Istanbul metro: a possible example of energy geostructure

ISTANBUL METRO: A POSSIBLE EXAMPLE OF ENERGY GEOSTRUCTURE

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Abstract

Exploiting heat by incorporating heat exchanger pipes into tunnel linings has been recently proposed. This paper investigates this topic by studying a possible application for a new metro line currently under design. The Dudullu-Bostanci line, planned to be excavated in the Turkish city of Istanbul is considered. The heat exchange potential for the tunnel is evaluated, together with the environmental and economical impacts.

1 Introduction

Today, more than 50 percent of the world's 7 billion people live in cities, and, by 2050, this will rise to 70 percent. Roughly, 75 percent of global world economic activity grow within cities, and, as the urban population grows, so will the urban share of global GDP and investments (McKinsey, 2011). Urbanization will increases over the next several decades, with the dynamism of cities representing a major sustainable development opportunity. A city's ecological footprint contributes significantly to climate change, as they consume two-thirds of the world's energy and produce approximately 70% of the greenhouse gas emissions. At the same time, cities are ideal focal points for strategies on reducing greenhouse gas emissions.

Urbanization has created a pressing need for infrastructure investment. Cities must have functioning traffic systems, intelligent logistics, efficient energy supplies, and environmentally compatible infrastructures.

Managing growing cities with decreasing budgets and increasing complexity, along with the expectation of a higher quality of life, places heavy demands on both infrastructure and environment. The megatrends urbanization, demographic change and climate change will shape the future. Mobility is key for cost-effective and environmentally friendly urban development. By relying on renewable energy, electro-mobility will significantly reduce environmental impact. This contribution to sustainability is magnified by the parallel use of the underground space, as it is for most of the urban metro lines. Putting infrastructures underground gives an unparalleled contribution to sustainability: saving land, reducing travel-time and unnecessary visual and noise intrusion.

Managing growing cities and their supply of resources is a formidable task that places heavy demands on infrastructure and the environment. The scientific community is focusing on finding solutions that will support economic growth while reducing pollution and waste.

Well-designed sustainability measures deliver multiple benefits. The effectiveness of a metro line reduces traffic and greenhouse gas emissions. Reducing congestion improves city dwellers' quality of life and cuts the cost of doing business by making delivery times more consistent and reliable.

Starting from these considerations, this paper fixes an innovative solution for adding to the intrinsic benefits of an underground metro line the use of thermal energy from renewable resources. The long metro tunnels (using heat exchangers integrated in the tunnel lining) became a remarkable source of energy exploiting the geothermal resources by active heat exchange with the ground.

Nonetheless, it is relevant to focus, as the exploitation of low enthalpy geothermal wells in urban areas must be planned with wisdom, considering the whole aspects of sustainability. A future underground space dense of deep vertical wells could impair the use of the underground spaces, paradoxically reducing the overall sustainability budget. The solution here discussed balances the reciprocal benefits of the three contributors; the metro line itself, the use of the underground (considering that the metro line itself consumes underground spaces, nevertheless less and with benefits for a larger community) the new frontiers of the geothermal exploitation.

The study described is based on the work performed in the last few years at the Politecnico di Torino on energy geo-structures and energy tunnels in particular. The application to the Istanbul metro case study is supported by Geodata S.p.A., designer of the metro line.

2 Description of the case study

Istanbul, one of the world’s fastest-growing metropolitan area, has advertised a number of incredibly ambitious infrastructure projects to be realized by 2023, the 100th anniversary of the founding of the modern Turkish republic. Istanbul is a mega city that stretches over two continents, separated by the Bosphorus Strait. Today more than 13 million people are living in Istanbul—18% of Turkey’s population. Mobility is the biggest problem facing the city, with the Bosporus Strait dividing the Anatolian from the European side. To address the increasing and urgent demand for improved connectivity, a total of more than 130 km of public transportation routes are under construction, including both metro and tramway systems, all representing part of the very ambitious development program of the Turkish Government to bring into service more than 500 km in a decade.

The Dudullu – Bostanci (DB) Line is part of this huge, expanding, network, in the Anatolian side (Kocaeli Peninsula) of Istanbul. It runs, completely underground, from south to north with a length of 14 km, 13 new stations, and a train depot. It crosses the Kadıköy–Kartal Metro Line, the trans-European railway line and the Üsküdar–Çekmeköy Metro Line.

The underground line starts from the Bostanci Station as a twin tube tunnel (both of which driven with Tunnel Boring Machines). After about 13 km, under-passing the densely urbanised Anatolian Istanbul, from the Yukari Dudullu station the line will be mined (with conventional excavation) for 1.5 km as a single tube tunnel. A fully automated metro system will be implemented (GoA4) with driverless trains, CBTC, and platform screen doors at stations. The line is expected to be completed by 2019. It is connected with the Bosphorus ferry (at Bostanci Harbour), the Marmaray railway, the Kadıköy-Kartal line and the Üsküdar-Çekmeköy line, under construction.

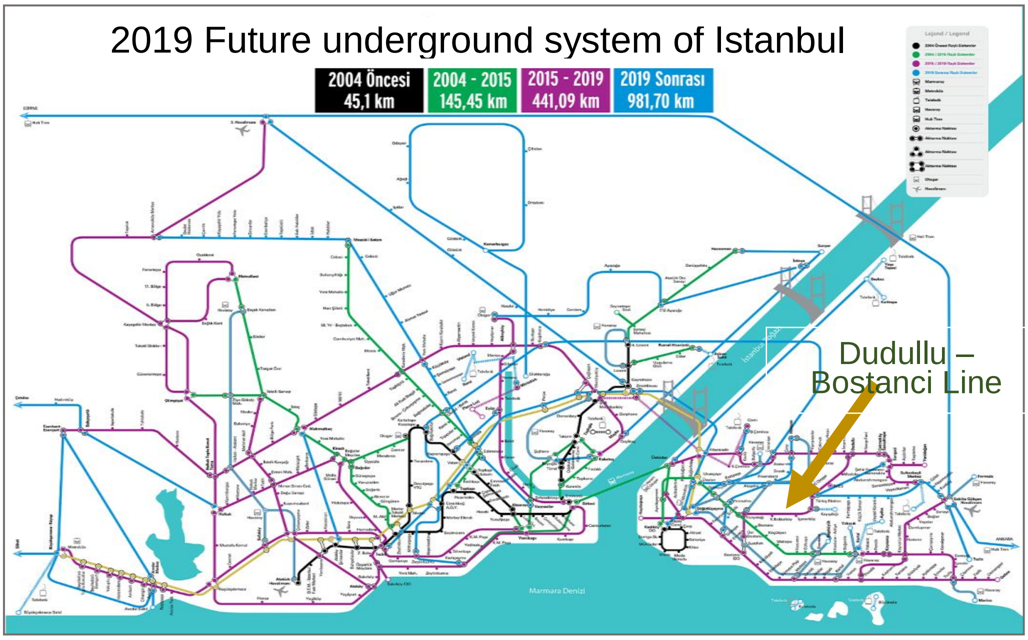


Figure 1. The development plan of the metro network in Istanbul, with the Dudullu-Bostanci Line.

The ground level above the tunnel alignment varies from about 4 m (Bostanci Station) to about 150 m above sea level, near Yukari Dudullu station. The hilly landscape is shaped by the presence of a, relative hard, paleozoic bedrock. This bedrock is covered by alluvial materials, slope deposits (eluvio-colluvium, deposits related to landslides) and anthropic filling along the stream valleys. A variable thickness of residual soil materials, somewhere deep, related with alteration/weathering processes, covers and/or penetrates the underlying bedrock units. Transitional (continental – marine) sediments border the shoreline. At a first level the conceptual hydrogeological model includes three main complexes: a first layer, discontinuous, of soils (porous), then a very variable (laterally discontinuous) thickness of altered/weathered rock masses (dual porosity, somewhere primary, somewhere along factures), then the hard rock masses (discrete fracturing, secondary porosity).

3 Determination of geothermal potential

In order to assess the potential of using the tunnel lining as heat exchanger with the subsoil, it is important to determine the heating potential of the different geological formation interested by the excavation. The heating potential can be defined as the specific capacity to transfer heat and is measured in W/m^2.

The heating potential is different for heating or cooling purposes, it depends essentially on the temperature of the subsoil, on the velocity and direction of the groundwater flow and on the thermal conductivity of the soil/rock. It also varies on the basis of the velocity of the heat transfer fluid in the pipes, on the spacing of the pipes, on the temperature of inlet fluid and the total length of the circuit.

The heating potential can be assessed by heat transfer and fluid flow finite element analyses. Examples are given by Barla et al. (2015) and Di Donna & Barla (2015). The output of the numerical analysis is the difference between the inlet and the outlet temperature of the heat transfer fluid from which one can compute the heat exchanged with the soil.

Based on extensive research performed at Politecnico di Torino, Di Donna & Barla (2015) also suggested a simplified and preliminary approach to assess the heating potential for specific site conditions based on the use of the design charts shown in Figure 4 which are affected by a number of simplifying assumptions:

- influence of neighbouring rings neglected;
- underground flow rate perpendicular to the tunnel axis;
- pipes located at 10 cm from the extrados and with a distance of 30 cm;
- inlet water temperature of 4°C in winter and 28 °C in summer;
- inlet water velocity equal to 0.4 m/s.

For the case study of interest in this paper, this latter approach was used to asses the geothermal potential of the project. For this purpose, the metro line was divided in sections homogenous from the geological and hydrogeological point of view, and for each section the corresponding parameters (temperature, groundwater flow rate and thermal conductivity) were assessed and, consequently, the heating potential.

3.1 Determination of underground temperature

The temperature of the subsoil was not investigated during the survey campaign related to the preliminary design process. The monthly air temperature of Istanbul is clearly not representative for the subsoil. As a first approximation, the ground temperature was assumed to be equal to that of the sea water temperature (Figure 2), based on the higher thermal inertia of water with respect to air and on the proximity of the track to the sea.

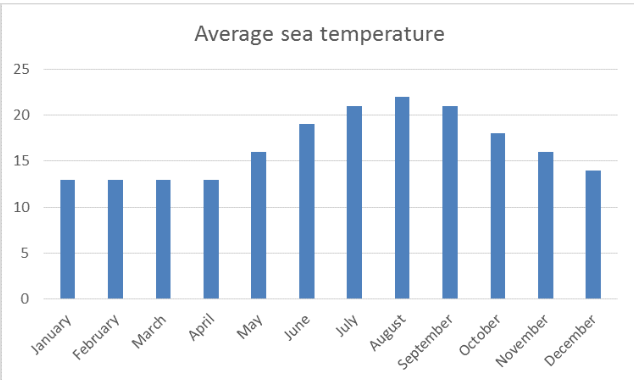


Figure 2. Average sea temperature in Istanbul.

Average temperatures for cooling and heating periods were considered based on Durmayaz A. (2000). The assumed temperatures are given in Table 1. It is clear that these values are a simplified assumption that should be assessed by proper site measurements in the case thermal activation of the tunnel lining will be effectively considered in the future.

Table 1. Average subsoil temperature for the heating and cooling periods.

Average subsoil temperature	
Heating [°C]	Cooling [°C]
14.29	19.80

3.2 Determination of thermal conductivity

Thermal conductivity was determined thanks to correlation with the Uniaxial Compressive Strength, (UCS) of the ground, according to Yasar (2008). Values of thermal conductivity are given in Figure 3 as a function of chainage. Only the sections with higher thermal conductivity are considered in the following for heat exchange application (i.e. PK from 8.8 to 9.6 km).

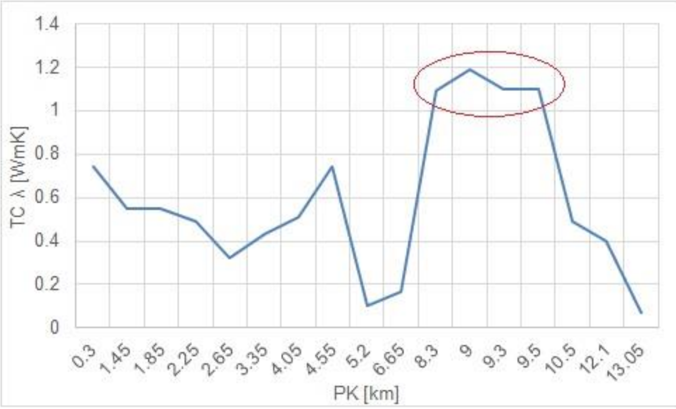


Figure 3. Thermal conductivity versus chainage.

3.3 Determination of groundwater flow rate

The groundwater flow rate strongly influences the geothermal potential of the tunnel, contributing to the heat exchange by convection. It depends on the permeability of the medium and the hydraulic gradient applied. It is possible to estimate the flow rate velocity using the Darcy's law. This was done for each section of the tunnel.

Lugeon tests were conducted to determine the hydraulic conductivity of the rock mass formations while Lefranc tests were performed in soils. Average values were considered. The hydraulic gradient was estimated thanks to the hydrogeological map (Istanbul Metropolitan Municipality 2014).

3.4 Estimation of the heat exchange potential

Di Donna & Barla (2015) design charts shown in Figure 4 were directly used for the evaluation of the heating potential for the most promising section in the rock mass formation (Section A), where higher conductivity is present, and in the soil (Section B), where the permeability is higher. Detailed data are given in Table 2.

The geothermal potential resulted to be higher for Section B (Tab. 3), both in heating and cooling mode, mainly because of the flow rate velocity that increases heat transport by convection.

Table 2. Heating and cooling potential for most promising sections along the tunnel alignment.

Section	Formation	PK [km]	Geological formation	Hydraulic conductivity k [m/s]	Flow rate v [m/d]	Thermal conductivity λ [W/mK]	Groundwater temperature	
							Heating [°C]	Cooling [°C]
A	Rock	8.8 - 9.2	Kurtköy	1.00E-06	~ 0	1.19	14.29	19.80
B	Soil	11.4 - 12.8	Sultanbeyli	2.60E-05	0.225	0.38	14.29	19.80

Table 3. Heating potential for Sections A and B.

Section	Heat extraction (W/m²)	Heat injection (W/m²)
A	10	15
B	20	20

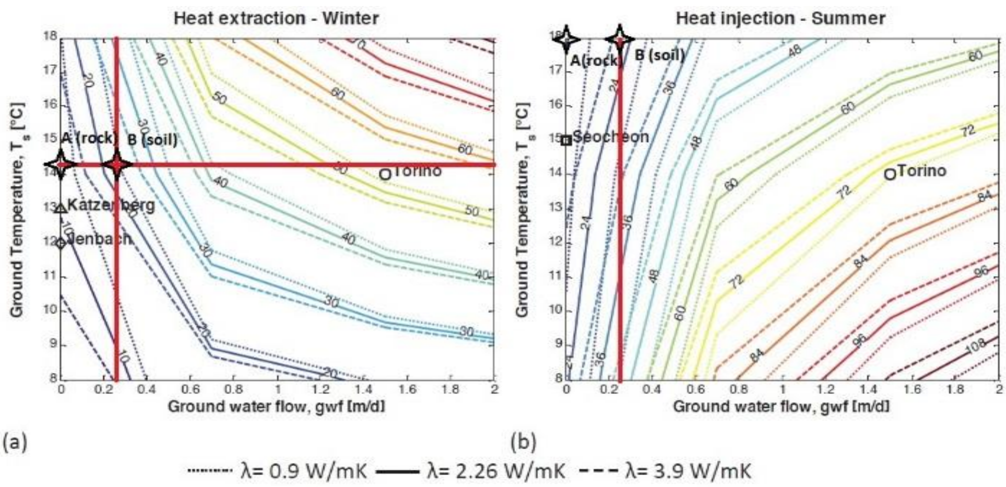


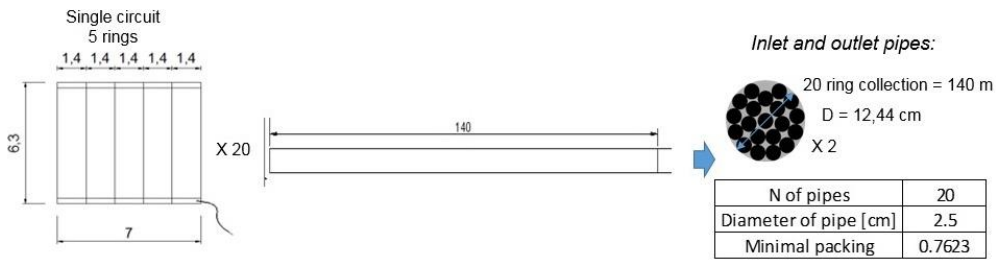
Figure 4. Evaluation of heat extraction (a) and injection potential (b) for Section A and B, according to Di Donna & Barla (2015).

4 Technological aspects for tunnel lining activation

Technological aspects related to the activation of the tunnel segmental lining with heat exchangers are similar to those proposed for the Jenbach tunnel (Frodl et al. 2010, Franzius and Pralle 2011) and for Turin metro tunnel (Barla & Perino 2014, Barla et al. 2015). The heat exchanger fluid flows into pipes embedded in the concrete of the lining segments, which are installed by the Tunnel Boring Machine. Joining of the circuit is accomplished after installation.

The absorber pipes consist of cross-linked high resistance polyethylene (PE-X). The external diameter of the pipe is 25 mm and the average spacing in the lining is between 25 to 30 cm. A good compromise between efficiency and practical application was found to be obtained by joining together 5 rings in series, to form a single circuit, and then connect each circuit in parallel with the others (Barla et al. 2015).

The tunnel external diameter for Istanbul metro is 6.3 m and the longitudinal thickness of the ring is 1.4 m. Therefore each circuit of 5 rings is 7 m long. Based on these assumptions, a group of 20 circuits, covering a total length of 140 m, will need 20 inlet and 20 outlet pipes, resulting in two equivalent tubes of 12.5 cm of diameter (Fig. 5).



N of pipes	20
Diameter of pipe [cm]	2.5
Minimal packing	0.7623

Figure 5. Geometry of the heat exchanger system.

Once the geometry of the problem is defined, it is possible to compute the total power generated by the system, based on the geothermal potential of the ground (20 W/m^2 both for heating and cooling) for the section with higher potential. The result is given in Table 4 with reference to a 140 m (2 tubes) and a 280 m (4 tubes) length.

Considering an operating time of 6000 h per year (i.e. 3500 h for heating and 2500 h for cooling), the total annual energy produced by the system can also be evaluated as shown in Table 5.

Table 4. *Heating power for Section B.*

Heating potential [W/m^2]					Heating power [kW]	
Winter	Summer	Number of equivalent tube	Tunnel diameter [m]	Length of installation [m]	Winter	Summer
20	20	2	6.3	140	55.4	55.4
20	20	4		280	110.8	110.8

Table 5. Annual energy produced for Section B.

Length of installation [m]	Heating power [kW]		Hours of working [h]		Annual energy produced [MWh]	
	Winter	Summer	Winter	Summer	Winter	Summer
140	55.4	55.4	3500	2500	194	138.5
280	110.8	110.8			387.9	277.1

5 Environmental and economical aspects

The application of heat exchangers in the tunnel lining is designed with the main purpose to exploit renewable energy for heating and cooling of buildings. Environmental impact as well as economical aspects needs to be evaluated within a cost/benefit analysis of such a system. This is done in the following, in a very preliminary form, by considering 1 km of tunnel activation for heating and cooling purposes.

The information needed are:

- the Coefficient Of Performance (COP) and Energy Efficiency Ratio (EER) of the heat pump, both assumed to be equal to 5;
- the annual electricity used by the Ground Source Heat Pump (GSHP) to heat and cool the water for the end user which can be determined dividing the annual energy produced by the heat exchanger system for the COP and EER of the heat pump;
- the emission for the electricity consumed in Turkey (Brander et al. 2011): 1009.75 gCO_2/kWh;
- the emission for natural gas boiler (www.biomassenergycentre.org.uk): 229 gCO_2/kWh;
- the emission [gCO_2/kWh] for air conditioner considering a EER equal to 3.2 (energy class B).

The computed reduction in CO_2 emission is shown in Table 6 if the GSHP system is compared to heating by gas boiler and cooling by air conditioning. Moreover Table 7 shows a simplistic comparison with the emission produced by a Fiat 500 1.3 Diesel (www.ilsole24ore.com).

Table 6. CO_2 emissions avoided with 1 km of tunnel activation for heating purposes.

	Winter	Summer	Total	Difference
Electricity need [MWh]	276	198	474	
Emission for GSHP heating [tCO_2/year]	279	200	479	-150
Emission for natural gas boiler [tCO_2/year]	*317*	-	*317*	
Emission for air conditioning [tCO_2/year]	-	*312*	*312*	
Total emissions for traditional systems [tCO_2/year]			629	+150

Table 7. Comparison with emission produced by a Fiat 500.

CO_2 savings [t/year]	CO_2 emission fiat 500 [kg/km]	Equivalent km covered [km]	Earth circumference [km]	Number of around the world laps
150	0.11	1363636.4	40075	34

The estimation of installation costs was performed with reference to a length of 280 m. Main installation costs are due to pipes installation, those embedded in the lining and those of the primary circuit. The total cost for a length of 280 m was estimated to be approximately 50,000 € that corresponds to a price of construction of less than 200 €/m, which is minor if compared to tunnel construction costs.

6 Conclusions

Thermal activation of urban tunnels is definitely a promising technique to exploit a renewable and local energy source. This paper has shown a possible application to the Istanbul metro line Dudullu-Bostanci by highlighting the steps needed to assess the energy potential, estimating the reduction on environmental impact when compared to traditional air conditioning systems and estimating the installation costs.

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