Factors affecting the energy efficiency of energy diaphragm walls

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POLITECNICO DI TORINO

PROJECT OBJECTIVE

Parametric analyses performed to investigate the relative influence of engineering parameters on energy walls efficiency.

STSM by Alice Di Donna and Francesco Cecinato

Host: Fleur Loveridge at Southampton University

Pictures from Amis et al. (2010)
INTEGRATING GEOTHERMAL LOOPS INTO THE DIAPHRAGM WALLS OF THE KNIGHTSBRIDGE PALACE HOTEL PROJECT

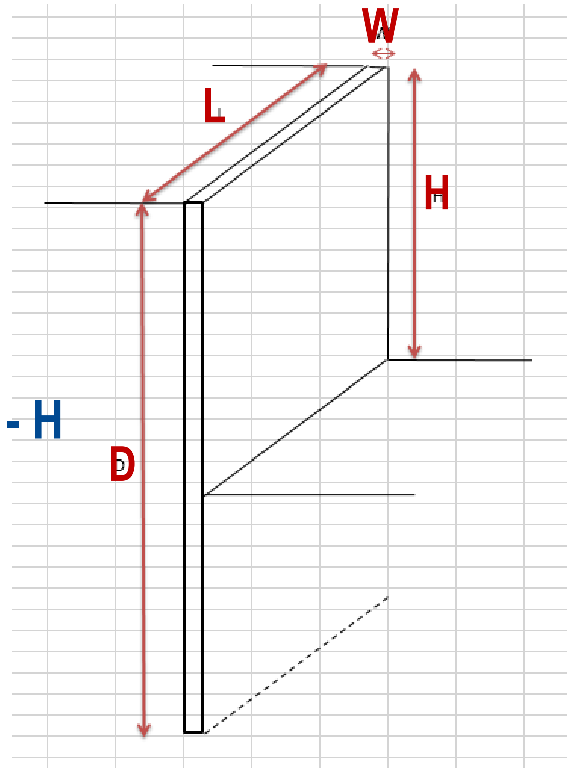
OVERVIEW

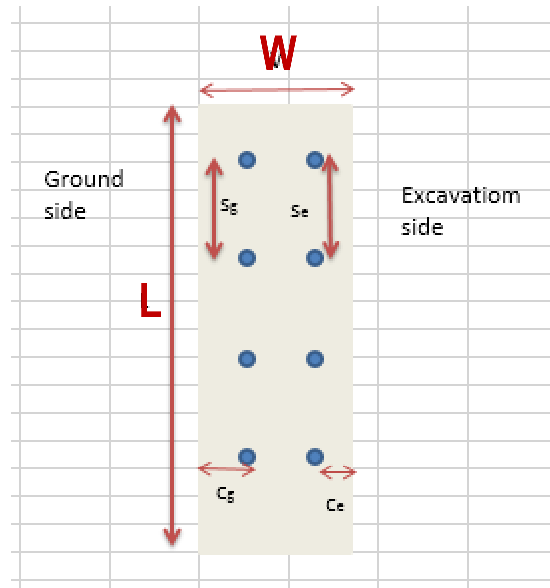
- Review of existing work and case study
- Choice of parameters and ranges
- Validation analysis
- Numerical models
- Definition of runs based on Taguchi method
- Results of numerical analyses
- Statistical analysis of results
- Conclusion and future work

REVIEW

Data from existing case studies and construction practices to ensure reliability of analyses

- Geometry
  - ✓ Panel width - W
  - ✓ Panel length - D
  - ✓ Embedment – (D-H)
  - ✓ Length open to excavation - H





- Number of pipes or spacing
  - ✓ U or W or ..
- Pipes on one or both sides
  - ✓ Both sides but on excavation side only in the embedded section (Austria)
  - ✓ Both sides – heat exchange with excavation air (tunnels)
  - ✓ Only ground side (preferable when construction imposed that the cage must be spliced on site)
- Concrete cover

REVIEW

Data from existing case studies and construction practices to ensure reliability of analyses

Case & References	Wall Depth	Embedment Depth[1]	Panel Width	Panel Length	Pipes spacing (Ground Side)	Pipes on Excavation Side?	Pipe cover	Pipe Size
U2 Taborstrasse Station, Vienna [11], [12]	31m	10.45m	0.8m		0.53m	Yes	60mm (to steel, pipes inside steel)	25mm
Shanghai Museum of Nature History [6], [7]	30 – 38m	12m – 20m	1.0m	3.7m	1 U-loop per panel	Yes	87.5mm	25mm/ 20.4mm
Bulgari Hotel (formerly Knightsbridge Palace Hotel) [13]	Up to 36m	11.65m	0.8m		0.84 (average)	No	75mm	
Dean Street Station, London [14]	41m	12m	1.0m					
Tottenham Court Road Station, London			1.2m	3m	0.5m	No	40mm (pipes in 75mm cover zone)	35mm
Moorgate Shaft, London	48.5m to 52.4m		1.2m		0.452m interloop, 0.603m between loops	No	62.5mm	25mm/ 20.5mm
Arts Centre, Bregenz, Austria [15]	Up to 28m	Up to 17m	0.5m to 1.2m		A wavy or slinky type arrangement was used			

REVIEW

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Different functions: basements? Car parks? Metro stations? Shallow tunnels?

Assumptions on boundary conditions on wall side – particularity of diaphragm walls

Constant Temperature (stations/basements)

Convective heat flux (link to wind speed)

$$q = h(T_{excavation} - T_{wall})$$

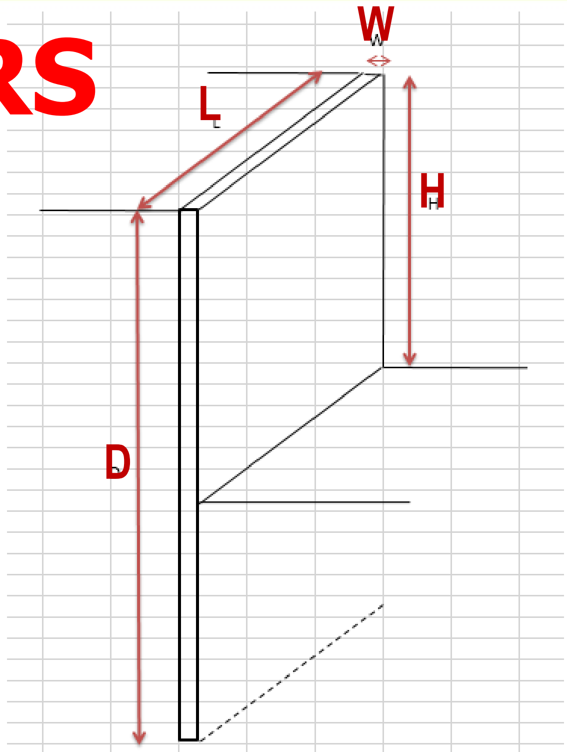
Case & Source	Scenario	Heat Transfer Coefficient (W/m²K)	Comments
Lainzer Tunnel Analysis[5]	Metro tunnels & stations	10 - 15	
General sensitivity analysis only [4]	Not specified	2.5 - 25	Depending on wind speed
Mongolian Road Tunnel [20][21]; note not diaphragm wall, but comparable analysis	Road tunnel	15	
Crossrail Tunnel [21] ; note not diaphragm wall, but comparable analysis	Rail tunnel	5	
Analytical model and laboratory experiments [17]	Basements	7.7	Based on ISO 6946

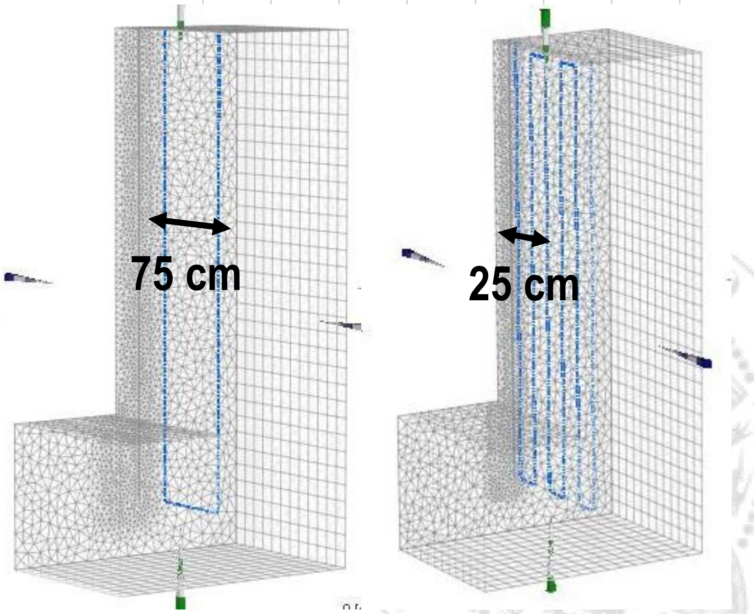
CHOICE OF PARAMETERS

Need to chose parameters that we want to investigate and range on variability for the subsequent statistical analysis

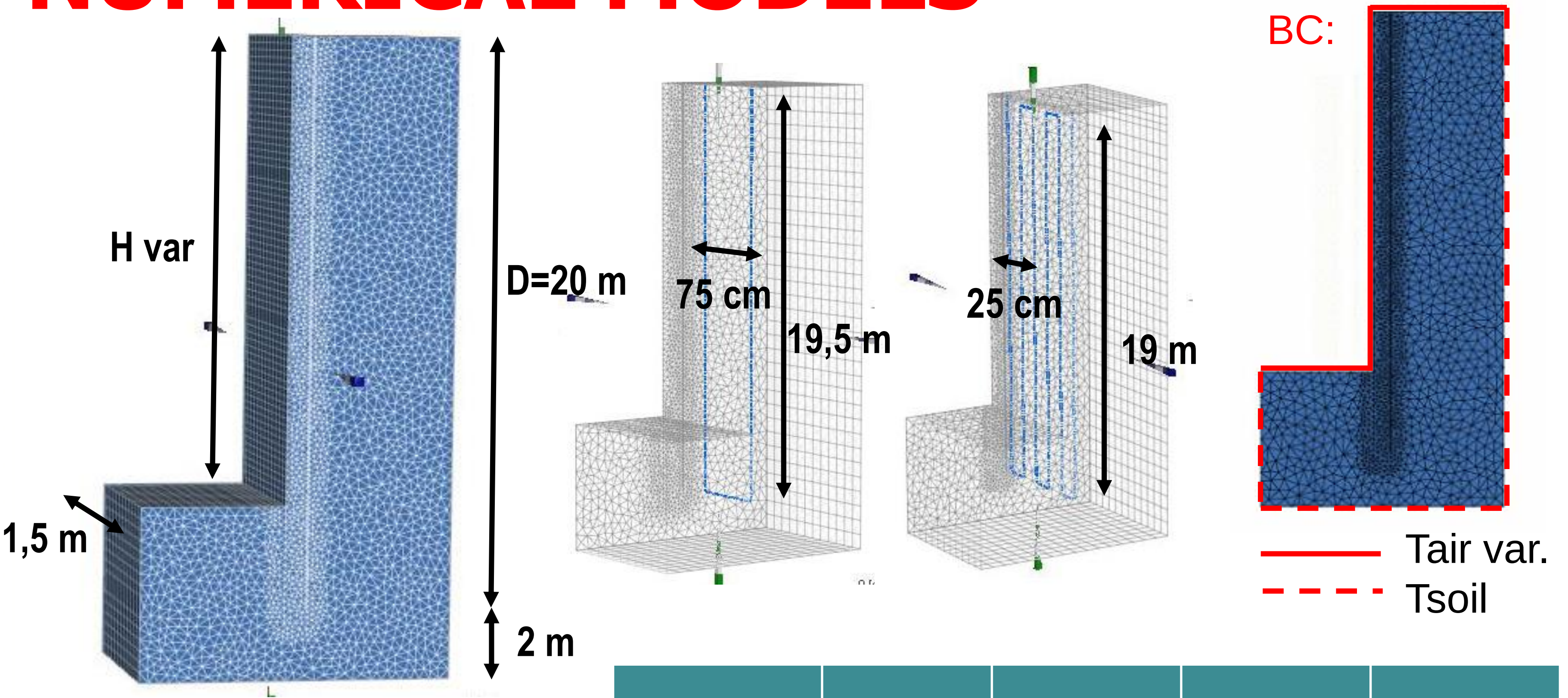
Parameters	Lower (1)	Upper (2)
Panel width - W	0.8 m	1.2 m
Depth/excavation ratio – D/H	1.25	2
Spacing of pipes	25 cm	75 cm
Concrete cover to pipes	50 mm	100 mm
Fluid velocity	0.2 m/s	1.2 m/s
Difference in temperature between the soil and external air *	2 °C	6 °C
Concrete conductivity	1.5 W/mK	3 W/mK

*** Assumption of constant temperature on the walls side**





NUMERICAL MODELS

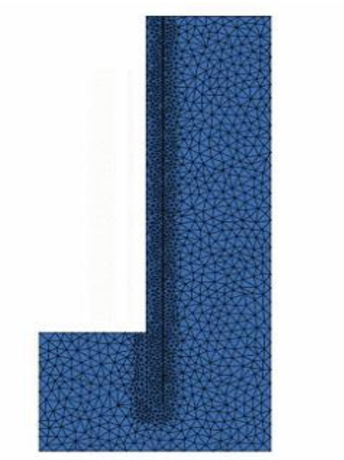


Property	Concrete	Soil	Water	Pipes
Bulk thermal conductivity [W/m/K]	Depends on the run	2.0	0.6	0.42
Bulk specific heat capacity [J/kg/K]	1600	1600	4200	2300
Density [kg/m³]	2210	1900	1000	950
Porosity [-]	0	0.3	-	-

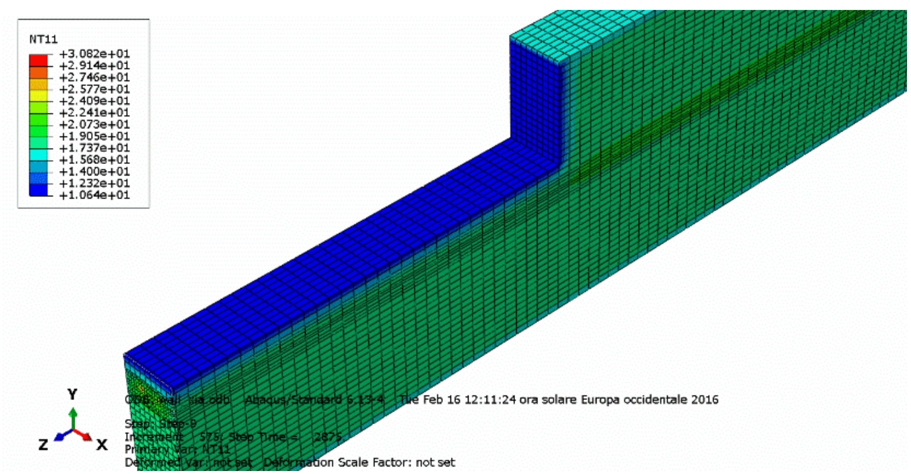
Pipes diameter = 25 mm
Pipes thickness = 2.3 mm
Initial temperature = 12 ° C
Inlet temperature = 20 ° C

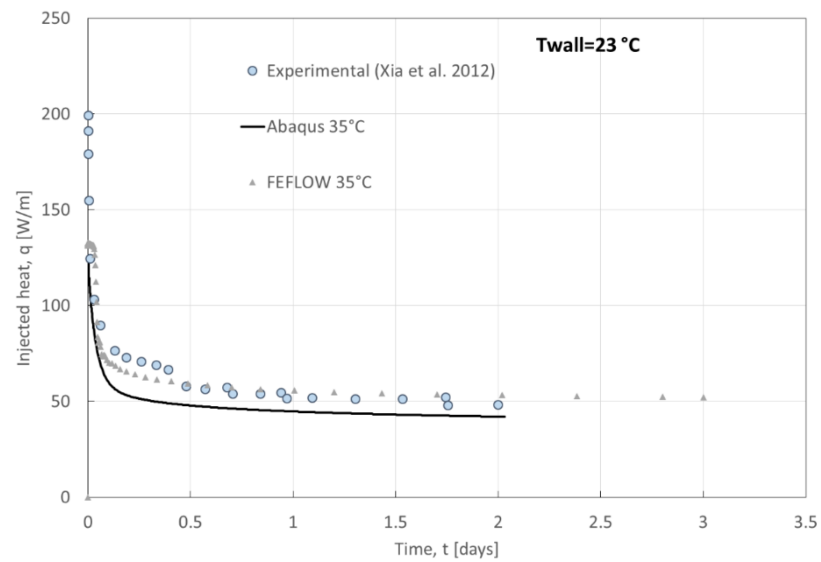
VALDIATION ANALYSES

- Xia et al., “Experimental study on geothermal heat exchangers buried in diaphragm walls”, Energy and Buildings 52 (2012) 50–55
- Sun et al., “Heat transfer model and design method for geothermal heat exchange tubes in diaphragm walls”, Energy and Buildings 61 (2013) 250–259



Property	Concrete	Soil	Water	Pipes
Bulk thermal conductivity [W/m/K]	2.34	1.74	0.58	0.42
Bulk specific heat capacity [J/kg/K]	1046	1690	4200	2300
Density [kg/m^3]	2500	1800	1000	950
Porosity [-]	0	0.3	-	-





ABAQUS MODEL

Use of software ABAQUS

- To integrate 3D transient conduction through the concrete & the ground

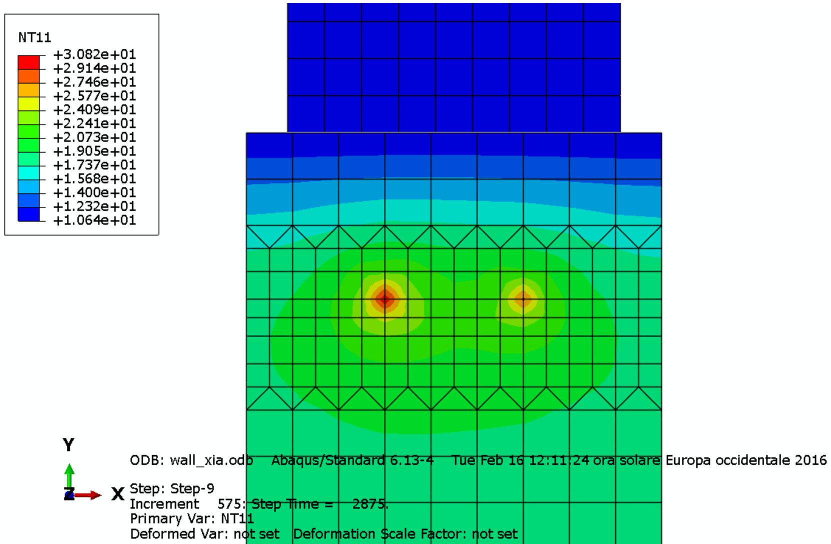
$$\rho_s c_{ps} \dot{T} = \nabla \left(\lambda_s \nabla T \right)$$

+ Bespoke user subroutines

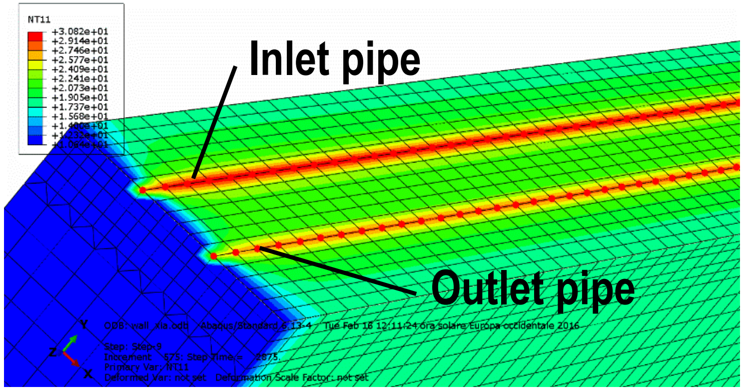
- To model the convective heat transfer at the fluid/solid interface and the temperature changes in the fluid along the pipe

$$\dot{m} c_{pf} \nabla T = h_{eq} \Delta T$$

- 3D FE mesh manually created to minimise computational time and to accommodate user subroutines



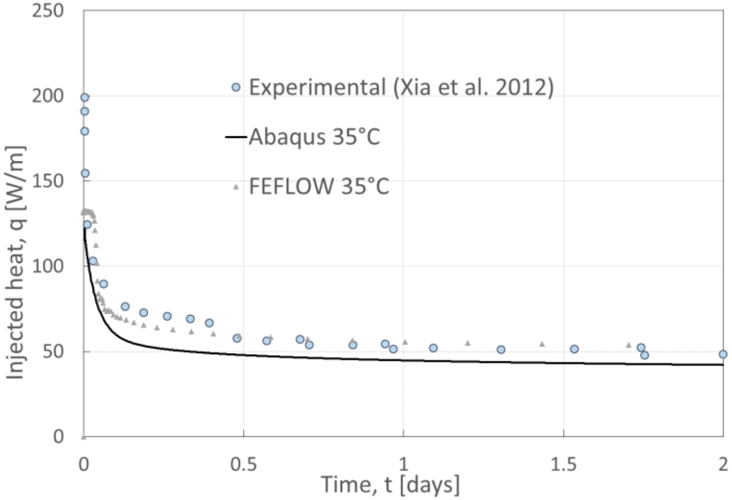
ABAQUS MODEL

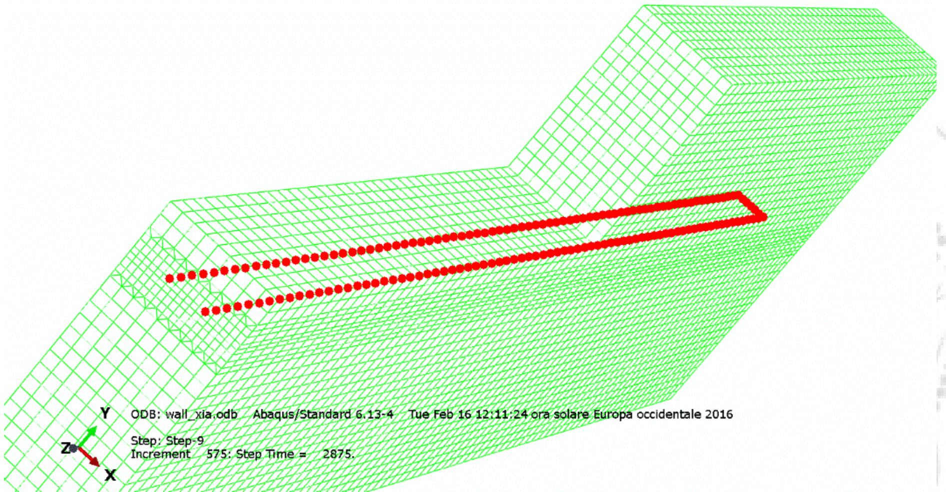


Details on pipe schematization

- Pipes are represented as lines of nodes (1D)
- The 3D nature of the pipes is accounted for via the user subroutines, by considering the lateral surface area of each pipe segment.
- The presence of pipe wall is accounted for by using an ‘equivalent film coefficient’ h_{eq} (Choi et al. 2009, Cecinato & Loveridge 2015).
- Possible reason for Abaqus simulation plotting ‘lower’ in validation compared to FEFLOW

$$h_{eq} = \left[\frac{D_{out}}{2\lambda_{pipe}} \ln\left(\frac{D_{out}}{D_{in}}\right) + \frac{D_{out}}{D_{in}h}\right]^{-1}$$





PARAMETRIC STUDY

- To identify the most most important design parameters in maximising energy efficiency.
- Focus on simulated q (W/m) after 30 days of heat injection

Parameters	Lower (1)	Upper (2)
Panel width - W	0.8 m	1.2 m
Depth/excavation ratio – D/H	1.25	2
Spacing of pipes	25 cm	75 cm
Concrete cover to pipes	50 mm	100 mm
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Concrete conductivity	1.5 W/mK	3 W/mK

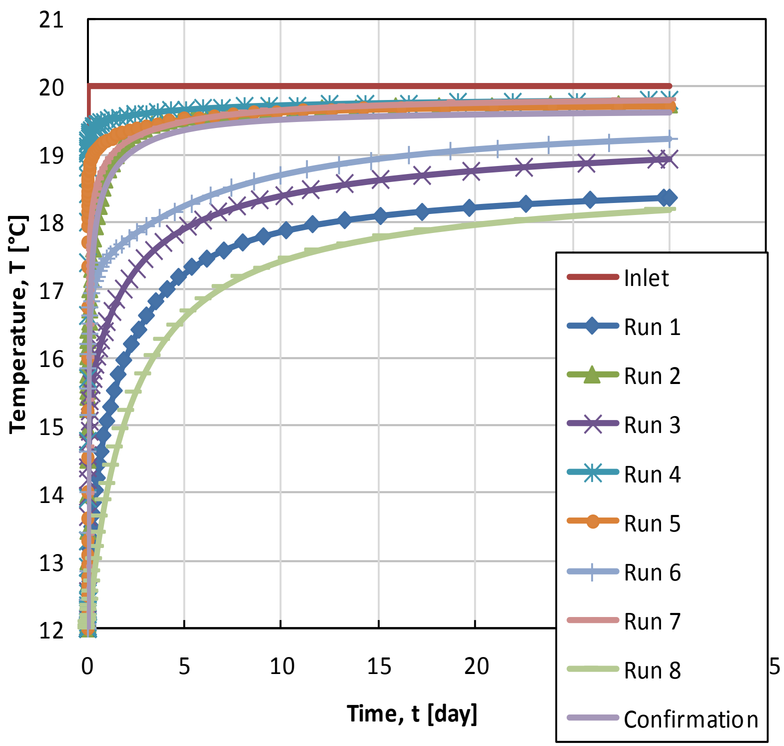
Explore ALL possible combinations of 7 parameters with 2 levels each:

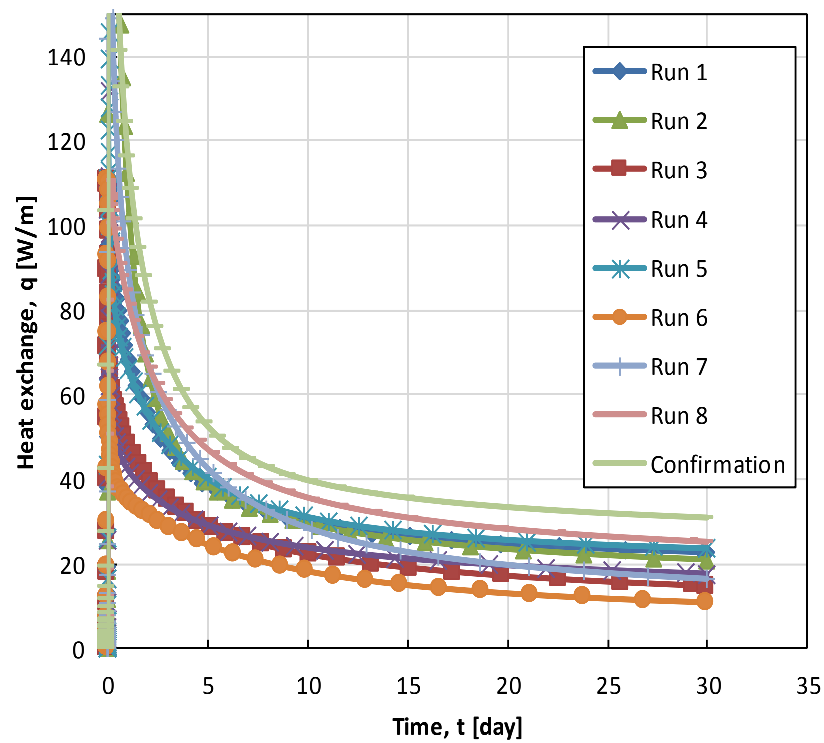
- "Full factorial" analysis
  -> exploring all possible parameter combinations would imply to perform 2^7=<u>128 runs</u>
- Exploring SIGNIFICANT combinations of 7 parameters with 2 levels each:
  "Taguchi" L8 array -> only <u>8 runs</u> needed

Experiment Number	Column 1	2	3	4	5	6	7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

RESULTS

		Parameters							
		Panel width	Depth/excavation	Spacing*	Cover	Fluid velocity	DT	concrete cond	*Response (W/m at end of simulation)*
Runs	**1**	0.8 m	1.25 (exc 16m)	25 cm	50mm	0.2 m/s	2 °C	1.5 W/mK	2.26E+01
	2	0.8 m	1.25 (exc 16m)	25 cm	100mm	1.2 m/s	6 °C	3 W/mK	2.09E+01
	3	0.8 m	2 (exc 10 m)	75 cm	50mm	0.2 m/s	6 °C	3 W/mK	1.47E+01
	4	0.8 m	2 (exc 10 m)	75 cm	100mm	1.2 m/s	2 °C	1.5 W/mK	1.76E+01
	5	1.2 m	1.25 (exc 16m)	75 cm	50mm	1.2 m/s	2 °C	3 W/mK	2.35E+01
	6	1.2 m	1.25 (exc 16m)	75 cm	100mm	0.2 m/s	6 °C	1.5 W/mK	1.08E+01
	7	1.2 m	2 (exc 10 m)	25 cm	50mm	1.2 m/s	6 °C	1.5 W/mK	1.63E+01
	8	1.2 m	2 (exc 10 m)	25 cm	100mm	0.2 m/s	2 °C	3 W/mK	2.52E+01





STATISTICAL ANALYSIS

So-called level average analysis, consisting of

1.calculating the average simulation result for each level of each factor,

2.quantifying the effect of each factor by taking the absolute difference between the highest and lowest average results

3.identifying the strong effects, by ranking the factors from the largest to the smallest absolute difference. Results are summarised in the response table:

	Panel width	Depth/excavation	Spacing*	Cover	Fluid velocity	DT	concrete cond
avg result min	1.89E+01	**1.95E+01**	**2.13E+01**	**1.93E+01**	1.83E+01	**2.22E+01**	1.68E+01
avg result max	**1.90E+01**	1.84E+01	1.66E+01	1.86E+01	**1.96E+01**	1.57E+01	**2.11E+01**
Effect	1.73E-02	1.01E+00	4.61E+00	6.83E-01	1.27E+00	6.53E+00	4.26E+00
Ranking for q (30 days)	**7**	**5**	**2**	**6**	**4**	**1**	**3**

PARAMETER RANKING

Most significant parameters (top 4 out of 7) in enhancing energy performance

1. Difference T_{soil}-T_{air} (>0) (the smaller, the better)
2. Pipe spacing (the smaller, the better)
3. Concrete conductivity (the larger, the better)
4. Fluid velocity (the larger, the better)

Preliminary observations

- Air temperature within excavation is very important -> benefits of exploiting the retaining walls installed for railway tunnels and metro stations
- In common with other ground heat exchangers increasing the number of pipes by reducing their spacing is the primary route to increasing energy efficiency
- Thermal properties of the wall concrete also important, but not always easy to engineer

CONCLUSION & FUTURE WORK

- Parametric study showed the relative importance of key design parameters for medium-long term energy performance
- Further analysis will be carried out to consider:
  - The use of varying values of heat transfer coefficients
  - The effect of the timescale of the study
  - The effect of variable heat/cool demand
- Guidelines will be provided for the energy design of energy walls
- Paper to be submitted to an ICE journal soon