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European and municipal scale drillability maps: A tool to identify the most suitable techniques to install borehole heat exchangers (BHE) probes

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ABSTRACT

The most suitable drilling technology for shallow geothermal applications in a given geological context plays a key role in the techno-economic evaluation of shallow geothermal solutions. The installation costs are one of the main constraints to the wider application of shallow geothermal heat exchangers and are due mainly to the drilling time and fees.

This paper defines drillability as a tool to select the most suitable drilling technique for borehole heat exchanger installations in a given geological and hydrogeological setting. Drillability maps at European and municipal scale are proposed as a guideline for drillers and ground source heat pump designers. The former summarizes the most suitable drilling technology based on lithology and borehole heat exchangers type, whilst the latter provides an insight in the ground thermal properties and the installation timing/costs. In the GEO4CIVHIC Project, a database correlating drilling technique to rock types, time needed to drill a borehole at 100 m depth and drilling costs was created. Local drillability features are compared to in situ real data in four test sites. Two out of four test sites, completed at the time of writing, shows a good agreement between local maps and real site conditions, validating the innovative methodology proposed.

1. Introduction

Ground Source Heat Pump (GSHP) systems are one of the most promising emerging technologies for building conditioning. Unfortunately, one of the main barriers preventing a wider market uptake and penetration results from the initial installation costs, mainly related to drilling time and methods used. Drilling operations vary considerably from country to country depending directly both on technical aspects (i.e. the local geological context, the local drilling techniques and machines state-of the-art), and on local social and economic aspects (i.e. regulations, market maturity …) [1,2]. Therefore, providing initial information about drilling cost and time is extremely useful for the planning and installation phases of borehole heat exchangers (BHEs). Generally, the geological context is a fixed factor for shallow geothermal system, where subsoil characteristics cannot be changed. On the other hand, the building and its heating and cooling demands can be modified [3,4]. The stratigraphic sequence and the hydrogeological condition affect the GSHP system design in terms of (i) the local equivalent heat exchange capacity; (ii) the best drilling methodology to be applied; (iii) the Ground Source Heat Exchanger (GSHE) type and its installation procedure, directly connected with the drilling technique [5,6]. The main variables determining the drilling methodology selection and the heat exchanger choice are the rock/sediment type, the compressive strength, related to consolidation/compaction state and rock integrity, and the local groundwater presence [7–11]. The rock hardness mainly influences the time

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List of abbreviations

GSHP	Ground Source Heat Pump
BHE	Borehole Heat Exchanger
GSHE	Ground Source Heat Exchanger
EU	European Union
EGDI	European Geological Data Infrastructure
INSPIRE	Infrastructure for Spatial Information in Europe
GIS	Geographic Information System
TRT	Thermal Response Test
DTH	Down-The-Hole Hammer
DTH + c	Down-The-Hole Hammer with casing
DTH w/o c	Down-The-Hole Hammer without casing
tricone	Rotary Drilling with Tricone
tricone+	Rotary Drilling with Tricone with Casing
tricone w/o c	Rotary Drilling with Tricone without casing
chevron	Rotary Drilling with Chevron
chevron + c	Rotary Drilling with Chevron with Casing
chevron w/o c	Rotary Drilling with Chevron without casing
ED	Easy Drill Piling
ED w/o c	Easy Drill Piling Without Casing

required for drilling, while the groundwater presence affects the thermal properties, the borehole stability often requiring casing operations and lengthening the drilling time and installation procedures [12,13]. For example, the classic Single-U-tube or Double-U heat exchangers require a hole diameter and a drilling depth reached only with specific drilling techniques (rotary or down the hole hammer depending on the kind of soil). Conversely, auger drilling at shallow depths and for large diameters holes, is preferred to install helix or special forms of heat exchangers. Finally, when loose sediments and no shallow aquifers are present, direct installation (without drilling) could be considered for shallow BHE or new coaxial heat exchangers [14].

Despite the expected geological and geothermal underground variations, this work aims to propose a new methodology to provide useful information when designing a geothermal heat exchanger. Defining drillability time and costs (time and costs of drilling operation based on geological information published or provided by national and local authorities or by suggestions of local expert) provides a key to assessing the feasibility of installing shallow geothermal systems everywhere. The new ‘drillability maps’, developed in the framework of the EU funded GEO4CIVHIC project [15], contain preliminary information useful to the local authority, and are able to support decision makers and designers in planning GSHE systems. The maps, developed with a multiscale approach, consist of maps at European scale (1:1.500.000) and large-scale maps at municipal scale (≤1:25.000. The former provides a first level of knowledge, and is mainly aimed at administrators and energy policy makers. The drillability maps are obtained starting from the lithological classification shown in the European Geological Data Infrastructure (EGDI) dataset. The municipal scale maps show an in-depth analysis of local conditions, adding thermal properties information to drillability. These are aimed at designers and local drillers to support a pre-design technical feasibility evaluation. The municipal scale maps have been developed for 4 locations across Europe (Dublin, La Valletta, Ferrara, Battel) that characterize different geological and hydrogeological conditions. The represented data afterwards were validated by direct comparison with real data collected on site by GEO4CIVHIC project partners. In order to be available for as many users as possible, these local maps were developed by using open source geographical digital information system (QGIS). Thus, the assessment of the most suitable drilling technique for a given geological setting and its related timing and costs, in particular in urban environment, could be very useful from both the technical and the economical points of view, especially if associated to local geothermal information.

1.1. Shallow geothermal mapping

In order to promote the deployment of low temperature geothermal closed-loop systems at European scale, it is fundamental to define and quantify the technical feasibility of the system. On this regard, proper thematic maps can provide clear indications in specific areas, thus allowing optimization of the decision process as well as supporting designers and stakeholders. Depending on the mapping scale, the procedure and results may differ. Small scale geothermal potential map at European scale (e.g. 1:1.500.000) [16,17] could be improved. For example, the territorial planning at national/international scale by commonly identifying the most suitable or unsuitable zones for the installation of new GSHP systems, based on the local geological setting. Different methods and algorithms are proposed to consider the vertical layering, in order to represent the stratigraphic sequence characteristics in a bidimensional map. Such maps have limitations in representing spatial variability and vertical heterogeneity, related for example to local groundwater or geological variations. To properly consider these site-specific variations, several maps at local scale (municipal or regional) [18] were proposed to provide technical data useful for designers and potential stakeholders [19,20]. At local scale, the mapping can be developed to cover in detail, for example, the local groundwater flow conditions [21–23]. Groundwater flow contributes significantly to the heat exchange between the underground and buildings, but at the same time existing groundwater resources require safeguarding and protection [24,25]. Local maps can also support local administrators and stakeholders by (i) indicating problematic zones where particular geological features or environmental assessments can limit the use of GSHP systems [26]; (ii) showing where new systems could thermally interfere with other already existing geothermal systems (thermal interference) [27]; (iii) determining preliminary techno-economic estimates or cost/return on investment for new shallow geothermal systems [27–29].

Given the input parameters complexity, the mapping approach, already proposed for identifying (i) geo-exchange potential, (ii) spatial-economic estimation of system costs, (iii) a wider systematization of performance indicators affecting GSHE systems, represents a good starting point. However, further analysis and subsurface characterization is needed to increase the local underground knowledge.

Among the technical and economical characteristics already mapped, this paper proposes “drillability” maps, both at European and at municipal scale, starting from the analysis of the stratigraphic sequence and the hydrogeological conditions (groundwater presence/flow rate). The drillability is defined by evaluating the main parameters affecting the drilling operations, such as the lithological variation and related rock hardness, depending on the degree compaction/consolidation of the rock itself. The drillability influences the GSHP system installation, the selection of the drilling methodology and BHE, as well as directly affects their costs and economic aspects. Therefore, drillability maps become a useful tool for designers in charge of the technical feasibility and pre-emptive cost-benefit analysis.

2. Materials and methods

2.1. Definition of drillability concept

‘Drillability’ is defined as the prediction of the most applicable drilling technique and related BHE based local geological underground characteristics. The BHE installation time as a function of the rig and drilling technique selected to complete the borehole were also considered. This approach was developed in collaboration with a multidisciplinary and international group of experts such as geologists, drillers and drilling machine manufacturers involved in the GEO4CIVHIC project. The main parameters affecting the perforation itself, such as the stratigraphic sequence and type of lithologies, ground hardness, degree of consolidation/compaction and hydrogeological conditions (groundwater presence and flow rate) were evaluated. A wide group of geological settings and lithologies were considered based on the EGDI dataset [30] in order to classify, at European level, the representative lithologies to define the drillability concept.

2.2. Assessment of the drilling techniques

In BHE installations, traditional drilling techniques used for water wells, prospecting, geotechnical investigations etc. can be used. The basic distinction among these conventional drilling methodologies is made by percussive, rotating, and combined percussion-rotation methods. In summary, for the purpose of creating "drillability" maps, the following traditional drilling techniques were considered [14]:

- rotary drilling with tricone (tricone) or chevron (chevron) bit, the classical method for drilling by rotating a drill bit and flushing the hole with mud or water, that could be completed both with or without casing according to the hydrogeological characterization of the site;
- the down-the-hole hammer (DTH), with or without casing, where rotation and percussive action are combined, allowing a relatively high drilling velocity in medium hard to very hard rock;
- the "easy drill" drilling technique (ED), developed especially for shallow geothermal applications within the EU project Cheap-GSHPs [31] and later on implemented in GEO4CIVHIC project as Hydra-RED method [15].

In detail the "easy drill innovation" consists in the development of a coaxial GSHE and related drilling machine using a piling technique. A pile-driving machine with a roto-vibrating head combined with high pressure water injection is used to reduce the installation time and, therefore, the cost of drilling in soft unconsolidated soil. Stainless-steel pipes with a diameter of 50 mm are used as drilling rods and installed in tight and direct contact with the soil. Once the drilling is completed, these pipes are left in place as geothermal coaxial borehole heat exchangers. This innovation allows to save time in rod handling compared to traditional drilling operations [32].

The experience and knowledge of drilling operators and experts in the GEO4CIVHIC project was used to associate drilling techniques and varying geological conditions in different European countries. For each of the 203 lithologies listed in the EGDI dataset [30], the drilling experts determined the best applicable drilling techniques, specifying in each case the casing requirements. This means they estimated the expected times (drilling time) and costs (drilling cost) based on local market knowledge of penetration rates and costs. The total costs include the drilling activities, the ground heat exchanger, the grouting material (if needed), the installation plus labour costs. Conversely, the costs associated with test-site setup, material transport, mud removal and superficial connection of the BHEs with the heat pump are excluded from the total amount, due to varying national regulations and market conditions.

The feedback received from partners was summarized in a table, where 5 penetration rate (time/meter) classes (<4 min/m, 4–7 min/m, 7–10 min/m, 10–15 min/m, and >15 min/m) and 3 cost (euros/meter) classes (≤30 €/m; 30 < x < 40 €/m; ≥40 €/m) were defined. An extract of this table is shown on Table 1.

Based on these indications, thematic maps were created by associating the suggested drilling technique with each lithology, obtaining spatial information at European level in a GIS.

2.3. European scale mapping

The European scale mapping aims to provide a broader overview of the best drilling techniques applicable all-around Europe for each specific lithology. As reference the European geological map, which contains 203 different geological settings [30] at 1:1.500.000 scale, and follows the INSPIRE (INfrastructure for Spatial Information in Europe) Directive [33], was used.

However, drilling time and costs are strongly affected by the hydrogeological conditions, not considered in the drillability map at European scale, due to the very high spatial variability and the lack of sufficiently frequent and mapped hydrogeological data at small-scale.

2.4. Municipal scale mapping

The municipal scale maps are based on local geological and geotechnical information, stratigraphies and hydrogeological conditions, that greatly affect the in situ-specific drillability. To define drilling time and cost at local scale, specific information is required to provide reliable support to stakeholders. High resolution geological, hydrogeological and geothermal data, retrieved through different sources (geological regional/federal services, Geographic Information System (GIS) regional database, official webGIS maps, bibliography, technical reports, personal communications, etc) were collected to fulfil the desired degree of information. The minimum essential data to be collected consists of the geological sequence (kind of sediments and bedrock), the thicknesses and depth of the main lithologies identified, obtained mainly by boreholes and well data, and the hydrogeological conditions (water table depth). The main challenge of the methodology proposed (Fig. 1) is to process and connect the large amount of required data, coming from different sources and characterized by different accuracy degree. GIS tools were used to achieve this integration as a way to homogenize, georeference and process a large amount of data. This workflow allows high quality and high spatial resolution maps to be generated for large territories. The data, once collected, were processed with both open source (QGIS [34]) and license-based (MatLab [35]) softwares. The former was used for spatial and geographic data representation, whilst the latter for data distribution analysis for each feature of interest.

The municipal scale drillability maps were developed to classify site-specific techno-economic aspects. Each of the maps consists of three separate sub-sheets: (i) the drilling method suggested, (ii) the drilling time and (iii) the drilling costs expected.

Once the study area is identified and a related specific database is created following the above workflow, the underground thermal properties are defined. At first, the stratigraphic column is defined using the geological profiles, the well logs and the bedrock depth data available for the case study sites in the database previously created. Based on the locally recognized stratigraphic sequence, thermal conductivity values (λ) are assigned to unconsolidated deposits, sedimentary, metamorphic and igneous rocks, according to the updated ground thermal properties database for GSHP applications developed during both Cheap-GSHPs and GEO4CIVHIC projects [5,36]. The rock lithologies identified along the stratigraphic column are assumed as vertically homogeneous, and

Table 1
Extract of the info datasheet built in GEO4CIVHIC to collect the information about drilling time and costs, based on the lithologies' listed on EGDI. *The time/meter and cost/meter evaluation represent each an average value of all the different time and costs obtained by the survey run between the drilling experts belonging to different EU countries. Deviations from the values indicated are expected locally due to the different existing local market and regulations.

Lithology	Drillability method (Dm)	Dm short	time/meter* (min/m)	cost/meter* (€/m)
Calcarenites and sands	Down-the-Hole Hammer (DTH) with casing	DTH + c	4–7	30 < x < 40
Chalkstones, limestones (jointed, karstified)	Down-the -Hole Hammer (DTH) with casing	DTH + c	7–10	≥40
Clays	Easy Drill Piling without Casing	ED w/o c	<4	≤30
Conglomerates	Rotary Drilling with tricone without Casing	tricone w/o c	10–15	≤30
Dolomitic limestones	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	4–7	≥40
Fine sands	Easy Drill Piling Without Casing	ED w/o c	4–7	≤30
Gneisses, mica schists, amphibolites	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	10–15	≥40
Gravels, sands	Easy Drill Piling without Casing	ED w/o c	<4	≤30
Limestones	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	4–7	≥40
Limestones and marls	Down-the -Hole Hammer (DTH) with casing	DTH + c	7–10	≥40
Marbles	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	4–7	≥40
Marls, clays	Rotary Drilling with Chevron with Casing	chevron + c	<4	≤30
Marlstones, sandstones	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	4–7	≥40
Marlstones, sandstones, limestones and clays	Rotary Drilling with tricone with Casing	tricone + c	10–15	30 < x < 40
Phyllites, schists, quartzites	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	10–15	≥40
Plutonic rocks	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	10–15	≥40
Pyroclastic rocks	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	10–15	≥40
Pyroclastic rocks and sands, clays	Rotary Drilling with tricone with Casing	tricone + c	10–15	30 < x < 40
Quartzites	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	10–15	≥40
Sands	Easy Drill Piling without Casing	ED w/o c	4–7	≤30
Sands and sandstones	Rotary Drilling with tricone with Casing	tricone + c	10–15	30 < x < 40
Sands, clays	Rotary Drilling with Chevron with Casing	chevron + c	<4	≤30
Sands, silts, clays	Easy Drill Piling without Casing	ED w/o c	<4	≤30
Sandstones	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	4–7	≥40
Sandstones, shales	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	4–7	≥40
Schists, gneisses	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	10–15	≥40
Serpentinites, ophiolitic series	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	10–15	≥40
Shales	Rotary Drilling with tricone without Casing	tricone w/o c	>15	30 < x < 40
Shales, phyllites, schists, sandstones	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	10–15	≥40
Silts, clays, gravels, boulders	Easy Drill Piling without Casing	ED w/o c	4–7	≤30
Silts, clays, sands, gravels and conglomerates	Down-the -Hole Hammer (DTH) with casing	DTH + c	<4	30 < x < 40
Silts, fine sands	Easy Drill Piling without Casing	ED w/o c	4–7	≤30
Travertines	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	4–7	≥40
Valley fillings	Down-the -Hole Hammer (DTH) with casing	DTH + c	<4	30 < x < 40
Volcanic rocks	Down-the -Hole Hammer (DTH) without casing	DTH w/o c	10–15	≥40

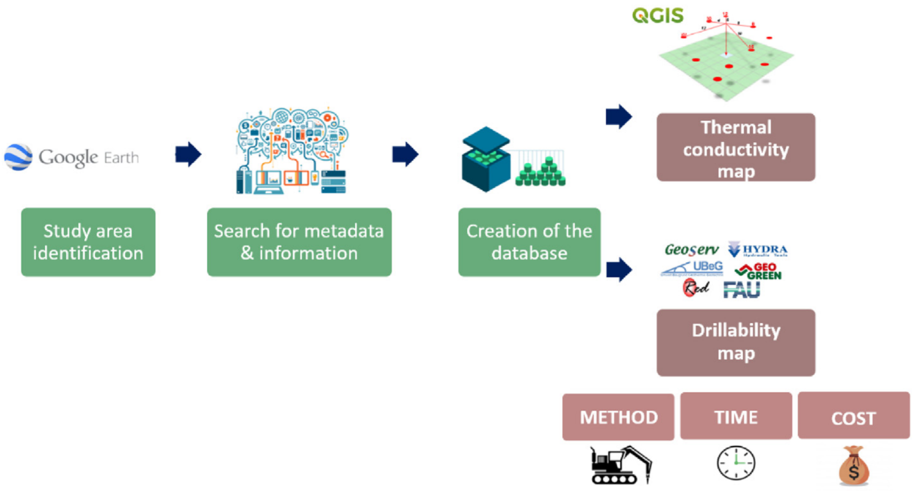

Fig. 1. Drillability local mapping implementation workflow.

consequently, a constant thermal conductivity is assigned to each of them. A weighted λ is subsequently estimated for the stratigraphic column up to 100 m depth, representative for BHE installations. Water saturated thermal conductivity values are assigned to the lithologies located below the locally mapped water table depths. GIS, numerical computing and programming platforms are used to consider the spatial and vertical 3D variability of the data. This step is replicated for every available stratigraphy to obtain a reliable graphical spatial representation of the weighted thermal conductivity over the first 100 m depth. The information represented in this map are helpful in sizing and designing a GSHPs borehole field, because a preliminary evaluation of the underground ability to transfer heat to BHEs in the first 100 m depth is provided.

Following the site-specific internal survey results performed in GEO4CIVHIC (Table 1), an optimal drilling methodology and expected drilling time needed to install the BHEs up to 100 m depth are assigned to the area under investigation based on the stratigraphic sequence. The results are summarized in the "Drillability-method" and "Drillability-time" sub-sheets. In addition, the installation costs, including all of the drilling activities, ground heat exchanger, grouting material (if needed) and installation plus labour costs are summarized in the "Drillability-cost" sub-sheet. The final step is the validation process that compares the mapped thermal conductivity parameters, drilling methodology, drilling times and costs with the in-situ data records compiled during the BHEs installation at the GEO4CIVHIC test sites.

Maps defining the four demonstration test sites across Europe, characterized by different geological contexts and different data availability as part of the GEO4CIVHIC were generated to test the drillability methodology mapping workflow. A new drilling technology developed derived from the "easy drill" methodology, the Hydra-RED method, was applied to buildings retrofitted with geothermal applications (Dublin, La Valletta, Ferrara and Battel).

To validate the maps at each demonstration site, data was collected during the BHEs installation characterising the local intersected stratigraphy, the groundwater table depth, the undisturbed ground temperature and the equivalent thermal conductivity along the entire vertical profile by thermal response test (TRT) measurement. In addition, the drilling method, drilling time requested for machine movement and preparation, and total costs for BHEs installation, were recorded.

To date, only two (Dublin and Battel) out of four test sites were completed, while in Ferrara and La Valletta the activity is still on going, due to the Covid-19 pandemic.

Therefore, in the following paragraphs the process that led to the development of the drillability maps is analysed for each test site, focusing on the specific constrains and the different data availability. However, the maps validation is provided only for Dublin and Battel.

3. Results and discussion

3.1. Drillability map at European scale

A general overview of the main lithologies distribution based on the European geological map released by EGDI was used to characterize the four main areas. Based on the drilling stakeholder feedback (Table 1) a preferred drillability method for each area was determined (Fig. 2A).

Northern Europe is characterized mainly by hard rock (magmatic or metamorphic) covered by a softer layer (overburden), mostly of glacial/periglacial origin. The overburden thickness ranges from less than a meter to several tens of meters. Here drilling operations consist of rotary with casing through the overburden and DTH in rock. BHEs are mostly not grouted, but just standing in groundwater. For very shallow BHEs, easy drill or similar drilling solutions are preferred in the unconsolidated sediments and with groundwater table very close to the surface.

In Central and Southern Europe, the geology is dominated by Mesozoic sediments where the preferred drilling methods are DTH or rotary, depending on rock hardness and local lithological sequence. BHEs need to be grouted in these geological conditions.

In European fold belts like the Pyrenees, Alps and Carpathians, sedimentary rocks are folded and faulted and often there are metamorphites outcrops. In these case drilling is done mostly by using DTH, sometimes rotary. In these regions, groundwater can be found in fissures and fractures, and grouting is always required and worthwhile.

The fourth important type of geological context is common in the recent alluvial basins of Europe, like the North German - Polish basin, the Bavarian Alpine foreland, the Po plain etc. Often younger sediments, mostly unconsolidated, are stacked on each other. Drilling can be done with rotary rigs, often using temporary casing to stabilise the hole; sometimes the risk of crossing confined or artesian groundwater exists, and all BHEs need to be grouted.

The suggested drilling method associated to each lithological sequence at European scale (Fig. 2A) are summarized as follow:

- Down-the-hole hammer (DTH) in Baltic and mountainous areas, such as Alps, Carpathians and Pyrenees, mainly characterized by hard and mid/hard rocks;
- the rotary drilling method with a tricone bit, dominant in the alluvial plain as the Po Plain, the Molasse Basin and the Pannonian Plain, characterized by gravel, sand and clay materials;
- the "easy drill" technology, for East European plains and some part of Italy where soft material as Pliocene rocks or loose sediments are present;
- the rotary drilling method with a chevron bit in some specific areas of North Europe or in the mountains.

On the other, the spatial distribution of the five drilling time classes defined on average according to the survey results conducted among the GEO4CIVHIC drilling experts (Table 1) is highlighted in Fig. 2B:

1. a drilling time lower than 4 min/m, associated mainly to ED and chevron technology with average costs lower than 30 €/m, in unconsolidated material (i.e. sand, silt, clay);
2. a drilling time between 4 and 7 min/m, involving DTH technology and sedimentary rocks (i.e. limestone, sandstones etc …) and reaching average costs equal or higher than 40 €/m;
3. a drilling time between 7 and 10 min/m, typical of DTH technology and sedimentary rocks characterized by higher hardness (i.e. dolomites, siltstones …) with average costs ≥40 €/m;
4. a drilling time between 10 and 15 min/m, associated both to tricone and DTH technologies, for rocks characterized by the presence of clay as well as magmatic and metamorphic rocks, respectively. Costs on average can be between 30 and 40 €/m or exceed 40 €/m;
5. a drilling time greater than 15 min/m belongs to shale rocks, where tricone technology are preferred and average costs between 30 and 40 €/m are assessed.

3.2. Drillability maps at municipal scale

The four demonstration test sites selected within the GEO4CIVHIC project shows very different underground conditions. In case of Dublin (Ireland) and Battel (Belgium), the well-structured national geological services allowed to obtain a large amount of detailed geological, hydrogeological and geothermal information. Instead, in Ferrara (Italy) and La Valletta (Malta) the stratigraphic information was not easily accessible, as it was provided or as printed database, requiring an additional effort to digitize the data, or was not available at all, necessitating to rely on bibliographic information. The local maps presented hereafter, clearly show that the accuracy and the amount of available data are directly related to the reliability of the empirical method proposed. In detail, the accuracy and reliability of the maps increases as the amount, kind and quality of available data improves (Dublin, Battel), resulting in more reliable outputs. However, even poor-quality data can be used to have, at least, preliminary maps (La Valletta, Ferrara). This confirms that the method proposed is

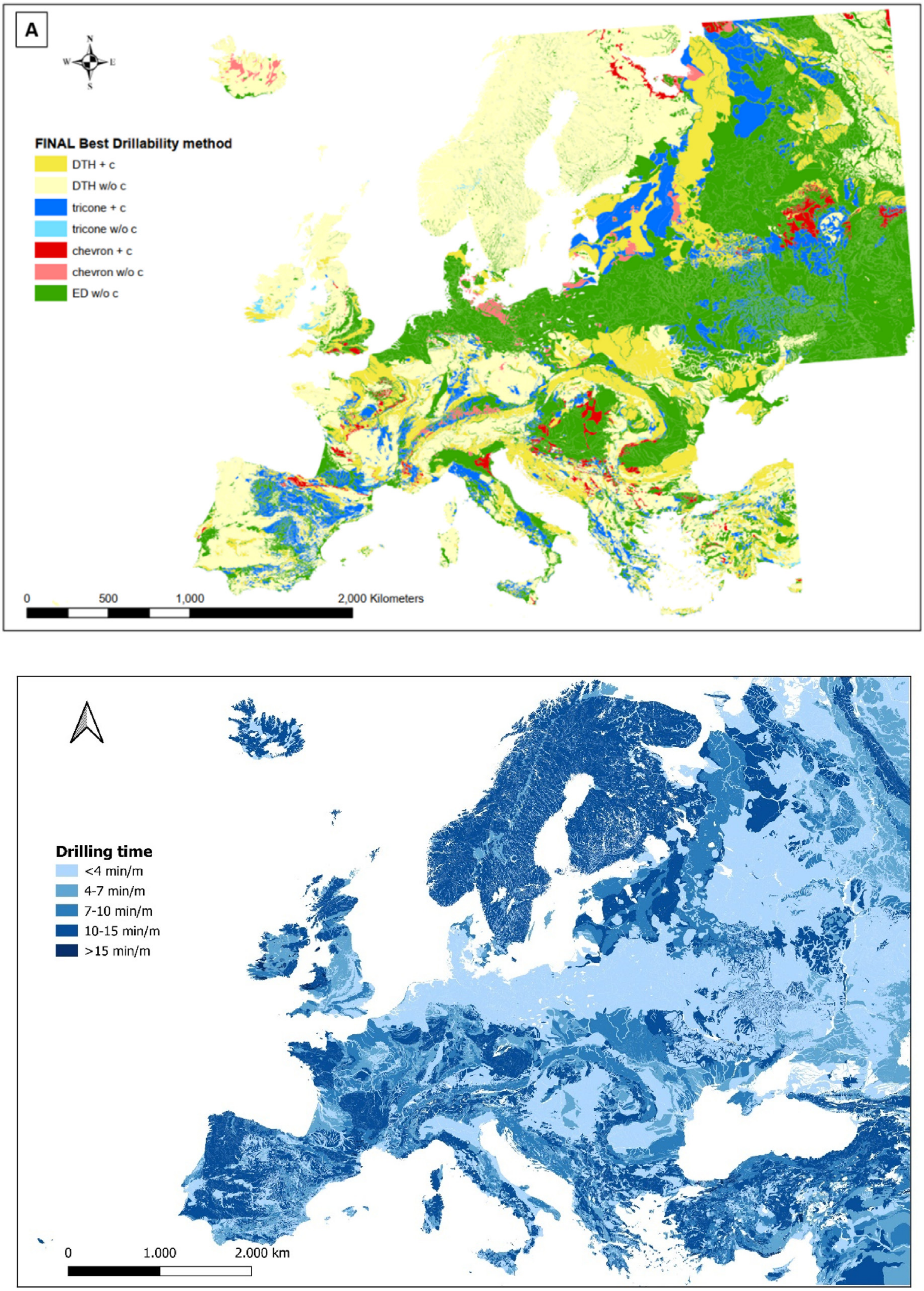

Fig. 2. Drillability map at European scale: suggested drilling method (A) and drilling time consuming (B). See Tab.1 for acronym explanation and drillability time classes definition.

quite flexible and can be applied and adapted to different conditions of data availability and accuracy.

3.2.1. Carnegie Clondalkin Library (Dublin, Ireland)

The Carnegie Clondalkin Library is located in the suburban town of Clondalkin, at the outskirts of Dublin city centre. The geological setting [37,38] is characterized by a first overlaying deposit of unconsolidated sediments, constituted by glacial limestone till containing black clay, sand, gravel-cobble limestone clasts. Local outcrops of gravel and rock are also present, while the bedrock is mainly made of granite and limestone. The sharp division of the bedrock lithologies is evident also in the thermal conductivity reconstruction presented in Fig. 3, where values around 2.4 and 3.0 W/mK are typical of limestone and granite, respectively.

Drilling parameters are affected by the bedrock variations: on the 100 m vertical depth of the stratigraphic sequence, the sediment thickness represents a small percentage, while limestone is the dominant lithology. Therefore, the DTH technology without casing was set as the best option in the study area, except for the use of casing when the overlying sediment exceeds 10 m of thickness. The drilling method sub-sheet is shown in Fig. 4 (left side). The difference between drilling with or without casing generates a variation both in the time/meter and in the cost/meter required to reach the desired 100 m depth (Fig. 4, central and right side). According to the classification defined at European scale, the drilling time classes 1 (<4 min/m) and 2 (4 ≤ x ≤ 7 min/m) with costs higher than 40€/m are expected. However, following the local partner indications, a more reliable idea of drilling time and cost is possible. In the area where DTH with casing is involved, corresponding to a sediment coverage thickness greater than 10 m, the drilling time reach a value of 3–7 min/m instead of 2–5 min/m and 4–7 min/m related to the limestone and granite bedrock. The longer time required by the casing operations is reflected in the drilling cost increase. As indicated by the local partners, casing costs are approximately twice as much (36–44 €/m) than simple DTH (20–28 €/m).

The local maps for the Dublin test site was validated based on the results of previous drilling and thermal response testing in close proximity to the Carnegie Library site. In fact, at the Carnegie Clondalkin Library the stratigraphy is constituted by an anthropogenic backfill material (0–5 m), followed by limestones and shale (5–120 m), with groundwater table found 9 m below the ground level. The TRT measured an equivalent thermal conductivity on site equal to 2.45 W/mK. The drilling has been conducted with DTH without casing, with a drilling time of 2–5 min/m and a drilling cost equal to 23–28€/m, so slightly larger than the foreseen one for DTH only.

3.2.2. Msida Bastion historic Garden (La Valletta, Malta)

The demonstration site is placed inside the Msida Bastion Garden, characterized by a rather homogeneous geology. The stratigraphy comprises relatively young sedimentary strata, originally deposited as marine sediments, consisting mainly of limestones. Relying on the stratigraphic information (rock unit sequence and member thicknesses) derived by the scientific literature [39,40], the thermal conductivity of the first 100 m depth was defined as the weighted heat transfer average value of the identified limestone lithologies (Fig. 5A).

Due to the lack of borehole information in GIS local portal or as shared documents by local authorities and experts, the drillability map (Fig. 5B) was obtained assigning a drilling method, cost and time according to the available bibliographic information, considering also the GEO4CIVHIC database [36].

In La Valletta, due to the limestone lithology dominance, the average thermal conductivity in the underground is assessed around 2.3 W/mK, while the preferred drilling method is DTH and a

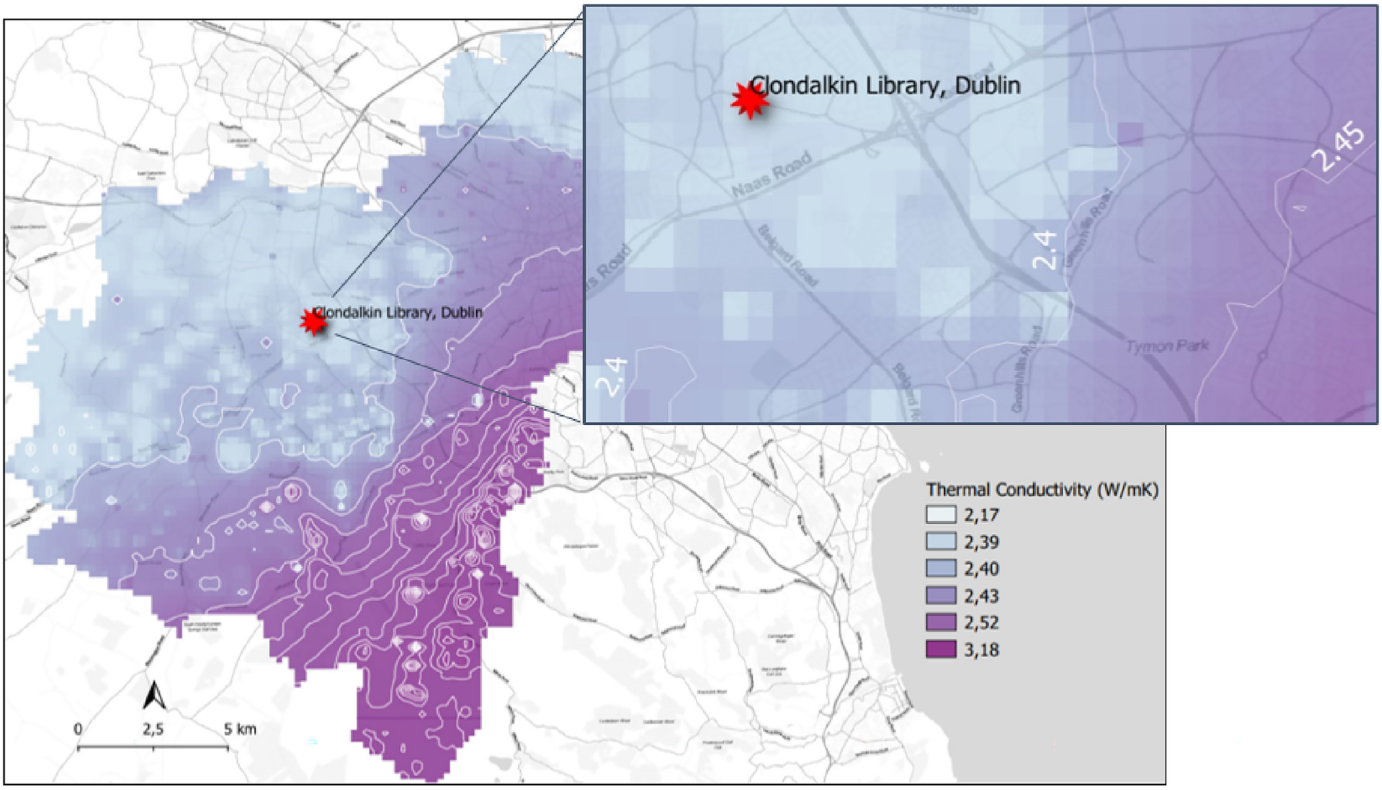

Fig. 3. The weighted thermal conductivity map of Dublin test site up to 100 m depth.

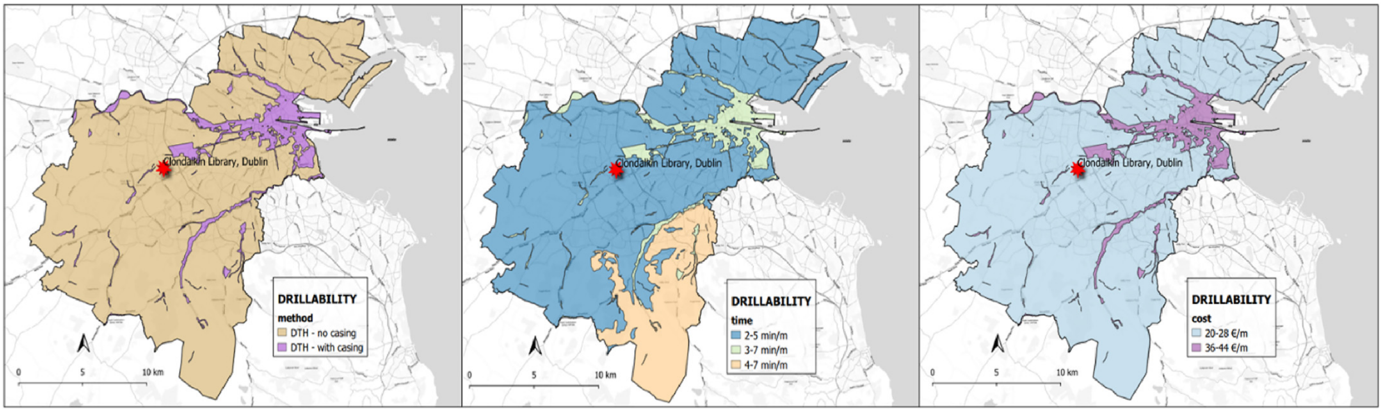

Fig. 4. The three local drillability sub-sheets maps for Dublin test site. From left to right, drillability method, time and cost, respectively.

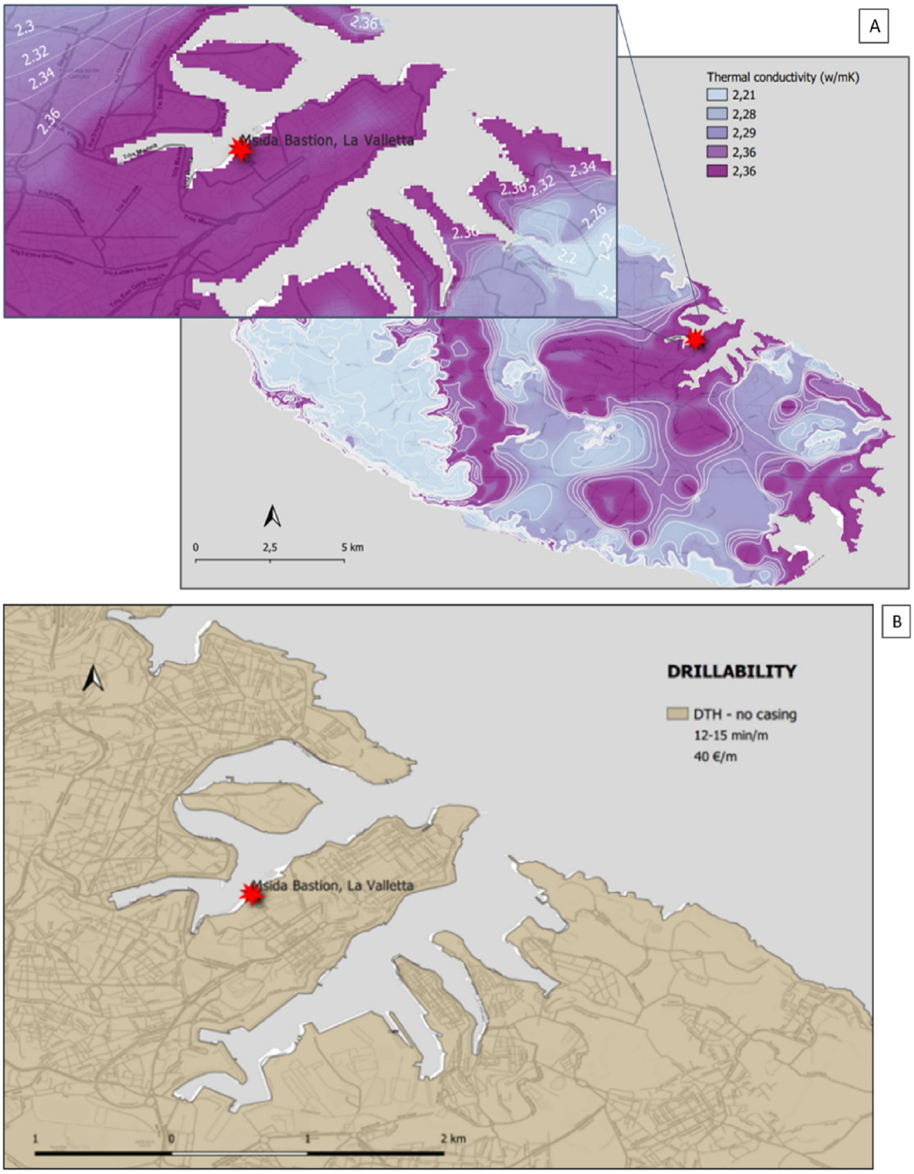

Fig. 5. La Valletta demonstration site: A) weighted thermal conductivity map up to 100 m depth and B) Drillability map (method, time, cost).

drilling time and cost of 12–15 min/m and 40€/m are expected, respectively (Fig. 5). However, in this case, the demonstration site refurbishment with shallow geothermal systems has not been completed yet, so the data provided by the map are still to be validated.

3.2.3. Porta degli Angeli (Ferrara, Italy)

The geological setting of the third demonstration site, located in the urban historical heart of Ferrara (Italy), is characterized by the alternating interbedded silts, fine sands and clays layers [41,42]. A very shallow groundwater table level occurs few meters below ground level, as is typical of the Po Plain multi-aquifer hydrogeological system. This hydrogeological configuration can lead, during drilling operation, to aquifers interconnection. To avoid this problem and guarantee the best drilling conditions, the preferable drilling technology in the area is the rotary drilling with chevron bit without the necessity of casing (Fig. 6).

No metadata, critical to the implementation of the drillability mapping, were available at the time of the realization of this project, except for an Access database provided by the Geological Service of the Emilia-Romagna Region, responsible for the city of Ferrara. This database includes hundreds of geological and geotechnical non-digitized data (core drilling, penetrometric and piezometric tests) [43].

Over 400 geognostic tests available for Porta degli Angeli surroundings were digitized and used to reconstruct a reliable stratigraphic model of the area, reaching the desired 100 m depth, thanks to MatLab GRIDWELL toolbox [44]. This code aims to reconstruct a reliable lithological sequence, by generating a dataset of modelled stratigraphies distributed on a square grid, every time the original data are not homogenous in depth and not equally spatially distributed. The statistical approach implemented within the code is applied also for geothermal energy exploitation purposes. At first, a surface stratigraphy coverage is obtained by interpolating single well-logs data. Then, once assigned the proper thermal conductivity value to each lithology, the equivalent thermal conductivity map for the study area is calculated (Fig. 7).

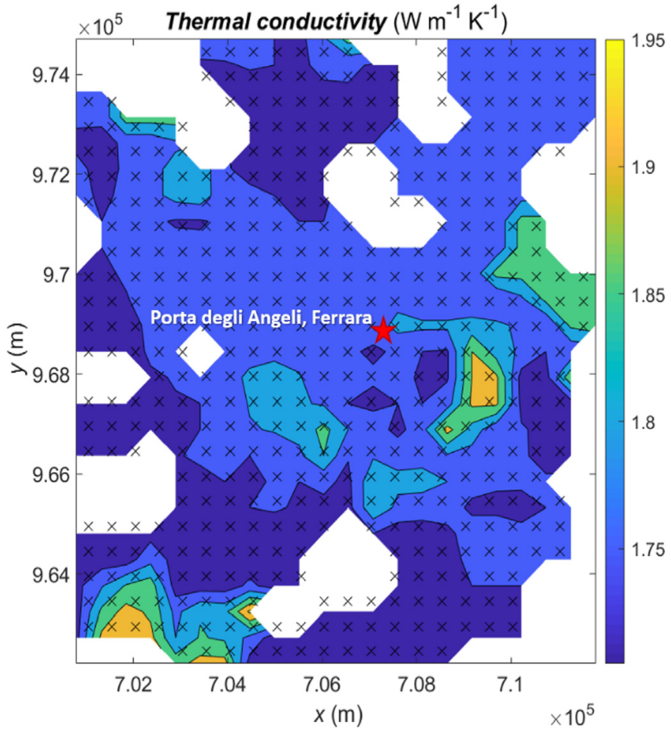

Fig. 7. Thermal conductivity map of Ferrara (Italy) retrieved from Gridwell toolbox from the available stratigraphic data up to 100 m depth.

The results show an expected underground thermal conductivity in the first 100 m depth of about 1.7–1.8 W/mK, while rotary drilling with chevron bit and without casing is the preferred technological solution, with a drilling time and costs of 3–4 min/m and 25–55 €/m, respectively (Figss. 6–7).

Also, in this demonstration site, renovation has yet to begin so the drillability data shown in the maps are still not validated.

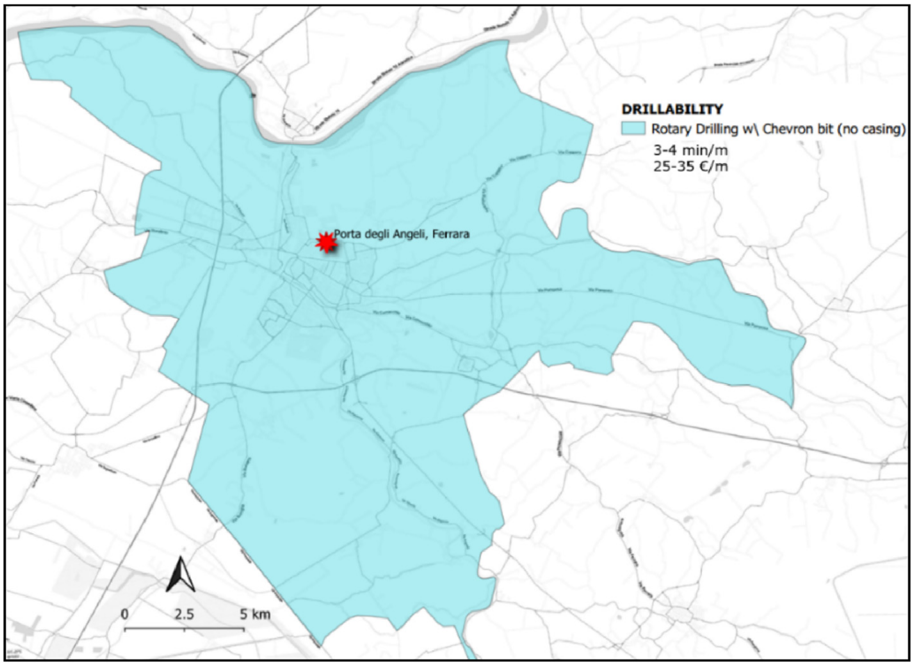

Fig. 6. Drillability map of Ferrara (method, time, cost).

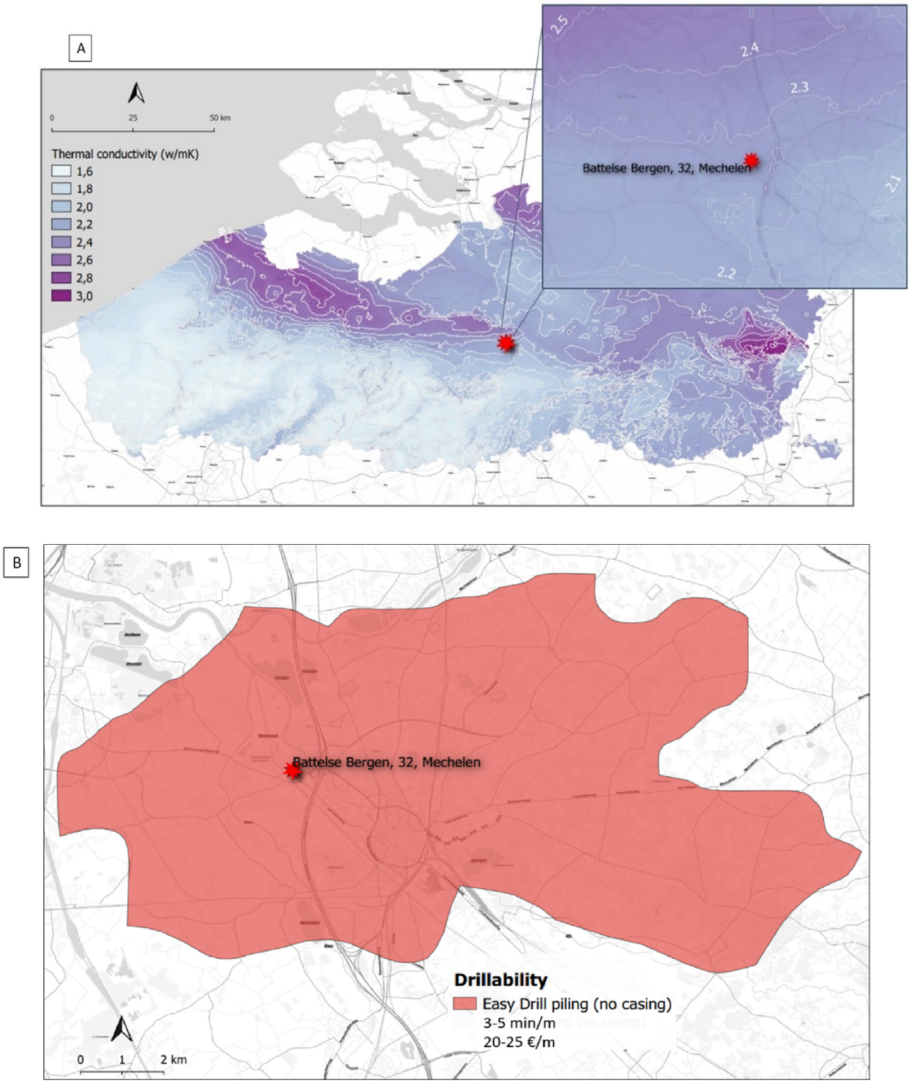

Fig. 8. Battel demonstration site: A) weighted thermal conductivity map up to 100 m depth and B) Drillability map (method, time, cost).

3.2.4. Residential house - Battel Bergen (Mechelen, Belgium)

The last demonstration site is located in Battel, a historical city near Mechelen in the Flanders region (Belgium). The local unconsolidated sediments show a high grade of vertical heterogeneity, consisting of a sequence of sands, silty sands and clays layers.

The reconstruction of the underground thermal conductivity was derived by the Flanders database [45]. The underground average thermal conductivity in the Mechelen area up to 100 m depth is expected to be in the range of 2.0–2.2 W/mK (Fig. 8A).

The presence of unconsolidated sediments favours the Easy Drill piling method without casing with a drilling time ranging between 3 and 5 min/m and costs of 20–25 €/m based on local drillers detailed information (Fig. 8B).

At the Battel-Mechelen demonstration site, the installation of two heat exchangers was performed.

For the purpose of a direct comparison, a conventional double-U heat exchanger was installed next to a coaxial stainless-steel probe, using the Hydra-RED drilling method, especially developed in GEO4CIVHIC as a technological improvement of the easy drill solution. The local stratigraphy provided by the cuttings indicates a succession of sand, clay, silty sand, fine sand, silty clay, silt, fine sand, coarse silt and clay, with a groundwater table at 0.8 m below ground level. The data collected on-site by TRT measurements provided a λ of 2.17 and 2.48 W/mK for the ground at the traditional double-U and at the coaxial heat exchangers, respectively. The slight difference could be explained by the higher heat exchange capacity of the steel coaxial probe, that is directly in contact with the surrounding ground. As for the drilling time, comprehensive of the installation procedures, the conventional method requires 3–5 min/m, while the innovative one 2.5–3 min/m, so it results quite faster. The drilling costs are confirmed to be in the range 20–25 €/m for both methodologies.

4. Conclusions

The workflow proposed focuses to define the underground drillability, represented on easy to consult maps, both at small and large scale. These aim of maps to provide useful information for stakeholders interested in the installation of shallow geothermal systems and conceived a preliminary guideline for drillers and ground source heat pumps designers. Given that drilling method time and costs vary considerably from country to country depending, among others, on the local geological context and regulations, they greatly affect the diffusion and penetration into the market of BHE solutions. Representing these parameters in a graphical way, supports administrators, direct users, designers and drillers in considering a BHE system as a valid alternative for building heating/cooling. Synthetic information about drilling operation, BHE installation costs and time-consuming activities plays a key role in determining the shallow geothermal planning feasibility. In detail, the main outcomes can be summarized as follows:

- a database coupling different drilling techniques with several geological context was created thanks to the know-how of the multidisciplinary GEO4CIVHIC group of experts;
- the expected drilling times and costs based on lithological variations and specific European market knowledge were assessed. Combining all the feedbacks received, five drilling time classes and three drilling cost groups representing an average of the European geological context were defined;
- a small-scale (1:1.500.000) European drillability map was created. A first sub-sheet identifies the most suitable drilling technology according to lithology and borehole heat exchangers type. The second focuses on the average drilling time at European level, required to drill a borehole for BHE up to 100 m depth.
- large scale (≤1:25.000) local drillability maps, providing insight on ground thermal properties, drilling method and installation timing/costs, assess detailed preliminary information useful for planning BHE installations up to 100 m depth in specific geological context were generated. Depending on the local availability of completed and affordable digitized geological and geothermal databases, maps with different degree of reliability are obtained.
- the drillability maps of two out of four GEO4CIVHIC demonstration test sites were validated by comparison with real data collected on-site. In both cases, the correspondence of the cartographic reconstructions with TRT measurements, drilling times and costs actually incurred in the BHE systems realization, confirms the effectiveness of the mapping workflows proposed. The remaining two sites will be validated once the building renovation will be completed.

The drillability map at European scale is expected to boost the acceptance of shallow geothermal systems among local administrators, by supporting them in territorial energy planning. Local drillability maps, assessing specific drilling time, costs and an overview of the average underground thermal conductivity up to 100 m depth, are a viable tool for different stakeholders. These are expected to facilitate the decision making and authorization processes for GSHP systems and encourage a better design for shallow geothermal solutions.

CRediT authorship contribution statement

A. Galgaro: Conceptualization, Supervision, Resources. **E. Di Sipio:** Data curation, Validation, Writing – original draft, preparation, Writing – review & editing. **A. Carrera:** Investigation, Methodology, Writing – original draft, preparation. **G. Dalla Santa:** Formal analysis, Visualization, Writing – original draft, preparation, Writing – review & editing. **A. Ramos Escudero:** Investigation. **J.M. Cuevas:** Investigation. **R. Pasquali:** Validation. **B. Sanner:** Resources. **A. Bernardi:** Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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