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BADGER

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Deliverable

D1.3 Soil study and soil interaction with robotics system

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Executive Summary

The present deliverable focuses on the soil study and the interaction with the robotics system. This analysis is very important for the following tasks and workpackages of this project, since the selection of the soils has an influence on the whole system design of the underground robot and the interaction with the soil.

In the first chapter of this analysis, a coarse differentiation in the two different soil types (displaceable and non – displaceable) is performed. This differentiation has a great influence on the design of the individual components of the underground robot. Based on this analysis, non – displaceable soils are the most feasible for the underground robot, since the system complexity is less than that of using displaceable soils. Alongside, given the BADGER target scenarios, the overall prevalence of non – displaceable soil is higher than displaceable soil.

In the second approach of the performed analysis, the focus lays on the different non – displaceable soils referring to the following criteria:

- Transportability
- Drillability
- Prevalence of the soil
- Technical Impact for BADGER
- Specific weight

The result of this analysis is, to use sand, gravel and loam for the underground robot.

This selection of soil types is supported by tests performed at premises of TRACTO-TECHNIK in cooperation with the University of Glasgow. The tests were performed in loam and sand and the results showed the feasibility of these soil types for the underground robot.

In the last chapter of the present deliverable, the three selected soils (sand, gravel, loam) are described in detail.

Summarized it can be stated, that based on the presented analysis, non – displaceable soils like sand, gravel and loam, are selected for the special use case “laying pipes and cables” (mentioned in D1.1) to showcase the proof – of – concept of the BADGER system within the project.

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1. Introduction

This deliverable focuses on the selection and the selection criteria for soil types, for which the underground robot should be designed for. There are two coarse types of soils:

- Displaceable
- Non – displaceable

The differences among these soils types have a huge influence on the design of the components of the underground robot. The pre – selection of the type leads to the selection of a tangible soil type. For the selection of the soil type, specific selection criteria were elaborated (e.g. drillabilty, prevalence of the soil type, ...).

Referring to the selected criteria – like drillabilty or the technical impact for BADGER -, the focus lays on non – displaceable soils, more specifically on sand, gravel and loam, which are described in detail in this deliverable.

1.1 Scope of the deliverable

The deliverable focuses on the interaction of the robotic system with different soil types. In the first chapter, a theoretical examination of various evaluation criteria is initially carried out. Subsequently, tests are described that have been carried out in 2 out of 3 selected soil types. On the basis of the criteria and the tests, soil types are suggested that are drillable for BADGER.

1.2 Relation to other deliverables

The present deliverable contributes to the following Workpackages of the BADGER project, WP2 and WP3. Also this deliverable takes input von the deliverable D1.1 and D1.2.

More specifically, this deliverable provides to the whole system design of the drill head, the steering and propulsion mechanism and the 3D printing unit (WP2) as well to the robot control system (WP3), because the selection of soil types might have an influence on the control of the underground robot.

1.3 Deliverable structure

The deliverable starts by giving a short overview on the different soil types and their distribution on the world in Chapter 2.

In the subsequent chapter 2.2, the soil types are divided in two categories (displaceable and non – displaceable soil). The two different type of soils has an influence on the design of the components of the underground robot, which is briefly described in this chapter.

Focusing on the results of the foregone pre – selection, further selection criteria were elaborated to show, which soil type is feasible for BADGER.

After this selection, the selected soil types are described in detail in chapter 3, before the deliverable come to the conclusion in chapter 4.

2. Soil Types and selection of soils for BADGER

2.1 Soil types

The world, countries, regions and even sub – regions consist of different soil types (Figure 1). These different types lead to different drilling methods for displaceable and non – displaceable soils. Even the type of soil leads to different drilling methods.

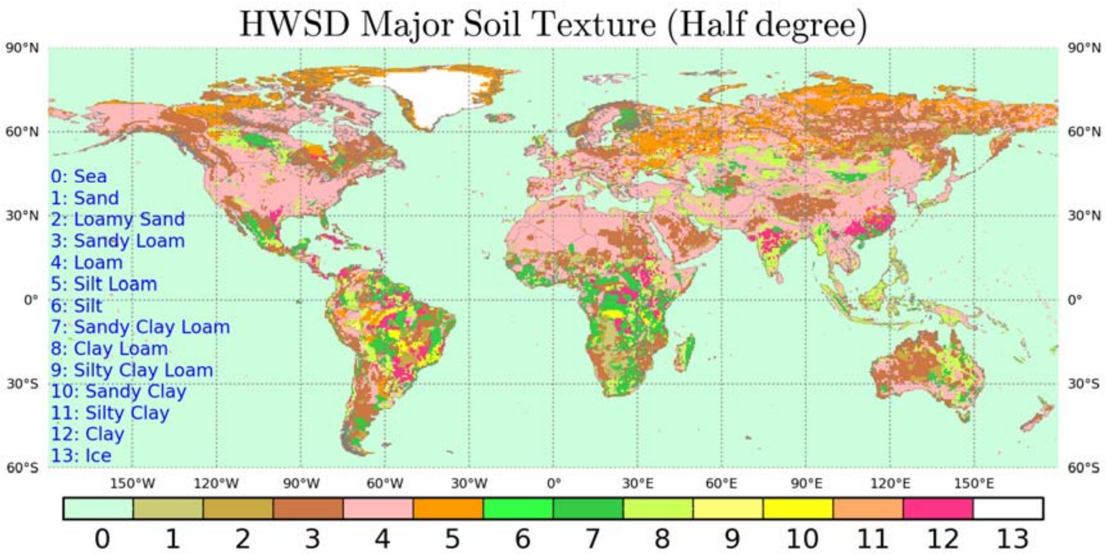

Figure 1: Major Soil Texture [1]

Based on the different soil types, in the next chapter, selection criteria for soil samples are described, to figure out the applicable soil types for BADGER.

2.2 Selection criteria for soil samples

Machines designed for future earthwork should be confronted in their development phase already with frequently encountered and challenging earth conditions, in order to ensure that they can meet the requirements of extremely diverse and very demanding situations.

In the context of the corresponding analysis performed herein for BADGER project, the selection of the soil types for BADGER is supported by selection criteria that have an influence on the design of the robot as well as drilling tests carried out at TRACTO-TECHNIK. In the following paragraphs the criteria for the selection are presented as well as some results from the tests carried out at TRACTO-TECHNIK, with a first iteration of the drill head design developed by TRACTO-TECHNIK and the University of Glasgow.

In the first instance the soil can be differentiate in two different classes:

- Displaceable
- Non – Displaceable

This first classification has an influence on the basic design of the underground robot. The influence on the different components is shown in the following table:

	soil type	
	displaceable	**non - displaceable**
drill head design	Material must be displaced with a method similar to an earth pircing tool. Problem: high propulsion energy is neccessary.	The material must be removed on the drill head. This requires a rotary driven drill head. The total energy needed for this type of drilling is less than displaceable soil
cuttings transportation	material does not have to be transported away	The drilled material has to be transported. Here the different soil types have to be considered. Especially wet clay causes problems during transport
clamping device	since the soil is displaced to the outside and thus compacted, the support can be carried out against a compacted soil	Because the soil is not displaced and compacted (by the drill head), the borehole wall tends to collapse. In addition, the surrounding soil may be relatively yielding, so the clamping mechanism must take this into account
steering & propulsion	Control can be difficult because the soil is compacted by the displacement and thus very high control forces are needed	Steering should be easier due to the lack of compacted soil
3D printing unit	Since the borehole wall is compacted by the displacement, the borehole is unlikely to be incident	Since the borehole wall is not compacted by the displacement, there is a risk that the borehole may collapse

Table 1: rough classification of the soil type and influence on the main components of BADGER

The above given rough classification of the soil type shows that the selection of the main type of soil has a huge influence on the design of the components of the underground robot.

The biggest influence of the soil type can be seen in the drilling head. If BADGER is designed for a displaceable soil, the drilling methods focuses on a principal similar to an earth pircing tool. Although displaceable soil has less technical impact on the other components, the recommendation in focus is on non-displaceable soil. The construction of the drill bit is much simpler and more compact, as using a displaceable drilling principle in the 250mm diameter range results in very high Drive energies and masses (moving hammer) are necessary.

Summarized it can be said, that using non – displaceable soil for BADGER has smaller influence on the complexity of the components (especially the drill head) of the underground robot.

Added to this is the fact that non-displaceable soil is more widespread than non-displaceable soil.

The following paragraph now deals in more detail with the different non - displaceable or partly displaceable types of soil. For this purpose, various evaluation criteria have been established:

- Transportability
- Drillability
- Prevalence of the soil
- Technical Impact for BADGER
- Specific weight
- Displaceable?

	sand	gravel	loam	rock
Transportationability	good	medium, depends on grain size	bad, sticks like glue when it is wet	medium, specific weight high
Drillability	easy	medium	easy	heavy
Prevalence of the soil	common	rare	most common	medium common
Technical Impact for BADGER *[system complexity]*	borehole stability might be difficult and has a high impact on the clamping device	borehole stability might be difficult and has a high impact on the clamping device	low impact, but difficult for transportation of cuttings	complex system, high forces & torques neccessary. Suction power for transportation very high
specific weight	1800 kg/m³	2000 kg/m³	2100 kg/m³	2500 kg/m³
displaceable?	no	depends on the grain size	yes, in some conditions	no

Table 2: selection criteria for the specific soil type

As the table shows, rock is not suitable for the underground robot, because it leads to a completely different drilling method than the one that can be used for the other type of soils. Also, transportation of cuttings could cause the need for further increased suction power, given the high specific weight of rock.

At the end of this analysis it can be said, that the focus on non – displaceable soils, especially on sand, gravel and loam is feasible for the underground robot.

2.3 Tests performed with different soil types

Based on the analysis performed in the foregone chapter, tests in cooperation with the University of Glasgow were performed together with TRACTO-TECHNIK in two above mentioned soil types (sand and loam). For this purpose, a first iteration of the drill head design including a system for cuttings transportation and integration of the ultrasonic drill bit was designed and manufactured.

Figure 2: Test setup

The first iteration of the drill head consists of a scraper disc with a diameter of approx. 250 mm, the integrated ultrasonic drill bit in the front, an internal suction hose which is connected to a vacuum box to suck the cuttings out of the borehole. The scraper disc is driven by a hydraulic motor. The feed is generated by an electrical cylinder.

2.3.1 Tests performed in loam

The first tests were conducted in loam. The drilling forces and torques were like expected. The suction of wet loam caused some issues regarding the cuttings transportation but in all, the test was positive.

Figure 3: drilled borehole in loam

2.3.2 Tests performed in sand

The second tests were performed in wet compacted sand. Forces and drilling torque were also as expected. The transportation of cuttings with the vacuum box worked well.

Figure 4: drilled borehole in sand

2.3.3 Conclusion: Selected soil types for BADGER

Based on the theoretical analysis referring to different selection criteria for the soil samples and additionally, the performed tests in two of three pre – selected soil types (sand and loam), it is recommended to focus on non – displaceable soil types like sand, gravel and loam.

The technical impact on BADGER focus on displaceable soils is unlikely higher and the risk to fail also. Moreover, the prevalence of non – displaceable soils is higher than displaceable soils, which leads to a greater opportunity for use of the underground robot.

In the following abstract the three selected soil types (sand, gravel and loam) will be described more in detail.

3. Description of the selected soil types

3.1 Soil type: Sand

Even though many of us first became acquainted with sand as sandpit sand, sand is not simply sand. Firstly, sand is a grain size designation and includes mineral grains with a size between 0.063 mm and 2 mm. This composition of the mineral grains is thus of subordinate importance. Sand belongs to the group of frictional or noncohesive, loose sediments. Sand grains therefore do not adhere to one another but rather roll off one another. The mineralogical composition of sand, its structure and thus its surface and grain shape vary considerably. Needless to say there are also significant differences within the bandwidth of the grain size and the grain-size distribution.

A conscious decision was made to select a **quartz sand** because of its very hard, high-strength and stable properties. Quartz consists of silicon dioxides, i.e. silicon and oxygen, and thus two elements that are extremely abundant in the earth crust. Our microchips and also our photovoltaic cells are made of silicon. However, quartz sand was ultimately chosen because it is considerably harder than tool steel. Or to be more precise: quartz is two and a half times harder than tool steel and three times harder than construction steel. A device test of any kind in quartz sand thus means a high stress test for steel components and for all carbide inserts in steel.

Figure 5: Sand

Quartz sand of medium to coarse grain roughness was also consciously selected, i.e. the quartz grains have a rough to angular grain surface shape, they are abrasive and behave towards metal like a grinding stone surface. With regard to its surface structure, this sand is thus the complete opposite of sandpit sand which has a perfectly rounded and smooth ball-shaped surface (almost like the balls in a ball bearing). Furthermore, the selected grain size is in the upper size range of the sand grain and thus predominantly in the range between 1 and 2 mm. This deliberately chosen coarse grain, in turn, is used for testing surface stress on metal.

In summary: quartz sand is selected to provide a hard initial material. Sand types based on feldspar, dolomite, lime or other minerals were consciously avoided because their difference in hardness to metals is relatively small and less meaningful for test purposes. Quartz sand of medium to coarse roughness was intentionally selected because well-rounded quartz grains reveal roll-off properties when they encounter penetrating metallic bodies, whereas rough quartz grains build up resistance, catch on to and attempt to notch into metal surfaces and exhibit high abrasiveness towards metals.

In addition, quartz sand is encountered frequently in nature. Numerous wide valley fillings in lowland areas have sand deposits and large shares of sand can be found in the core of large river deltas. The same applies to sandstorm areas, sand deserts (ergs) and weathering products over the magmatic and metamorphic rocks.

Figure 6: Typical coastal sand outcrop in form of a sand dune, often at many beaches of Europe's coast [2]

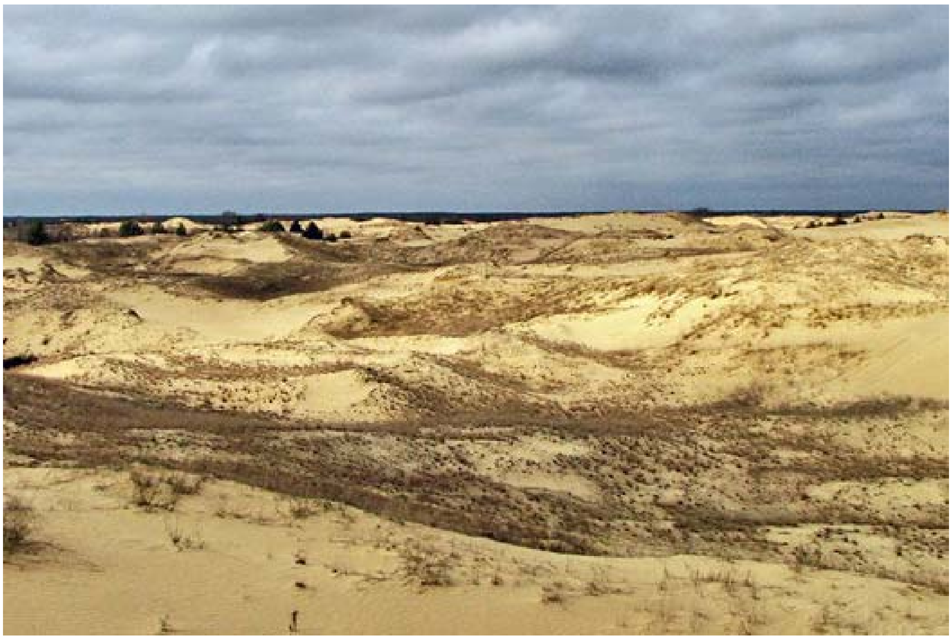

Figure 7: Sand Soils in Europe are typical in delta regions, in former glacial smelt flow valleys and e.g. in weathered sandstone regions [2]

Sand has high economic importance; it is a very common product for the construction industry and is for example needed for embedding pipes and mains when using trenches and for artificial stone products for constructions. Sand is needed for the ceramic industry, for the glass industry, for silicon products (microchips), for the casting industry and many other applications.

3.2 Soil type: Gravel

Gravel is primarily a grain size designation for a loose stone and contains mineral grains of sizes between 2 mm and 63 mm. Gravel belongs to the group of noncohesive (i.e. not adhering to one another, rolling off one another) loose stones and usually consists of very varied stone or mineral grains and is also very widespread. Gravel is also a very important stone and earth raw material. It is used, for example, in path and road construction as a substructure but it is also the most important concrete aggregate.

Due to its coarse grain size and complicated penetrability, it is used for trenchless earth-moving plants. Just like sand, types of gravel can vary considerably. The mineralogical composition of the gravel grains can be completely different. It can therefore consist of soft or hard stones, but also of homogeneous and very inhomogeneous stones. As far as the classification of grain sizes is concerned, gravel can fluctuate greatly and is completely inhomogeneous and, of course, it can also have widely varying surfaces roughness.

Figure 6: Gravel

The selection was very **inhomogeneous and coarse** gravel (from the Neckar Valley beside Tübingen) because this gravel consists of hard stone components from the Black Forest and the individual gravel grains often have a compressive strength of 150-300 megapascal. The stone components are sandstone, granite, gneiss, limestone, dolomite, chert, etc.). The gravel here also contains a high share of coarse gravel and also has medium surface roughness. Gravel with this composition and structure should be regarded as complex for all trenchless excavation systems because there is no stability of any kind, the roughness makes displacement between the grains difficult and the grain size and thus also its weight result in a permanent risk of incasion (= danger of falling in and collapse). For all types of excavation work, gravel of this type forms a large number of blocking elements that also block displacement of grains among one another and provides gravitation considerable room for play. Gravel of this type provides new excavation systems with regular "borderline experiences" with regard to feasibility limits and the necessary optimisation with regard to penetration geometry, precautions against incasion and drilling hole stabilisation.

Figure 8: Gravel open pit mining in a broad river valley [3]

Gravel of this type is widespread throughout the world. It can be found mainly in river valleys from high mountains to low mountain ranges and their foreland regions. Many large cities such as Munich, Turin, Milan, Augsburg, Freiburg, Heidelberg, Mannheim, Cologne, Lyon, Vienna, Salzburg, Bratislava, Budapest, etc. are built on top of such gravel occurrences. The foreland regions of high mountain ranges as well as the valleys in low mountain ranges throughout the world have abundant gravel deposits (whereby, transitions can also exist of course to boulders and sand).

Figure 9: Gravel pit in the Alpine mountains. Gravel is enormous important for the production of concrete. Every inhabitant of Central Europe “consumes” per year about 10 tons of gravel and sand.

Gravel is one of the most essential products for the construction industry, is basically needed for all concrete products, for street construction (freezing protection zone below asphalt), for water filtering, for water constructions, for ground stabilisations in week ground (foundations) and for many other construction demands.

3.3 Soil type: Loam

Loam is a not a grain size designation but rather the designation of a very fine-grained mixture of ultrafine sand to coarse clay. A grain size is also embodied indirectly in which the mineral ingredients of loam can be found. The grain size mainly corresponds to that of silt, which ranges from 2 µm to 63 µm (= 0.002 to 0.063 mm). The definitions of silt and loam are often confused. Silt, however, is a grain size designation and loam is a designation for a mineral mixture between ultrafine sand and coarse clay. Due to the clay share, loam also has cohesive properties, i.e. loam particles can adhere and stick to one another. This binding together creates support characteristics that can be very helpful for underground excavation and guarantees a high degree of natural stability. On the other hand, the cohesive properties of loam can also lead to the agglutination of excavation tools which presents development challenges of a different type. Cohesive soil can more or less "thwart" excavators, making ground penetration without a agglutination effect a difficult task.

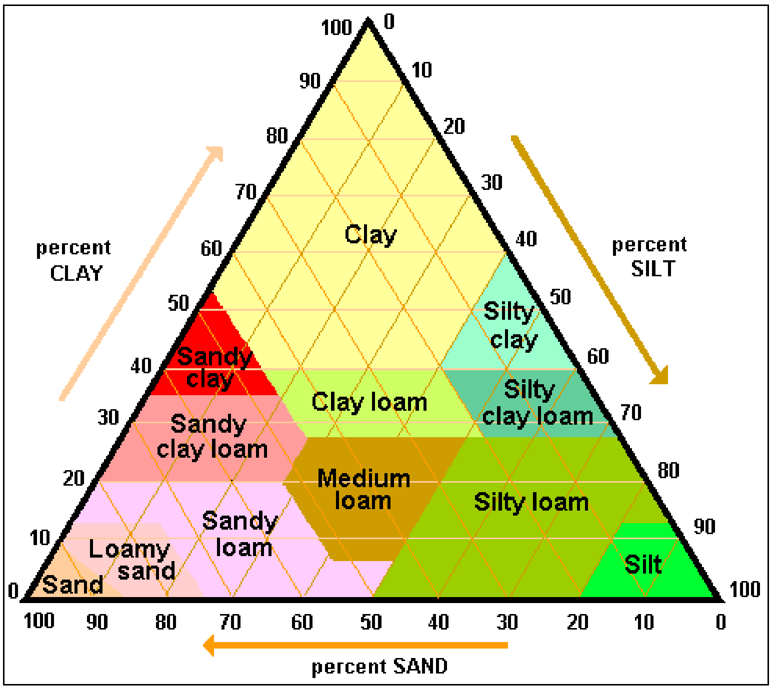

Figure 10: Soil texture triangle [4]

There are huge loam deposits throughout the world, whereby glacial loam, created through stone crushing at the base area of glaciers, has a particularly high share. Approximately 40% of Germany is covered in loam, in particular, glacial loam. The share is similarly high in England and Denmark, whereas in Poland, the Baltic States, Hungary, the Ukraine, etc. the loam share can be as high as 70%. Large areas of the American Mid West and southern Canada are covered in loam, which also applies to Argentina, Bangladesh, Vietnam, China, Mongolia and also Russia.

Figure 11: Loam

Loam can, however, have different consistencies; it can be both loose and airy loess loam as well as **heavy alluvial loam** or even heavier glacial loam. According to its density, therefore, loam can be easy or difficult to penetrate. Rivers in regions with a lot of loose loam, for example, central China, turn yellow after heavy rainfalls (Hwang Ho = yellow river) because the fine mineral particles are conveyed in the water more or less as dispersion. The challenge lies, however, not in the densely layered loam because, in this case, the high density permits almost no displacement of the mineral particles. High-density loam often does not a transition to marl; these are natural clay-lime dust mixtures that have even higher levels of compactness because the lime share can act as a light hydraulic binder. Glacial loam often has transitions to glacial marl; the same applies to weathered loam over marl stone. For this reason, such a weathered loam is selected because it involves a demanding spectrum for earth-moving plants.

Loam is very widespread distributed in Europe. Loam should be divided in 3 types, which more or less show differences in their density. Glacial loam has normally a high density, because of the load of former glacial cover (depends of the thickness of the former glaciers). Fluvial loam and loam by a weathering process are of medium density, very common and much liked by the agriculture and gardening use. Loess loam is an aerial sediment and with air pores “enriched” loam, which results from times direct after the big ice smelting process at each end of glacial periods in the Quarternary (youngest period of the earth). By ice smelting times, big areas of glacial loam became exposed and wind could transport the finest particles away blown them in the flat areas of basins and in the foreland of mountain ridges. Loess loam areas are extreme fertile, they are most liked by farmers and gardeners. Loess loam is easy to be penetrated by trenchless instruments, therefore we decided for weathered loam, for getting average values in loam density.

Figure 12: Typical soils with loess loam in the ground [5]

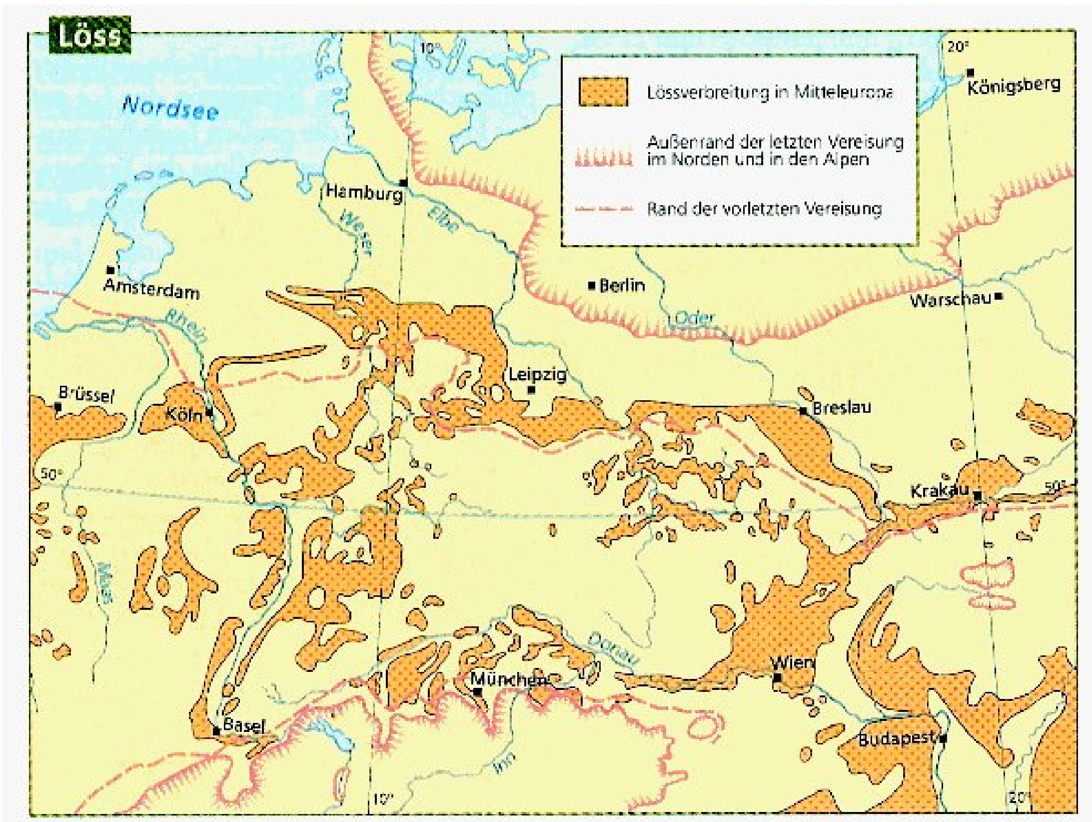

Figure 13: Distribution of “weak” loess loam in Central Europe [5]

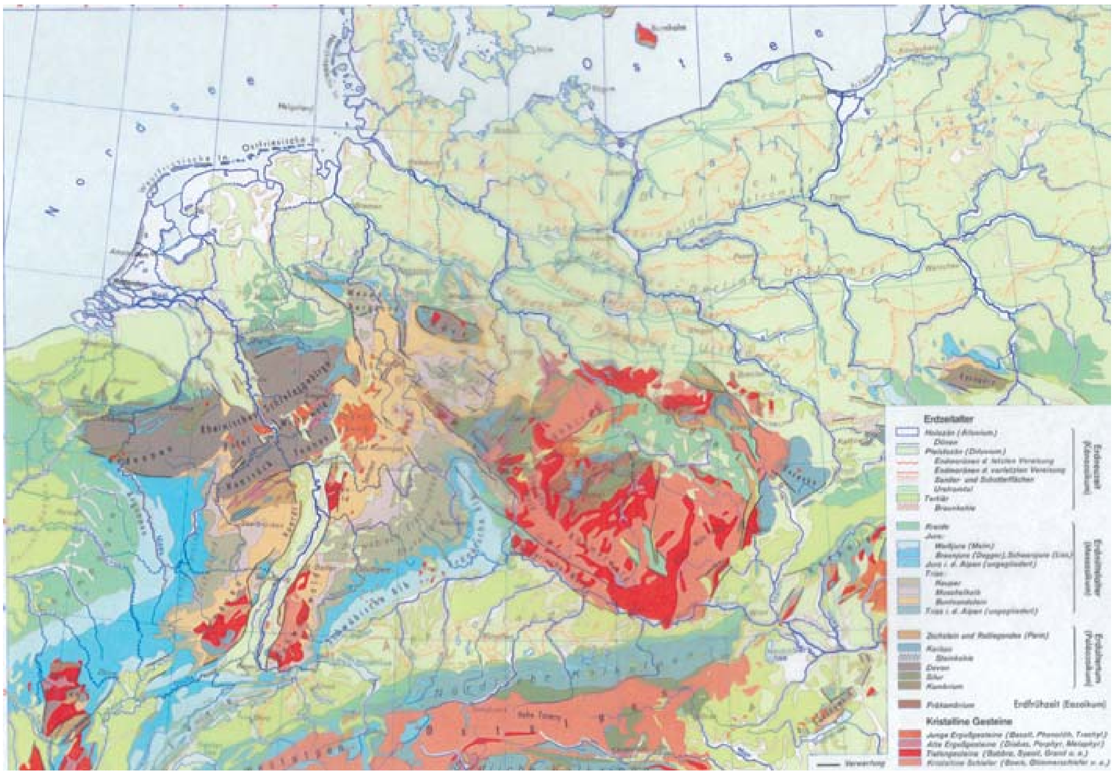

Figure 14: The large light green and light brownish areas show loam dominated areas with compact loam, created in former glacial times in Europe [6, showing the geology of Central Europe]

4. Conclusions

The world, countries, regions and even sub – regions consists of different soil types. These different types lead to different drilling methods for displaceable and non – displaceable soils. Even the type of soil lead to different drilling methods.

This deliverable focuses on the selection and the selection criteria for soil types for which the underground robot should be designed for.

The differentiation in two coarse soil types (displaceable and non – displaceable) is inspected in the first part of this analysis. The result of this analysis is, to use non – displaceable soil for the underground robot.

Reasons for this are the reduced complexity of the underground robot components (especially the drill head) and the prevalence of the non – displaceable soils on the world.

The second analysis of this deliverable then focuses on the different non – displaceable soils, referring to the following criteria:

- Transportability
- Drillability
- Prevalence of the soil
- Technical Impact for BADGER
- Specific weight

The result of this analysis is, to use sand, gravel and loam for the underground robot.

Based on the above analyses, tests were carried out at premises of TRACTO-TECHNIK in cooperation with the University of Glasgow. The tests were performed in loam and sand and the results showed the feasibility of these soil types for the underground robot.

In the last chapter of the present deliverable, the three selected soils (sand, gravel, loam) are described in detail.

Summarized it can be said, that the focus for the underground robot lays on non – displaceable soils - especially sand, gravel and loam. This is confirmed on the one hand by the analysis on the basis of the established criteria and also by the experiments carried out.

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[6] Westermann School Atlas