted to be impassable under any meteorological conditions (Table 2 – first row).
Utilizing the recorded values of penetrometric resistance of soils, the CI and the RI were computed for each location and measurement date, following the methodology delineated in the referenced literature [7, 8]. Subsequently, the rating cone indexes (RCI_1 and RCI_{50}) were derived. The computed values of the rating cone indexes were juxtaposed with the vehicle cone indixes (VCI_1 and VCI_{50}). This approach facilitates a comprehensive understanding of the soil onditions and their implications on vehicle passability in all localities.

$$if\ RCI_i > VCI_i \quad \rightarrow \quad GO, \tag{1}$$

$$if\ RCI_i < VCI_i \quad \rightarrow \quad \text{NO}\ GO, \tag{2}$$

where: $i = 1$ or $i = 50$.

As per Equation 1, if the computed RCI value at a specific location surpasses the VCI value of the observed vehicle, the location is deemed passable. Conversely, as dictated by Equation 2, the site is assessed as impassable. As an integral component of the problem resolution, the passability was ascertained for all fundamental categories of vehicles utilized in the Czech Armed Forces across all fourteen measurement dates. In the context of trucks, the scenario of a fully loaded vehicle was consistently considered for comparison. This systematic approach provides a comprehensive evaluation of vehicle passability in all localities under varying conditions.

The results obtained indicate the anticipated unreliability of the soil passability model GEOSL2000. Based on the collected data, it is evident that despite favourable meteorological conditions, certain locations, specifically Záhlinice A, Záhlinice B, and Křtiny, are often impassable or extremely challenging to traverse. In some instances, the localities of Štětovice, Olšany, and Tovačov also become difficult to navigate. All other sites were navigable for all types of monitored equipment, with a few exceptions of poor passability for certain trucks (notably the Tatra T815 4×4).

In addition to the actual soil conditions, the reduced passability at these locations was partially attributed to agricultural activities. The results also clearly indicate that a universal assessment of soil passability, as implemented by the GEOSL2000 procedure, is not suitable. In locations with passability issues, it is imperative to evaluate individual vehicles, or at the very least, groups of vehicles. The obtained results reveal similar calculated passability outcomes for the following groups of vehicles:

- off-road passenger car (OPC);
- off-road truck (OT);
- wheeled combat vehicles (WCV);
- tracked combat vehicles (TCV).

Differences can also be discerned among individual groups of vehicles, primarily dependent on the total weight of the vehicles and the configuration of the chassis. However, with a degree of generalization, this basic categorization could be utilized to modify the existing model or to devise a new method for assessing soil passability.

Table 3.

Evaluation of the passability of selected locations at certain measurement dates for defined groups of vehicles

Locality	**Group of vehicles**	**Selected measurement dates**										
		9. 12. 2014	26. 3. 2015	13. 8. 2015	14. 10. 2015	19. 11. 2015	10. 12. 2015	19. 1. 2016	17. 2. 2016	14. 4. 2016	16. 6. 2016	6. 9. 2016
Záhlinice A	OPC	N	N	S	G	S	S	G	N	N	S	S
	OT	N	N	N	N	N	N	S	N	N	N	N
	WCV	N	N	N	G	N	S	G	N	N	S	S
	TCV	N	N	S	G	S	S	G	N	N	S	S
Tovačov	OPC	G	G	G	G	G	G	G	S	G	G	G
	OT	N	S	G	G	G	G	G	N	S	G	G
	WCV	G	G	G	G	G	G	G	S	G	G	G
	TCV	G	G	G	G	G	G	G	S	G	G	G
Štětovice	OPC	N	G	G	G	S	G	G	S	G	G	G
	OT	N	N	G	N	S	S	S	N	N	S	G
	WCV	N	G	G	S	S	G	G	S	S	G	G
	TCV	N	G	G	G	S	G	G	S	G	G	G
Olšany	OPC	G	G	G	G	S	S	G	N	S	G	G
	OT	G	G	G	G	S	S	G	N	N	G	G
	WCV	G	G	G	G	S	S	G	N	S	G	G
	TCV	G	G	G	G	S	S	G	N	S	G	G
Křtiny	OPC	N	N	G	S	S	N	S	N	N	N	S
	OT	N	N	S	N	N	N	N	N	N	N	N
	WCV	N	N	G	S	S	N	S	N	N	N	S
	TCV	N	N	G	S	S	N	S	N	N	N	G

Across all locations, varying capabilities of vehicles to traverse a given site can be observed. The passability fluctuates on different dates for individual vehicle groups. There are instances when some groups of vehicles can navigate without any issues, while others have a limited number of passages, or the site is generally impassable due to the low bearing capacity of soils. This is primarily attributed to weather conditions, agricultural activities in the case of cultivated soils, or a combination of both. To evaluate the passability of soils for individual groups, the following limiting conditions have been adopted. These conditions allow the passability of the territory to be defined for a given group of vehicles in terms of the influence of soils as follows (Table 3):

- GO – all vehicles in a given group can make at least 50 passes;
- SLOW GO – all vehicles in a given group can make at least single passes;
- NO GO – at least one type of vehicle in a given group will not pass at all.

Under such defined conditions, the passability of individual locations varies significantly. The results clearly indicate that trucks represent the most problematic group of vehicles. Upon detailed examination of the results for individual vehicles, the T815 4×4 emerges as the least suitable vehicle for off-road driving. Owing to its chassis layout and relatively large weight, it frequently encounters prerequisites for getting stuck due to the low bearing capacity of soils.

4. Conclusions

The comparison of soil bearing capacity, determined based on field-measured data, with the passability ascertained by the GEOSL2000 model, demonstrated the low reliability of the modeled soil passability. From the analysis of the results, several conclusions can be drawn:

1. Modelling soil passability in general, without addressing a specific type of vehicle or vehicle category, is inappropriate and cannot yield valid results to support decision-making. A modified or new soil passability model must consider this fact and classify soil passability based on at least vehicle groups of similar parameters.
2. The current model, which assesses passability based on the amount of precipitation over three consecutive days, does not align with reality. The measured passability values showed that precipitation is a significant factor influencing soil passability, but likely not a decisive one. Similarly, an interval of three days is probably not optimally chosen. According to available sources dealing with the evaluation of soil passability [23, 24, 25, 26], soil moisture is the decisive factor. Therefore, to create a model, it is necessary to analyze the influence of soil moisture on soil passability, as well as meteorological elements and phenomena that affect it.
3. The accuracy of the drawing and classification of soil areas in the SPSD does not correspond to the real situation. Given the time of creation of this database, the base map, and the technology of creation, this finding is expected. For this reason, it would be appropriate to replace the SPSD with a more accurate soil database.

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