MAPPING THE PASSABILITY OF SOILS FOR VEHICLE MOVEMENT

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1. Introduction of the Term Trafficability

There are different types of trafficability – the trafficability of woods, waters, soils, towns, etc. This means that trafficability is a very broad concept and concern. Soils are a major continuum of the landscape, and significantly affect trafficability. This is especially true for areas where transportation infrastructure is sparse, or for those areas where circumstances make it impossible to use established transportation corridors. Military Units prefer trafficking through open terrain, as it is usually the simplest way. Taking this into consideration, this text primarily focuses on the trafficability of soils. Why is trafficability so important? There are many critical situations wherein military forces must traverse diverse types of terrain and cannot be limited to roads or existing corridors. Because these types of infrastructure are vulnerable to destruction from either enemy attack or natural disasters, the ability to remain mobile and cross many different terrain types is a necessity for the armed forces. Therefore it is of utmost importance to know whether a terrain is actually trafficable. Trafficability is the capacity of soils to support vehicles.

From time to time, extraordinary situations arise in our region as well as in other regions of the world and the cause of these situations can be either natural or man-made. As a result of these situations, transport corridors may become impassable (a bridge damaged by flood, etc.). Often it is necessary to reach an area that cannot be approached by conventional means, in a short period of time. A detour is not always possible, or may take too much time. Thus, it becomes necessary to travel off road. The question then arises as to whether the terrain is suitable for certain type of vehicles or not. There are various instruments that can be used to judge the trafficability of a terrain. A comparison of two possible methods is described here.

The trafficability of fine-grained soils (silts and clays) and sands that contain enough fine-grained material to behave like fine-grained soils when wet, is more difficult to assess than the trafficability of coarse-grained soils (clean sands). This study does not address the trafficability issues associated with natural or man-made obstacles (such as forests or ditches).

Figure 1. An example of mire

A very detailed mapping of soil conditions took place in the 1960's in the former Czechoslovakia. The mapping was primarily intended to be of assistance to the agriculture industry, but it has also been used for other purposes as well. One such purpose is the production of soil trafficability maps for the Czech Republic. These maps are one of the input layers of the Cross-Country Movement (CCM) assessment, which is necessary for the deployment requirements of rescue teams and military units. These maps were a result of the original soil mapping, which was based on measurements of the penetrometric resistance of soils at various locations throughout the Czech Republic. The data collection process lasted for several years. Specialists at the Department of Military Geography and Meteorology carried out the measurements in different seasons, and under various meteorological conditions. The results of the CCM analysis were validated using the technical parameter data of the vehicles, values obtained from the measurements, and actual vehicle tests on different soil types. These results were converted into soil trafficability maps, terrain trafficability databases and other products provided for the Czech army.

When studying soils, a large number of parameters are evaluated. The fundamental parameters [8, 6] include the physical characteristics, the chemical composition, the physical and chemical processes occurring, the amount of organic matter it within the soil and the effect of organic matter on the overall soil properties. There can also be other parameters depending on the orientation of the research. For several years already, the research team of the Department of Military Geography and Meteorology at the University of Defence in Brno has been working on problems related to the impacts of vehicle movement on terrain. As soils are an important aspect of the landscape, and have a great influence on mobility, they have also been a subject of investigation. Tertiary goals of the research have focused on the following areas:

- verification of the source soil data quality in the Czech Republic;
- measuring the load capacity of different soils in different weather conditions;
- analysis of the impact of different types of military and rescue team vehicles on soils;
- use of soil data for the production of soil permeability maps.

2. Trafficability Evaluation Methods of the Army of the Czech Republic

The army field manual "Military Roads and Ways" addresses trafficability in the Czech Republic. The manual shows how to assess trafficability using visual observation, although this method is not very precise. Another way to determine trafficability is by making a footprint in the soil. This method is also not very reliable. Ostensibly, if a full footprint can be made in the ground, then the terrain is not trafficable by wheeled vehicles. A better method than the aforementioned two makes use of two simple instruments – an engineer crowbar and a telescopic penetrometer (PT-45). These instruments can be used to find soil resistance. The telescopic penetrometer is the instrument most frequently used by engineer units.

A second possible way to assess trafficability is offered by the American Field Manual 5-430-00-1 "Planning and Design of Roads, Airfields and Heliports in the Theater of Operations – Road Design". This manual suggests the use a cone penetrometer to determine the soil bearing capacity. The following passages will describe the two types of penetrometers.

2.1. The Telescopic Penetrometer

The telescopic penetrometer has a conical tapering tip, which can be pressed into the soil. The instrument has a gauge, which allows the operator to determine the pressure needed to push the cone to different depths. Each measurement is carried out three times at one-meter distances.

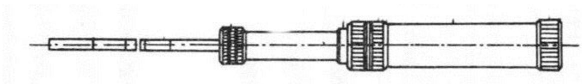

Figure 2. Telescopic penetrometer [4]

The number of vehicles able to negotiate the measured area is determined by a table. If the value from the telescopic penetrometer is lower than 3 MPa, then the area is considered to be a low-supporting terrain. This only applies to wheeled vehicles. Vehicles are divided into three categories according to their weight (4.5, 9 and 15 tons). The number of passes is determined by the weight category.

Figure 3. Measurements with telescopic penetrometer

2.2. The Cone Penetrometer

The field manual shows two indexes that can be used to determine the trafficability of soils – the rating cone index (RCI) and the vehicle cone index (VCI). These two indexes are calculated using a formula called the Trafficability Test Data Formula. As soon as the values of these two indexes are known, they can be compared. It is then possible to judge whether the soil is trafficable for a given number of vehicles. GO means that the vehicles can go and NO GO means that the vehicles will get stuck.

$$RCI > VCI \rightarrow GO$$
$$RCI < VCI \rightarrow NO\ GO \quad (1)$$

The Rating cone index [3]. The RCI is conducted using a set of soil-trafficability test instruments. The set of instruments are contained in a canvas carrying case, and consist of a cone penetrometer, a soil sampler, remolding equipment, and a bag of hand tools. The sampling set is shown in Figure 3. The RCI is the subsequent product of two other indexes – the cone index CI and the remolding index RI.

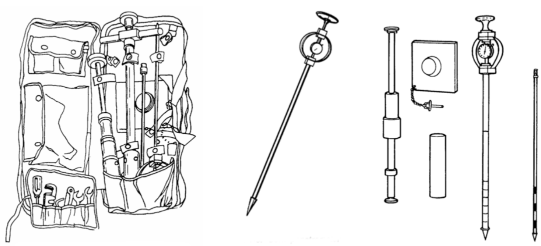

Figure 4. The instruments of the trafficability test set, the cone penetrometer, and the remolding test set [3]

The CI is measured using a cone penetrometer. This instrument is used to determine the shearing strength of low-strength soils. When the cone is forced into the ground, the proving ring becomes deformed in proportion to the force applied. The amount of force required to move the cone slowly through a given plane is indicated via the dial inside the ring. This force is the index of the soil's shearing resistance. It becomes the soil's CI for that plane. The cone penetrometer cannot be used to measure gravels. Gravels are considered excellent for 50 passes, after that any problems can be determined by visual observation.

Figure 5. Measurements with cone penetrometer

The index for the RI can also be measured with this set as well. A piston-type soil sampler is used to extract soil samples for the remolding tests. The equipment for the remolding test consists of the following: an approximately 2.5 pound steel drop slide hammer inside of a steel cylinder, and a cone penetrometer.

So how are the measurements taken? Soldiers must first obtain the data to determine the number and type of vehicles that can cross a given area, and also consider the steepness of the slopes that the vehicles are able to climb. The number of measurements that can be taken depends on the amount of time available, the range of soil strengths, and the general uniformity of the area.

Trafficability-measuring instruments are designed to facilitate rapid observations. The accuracy of the average of any series of readings increases with the number of measurements taken. Variations in soft soils require that at least 15 readings should be taken to establish the true average CI for any spot at a given depth. These 15 readings should be dispersed throughout a uniform area. If there is not time to take a large number of measurements, then judgement must be used to reduce the number.

The Vehicle cone index.[3] For conventional types of vehicles such as those used in some of the NATO countries, the values of the vehicle cone indexes are already known and tabulated. As it is also necessary to have the VCI for vehicles used by the army of the Czech Republic a mobility index (MI) for each type of vehicle must first be determined. From there it is then possible to determine the vehicle cone index based on the curve from the chart. Here is the formula for counting MI [3]:

$$MI = \left[\frac{(CPF) \times (WF)}{(TF) \times (GF)} + (BF) - (CF) \right] \times (EF) \times (TSF) \quad (2)$$

where: *PF* – contact pressure factor,
WF – weight factor,
TF – track factor,
GF – grouser factor,
BF – bogie factor,
CF – clearance factor,
EF – engine factor,
TSF – transmission factor.

This method of determining trafficability takes two factors into consideration. The first is the soil factor, which consists of soil resistance combined with a simulation of passes. The second is the vehicle factor, which considers not only the weight of the vehicle, but also its clearance as well as its engine, and other factors as well. After the initial evaluation of trafficability it is then possible to use the data to create maps.

3. The Mapping of Soils in the Czech Republic, and the Soil Database

There are a number of organizations working on the mapping of soils in different parts of the world. Their methods and procedures vary considerably. The most accurate method for mapping soils is by collecting soil samples (soil pits). Unfortunately, this method is expensive and time consuming. It is also not always possible to conduct soil sampling in areas of interest. For this reason, other methods for soil mapping have also been developed. Such methods include the use of penetrometric measurements [14], analysis of multispectral images [15, 16] the use of a variety of data sources, and comprehensive assessment using GIS tools [17]. A comprehensive soil survey was carried out in the former Czechoslovakia in the 1960s and 1970s. The main objective of this pedologically unique large-scale survey was to map agricultural soils and conduct a basic survey of agricultural land across the entire country. About 700,000 basic soil pits were excavated from throughout the Czech Republic and another 300,000 soil pits were obtained for drainage studies (melioration) [18]. Together with other documents, this extensive data set forms is an important foundation for the creation of soil maps. To a certain degree, it could be argued that during this period there was at least one soil pit taken from every ten hectares of agricultural land in the Czech Republic. In the comprehensive soil survey, the soils were classified according to their genetic-agronomic soil characteristics [19]. A representation of the individual soil types can be seen in Figure 6 [3].

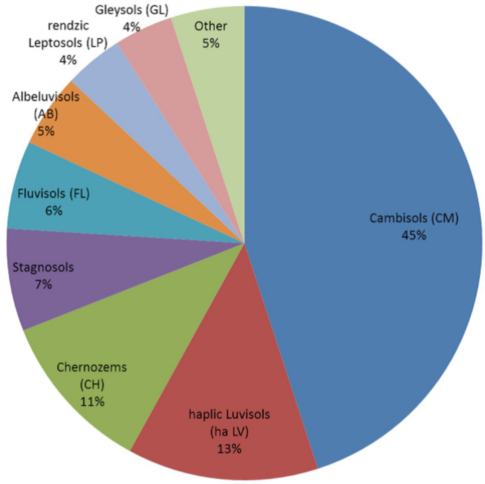

Figure 6. Representation of soil types in CZ

Classification based on grain-size composition was performed concurrently with the classification of the soil types in the comprehensive soil survey. This resulting file was enormous and was primarily used to create the maps of soil bonitation that are used for agriculture. The other use was for the geological services and it is related to the protection of soil and the implementation of flood protection actions.

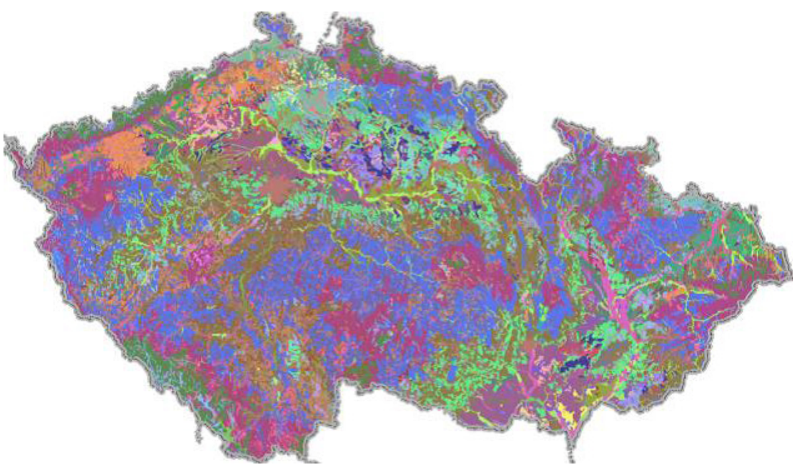

Figure 7. Map of soil types from geodatabase

The synthetic soil map of the Czech Republic 1:200 000 is another result of the comprehensive soil survey [20]. The map shows agricultural and forest soils in a unified classification system. All of the basic soil types are marked on the map, which further enables various super-structural analyses to be conducted. The map is based on the principle of soil association. For a given scale, a demarcated area cannot be identified with only a single unit of the genetic soil classification. The same usually applies to the variability of the soil substrate, the grain size, and the water regime. The dominant and ancillary soil units are defined for large parts of an area. The synthetic soil map was converted into a digital format for military purposes in the 1990s. A digital geodatabase in the vector format defined four basic attributes for each polygon. The first three have the same characteristics as those that can be found in the synthetic soil map:

- the sort of soils;
- the type of soils (Fig. 7);
- the soil substrate.

The last attribute is related to how the soils of a given area affect trafficability. Experts from the Research Institute of Melioration and Soil Protection assessed the ways in which soil behaviour affects trafficability. The influence of the soils, however, was generalized and did not take into consideration exactly which vehicle types can travel through an area [20]. It is possible to create a map of soil impact on vehicle movement (see Fig. 8).

Individual colours represent the following parameters:

- Green – GO in all weather conditions;
- Orange – GO SLOW during the wet season;
- Red – NO GO during the wet season;
- Black – NO GO throughout the year.

The wet season is defined as follows: rainfall in a liquid state that accumulates to more than 40mm in three days from October to April, and rainfall that accumulates to more than 70mm in three days from May to September.

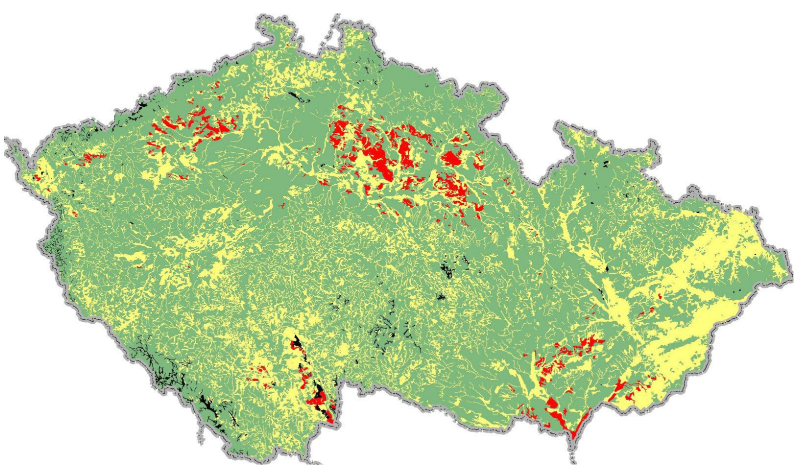

Figure 8. Map of soil impact on vehicle movement

4. Creation of New Trafficability Maps

As previously mentioned, the soil database (UDB) contains an attribute that classifies trafficability according to soil properties and meteorological elements. Such a database makes possible the creation of a map of soil trafficability for the whole of the Czech Republic. The map, however, provides only an initial overview of the impact of soils on trafficability and the classified database can only be used in a limited way for complex terrain analysis. This is further explained in the sources [5, 21, 22, 23 and 24]. When this method is used for making determinations of trafficability, the influence of the soil type on a particular vehicle is not taken into consideration and the determination is rather based on the opinion of soil specialists. The specific properties of a given vehicle are not considered.

For this reason, it was decided to create a new map of soil trafficability. To create a new map penetrometric measurements were chosen as the tool to assess soil trafficability. Over the past decades penetrometric measurements have become an effective tool for analysing soil conditions. They are used extensively in geotechnical engineering, foundation engineering, and in other related fields [25].

The majority of the penetrometric methods are based on the use of the conical penetrometer (CPT) [26]. It is possible to use a portable (handheld) or even a large penetrometer, which can be fixed on a vehicle or on a platform. The US army and NATO have created a portable version of the penetrometer – the E-960 Soil Trafficability Set.

This standardized E-960 Soil Trafficability Set has become the standard tool for measuring soils trafficability in the Czech Republic. In cooperation with specialists of pedology at the Mendel University of Agriculture and Forestry in Brno, 12 locations with soils representative of and typical to the Czech Republic were selected. Periodic measurements were carried out in selected locations over the past five years. Measuring days have been divided into these three categories:

- the dry period;
- the humid period;
- the wet period.

Penetrometric measurements and analysis of soil cores was conducted at each of the selected locations. The soil cores served as the basis of soil analyses, and were used to ground truth the soil plots, the synthetic maps, and the geodatabases. The protocol for soil core sampling consisted of detecting the soil moisture of a core from each location. This was measured in situ, at the time of measurement. The results were then later crosschecked against the values that had been reached at the laboratory. The measured parameters were: rainfall, the amount of sunshine, temperature, and other meteorological parameters inherent to the selected locations. In addition to the measurements of soil moisture, data from meteorological stations and meteorological radars was used as well.

Soil analyses performed during the course of penetrometric measurements showed that the digitization of the original data was not without its problems. As it turned out, analysis showed that the soil core samples from the selected locations were linked to the soil types of the neighbouring polygons in about 30% of cases. The reasons for these errors may include the following:

- error of the digitizing surface during creation;
- mismatched coordinate systems between the original map and the new map (geodatabase);
- errors in the position of collected core samples (determined only on the basis of recognition of landmarks in the field);
- indistinct boundaries between particular soils.

The differences that arise as a result of the creation of trafficability maps may cause errors in the determination of the actual impact of a soil on a particular vehicle's mobility. For vehicles that are part of a mission, this can result in getting stuck and consequently make impossible the fulfilment of a certain task. Therefore, it becomes a question of finding the best way to deal with this problem and avoid the degradation of the results. It was thought that perhaps the best way would be to make corrections to the soil attribute information based on newly measured values, but this would only cover a limited part of the territory, which represents less than one per cent of the country. Thus, it was decided to use fuzzy logic to model the impact of soil formation for the new generation soil trafficability maps. In pedology, several authors have suggested ways to apply fuzzy logic towards soil classification and the creation of soil maps [29, 30]. Computation of the coefficients for individual vehicles and climatic seasons is based on the measured penetrometric values. The calculated coefficient values are assigned to soil areas.

The final cost map was created by unifying the individual soil layers and expressing the coefficient of a vehicle's deceleration as it moves through a terrain. The map does not reflect other objects of the terrain. The information displayed on the map provides an overview of the impact of soils on a vehicle's ability to move through a given terrain. The map section below (Fig. 9) shows traversable areas for the T72M4 CZ tank during wet periods. The green colour in the map expresses a zero rate of deceleration (value 1). Other shades (from orange to red) assume values smaller than one. A value of zero (NO GO) is shown in black. The same cut-out from the old maps is shown for comparison in Figure 10.

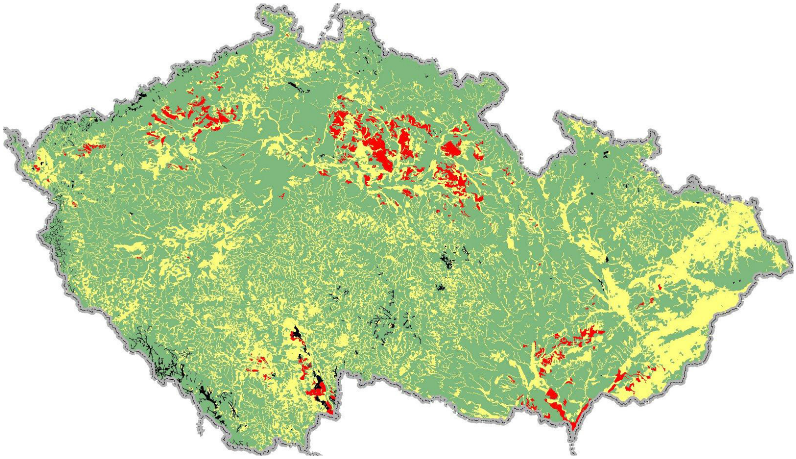

Figure 9. The new trafficability soil map

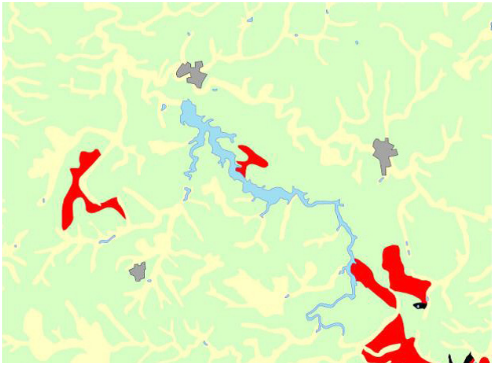

Figure 10. The old trafficability soil map

5. Discussion and Conclusion

In conclusion, the authors would like to emphasize the importance of the concept of terrain trafficablility. There are two spheres of utilization for this concept – military and civilian. In the military sphere it is necessary to negotiate terrain very quickly during an operation. And, if it is not possible to use the original route, then troops will tend to choose the shortest way through the terrain. In the civilian sphere this method can be used to judge the trafficability of a terrain when normal roads or bridges are damaged due to a natural disaster. In such instances there will be a need to quickly gain access to an affected area in order to provide food, material, and reconnaissance. Accesses for rescue vehicles, such as ambulances, are an important factor. If the trafficability of the given terrain can be assessed quickly and reliably then assistance can be provided quickly in the above-mentioned scenarios.

There are many ways to determine trafficability. Two possible systems have been mentioned in this article. The first is based off of the procedures recommended by the field manual "Military Roads and Ways". Here measurements are taken using a telescopic penetrometer. Another method is described in the field manual "Planning and Design of Roads, Airfields, and Heliports in the Theater of Operations – Road Design". This is used when the number and type of the vehicles is known, and it is necessary to find out whether the vehicles can pass through an area or not. The second approach has been used for the creation of the new trafficability maps.

The aim of this article is to demonstrate the possibility of using the existing soil database of the Czech Republic and the results of penetrometric measurements of soil trafficability to create a new generation of trafficability maps. The proposed solution is not yet final. The results show that soils are not a significant factor in restricting the movement of vehicles through the terrain of the Czech Republic for most of the year. Penetrometer measurements confirmed the assumption that during the dry season it is possible for all types of off road vehicles used by the army and rescue units to pass through the whole territory of the Czech Republic without problems. The only exceptions are permanently waterlogged soils, such as peat, gleysol, etc. Similarly, most soils can also be considered passable during the humid period if precipitation is taken into consideration. It is during the wet season that significant problems arise in one-third of the country. This period can be particularly critical for units deployed during natural disasters, such as a flood.

The new map provides more realistic results than the original output from the database. Nevertheless, it is not 100% reliable. The impact of soil on trafficability is not the same within a homogeneous soil area. Trafficability is influenced by many other aspects and is especially related to the amount of rainfall in a given area, the drainage and accumulation ratio, and the ability of soil to dry.

Therefore, the proposed model cannot be considered as final. Further modifications will be carried out in the future. Other field measurements and analyses using meteorological data are currently being carried out. Seven-day rainfall totals for individual locations are derived from both radar images and data measured at individual meteorological stations in the Czech Republic. Water accumulation areas are calculated based on the elevation model derived from airborne laser scanning. In the future, we also plan to include short-term forecasts of rainfall and other meteorological phenomena.

References

[1] **Field manual 5-33**. 1990. Terrain analysis. Headquarters, Department of the Army, USA.

[2] **Field manual 5-410**. 1992. Military soils engineering. Headquarters, Department of the Army, USA.

[3] **Field manual 5-430-00-1** Planning and design of roads, airfields, and heliports in the theater of operations – road design. Headquarters, Department of the Army, USA, 1994.

[4] **Žen 2-16** Vojenské silnice a cesty [military roads and ways]. Praha: Ministerstvo obrany, 1987.

[5] **Sobotkova, S**. 2002. The trafficability of wheeled vehicles depending on the capacity of terrain. [habilitation work]. Brno: Military academy in Brno.

[6] **Sarapatka**, **B**. 1996. Pedologie. Olomouc: Univerzita palackého, (in czech).

[7] **Rybansky, M**. 2009. Cross-country movement: the impact and evaluation of geographic factors. Brno: CERM.

[8] **Koolen, A. J**. ***et al***. 1983. Agricultural soil mechanics. Berlin-Heidelberg: Springer-Verlag.

[9] **Koolen, A. J**. ***et al***. 1983. Agricultural soil mechanics. Berlin-Heidelberg: Springer-Verlag.

[10] **Rooney, D. J**.; **Lowery, B**. 2000. A profile cone penetrometer for mapping soil horizons. – Soil Science Society of America Journal, Vol. 64(6), pp. 2136–2139.

[11] **Barnes, E. M.** ***et al***. 2000. Multispectral data for mapping soil texture: possibilities and limitations. – Applied Engineering in Agriculture, Vol. 16(6), pp. 731–741.

[12] **Kristof, S. J.; Zachary, A. L**. 1974. Mapping soil features from multispectral scanner data. – Photogrammetric Engineering, Vol. 40(12), pp. 1427–1434.

[13] **McBratney, A. B.; Mendonça Santos, M. De L.; Minasny, B**. 2003. On digital soil mapping. – Geoderma, Vol. 117, Issues 1–2, November 2003, pp. 3–52.

[14] **Prax, A., J.; Hraško, J. A.; Němeček, J**. 2008. The importance of comprehensive agricultural soil survey in the former Czechoslovakia and processing the result thereof. – Soil in modern information society: 1st Conference Of The Czech Society Of Soil Science And Societas Pedologica Slovaca. Bratislava: výskumný ústav pôdoznalectva a ochrany pôdy, p. 22–28.

[15] **Němeček, J.** ***et al***. 2001. Taxonomický klasifikační systém půd České republiky. Vyd. 1. Praha: Česká zemědělská univerzita (in czech).

[16] **Novak, P.** ***et al.*** 1991. Syntetická půdní mapa české republiky 1:200000. Praha: VÚMOP (in czech).

[17] **Hubáček, M.; Rybansky, M**. 2013. The cross-country movement in sandy areas. – International Conference in Military Technology Proceeding, ICMT 2013. Brno: University of Defence, pp. 1431–1436.

[18] **Hofmann, A.; Hoškova-Mayerová, S.; Talhofer, V**. 2013. Usage Of Fuzzy Spatial Theory for Modelling of Terrain Passability. – Advances in Fuzzy Systems, Vol. 2013, pp. 1–7.

[19] **Hoškova-Mayerová, S.; Talhofer, V.; Hofmann, A**. 2011. Mathematical model used in decision-making process with respect to the reliability of geo database. – Procedia – Social and Behavioral Sciences, Vol. 9, No. 1, pp. 1652–1657.

[20] **Bemmelen, J. van.** ***et al.*** 1993. Vector vs. raster-based algorithms for cross country movement planning. – Proceedings Auto-Carto, 01/1993. p. 11.

[21] **Hatipkarasulu Y.; Tumay M. T**. 2011. Practical Visual Presentation Approach for CPT-Based Soil Characterization and Modeling. – Geo-Frontiers 2011: Advances in Geotechnical Engineering, pp. 2387–2396.

[22] **Meigh, A. C**. 1987. Cone penetration testing: methods and interpretation. Butterworth-Heinemann.

[23] **Zhongjie Z.; Tumay M. T**. 1999. Statistical to Fuzzy Approach Toward CPT Soil Classification. – Journal of Geotechnical and Geoenvironmental Engineering, Vol. 125(3), pp. 179–186.

[24] **Kremenova, O**. 2004. Fuzzy Modeling of Soil Maps. Master's Thesis. Helsinki: University Of Technology.

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