Geothermal activation of urban tunnels: a concept for sustainable infrastructures

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in collaboration with Prof Marco Barla (Geosolving srl)

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Summary

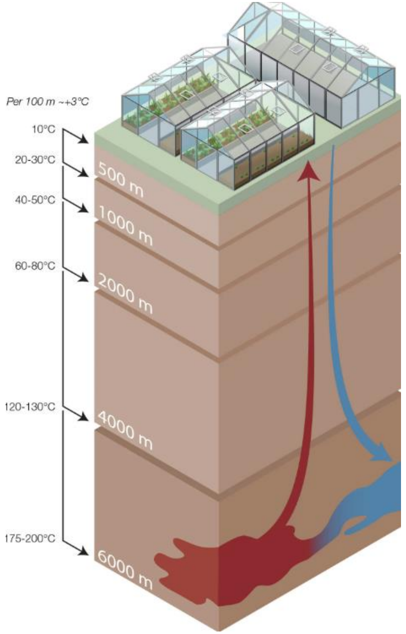
- Introduction: general principles of shallow geothermal solutions and why to apply to urban tunnels
- Thermal Activation of Urban Tunnels: the real-scale prototype in Metro Turin line 1
- Feasibility study at Metro Istanbul
- Feasibility study at Metro Lisbon
- Conclusions: challenges and potentials

Introduction

Geothermal energy is thermic energy extracted from the earth's crust

Geothermal energy/systems can be split in:

- Deep geothermal energy: extracted at depth range between 150 m and 5000 m, using high temperatures (30°C ÷ 200°C) with typical applications in industrial processes and centralized heating networks
- Shallow geothermal energy: extracted at depth less than 150 m, with typical temperature < 30°C with typical applications for individual buildings or de-centralized low-temperature grids

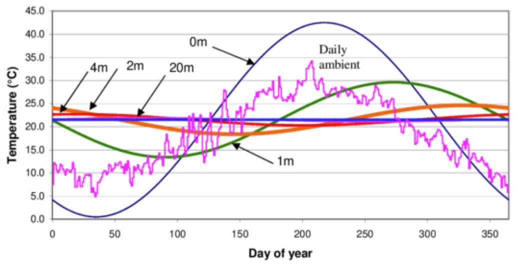


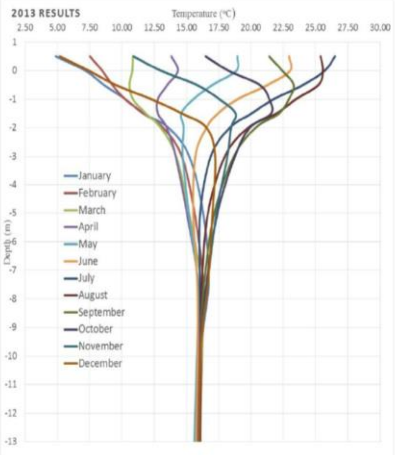
→ Let's focus on shallow geothermal systems

Introduction

Shallow geothermal systems mainly take advantage that ground (and ground water) has almost a constant temperature already 10-15 m below ground and, hence, of temperature difference between ground at depth and surface, exchanging heat:

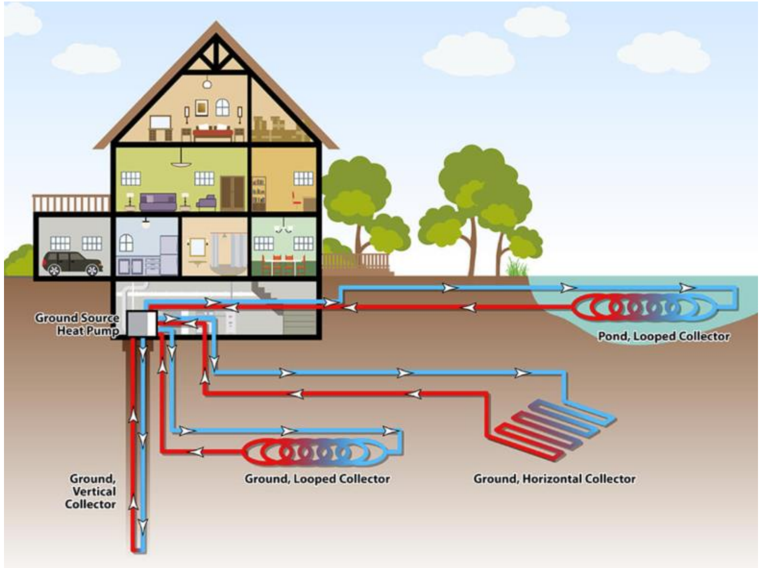
- During winter heat is extracted by the ground for heating purposes
- During summer heat is brought to depth for cooling purposes



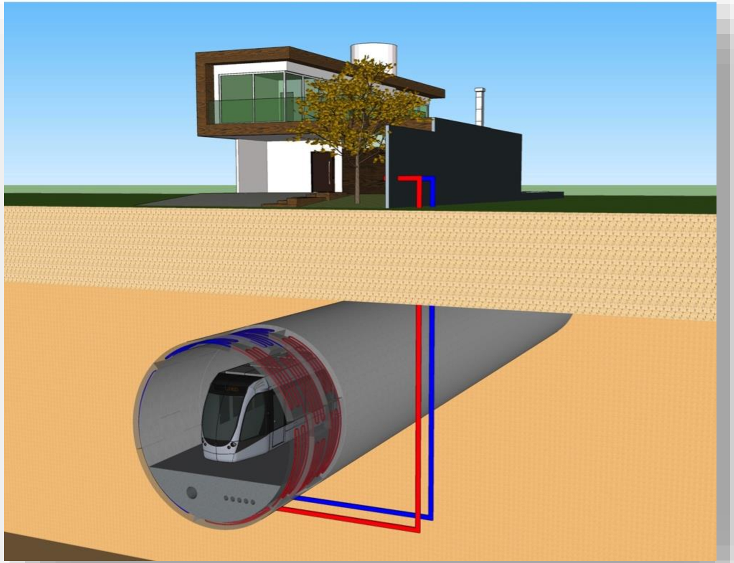


Typical geothermal system:

- Heat exchanger to transfer heat between the ground (and ground water) and air or fluid in a circuit
- Heat pump to obtain water/air at desired temperature.
- Main installation cost of the system: realization of the heat exchanger (due to drilling / excavation)



Thermal activation of tunnels



A tunnel is a natural geothermal heat exchanger, although realized for a different purpose and that need just to be equipped to be able to act as such.

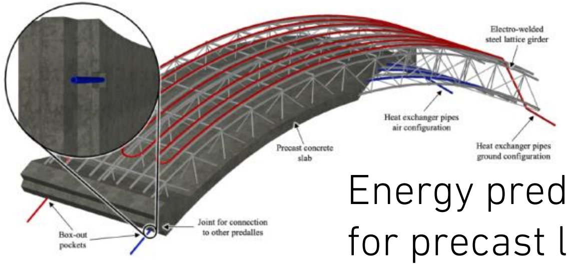
Compared to building foundations, tunnels involve a larger volume of ground and surface for heat exchange.

Possible uses:

- Heating and cooling of metro stations
- Heating and cooling of adjacent public and private buildings
- De-icing of surfaces around stations during winter (pedestrian paths, stairs,...)
- During summer, cooling of the tunnel itself near the station areas (compensating breaking heat)

Thermal activation of tunnels

Possible application both in conventional and mechanized tunnellings, both in new tunnels and existing ones during rehabilitation:

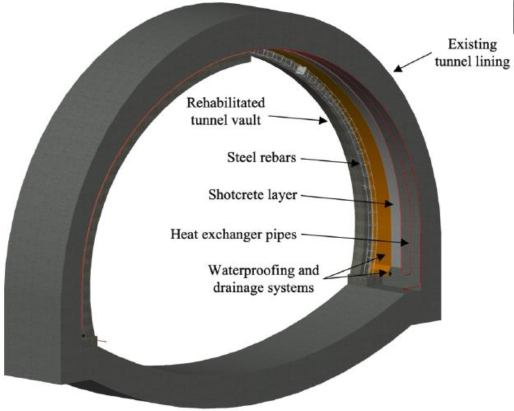


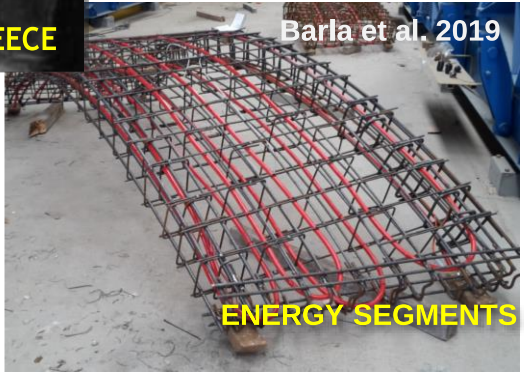
De Feudis et al. 2024

Energy predalle for precast lining

Conventional tunnelling

Energy mat applied to partial rehab of a tunnel vault (appl. both to cast in situ and shotcrete lining)



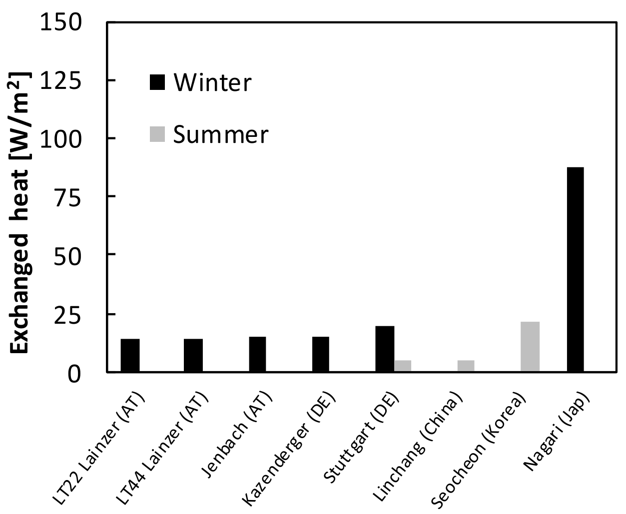


Mechanised excavation

Thermal activation of tunnels

Efficiency of a tunnel as heat exchanger depends on a number of factors: tunnel geometry, presence of water table, water flow (i.e. hydraulic gradient, ground permeability), heat conductivity of the ground, water/ground temperature,…

For a first approximate assessment of the exchanged heat in winter heating and summer cooling by thermally activating a tunnel lining it is possible to refer to existing cases that have documented values in the range 10-30 W/m^2, depending on the thermo-hydro-geological conditions at the specific site.



Heat exchange per square meter

Di Donna, Barla & Amis (2017)

Thermal activation of tunnels

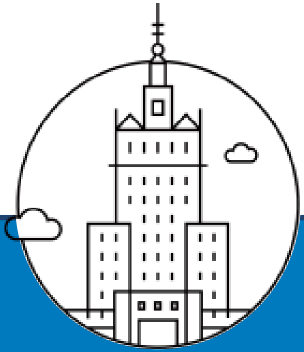
Istanbul

Metro line
Dudullu-Bostanci

10-20 W/m^2

10-15 W/m^2

Furno et al., 2015



Warsaw

Metro Line 2
NE extension

13-15 W/m^2

29-42 W/m^2

Baralis et al., 2018

Torino

Metro Line 2

32-65 W/m^2

10-48 W/m^2

Barla et al., 2019

Paris

Ligne 15O

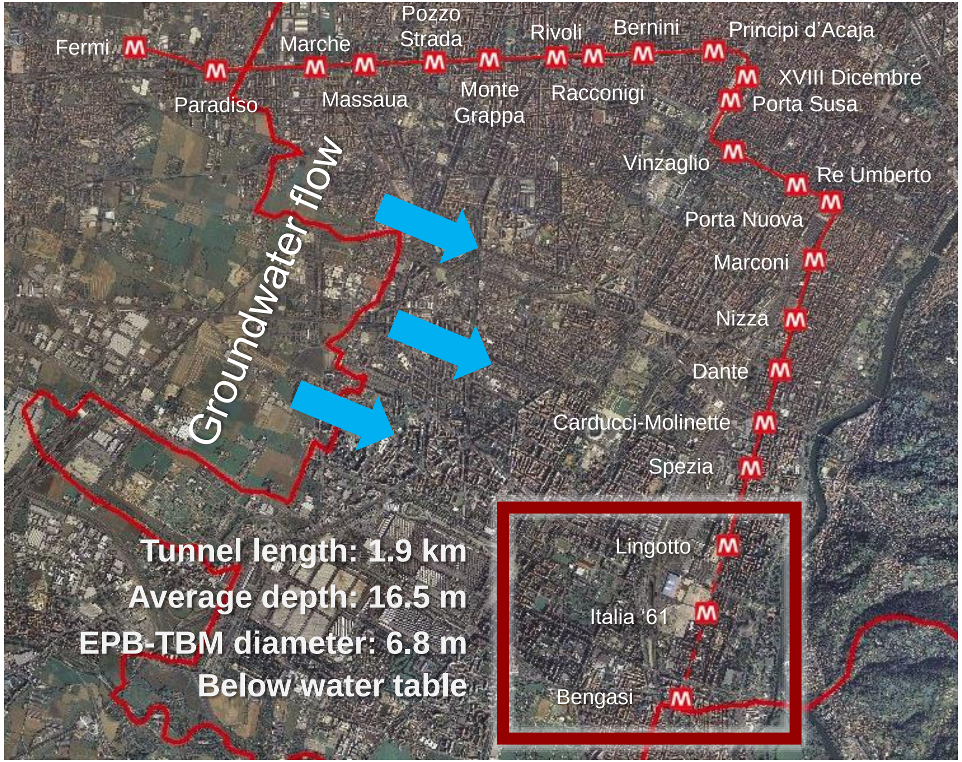
27-31 W/m^2

11-16 W/m^2

Geosolving, 2019

Prototype in Turin ML1

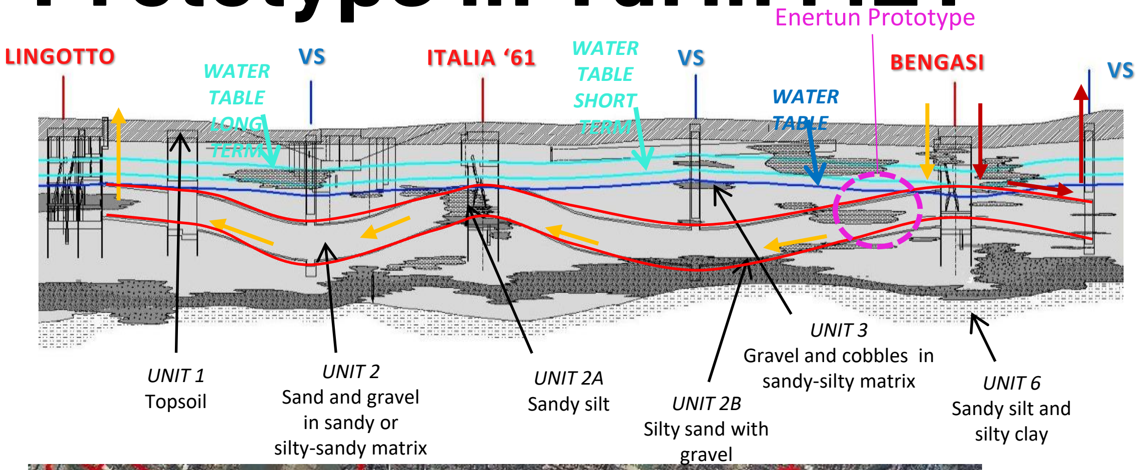
Barla et al., 2019
Insana & Barla, 2020

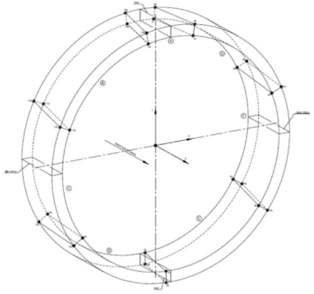


- Gravel, cobbles and sand in sandy-silty matrix (surface horizon, 25÷50 m).
- Random distribution of cementation due to calcareous deposition (horizontal layers from few cm to m).
- Free aquifer in the sandy gravel strata (1.4 m/dd). Temperature 15°C.

Prototype in Turin ML1

Barla et al., 2019
Insana & Barla, 2020





TBM Excavation 1st phase

TBM Excavation 2nd phase

- Gravel, cobbles and sand in sandy-silty matrix (surface horizon, 25÷50 m).
- Random distribution of cementation due to calcareous deposition (horizontal layers from few cm to m).
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Prototype in Turin ML1

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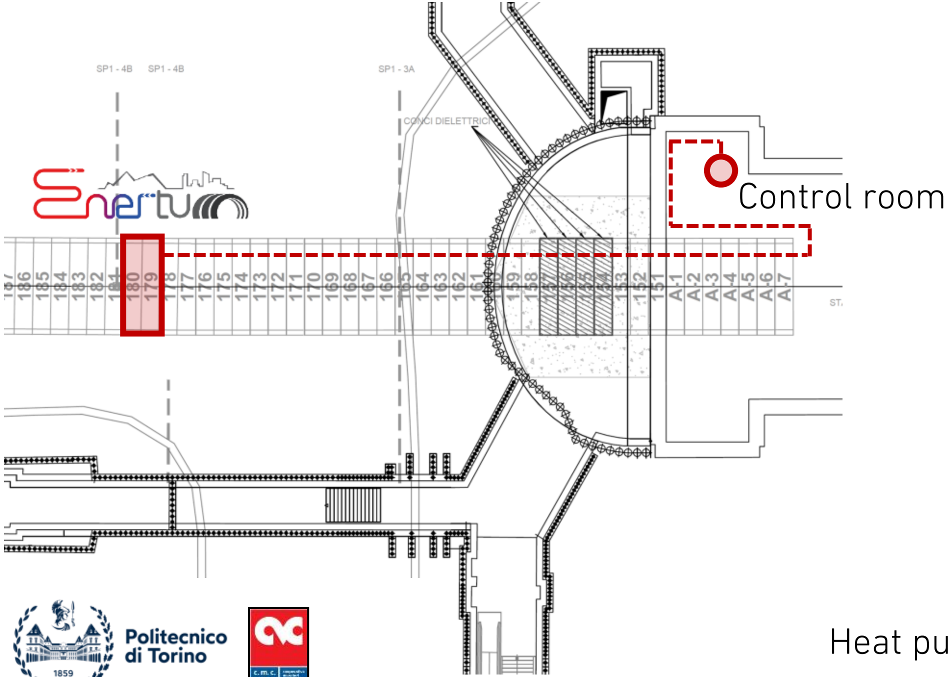
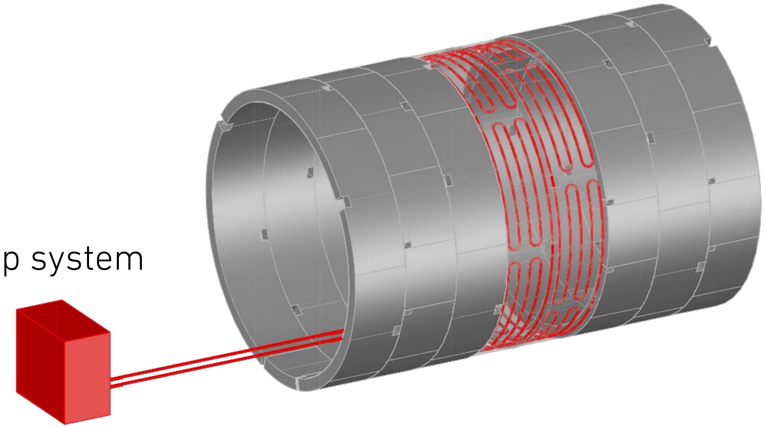


Politecnico di Torino
INFRA.TO
infrastrutture per la mobilità

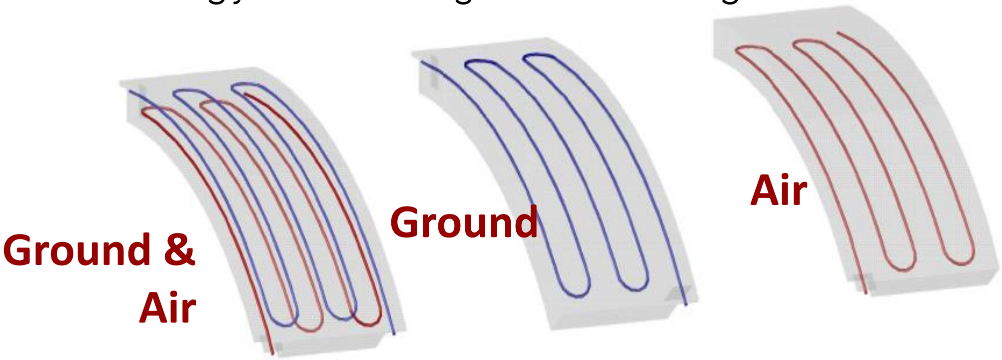
TEST CONFIGURATION

Two rings of ENERTUN segments were installed to test heating and cooling cycles. The control room hosts the heat pump, the sensors data logger and a fan coil to dissipate heat.



Prototype in Turin ML1

Improved energy tunnel segmental lining



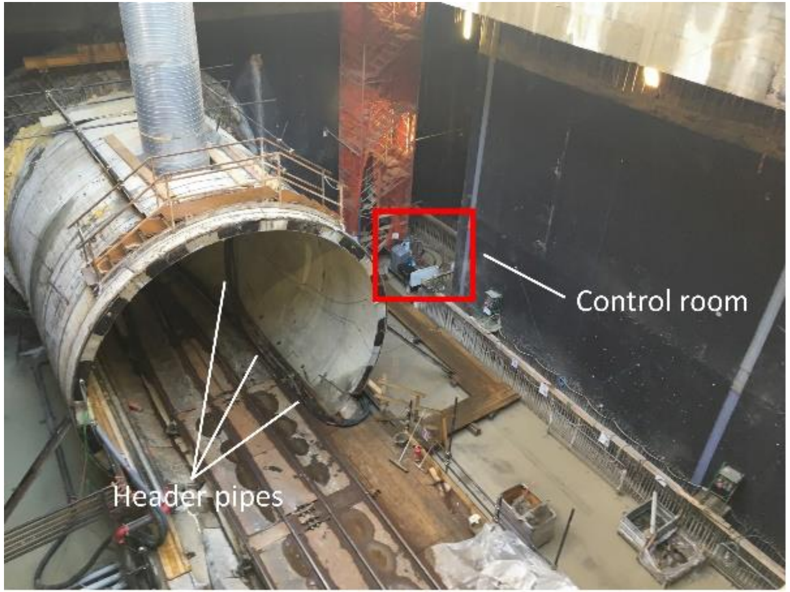
ADVANTAGES:

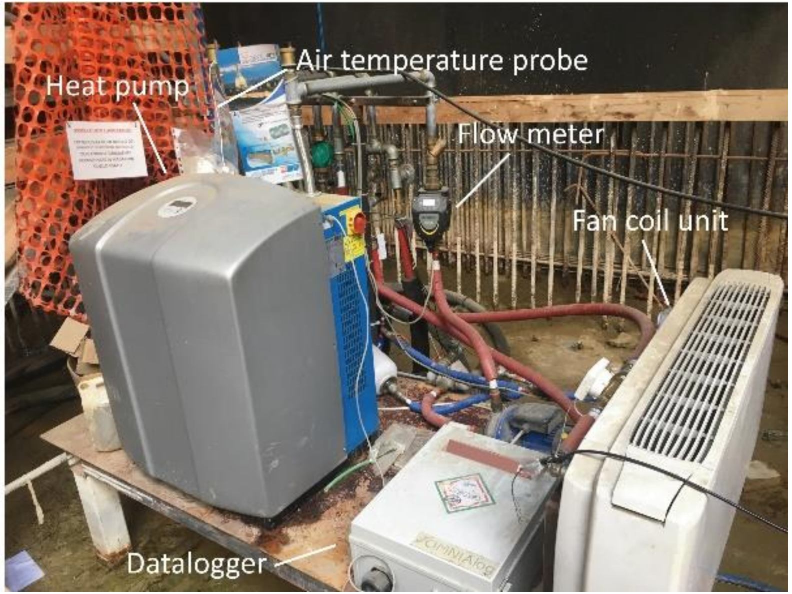
- Reduced head losses
- Optimization of heat exchange
- Three different configurations to exchange heat with the ground or the internal tunnel air
- Reduction of ventilation costs when used to cool the tunnel

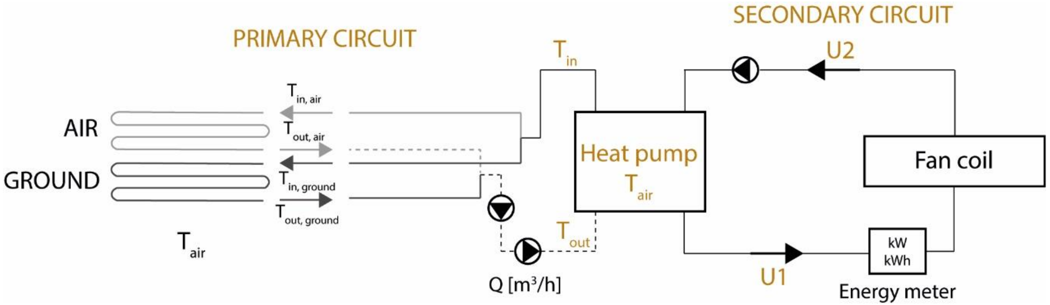
Barla & Di Donna 2016
Patent: 102016000020821

Prototype in Turin ML1

During construction / tests





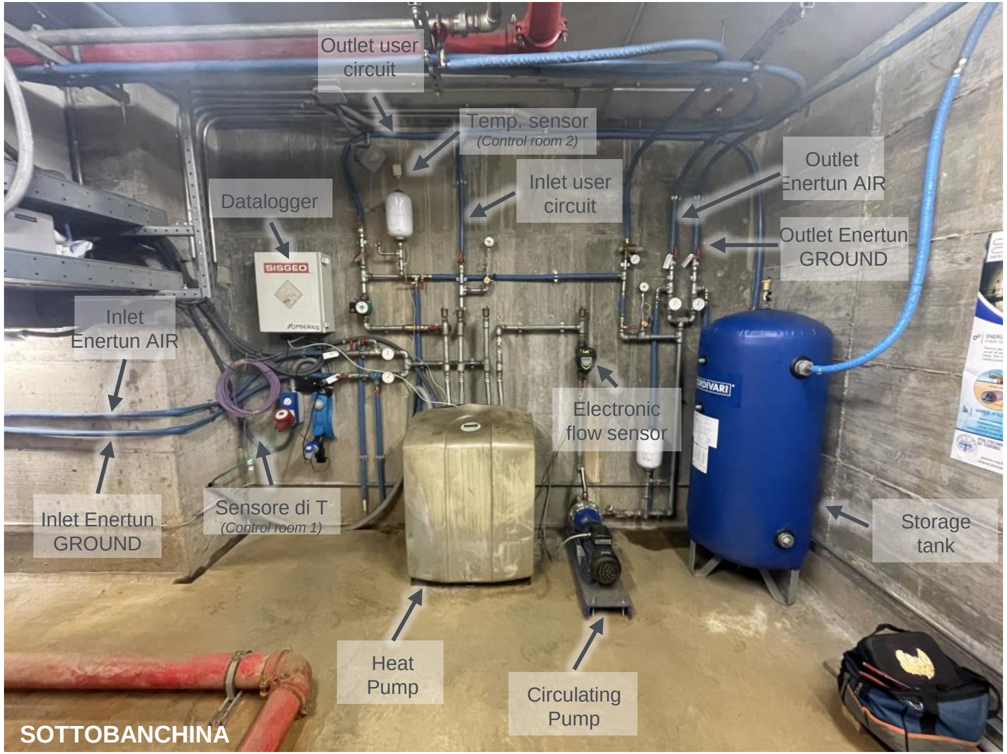


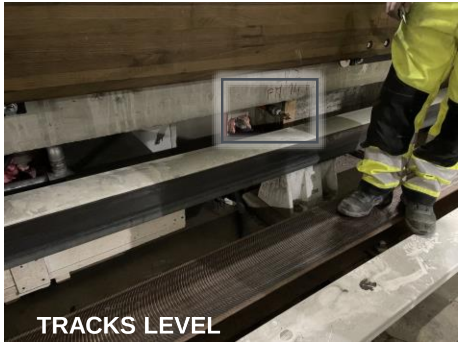
Barla et al., 2019

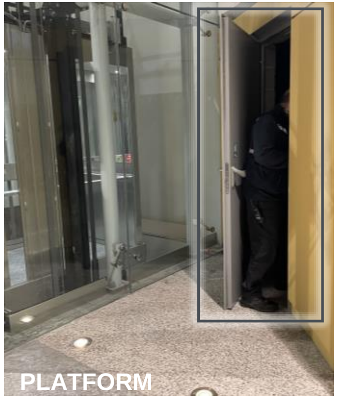
Insana & Barla, 2020

Prototype in Turin ML1

Today with ML1 in operation
Enertun used to heat/cool service rooms







Prototype in Turin ML1

Barla et al., 2019
Insana & Barla, 2020

Rockmech PoliTO https://www.youtube.com/watch?v=0xmYvY_N8oM

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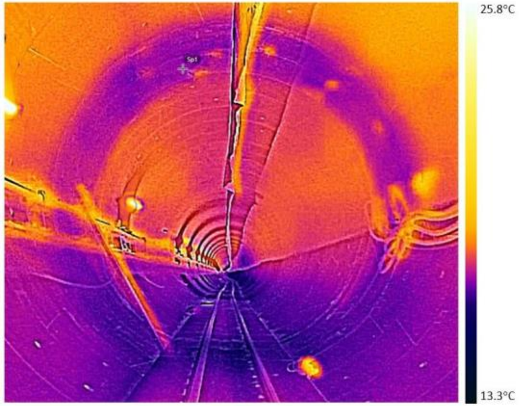
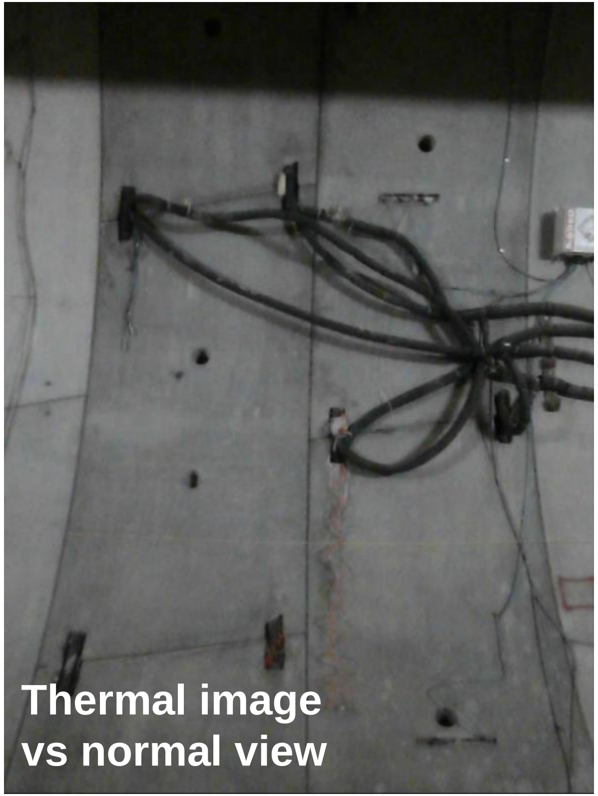
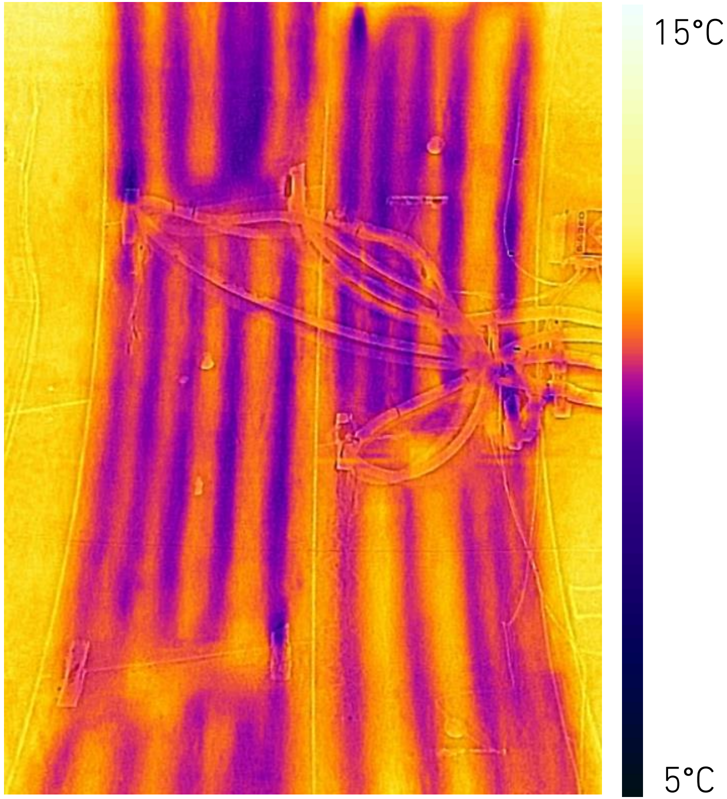
Prototype in Turin ML1

Barla et al., 2019
Insana & Barla, 2020

Some thermal evidences: AIR plant thermal activation

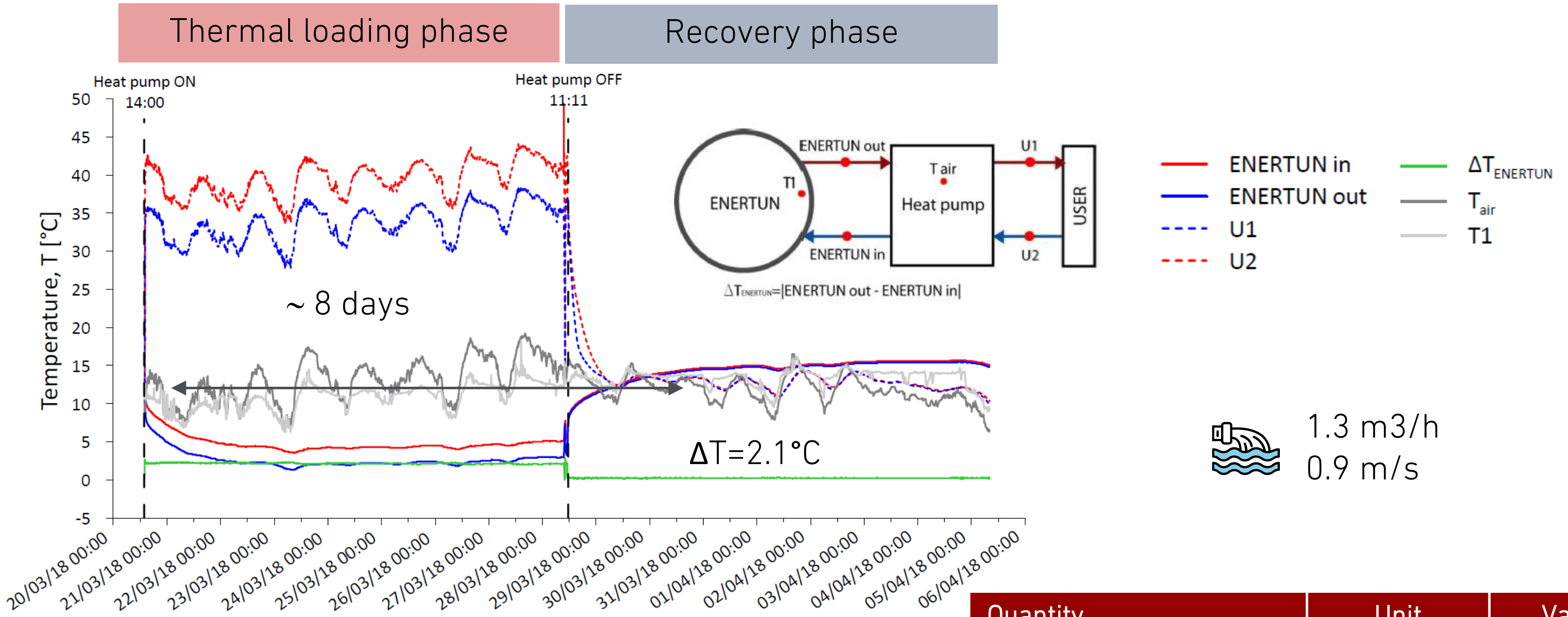






Thermal activation of tunnels

Barla et al., 2019
Insana & Barla, 2020



1.3 m3/h
0.9 m/s

Quantity	Unit	Value
Thermal energy exploited	kWh	601.1
Power x lining surface	W/m2	48.3
Power x tunnel length	W/m	1135

MEASURED PERFORMANCE

1.1 MW/km → in agreement with numerical predictions

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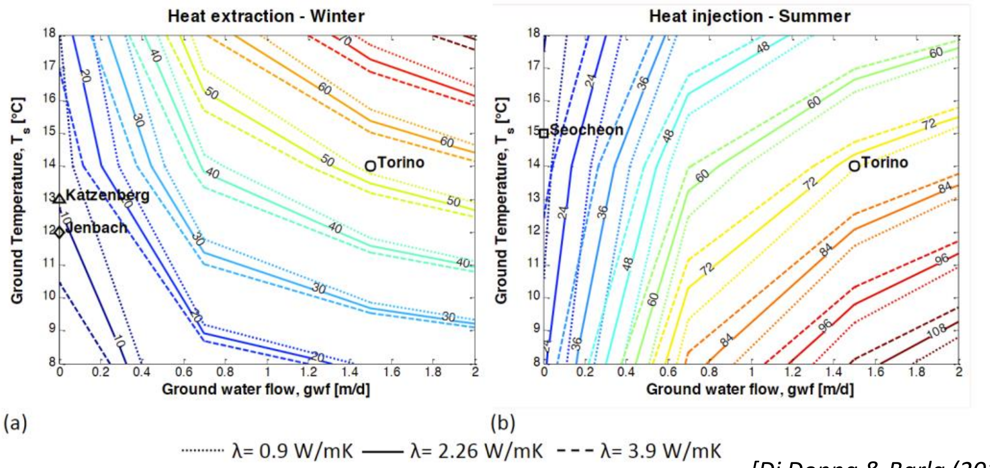
Thermal activation of tunnels

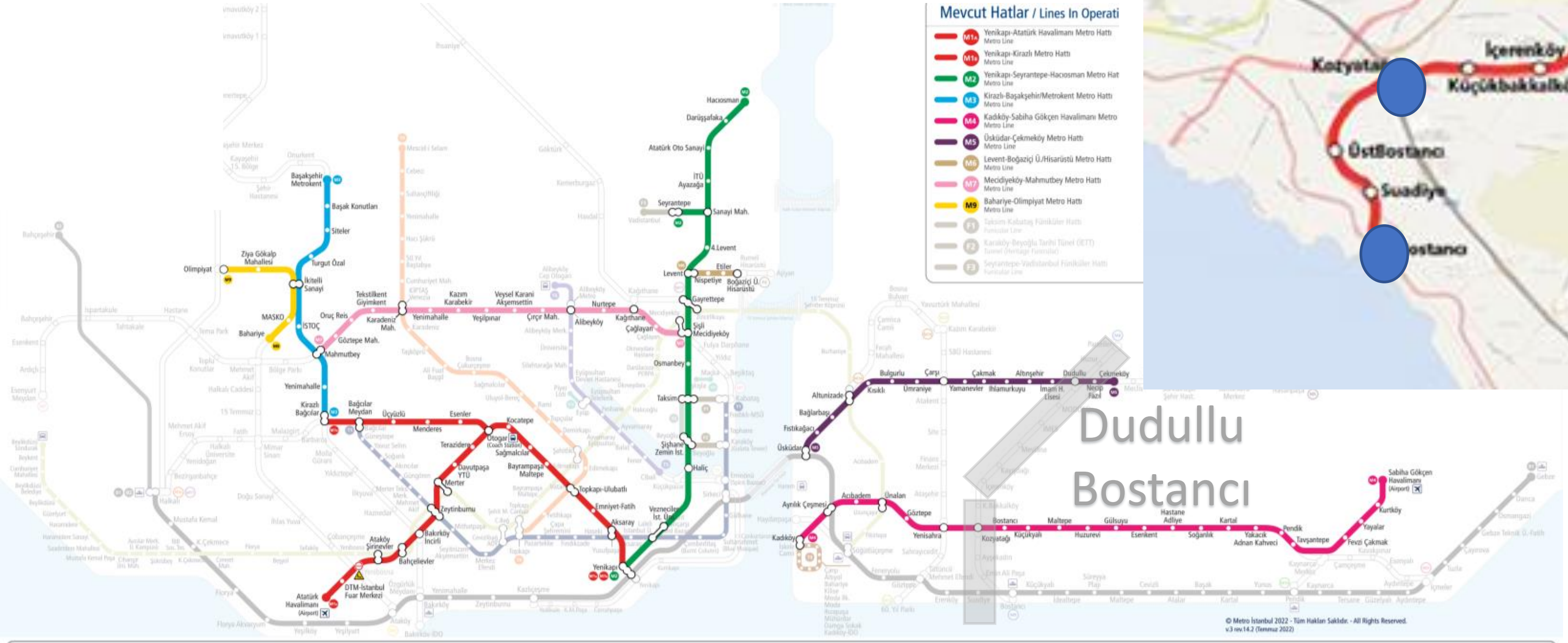
Based on real-scale prototype in Turin, a number of numerical simulations based on parametric studies and the results of applications done by others, nomograms to estimate heat exchange potential have been obtained to be used for preliminary / feasibility studies

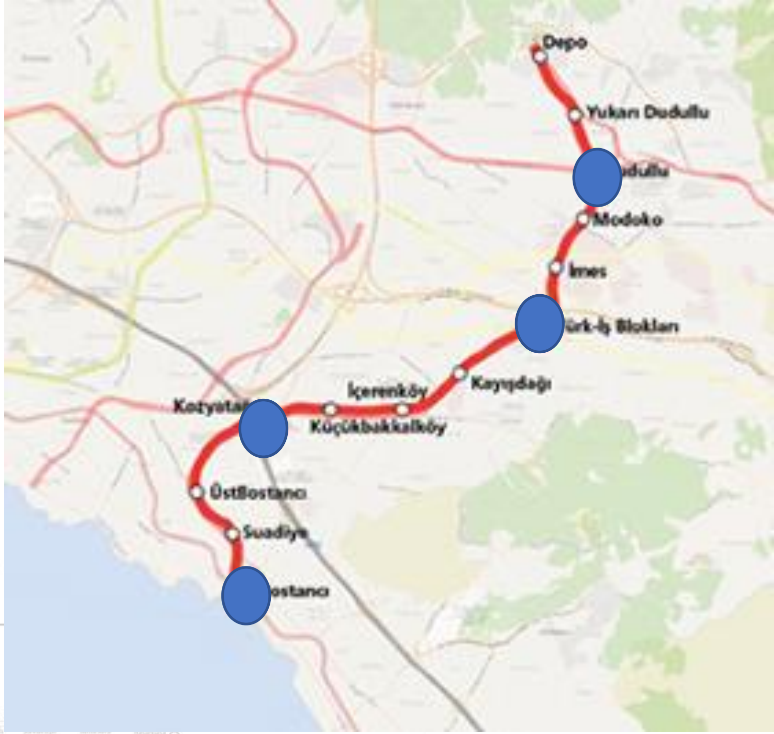


[Di Donna & Barla (2015)]

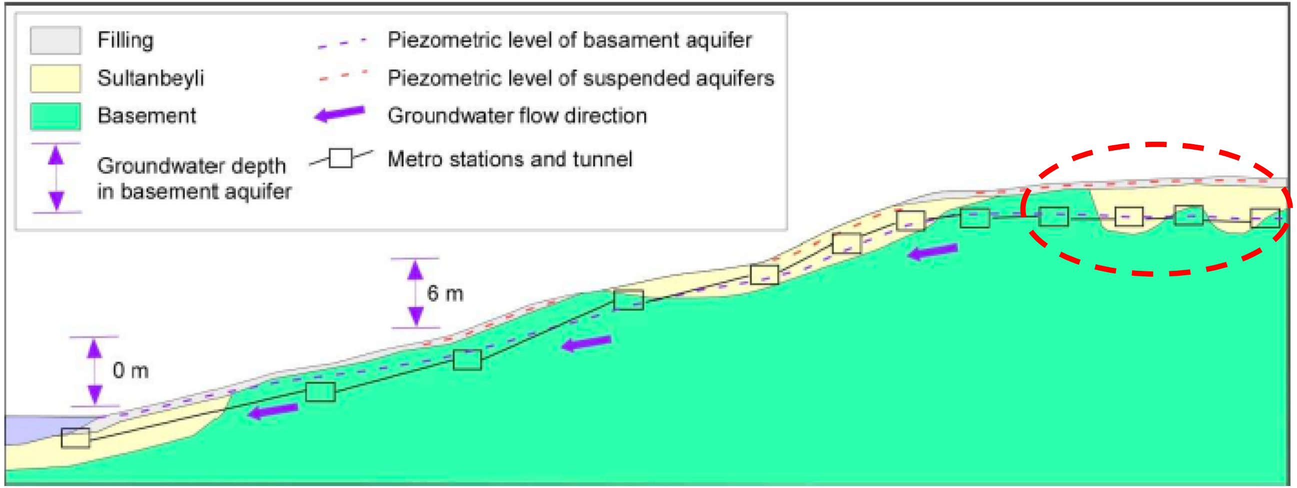
Metro Istambul

Interchange Stations





Metro Istambul (Dudullu-Bostanci)



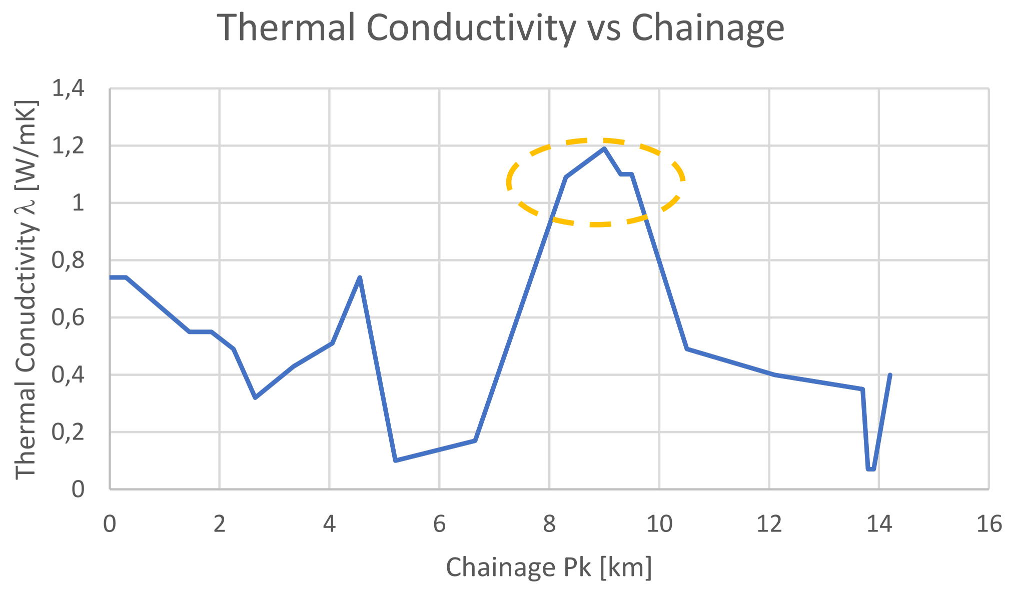
INFLUENCING FACTORS

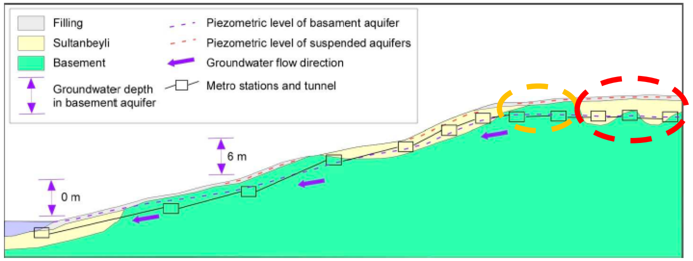
- Permeability
- Thermal conductivity
- Hydraulic gradient
- Groundwater temperature

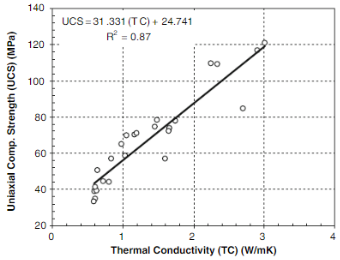
- Water table above the metro line for part of the alignment
- groundwater in movement following the hill side (hydraulic gradient)
- Tunnel stretches in soil with variable composition (deposits)
- Groundwater temperature ranging 14,3 ÷ 19,8

➡ identified one suitable stretch in soil and under water table (section A)C

Metro Istambul (Dudullu-Bostanci)







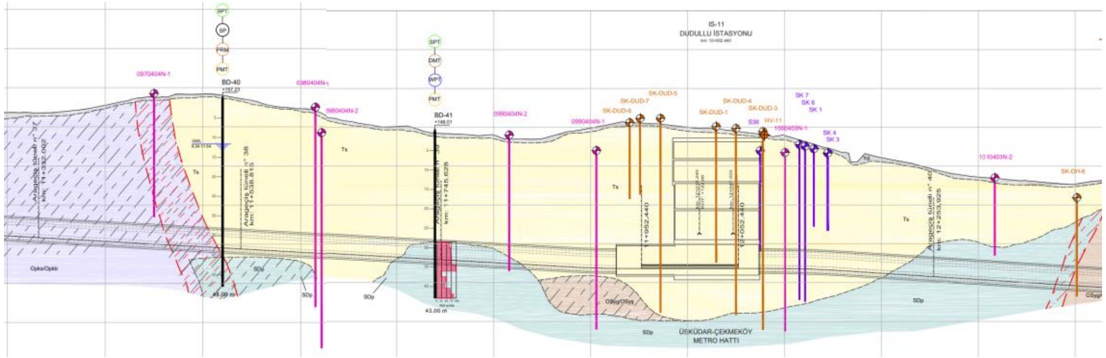
[Yasar (2008)]

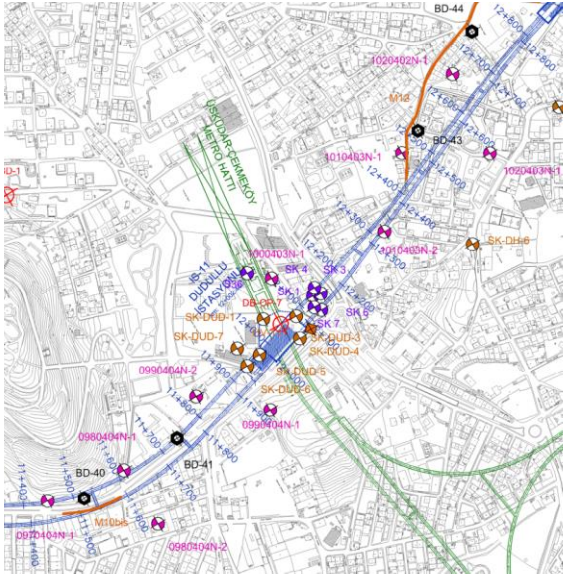
- Analysis of bedrock/soil thermal conductivity along the alignment

➡ identified second potential stretch in bedrock under water table (section B)

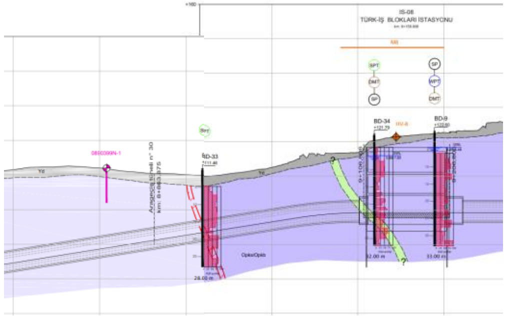
Metro Istanbul (Dudullu-Bostanci)

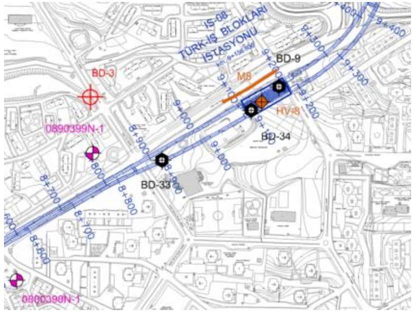
Section A





Section B





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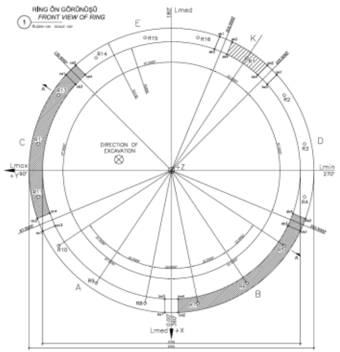
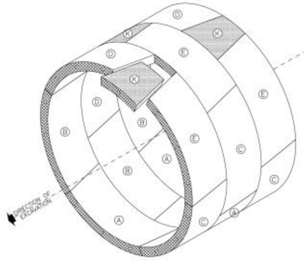
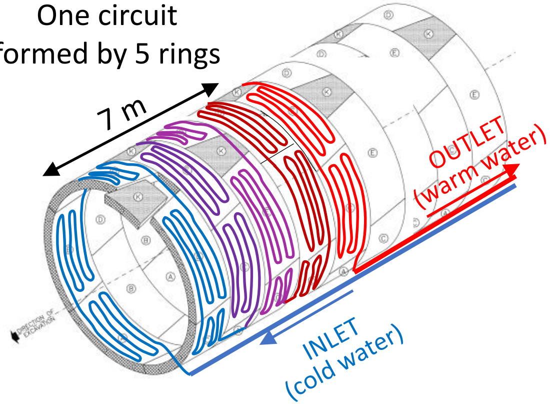
Metro Istambul (Dudullu-Bostanci)





LINING MAIN CHARACTERISTICS:

- Type of ring: universal
- N° of segments: 6 (trapezoidal)+1(key)
- Inner diameter: 5.70m
- Outer diameter: 6.30m
- Thickness: 0.30 m
- Width of ring: 1.40m



GEOTHERMAL SYSTEM MAIN CHARACTERISTICS:

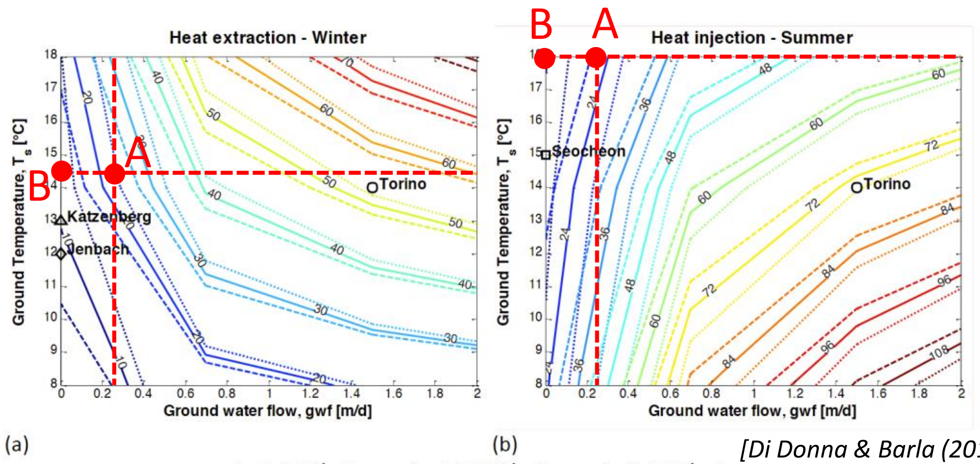
- High resistance polyethylene pipes (PE-X), d_{ext} = 25 mm
- Spacing between absorber pipes: 25 ÷30 cm
- 5 rings in series to form a single circuit
- Each circuit connected in parallel with the others

Metro Istambul (Dudullu-Bostanci)

INPUT DATA

Section	Formation	Pk [km]	Geological Formation	Permeability [m/s]	Flow rate [m/d]	Thermal conductivity λ [W/mK]	Groundwater Temperature	
							Heating [°C]	Cooling [°C]
A	Soil	11.4 - 12.8	Sultanbeyli	2.60e-05	0.225	0.38	14.29	19.80
B	Rock	8.8 - 9.2	Kurtköy	1.00e-06	≈ 0	1.19	14.29	19.80

NOMOGRAM FOR HEAT EXCHANGE POTENTIAL



⋯⋯ λ= 0.9 W/mK —— λ= 2.26 W/mK - - - λ= 3.9 W/mK

[Di Donna & Barla (2015)]

Section	Heat extraction	Heat injection
A	20	20
B	10	15

W / m^2

Thermal Power — Exchange surface

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Metro Istambul (Dudullu-Bostanci)

EXAMPLES:

- System formed by 20 circuits (140 m) in section A
- System formed by 40 circuits (280 m) in section A
- System formed by 20 circuits (140 m) in section B
- System formed by 40 circuits (280 m) in section B

SECTION A

Heating Potential [W/m2]					Heating Power [kW]	
Winter	Summer	Tunnel Diameter [m]	Length of Installation [m]	Exchange Surface [m2]	Winter	Summer
20	20	6,3	140	2771	**55,4**	**55,4**
20	20	6,3	280	5542	**110,8**	**110,8**

SECTION B

Heating Potential [W/m2]					Heating Power [kW]	
Winter	Summer	Tunnel Diameter [m]	Length of Installation [m]	Exchange Surface [m2]	Winter	Summer
10	15	6,3	140	2771	**27,7**	**41,6**
10	15	6,3	280	5542	**55,4**	**83,1**

Metro Istambul (Dudullu-Bostanci)

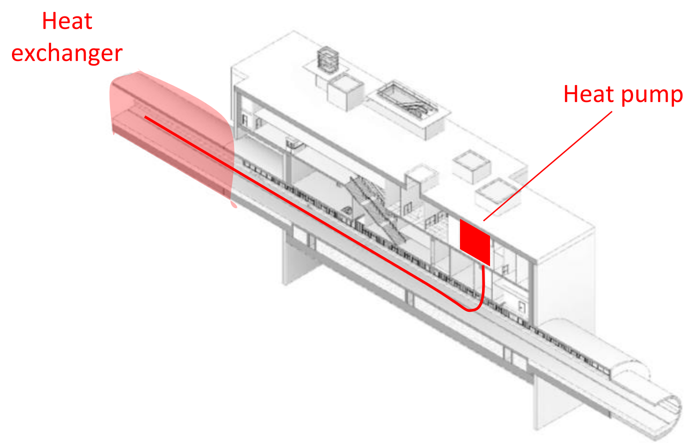
APPLICATION IN SECTION A FOR HEATING/COOLING BUILDINGS:

- Max building heat requirement (according to Turkish standard 825) in this area: 48kWh/m^2
- Ratio exposed surface / volume: A/V= 0.2
- Assuming operating time of the system 6000 h (8 months): 3500 h for heating and 2500 h for cooling)

Length of Application [m]	Operating hours [h]		Total Annual Energy [MWh]		Building Heating demand [kWh/m^2]	Heated surface [m^2]	Building Cooling demand [kWh/m^2]	Cooled surface [m^2]
	Winter	Summer	Winter	Summer				
140	3500	2500	193,9	138,5	48	**4040**	50	**2770**
280			387,8	277,0		**8079**		**5540**

➡ A section of 560 m suitable for heating/cooling Dudullu station (≈ 10'000 sqm)

Estimated additional cost of tunnel lining for installation of the heat exchanger: ≈ 2% of lining cost



Metro Istambul (Dudullu-Bostanci)

ADVANTAGES (COSTS & ENVIRONMENT):

- Coefficient of performance (produced thermal energy / consumption of electric energy): ≈ 4

➡ Reduction to 20-25% of electric energy consumption compared to direct electric heater

➡ Reduction of CO2 emissions (assuming only heating function):

Heat Exchanger with Heat Pump (*) [kgCO_2/year]	Electric heater (*) [kgCO_2/year]	Natural gas boiler (**) [kgCO_2/year]
77.595	**310.380**	**177.693**

(*) assumed average in Turkey: 400 gCO_2 / Kwh
(**) assumed emissions for natural gas boiler: 229 gCO_2 / kWh

Metro Istambul (Dudullu-Bostanci)

ADVANTAGES (COSTS & ENVIRONMENT):

- Coefficient of performance (produced thermal energy / consumption of electric energy): 4 ÷ 5

➡ Reduction to 20-25% of electric energy consumption compared to direct electric heater

➡ Reduction of CO2 emissions (assuming only heating function):

Heat Exchanger with Heat Pump (*) [kgCO_2/year]	Electric heater (*) [kgCO_2/year]	Natural gas boiler (**) [kgCO_2/year]
77.595	**310.380**	**177.693**

- 101 t CO_2 / year compared to gas boiler

(*) assumed average in Turkey (year 2023): 400 gCO_2 / Kwh
(**) assumed emissions for natural gas boiler: 229 gCO_2 / kWh

➡ Adopting CO_2 emission for electricity in Norway

Heat Exchanger with Heat Pump (*) [kgCO_2/year]	Electric heater (*) [kgCO_2/year]	Natural gas boiler (**) [kgCO_2/year]
3.492	**13.967**	**177.693**

- **11 t CO_2 / year** compared to electric heater (equivalent to ≈100’000 km by gasoline car

(*) assumed average in Norway (year 2023): 18 gCO_2 / Kwh
(**) assumed emissions for natural gas boiler: 229 gCO_2 / kWh

Metro Lisboa (Red Line Extension)

- 4 new stations (3 of which, underground)
- 3.5 km new line
- Excavation through conventional tunnelling

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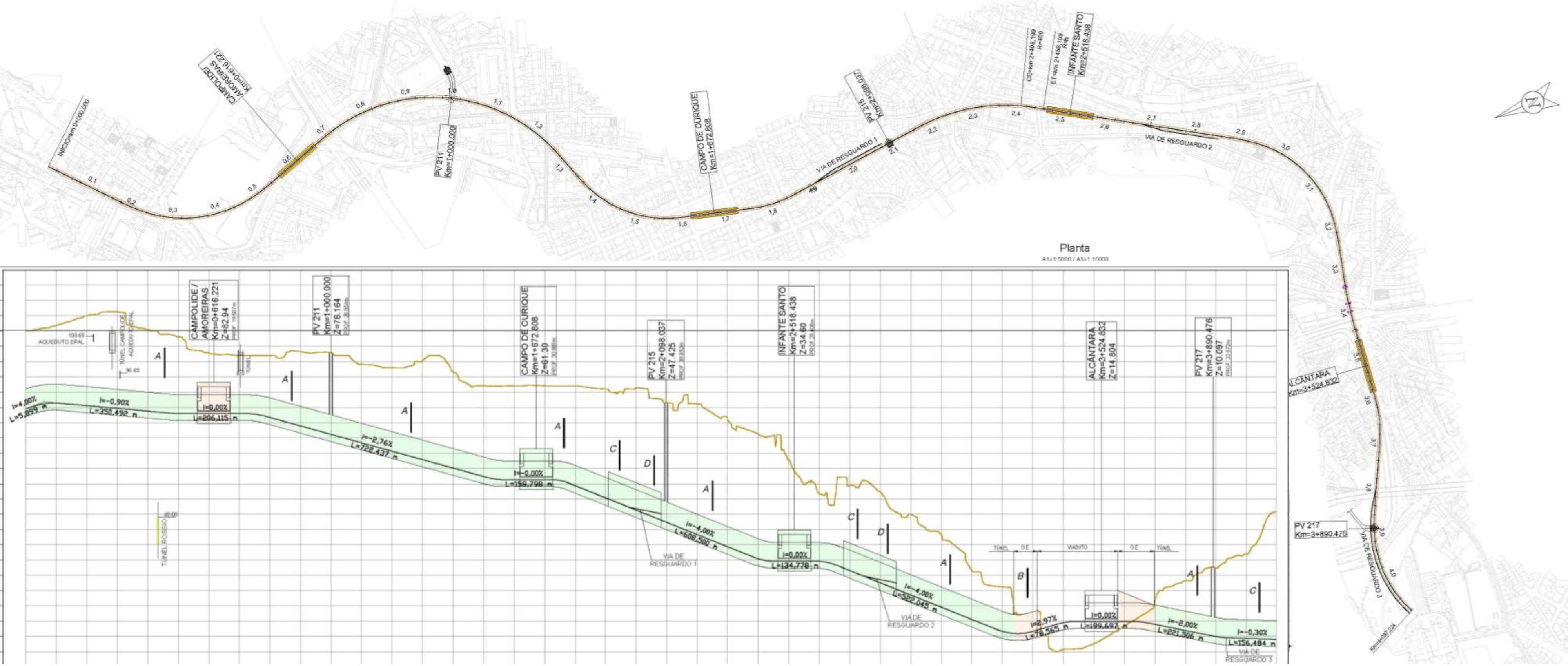
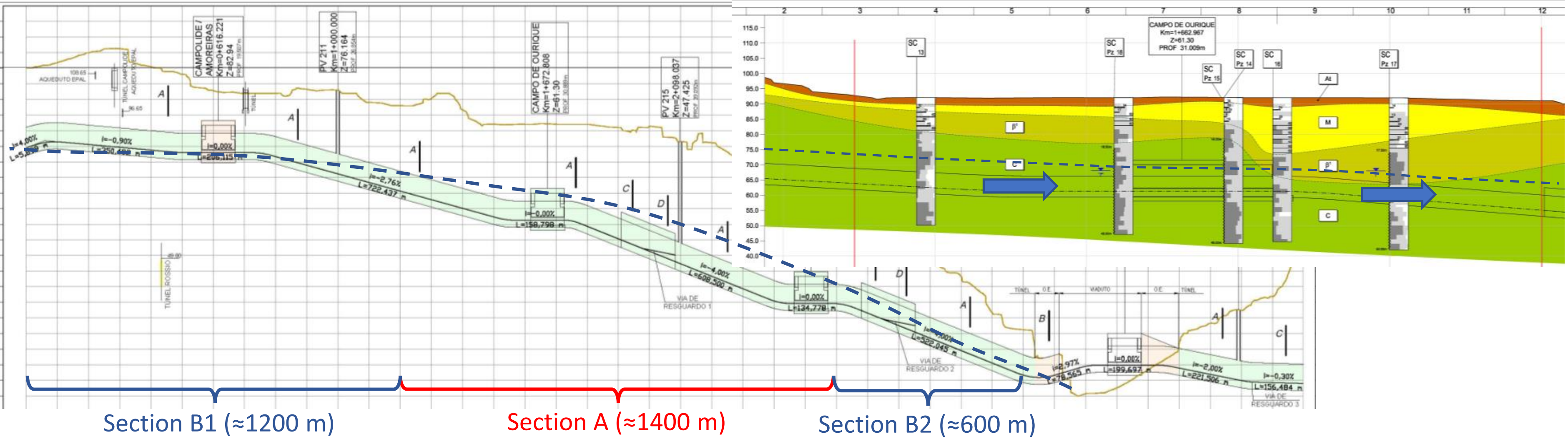
Metro Lisboa (Red Line Extension)



Metro Lisboa (Red Line Extension)

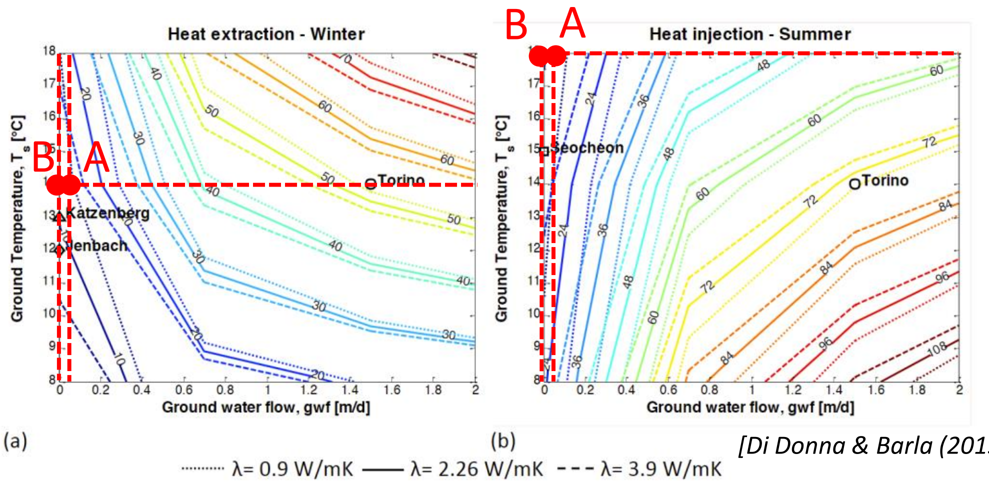


- Highly fractured limestone (thermal conductivity ≅ 1,3 W/mK above water, 2,0 W/mK below water)
- Permeability range: 2-4 x 10-6 m/s
- 20 m overburden
- Water table permanently above tunnel along ≅ 1400 m (section A);
- water movement along the tunnel due to water head gradient (Δh/Δl ≅ 3.5%)

Metro Lisboa (Red Line Extension)

Heat Extraction Potential

Section	Formation	Pk [km]	Geological Formation	Permeability [m/s]	Flow rate [m/d]	Thermal conductivity λ [W/mK]	Groundwater Temperature	
							Heating [°C]	Cooling [°C]
A	Fract. Rock U.W.	1.20÷2.60	Bica Formation	3.0e-06	0.01	2.0	14.0	18.0
B	Fract. Rock A.W.	0.0÷1.2 + 2.6÷3.2	Bica Formation	3.0e-06	0.01	1.3	14.0	18.0



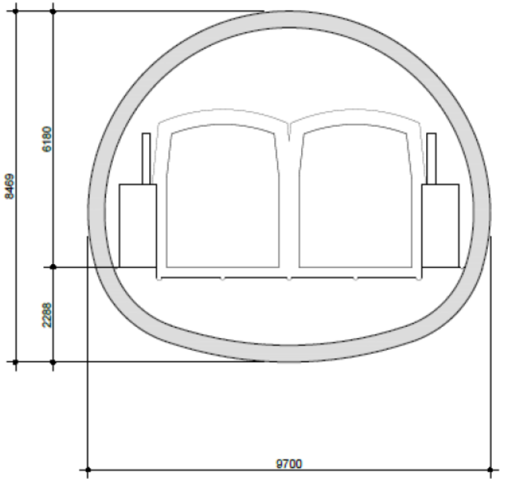
[Di Donna & Barla (2015)]

Section	Heat extraction	Heat injection
A	12	15
B	8	10

Metro Lisboa (Red Line Extension)

APPLICATION ALONG THE FULL METRO EXTENSION (3.2 km)

Section	Heating Potential [W/m^2]		Tunnel Diameter [m]	Length of Installation [m]	Exchange Surface [m^2]	Heating Power [kW]	
	Winter	Summer				Winter	Summer
A	12	15	9,1	1400	40024	**480,3**	**600,4**
B	8	10	9,1	1800	51459	**411,7**	**514,6**



Preliminary estimated results (for both cooling and heating):

- ≈ 0.9÷1.1 GW
- 5.7 GWh / year
- ≈ - 1’000 ton CO_2 / year
- Cooling/heating for ≅ 52’000 sqm of buildings

Section	Length of Application [m]	Operating hours [h]		Total Annual Energy [MWh]		Building Heating demand [kWh/m^2]	Heated surface [m^2]	Building Cooling demand [kWh/m^2]	Cooled surface [m^2]
		Winter	Summer	Winter	Summer				
A	1400	3200	2500	**1536,9**	**1500,9**	52 (*)	**29556**	52 (*)	**28863**
B	1800	3200	2500	**1317,4**	**1286,5**		**25334**		**24740**

(*) [Stavropoulos (2013)]

Conclusions

- Thermal activation of urban tunnels allows to obtain renewable/clean energy directly at user place, reducing considerably electric power need of the infrastructure for heating/cooling purposes and, consequently, also its CO_2 footprint (considering its LCA)
- Cold climate (Nordic countries and mountain area) , it can be used directly (without heat pump) also for deicing of public outdoor surfaces
- Obtained thermal power is always available when needed (both day and night, during all cold and warm seasons)
- Installation costs are low compared to the infrastructure itself (negligible impact on the overall budget of the project), since costs are limited to installation of pipes inside structures already foreseen for other purposes

Conclusions

- Applicability of the system depends on geological and hydrogeological local conditions; hence, a proper feasibility study has to be performed before to consider its application for a specific infrastructure in order to estimate its performance and conduct a cost/benefit analysis

- The heat exchanger is installed directly inside the lining itself of the tunnel and, hence, has to be planned well in advance compared to execution: the owner of the infrastructure need to include the system already in the tender design or at least as a requirement on tender documentation

- The design of the thermal system is connected to the design of the tunnel lining and stations: this may limit contractual strategy on splitting the construction in different lots/contracts

- The Company owner of the project sometimes does not benefit of the advantages obtained by the thermal activation system (different company responsible of the project and of the infrastructure maintenance)

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