Energy Walls

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FOURTH-YEAR UNDERGRADUATE PROJECT

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I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

Signature: Date: 28/05/2014

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1 Introduction

Fossil fuels have always been the prime energy source for generating electricity, car fuels, etc. A large amount CO_2 is emitted throughout the production and usage of the fossil fuels. The increase in CO_2 concentration in the atmosphere intensifies the greenhouse effect which links with climate change.

Also, it is a non-renewable energy source and would be exhausted in the near future. These are further exacerbated by the increase in global energy demand due to the rising global population and improvements in living standards.

Hence it is imperative to develop renewable energy technologies to reduce the usage of finite energy sources and CO_2 emissions. Although the dependency on fossil fuels has to be reduced, but the current and future energy requirements accounting for future developments need to be satisfied.

Space heating and cooling account for more than one ninth of the global energy consumption (International Energy Agency, 2013). This consumption can be cut down by improving the insulation of buildings or by using a more efficient space conditioning system.

Ground Source Heat Pump(GSHP) is one of the low-carbon and most energy-efficient heating and cooling technologies for buildings. This technology exploits the geothermal energy exhibits in ground and can be implemented in structures foundations. These are called Energy Piles or Energy Walls for installations of GSHP in piles or diaphragm walls.

1.1 Literature Review

1.1.1 Ground Source Heat Pump(GSHPs)

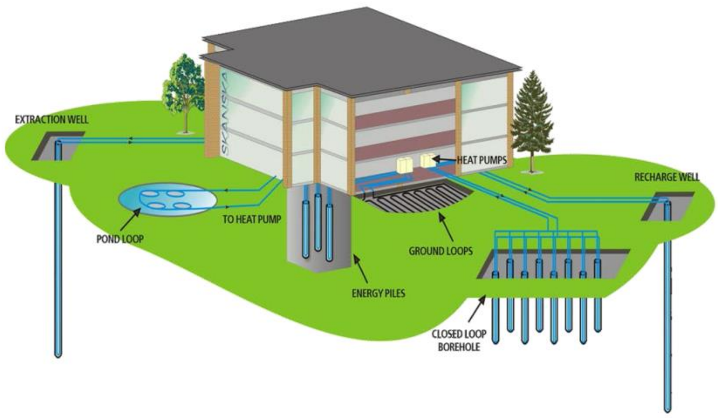


Fig. 1 - Different type of GSHP solutions(T.Amis, 2011 , Bibliography [4])

The variation in ground temperature is small at depth greater than 10m (Fig. 2), and stays ~12^{o}C in UK. GSHPs utilise this difference in temperature between surface atmosphere and the subsurface soil to provide a sustainable space heating and cooling for buildings. They are suitable for many residential and commercial buildings such as housings, offices and retail stores. Some examples of the application of GSHP are shown in Fig. 1.

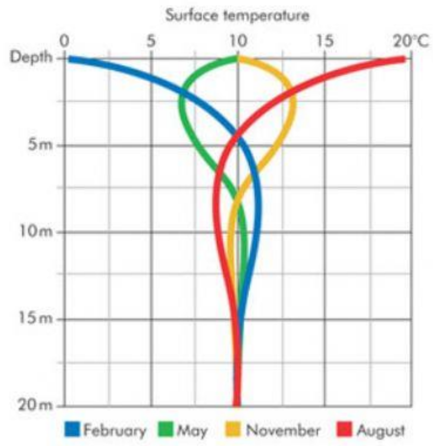


Fig. 2 - Seasonal ground temperature variations with depth(FWT Ltd, Bibliography [12])

The main components of a GSHP (Fig. 3) consist of a primary circuit for thermal exchange, a secondary circuit for thermal energy distribution in the infrastructure and a heat pump connecting the two circuits together. The primary circuit is a closed-loop absorber pipes installed in ground, containing water and anti-freeze for heat exchange in ground. The secondary circuit is a thermal distribution system such as water pipes or conditioned-air. In winter, the heat pump is operated by electricity to convert the low temperature heat energy from ground, to a higher temperature for space and water heating. The process can be reversed for space cooling in the summer. A Coefficient of Performance (CoP) greater than 4 is generally required for economic reasons. This means the output heat energy is at least fourfold of the input electrical energy.

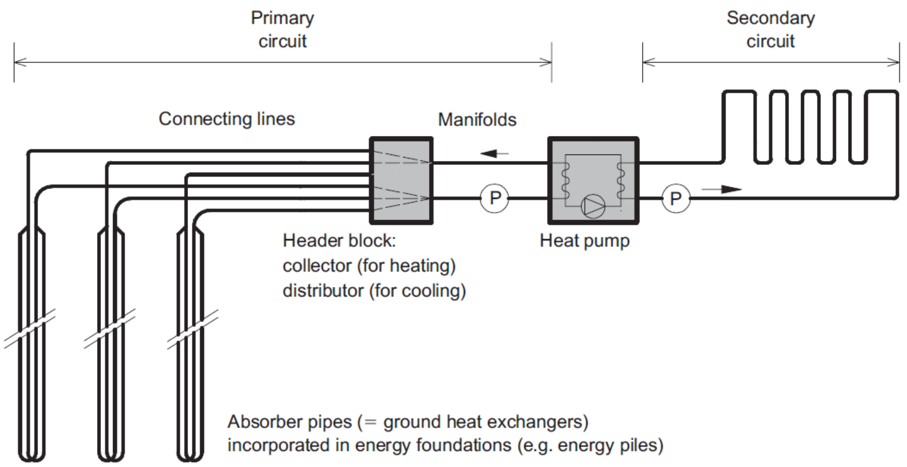


Fig. 3 - Schematic of a typical GSHP system(Brandl, 2006, Bibliography [1])

GSHPs typically have a higher capital cost than conventional heating systems, but have a lower maintenance cost. They are cheaper to operate and don't require fuel storage on-site. The system produces no emissions and consumes less energy and thus reducing the carbon footprint of the process.

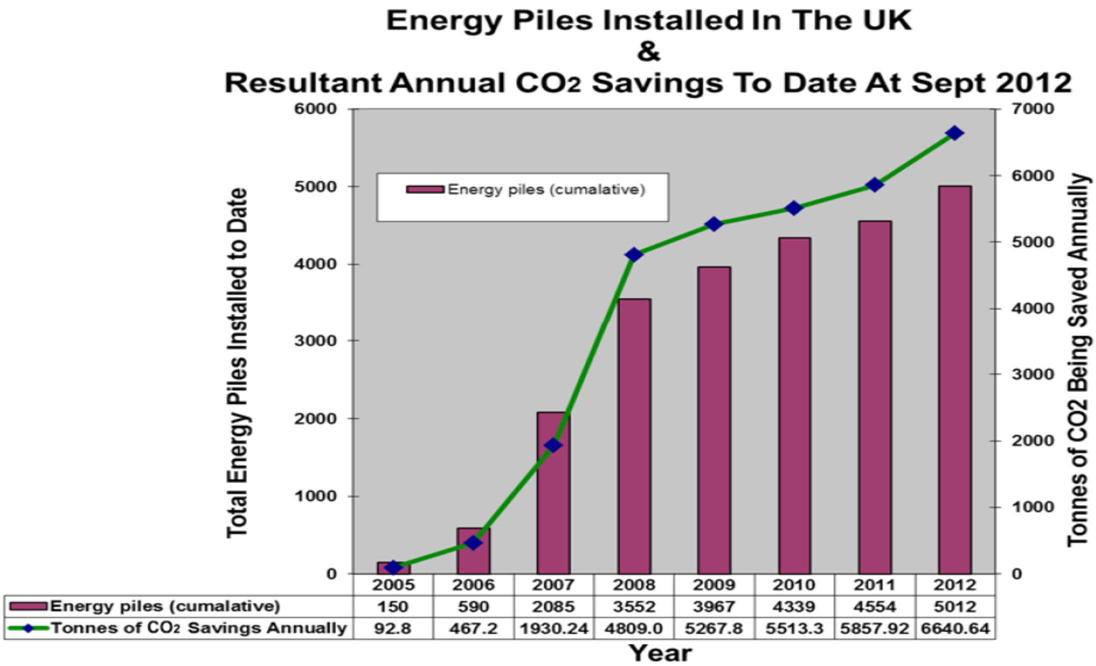
1.1.2 Energy Foundations

GSHP is a well-established and more cost-effective renewable technology for heating and cooling in comparison with others such as solar thermal, thermal energy storage.

It can also be integrated within the structural elements of a building like piles, diaphragm wall, raft foundations, tunnel linings, etc. By installing the primary circuit (absorber pipes) within the foundations (Fig. 4), they become thermo-active and provides both load-bearing and energy for the building.

Fig. 4 - Geothermal loop at Bulgari Hotel(T. Amis, 2010, Bibliography [6])

The first uses of energy piles and walls date back to 1984 and 1996 in Austria and Switzerland respectively (Brandl, 2006). This technology was only first implemented in the UK in an energy pile project in Keble College (Oxford 2001). There are an increase in popularity for energy piles ever since (Fig. 5), e.g. Lambeth College (London 2007) and One New Change (London 2010). The first energy wall installed in the UK(Fig. 4) was at Bulgari Hotel (London 2010).



	2005	2006	2007	2008	2009	2010	2011	2012
Energy piles (cumalative)	150	590	2085	3552	3967	4339	4554	5012
Tonnes of CO_2 Savings Annually	92.8	467.2	1930.24	4809.0	5267.8	5513.3	5857.92	6640.64

Fig. 5 - Energy Piles installed in UK & Resultant annual CO2 Savings (T. Amis, 2014, Bibliography[2])

Embedding the absorber pipes in the concrete of foundations not only save construction costs, it also saves underground space. The delivery of energy foundations depends on its size, construction details, surrounding soil types and how the system is operated (Bourne-Webb, 2013).The heating and cooling costs of a building can be reduced by up to two-thirds over conventional systems with energy foundations (Brandl, 2006).This technology can be applied in both residential and commercial buildings, and is particularly attractive to those that requires high space heating/cooling demand such as rail stations.

1.2 Current research on energy foundations

Many researches have been conducted since the first implementation of GSHPs in structures foundations to improve the knowledge in the geothermal structures. The performance of the energy foundations can be assessed by its efficiency/delivery of energy and structural capabilities.

Several researches have been investigating the effects of the operation of the energy piles on the structural performance of the foundations. It is found that the shaft resistance, base pressure and bearing capacity of the soil of energy piles are not affected by the heat transfer that occurs (Brandl, 2006). This means the settlement or heaving cause by the change in temperature will have negligible effect in relation to displacements caused by static load.

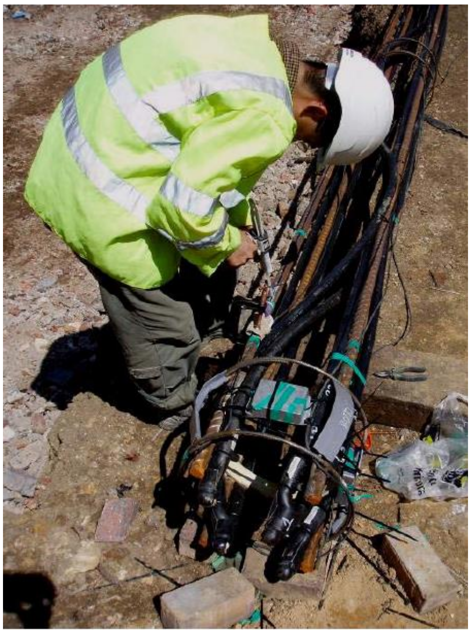


Fig. 6 - Instrumentation on test pile at Lambeth College (Cementation Skanska, Bibliography [5])

A thermo-hydro-mechanical (THM) finite element analysis on the operation of energy piles by Laloui (2006) shows top surface soil would swell during heating of pile. The vertical are mainly dilative and compressive near the bottom of pile. The mechanical and heat induced strains are low, so it has negligible effect on the pore pressures and effective stress.

An in-situ test on energy piles (Fig. 6) was performed at Lambeth College (Bourne-Webb *et al.*, 2009). The shaft resistance and axial load of the pile are affected by the changes in temperature of the pile. Therefore a high safety factor should be used to cope with the induced thermal stresses during cooling and heating. This factor of safety could be reduced if the thermal effects are better understood saving material and cost.

In a more recent paper(Amis, 2010) described installation of energy wall(Bulgari Hotel) and discussed the potential effects of thermal changes during operation. It is found that the fluctuations of loop temperature during winter are less than the concrete-soil interface. There will be temperature variation between the loops and the concrete surface, so thermal bending stress would be induced, but this effect on the structural performance of the wall wasn't discussed on the paper.

1.3 Outstanding issues

The performance of a thermo-active diaphragm wall would be different to an energy pile because the pile would be surrounded by soil, whereas only one side of the wall is exposed to soil. The temperature difference between the soil side and excavating side of the wall would induce bending stress on the wall. Also, it is known that both the wall and soil would expand and contract due to thermal stresses, but their significance are still uncertain.

Also, the heating and cooling of soil would cause soil to expand or shrink. The expansion/shrinkage of soil will induce displacement and results in bending moment in the wall. If hysteresis occurs between heating/cooling cycles, it may affect the structural performance of the diaphragm wall. In the worst case, it may lead to collapse.

Literature review on energy foundations shows that there are many researches on energy piles, but limited research has been performed on energy walls. No one has conducted a research on fully coupled thermo-hydro-mechanical (THM) FE model on energy wall. It is imperative to analyse the effects of the heating and cooling cycles on the wall's short and long term performance to ensure the suitability of this application of GSHPs. This requires both computational and field-tests to obtain full understanding in the area.

1.4 Project Objectives

The Energy Walls project is based on the redevelopment of a Cross Rail Station, Tottenham Court Road (TCR) Station. A new ticketing hall (along with the upgrade of the existing station) is to be constructed at Dean Street to cope with the expected rise in passenger numbers interchanging at the station in 2018. The Dean Street Station box would be incorporating GSHPs forming energy walls and energy piles. This sustainable energy source would help to reduce the project carbon emissions by 20% (Bachy Soletanche, 2013).

The scope of this project involves the analysis of the seasonal operation effects of an energy wall on the structural performance of the wall and the surrounding soil. A 2D coupled thermo-hydro-mechanical (THM) finite element model of the Dean Street Station was created and used for the analysis. The analysis is split into two phases, Construction Phase and Operation Phase. The main aims of the project are:

1. Construction Phase (Hydro-Mechanical Response)
    - Calibrate the governing model parameters for soil behaviour using displacement data obtained during construction of the wall.
2. Operation Phase (Thermo-Hydro-Mechanical Response)

- Analyse the complex THM interactions between the soil and diaphragm wall during heating and cooling cycles, to assess the structural response of the wall.
- To deduce whether the THM response in the soil would affect the wall's structural performance by evaluating the earth pressure in the soil and bending moment and displacement of the wall

1.5 Dean Street Station

Crossrail is a major infrastructure project in London. Various stations are currently being constructed or redeveloped to reduce train journey times and to expand the connections in London rail transport. Ten of twelve of the new station boxes are to include energy foundations. Dean Street is one of these boxes and will include energy walls as well as energy piles, making it the 2^{nd} Energy Wall project in UK. The geothermal capacity is 500kW. The purpose of the new station box is to relieve the pressure from the TCR station because it wasn't designed for the current passenger demand at the time.

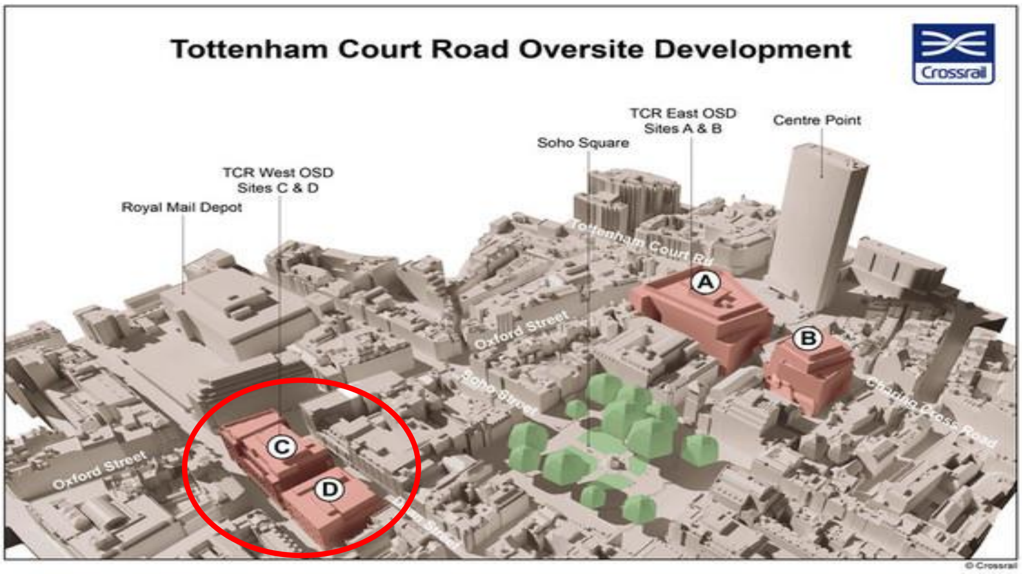


Fig. 7 - Location of Dean Street station box(circled in red) (Crossrail, Bibliography[15])

The station box is situated at the intersection of Dean Street and Oxford Street (Circle in red in Fig. 7), and is constructed using the 'bottom up' method. The 1m thick diaphragm wall (up to 40m depth) is first installed by excavating a trench at a required depth. The absorber pipes are attached to the reinforcement cage and lowered into the trench, where concrete is poured in to cast the diaphragm wall. The soil is excavated 25m deep and adding temporary props to support the excavation. Slabs are casted from the bottom and work upwards replacing props with slabs forming five levels for the station box.

In the original design, five temporary props are used to support the opening (Fig. 8(LHS)). However, the lowest prop was omitted in the actual construction to reduce both time and cost. Also, it can provide a bigger working space for construction equipment. The soil strata of the site and station box schematic are shown in Fig. 8 below. The top soil is 9m of made ground and river terrace, with mostly London Clay(23m) and Lambeth where the wall is installed.

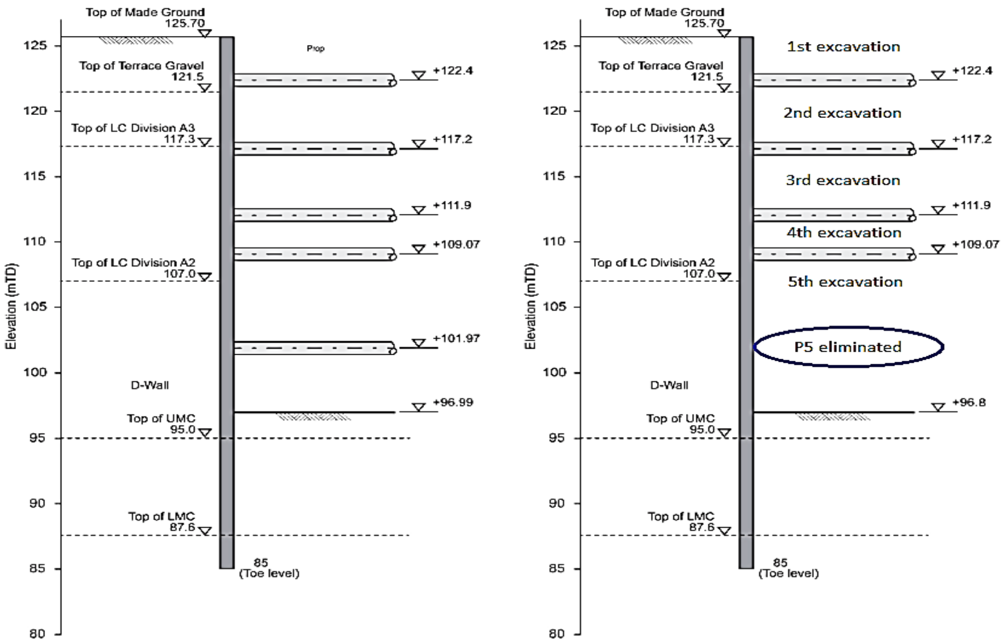


Fig. 8 - Alteration in original design (Arup, 2012, Bibliography [14])

2 Theoretical Basis

The FE numerical simulation of the model is performed using a FE code developing in the Cambridge University Engineering Department for solving fully coupled THM models (Rui, 2011). There are several aspects in an energy foundation system need to be considered. In GSHP, there are fluid-structure interactions and hydro-thermal problem in the pipes. Soil is a multi-phase material containing soil particles, water and air. The heating and cooling of the energy foundation would cause thermal deformation and change the permeability of the soil skeleton. The change in permeability would affect the transfer of pore pressure influencing effective stress in the soil. The function pattern for the fully coupled model used is shown in Fig. 9 below. The three factors are interlinked to another, and cannot be calculated independently.

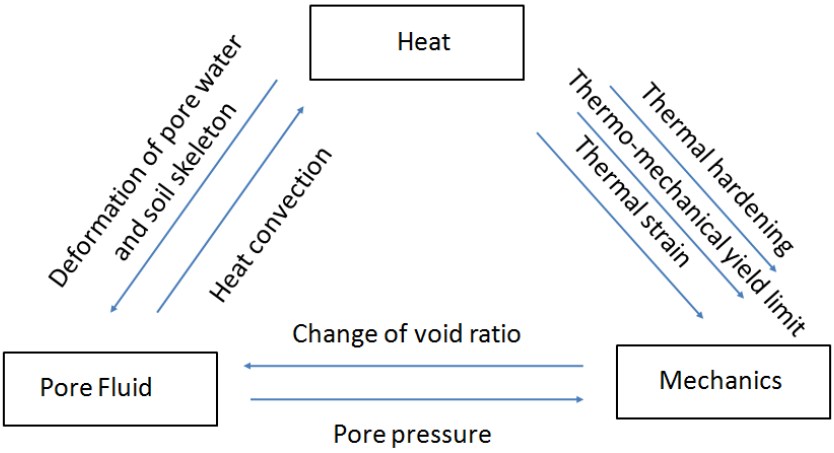


Fig. 9 - Function pattern for fully coupled THM model (Rui, 2011, Bibliography [11])

2.1 Governing Equations

Mass Continuity

$$\frac{\partial \rho}{\partial t} = \Delta.(\rho \boldsymbol{v}) = 0$$

Momentum Conservation (for each single-phase material)

$$\frac{\partial(\rho \boldsymbol{v})}{\partial t} = \Delta.(\rho \boldsymbol{v}^2) = \Delta.\boldsymbol{\sigma} + \rho \boldsymbol{g}$$

Energy Conservation

$$\frac{\partial(\rho c_p T)}{\partial t} + \Delta(\rho c_p T \boldsymbol{v}) = \Delta.k\Delta T + H$$

where, ρ is the density, **v** is the vector for velocity, t is time, **g** is the vector term for gravitation acceleration, **σ** is the stress tensor in the material, k is the thermal conductivity, T is the temperature, c_p is the specific heat at constant pressure, and H is the heat input from all sources.

Effective Stress

Assuming the soil follows Terzaghi's principle of effective stress:

$$\sigma = \sigma' + p$$

Thermo-Hydro-Mechanical(THM) equations(Rui, 2011):

$$\begin{cases} \partial^T[D]\,([\partial]\{d\delta\} - \{d\varepsilon\}^H) - \nabla dp = 0 \text{ (Equilibrium)} \\ \nabla^T[k]\nabla p + \frac{\partial}{\partial t}\nabla^T\{\delta\} + \frac{1}{k_w}\frac{\partial p}{\partial t} + (\alpha_s - n\alpha_w)\frac{\partial}{\partial t}T = 0 \text{ (Diffusion equation for pore pressure)} \\ \rho_w c_p \frac{\partial}{\partial t}\mathrm{T} - \nabla^{\mathrm{T}} D \nabla T + c_p^w k_h \nabla^T(T\nabla p) = 0 \text{ (Diffusion equation for temperature)} \end{cases}$$

where $\{d\varepsilon\}^H = \alpha[1\ 1\ 1\ 0\ 0\ 0]^T dT$, δ is the displacement, p is the pore pressure, D is the stiffness matrix, k_w is the bulk modulus of water, α_s and α_w are the thermal expansion coefficient for soil and water and k_h is the permeability of soil. All other variables are defined in previous equations.

2.2 Heat transfer mechanism

The heat transfer in soil occurs mainly by conduction followed by convection, and radiation has negligible effect (Brandl, 2006). Therefore, only conduction and convection are modelled in the FE analysis. Conduction occurs in soil particles and pore fluid; and since soil particles are static, so convection occurs only in pore fluid.

3 Finite Element (FE) Model

3.1 Model creation

Dean Street Station consists of two main boxes with different base levels. A combination of energy piles and energy wall are installed in the station. The width of the box isn't constant across the whole length of the box, so the dimensions of the model are taken from a typical cross-section of the box. For the purpose of analysing the THM responses, the box is simplified into a 2D model to save computation time and reduce in geometry complexity. By assuming the box is symmetrical, only half the box is required to be modelled.

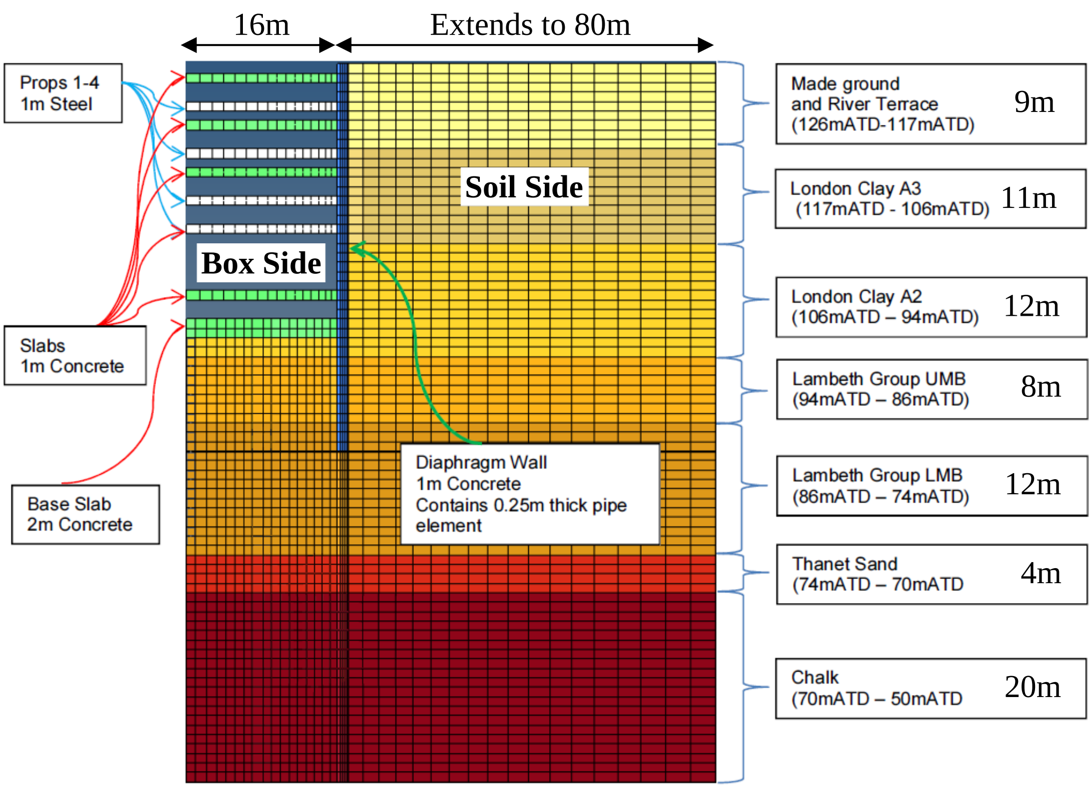


Fig. 10 - 2D mesh of Dean Street Station Box (Zhao, 2013, Bibliography [16])

Dean Street Station box 2D mesh is created in Hypermesh (Fig. 10) by Zhao (2013), composing of rectangular elements. The element size is finer near the energy wall where greater accuracy is required and has greater variation in stress. The far-field elements are coarser to compromise between computing time and accuracy.

The model has four temporary props (white) and six slabs, where one slab is a direct replacement of a temporary prop. The box side is 16m wide and 29m deep, the diaphragm wall is 1m wide and 41m deep, the soil is 76m deep and originally extends for 50m from the wall. However, it was found in the early analysis that the pore pressure boundary was affecting the results, so the soil was extended to 80m using coarser element sizes. The absorber pipe is 0.25m wide and 40m deep, and its centre-centre distance with the wall is 0.25m towards the soil side. This is because in practise the absorber pipes would be installed on the outer reinforcement cage for health and safety and ease of installation reasons. The last 1m of the wall doesn't have pipes in the design, hence the modelled pipe depth is 40m.

The operation phase of the wall accounts for 20 years, where each time step is 6 months for a heating/cooling cycle. This is a compromise between computational time and the number of analyses has to be covered.

3.1.1 Boundary Conditions

It is important to set the appropriate boundary conditions. These restraints ensure the output of the analysis has physical meaning and is representable for the problem.

The pore pressure distribution is hydrostatic for both vertical edges initially, and the far-field soil boundary (RHS of mesh) is kept hydrostatic throughout. Drainage is allowed at the bottom and RHS edges. The maximum negative pore pressure is capped at -100kPa, because realistically suction does not usually go below this value.

Both horizontal and vertical displacements are restricted in the RHS edge. This is because it is far enough from the wall to be affected. Whereas the top soil edge allows the displacement changes to see the possible settlements induced by the operation of the wall.

Temperature boundary conditions vary with the operation of the wall. The permanent conditions are for the station box and the far-field soil is kept at 18^{o}C and 12^{o}C respectively at all times. The initial soil temperature is 12^{o}C, and it is allowed to vary with the temperature changes in the pipes in between winter and summer cycles. In the winter and summer, the pipe temperature is 2^{o}C and 18^{o}C respectively. The temperature boundary conditions applied is summarised below in Fig. 11.

The water table is kept constant at the surface of the soil for simplicity, but in practise, the water table is often lowered by pumping water from ground(dewatering) to avoid seepages in the excavation zone.

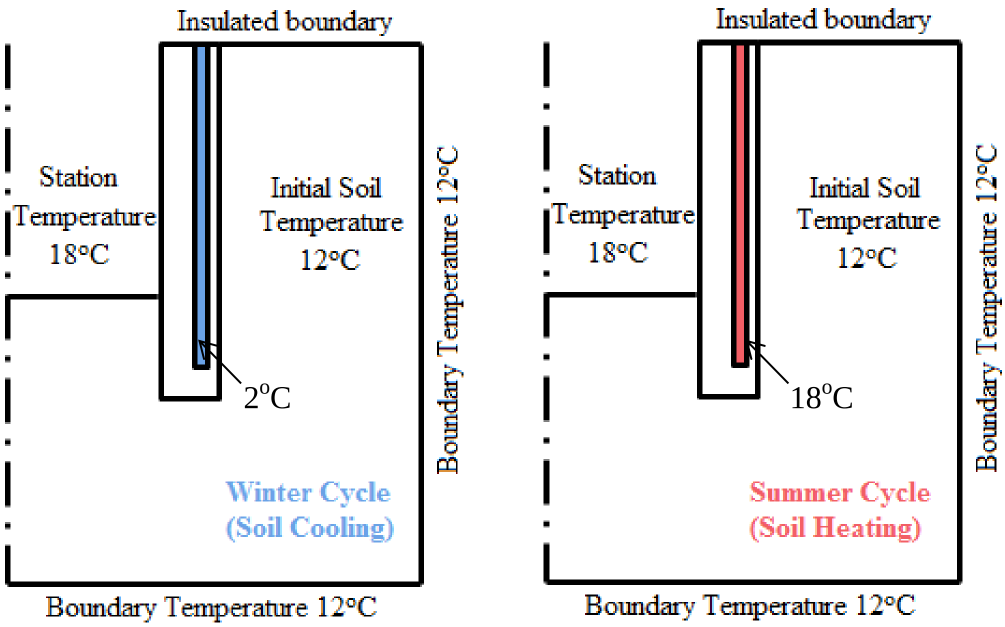


Fig. 11 - Temperature boundary conditions of the energy wall (Not to scale)

3.1.2 Parameters

Description	E_0 [kPa]	Unit weight [kN/m^3]	Lateral Pressure Ratio k_0	Friction AngleΦ' [º]	Cohesion c0 [kPa]	Possion ratio	Thermal expansion	Thermal Conductivity (W/m)	Permeability(m/s)	Dialation AngleΦ' [º]
Made Ground (delta = 0)	10000	20.00	0.6	22.18	0.00	0.20	5*10-6	2.50	1*10^-4	0.00
Terrace Gravel (delta = 0)	50000	21.00	0.4	35.77	0.00	0.20	5*10-6	1.80	1*10^-4	0.00
London Clay A3 Undr (Cw/Cu =0	76000	20.00	1	0.00	57.14	0.20	5*10-6	1.61	3*10^-11	0.00
London Clay A2 Undr (Cw/Cu =0	109000	21.00	1	0.00	116.00	0.20	5*10-6	1.61	3*10^-11	0.00
Lambeth Group UMC(Cw/Cu =0.	300000	21.00	1	0.00	178.57	0.20	5*10-6	4.20	3*10^-11	0.00
Lambeth Group LMC (delta=0)	270000	21.00	1	23.04	10.00	0.20	5*10-6	4.20	3*10^-11	0.00
Thanet Sand Dr (delta=-0.84)	400000	19.00	1	32.01	0.00	0.20	5*10-6	2.54	1*10^-4	0.00
Concrete	23000000	25.00	0.5	0.00	0.00	0.20	5*10-6	1.40	0	0.00

Table 1 - Material Properties used in model

The thermal conductivity and the permeability used in the model are isotropic for simplicity. In reality, it is likely to be anisotropic where horizontal is higher than the vertical values. E_0 are the calibrated values.

3.2 Finite element analysis (FEA)

1. <u>Construction Phase</u>
    - The excavation is split into five stages, where each stage is excavating soil to the prop level and installing the steel prop.
    - The base slab is casted from the final excavation level followed by a bottom up construction of concrete floor slabs.

- The time frame for each stage is set according to the actual excavation date obtained from Arup.
- The modelled displacement of each stage is compared with actual measured SAA displacement data (obtained from Arup) during construction for calibration of the stiffness in soil.

Two cases are considered in this study; (a) construction phase + no GSHP (but consolidation) operation and (b) construction phased followed by GSHP operation for 20 years.

2(a). No Operation Phase (20years)

- Both the short and long term responses of the soil due to construction only are analysed. This includes: Earth pressures, displacements, and bending moment.
- This sets a reference point to compare with results obtained from With Operation Phase.

2(b). With Operation Phase (20years)

- Analyse the cumulative effects due to construction and heating/cooling cycles of the energy wall.
- Both the short and long term responses of the soil due to construction only are analysed. This includes: Earth pressures, displacements, and bending moment.
- Compare results with No Operation phase to deduce the effect due to the operation of the wall.
- Parametric Study to investigate the different responses that maybe induced by changing possible governing parameters such as heat conductivity, permeability and expansion coefficient.

3.2.1 Paraview

The FE numerical analysis code used runs on C++ and the results cannot be visualised in the same software like most commercial FE packages. An open-source visualisation tool called Paraview is used for this purpose. However, because the tool isn’t specifically designed for these results, there are limitations on using this software which would be discussed later. The main uses of this software are to generate contour plots and exports the results into excel files for data processing.

3.2.2 Matlab

There are a lot of limitations on processing the results using Paraview. By using the exported excel files, there are more flexibility on handling the data into the desired form. For example, the actual displacement data of the wall is in excel files which cannot be imported into Paraview to compare the results, Matlab can be used to create such plots to analyse the data.

3.2.3 Software limitations

Paraview

-Visualising

A lot of manual work is required when using Paraview. There are different time steps in the model for different elements to be added/removed representing various stages. Changing the time steps in Paraview wouldn't edit the elements, and these have to be implemented manually by knowing which set of elements occur at each step. If the elements weren't added/removed before exporting data, the effects of these elements would remain and corrupt the data being exported, leading to a set of incorrect results.

-Exporting data

The elements need to be grouped and a line can be drawn in the group to obtain data from the elements along this line within the group. If some elements were not included, this would again lead to errors in results.

Matlab

-Importing data

Due to a large amount excel files need to be imported, the computational time just for importing can vary from 1minute to 20minutes depending on which area of the model is of interest. Typically, 45-60 minutes are required for importing all the area of interests in the model into Matlab.

4 Results and Discussions

4.1 Construction Phase

The Energy Wall is constructed using 'bottom up' technique. The diaphragm wall is first installed, then the soil at the proposed box side is excavated (from +126m) to the final excavation level (+96.8m) with four temporary props (P1 to P4) installed at different intervals. When it is excavated to the final level, concrete is casted to form the base slab. Working from the base slab, the construction is worked upwards where the temporary props are removed and replaced by slabs one by one and finally casting the roof slab at the top of the excavation forming the station box. The excavation sequence is shown below in Fig. 13.

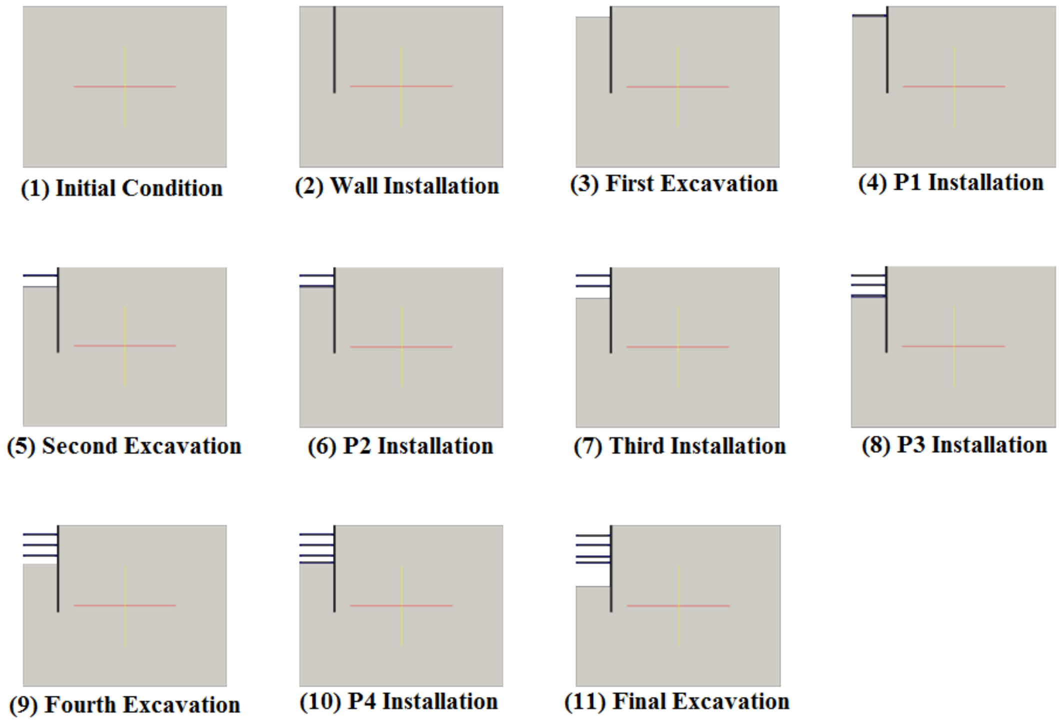


Fig. 13 - Excavation Sequence (1-11)

4.1.1 Pore Pressure

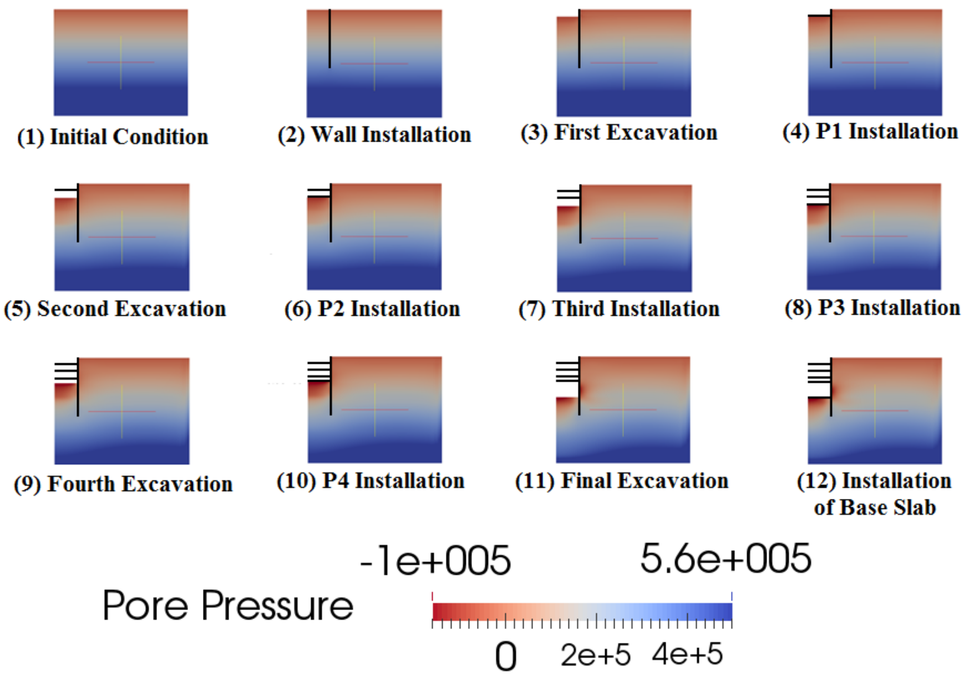


Fig. 12 - Contours of changes in pore pressure during excavation (1-12)

Fig. 12 shows the variations of pore pressure distributions during the excavation sequence. Initially, the pore pressure distribution is hydrostatic so it increases linearly with depth by a factor of 9.81kPa/m. As the excavation begins, the pore pressure is reduced. The excavation of soil leads to a drop in vertical total stress on the remaining soil at the box side and also the total horizontal stress acting on the soil at the soil side. The soil has low permeability, so the water could not dissipate from the soil skeleton, it is in undrained condition. If the total stress is reduced, negative excess pore pressure is developed because the effective stress stays constant in undrained conditions. Hence during excavation in the box side, the pore pressure in both box side and soil side are reduced. This is shown in the changes in contour in Fig. 12.

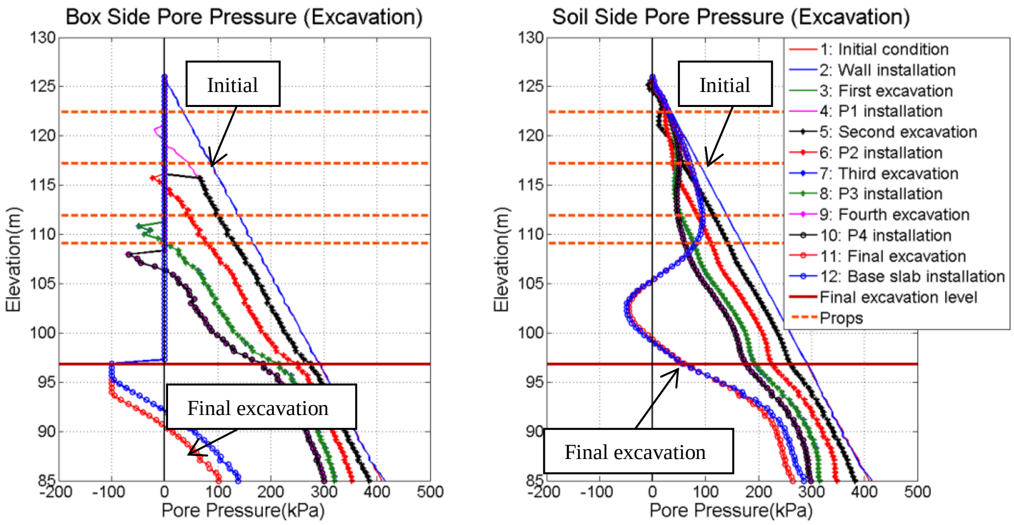


Fig. 14 - Plots of changes in pore pressure during excavation(1-12)

The maximum decrease in pore pressure at the soil side is during the excavation to the final level (Fig. 14), this is due the excavation is relatively larger than the previous excavation because a proposed prop (P5) wasn't installed.

For the box side, the negative pore pressure keeps increasing magnitude (capped at -100kPa) as excavation continues, because the excavation time is less than the dissipation of pore water. The curves starting at different elevations due to the removal of soil, so each curve start at the latest elevation.

During the replacement of prop supports with slabs, the pore pressure increased. However, this increase is mainly due to the natural dissipation of excess pore pressure. The effect of the replacement is negligible, because the stress is simply redistributed in the slab and props through the wall, so the soil only experience a very small change.

4.1.2 Total and Effective stress

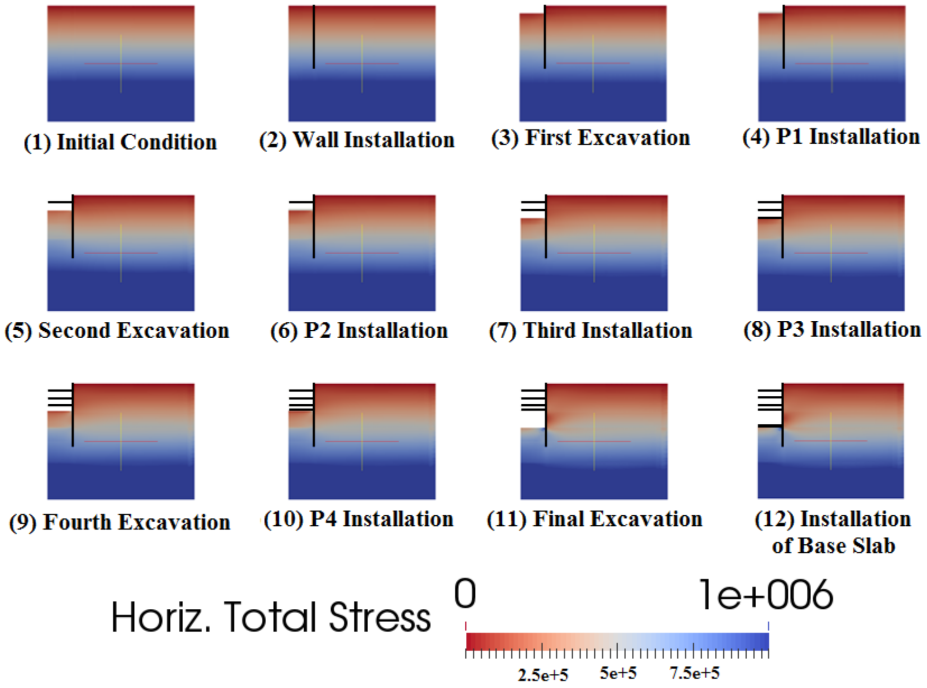


Fig. 15 - Contours of changes in horizontal total stress during excavation (1-12)

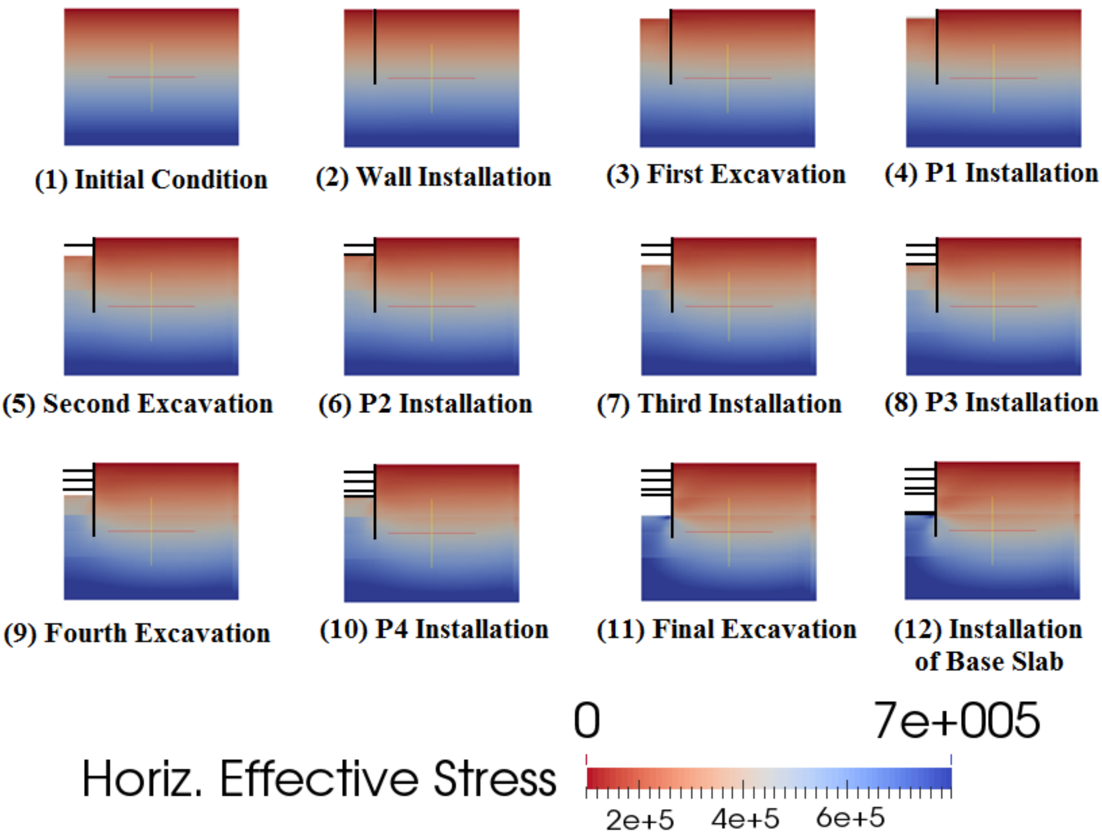


Fig. 16 - Contours of changes in horizontal effective stress during excavation (1-12)

Fig. 15 and Fig. 16 show the horizontal total stress and effective stress variations throughout the excavation stages respectively. The vertical total stress of the soil side remains the same since there are no addition loads or removal of loads, whereas the box side will reduce because the removal of soil. During the excavation, the horizontal total stress in the soil side reduces because the soil that was previously providing the lateral support is removed. The largest change can be seen at step 11 in Fig. 15, where the final excavation was taken place. This excavation stage removes ~12m of soil which is at least twice the amount of soil removed in the second largest excavation (~5m).

The horizontal effective stress stayed almost constant throughout the excavation phase until the final excavation. This is as expected because of the low permeability nature of the soil, the reduction in total stress is compensated by negative excess pore pressure as discussed earlier. However, the last excavation removes so much soil that effective stress can no longer remain constant in both the soil side and box side. The soil side is due to the removal of the soil; and the box side is due to the soil pushing the foot of the wall towards the station, which led to an increase in total stress resulting in an increase in effective stress.

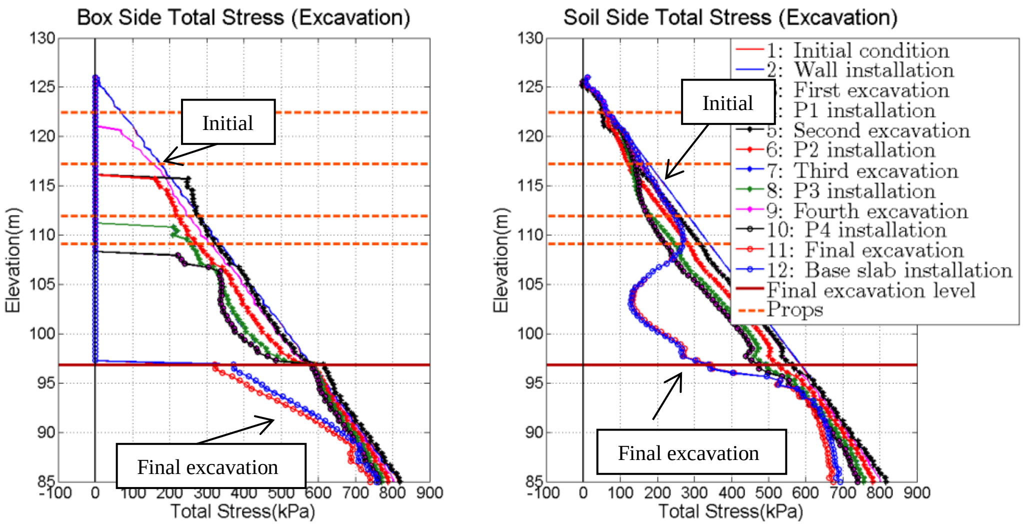


Fig. 17 - Plots of changes in horizontal total stress during excavation(1-12)

Fig. 17 shows the total horizontal stress throughout excavation. The total stress reduces as explained before. The total stress in the soil side reduces to 120kPa at elevation +103m. The total stress in the box side starts at different elevation due to the removal of soil during excavation. The plots for the box side use the data at the line of symmetry of the wall (LHS edge of mesh), so the increase in total stress is not seen in the plot because the effect of wall movement has decayed.

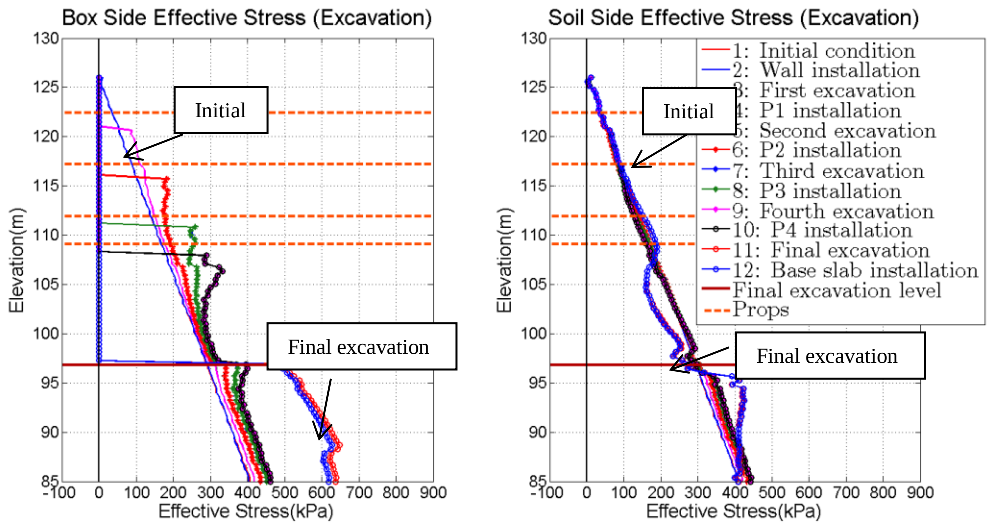


Fig. 18 - Plots of changes in horizontal effective stress during excavation(1-12)

The horizontal effective stresses increase because the diaphragm wall movement pushing the soil inwards, but the plots(Fig. 18) show only the effective stress has increased because the removal of vertical loads caused the pore pressure reduced, effective stress is increased to support the lateral load from diaphragm wall.

4.1.3 Displacement

All constructions would initiate ground movements because the soil is disturbed. It is clear that the surrounding soil would move towards any excavation if not supported. The diaphragm wall is used to claim the ground space required for the station box.

The model displacements were calibrated with actual monitoring data from Arup to obtain a set of stiffness in the soil stratum, so the future operation phase analysis can be done to assess the soil-wall interaction due to the thermal loads.

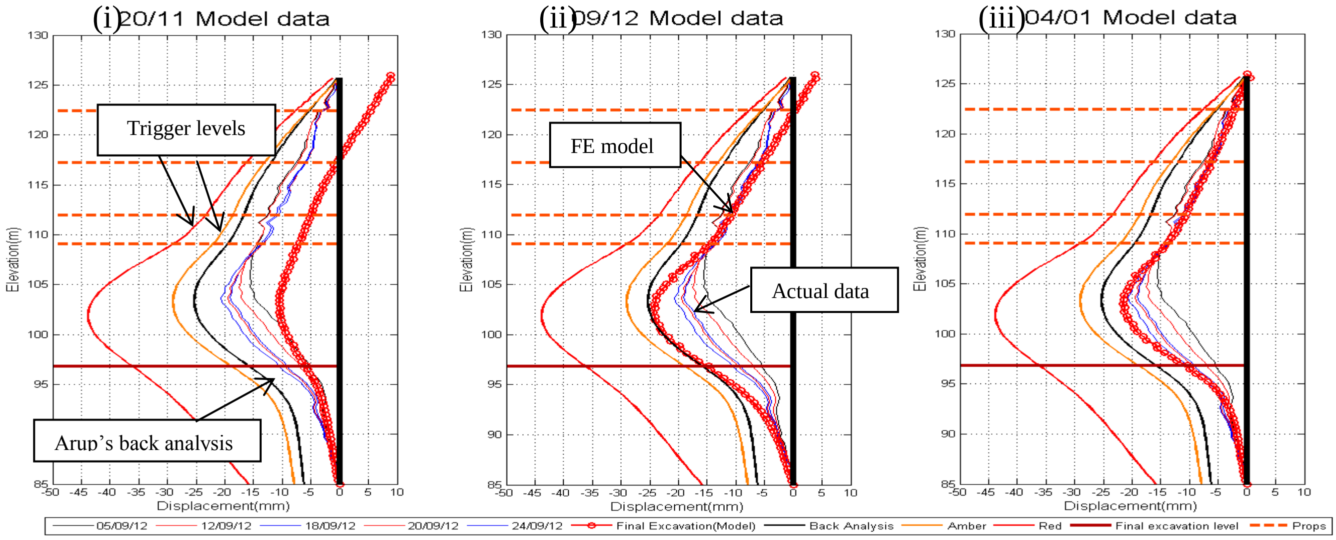


Fig. 19 - Examples of calibration (Final excavation)

The displacement is zeroed at the root of the wall, as the model was calibrated to the actual movement to the wall where Arup's referenced the SAA measurements to the root of the wall.

The calibration process is conducted by trial and error on varying the stiffness of different layers of soil trying to match the model displacement (red circled line) with the actual monitoring data (thin lines). If a section of the model line is on the right of the thin lines, the stiffness of the corresponding layer of soil is reduced because it is too stiff (Fig. 19 (i)). The stiffness of layer is increased if model line lies on the left (Fig. 19 (ii)).

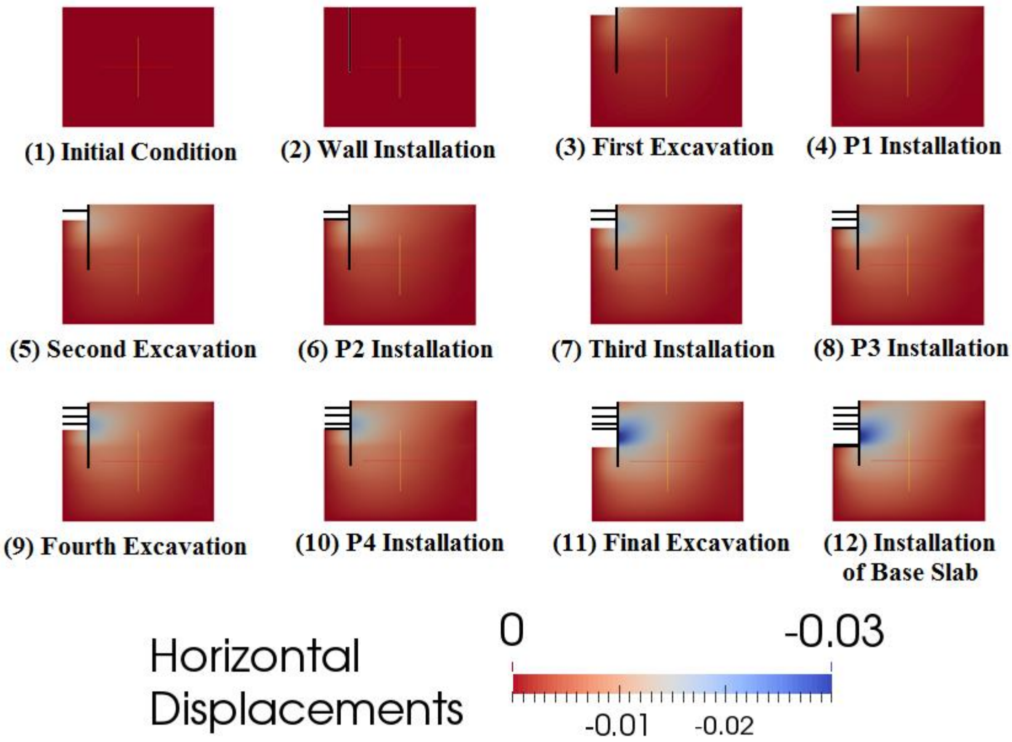


Fig. 20 - Contours of changes in horizontal displacements during excavation (1-12)

The soil is undisturbed initially, so the displacement is zero everywhere at the beginning. It is assumed that the installation of the wall did not cause large displacement which requires further investigation. In reality, drilling mud would be used for the opening of the excavated trench, so the soil stresses would be balanced and negligible movement would be observed.

Fig. 20 shows the contours of horizontal displacement in soil during excavation. During excavation, the ground movement tends to push towards the box side because of reduction in horizontal stress for support. This is indicated by the changes in colour from red to blue in Fig. 20. It can be seen in steps (11) and (12) that the soil is displacing to the left showing the wall is causing the box side interface soil to move. This results in the increase and total stress and effective stress locally in that area. The maximum wall movement is ~20mm at elevation +103m at the base slab installation stage(Fig. 21). It occurs roughly at the mid-point between the base slab and P4 because these points are supports, and maximum bending of a simply supported beam occurs at the centre. It is not exactly at the centre because of the effects from the other 'spans'.

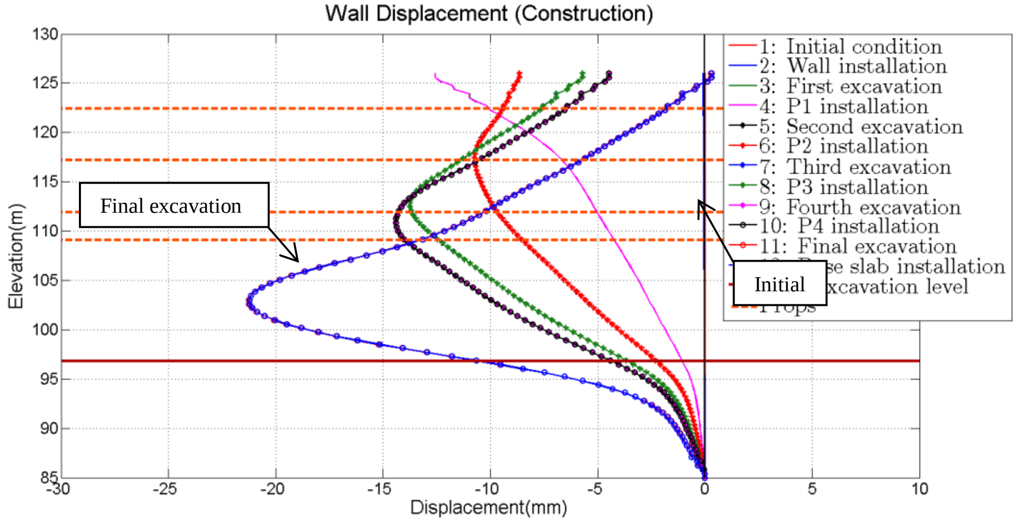


Fig. 21 - Plot of changes in wall horizontal displacement during excavation(1-12)

4.1.4 Moment

The bending moment of the wall needs to be predicted and monitored as this is the utmost important factor in terms of the structural performance of the wall. If the applied moment on the wall exceeds the limit of the design values during the construction, the wall would fail in bending and the open excavation would collapse which costs not only money but possibilities of injuries and deaths.

The moment of the wall is calculated by using the variation in vertical stress of the wall along its thickness. The wall thickness is modelled with four elements, the vertical stress of each element's centres are taken to form the stress profile of the wall at that elevation. The bending stress is obtained by referencing the vertical stress at each element with the mean vertical of the four elements. The moment at each elevation can then be determined using the bending stress profile deduced from the vertical stress profile.

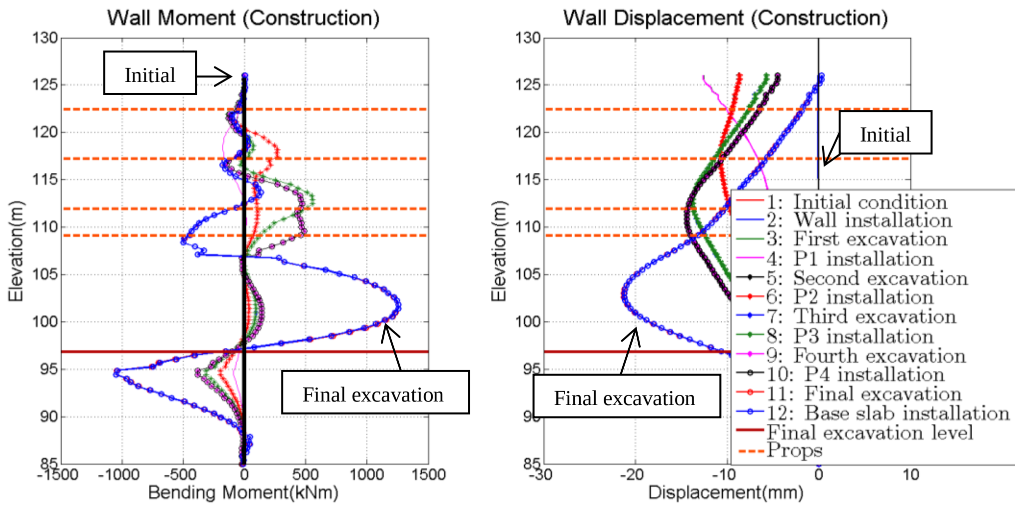


Fig. 22 - Plots of wall moment and horizontal displacements during excavation (1-12)

Fig. 22 shows the bending moment distributions in the wall during excavation. Moment is induced when excavation starts due to the removal of supporting soil to the wall at the excavation side. This magnitude of moment increases with excavation progresses, and the temporary props supports the wall restricting the displacements. The turning points of the moment curve mostly lie on where the props are because the curvature is the greatest as it changes direction due to the support. The final excavation has the biggest displacement and curvature at +103m, so the maximum moment is at that elevation as it is shown in the figure. The bending moment would be reduced if the proposed prop was installed because the displacement and curvature would consequently reduce.

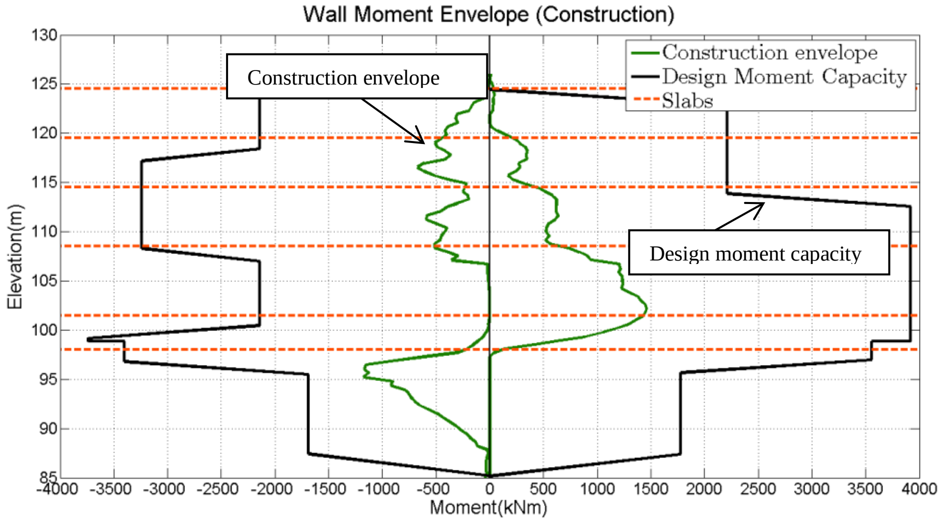


Fig. 23 - Moment envelope in construction stage

During the replacement of props with slabs, the moment doesn't vary greatly, the turning points shift from the props to the slabs. From Fig. 23, the full construction stage (including slabs installations) moment envelope is well within the maximum allowable moment envelope deduced by Arup. It shows the similar shape, but shifted upwards by ~2m, this could be the props/slabs elevations used differ slightly with the values used by Arup.

4.2 No Operation of Energy Wall

The performance of the diaphragm wall and the responses of the earth pressure are modelled without operation of GSHP. The ground movements and consolidation of the soil can be analysed without the thermal effect. This sets a reference point to be compared with the model of the operating Energy Wall, so the thermal effect of the operation can be analysed.

4.2.1 Pore Pressure

The changes of pore pressure from hydrostatic to after constructions were discussed in the previous section, where negative excess pore pressure developed by the reduction of total stress during the excavation.

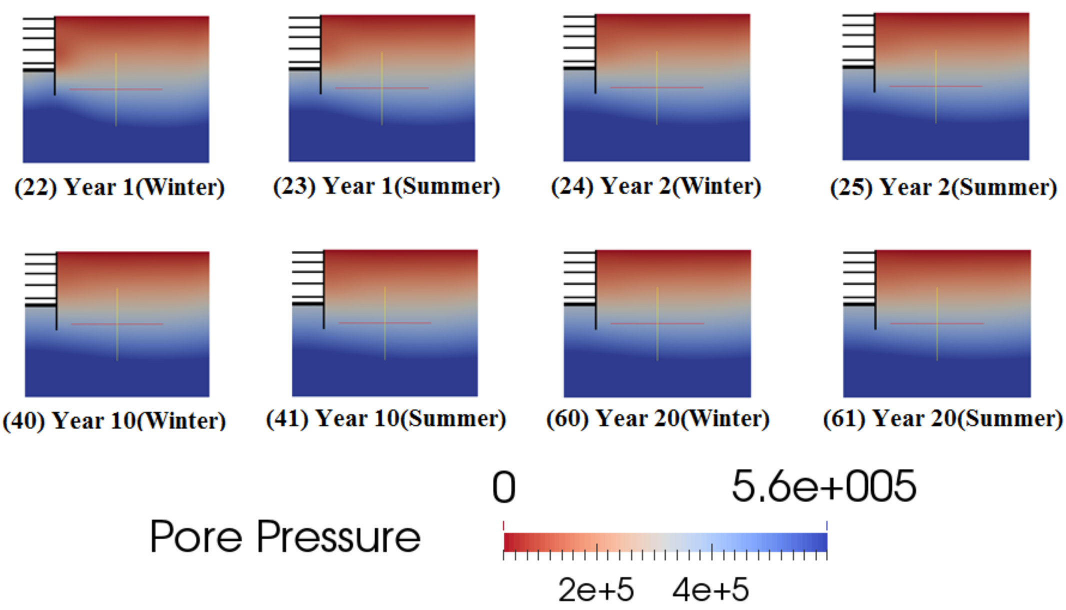


Fig. 24 - Contours of changes in horizontal displacements with No Operation of Energy Wall

Fig. 24 shows the contours of horizontal ground movement due to consolidation. Post-construction (installation of slabs), the pore water is allowed to dissipate with time, allowing the soil to consolidate. The pore pressure would slowly converge to the initial hydrostatic distribution and re-equilibrate, and can be seen after 10 years in Fig. 24. The excess pore pressure developed in the soil adjacent to the final excavation has almost dissipated completely within the first 10 years by water migration into the soil skeleton. This can be seen more clearly in Fig. 25.

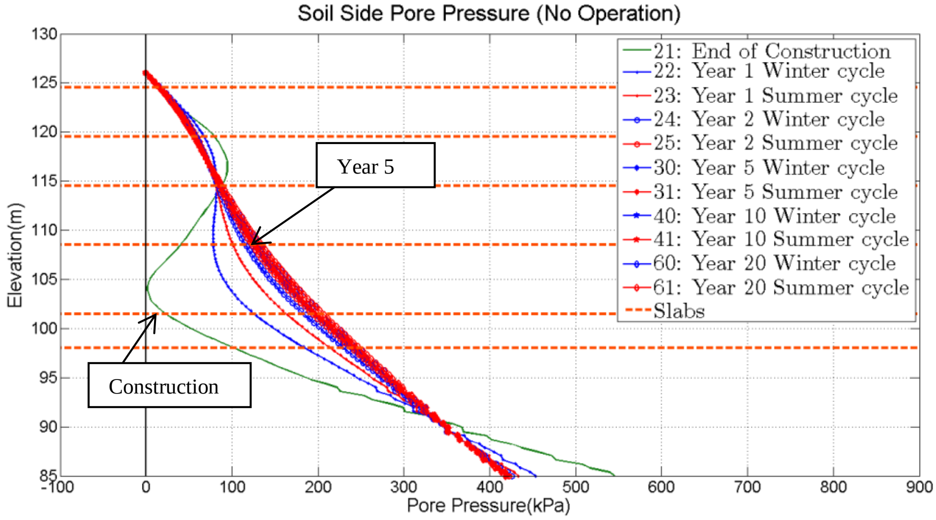


Fig. 25 - Plot of changes in pore pressure post-construction with No Operation of Energy Wall

Fig. 25 shows the pore pressure profile post-construction. The pore pressure distribution immediately after construction is shown as green, the final excavation stage has drawn the pore pressure to almost zero. Although the pore pressure at the toe of the wall (+85m) is around 410kPa, but the curve is not straight, so the pore pressure isn't hydrostatic. The rate of the dissipation reduces with time as expected because suction is reduces when water migrate into the soil skeleton resulting in a decrease in rate.

4.2.2 Total and Effective Stress

After construction, the total vertical stress in the box side will be constant, because there'll be no changes in applied loads. However, for effective stress, the negative pore pressure developed in the soil below the base slab will dissipate with time. This means that the soil swells.

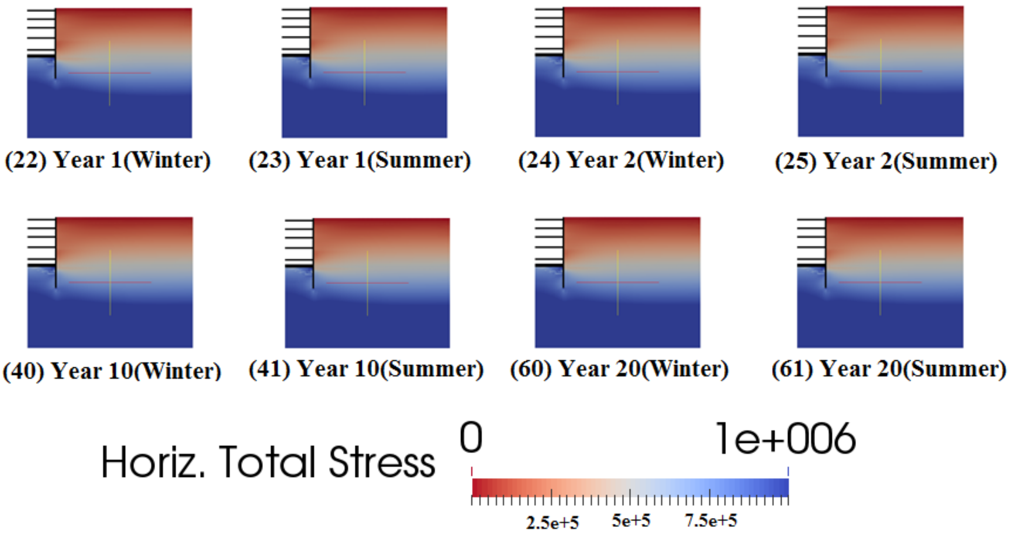


Fig. 26 - Contours of changes in horizontal total stress with No Operation of Energy Wall

Fig. 26 and Fig. 27 show the total horizontal stress and effective stress contours after construction respectively. Similarly, the horizontal total stress doesn't vary after construction (Fig. 26). This may happen because the ground deformation may induce stresses in slabs. The effective stress contours (Fig. 27) show it decreases with time, this is because of the swelling of the soil where the excess negative pore pressure is dissipated. The discontinuity in Fig. 27 is due the parameter difference in the soil layers, and could possibly be eliminated if the parameters are more similar. Further work is needed to examine this layering effect. However, this discontinuity shouldn't affect the overall picture of the problem.

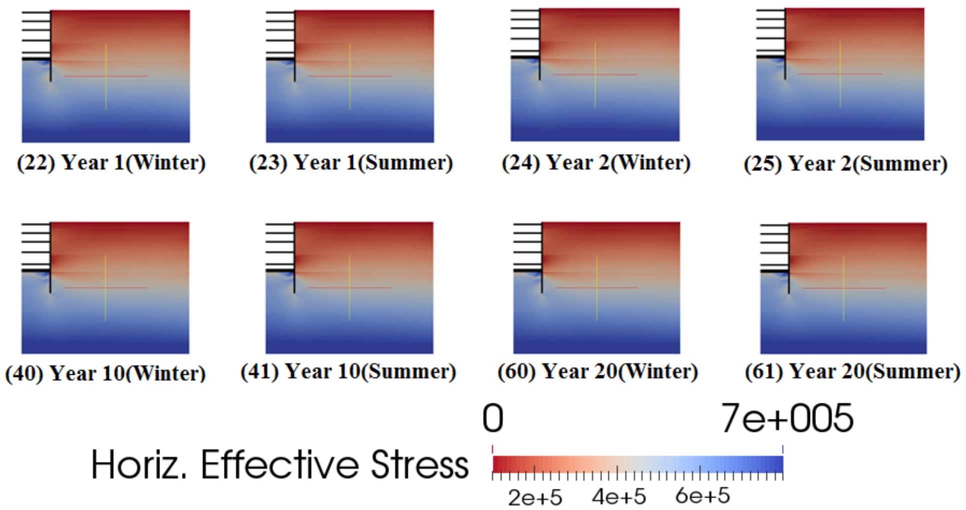


Fig. 27 - Contours of changes in horizontal effective stress with No Operation of Energy Wall

4.2.3 Displacement

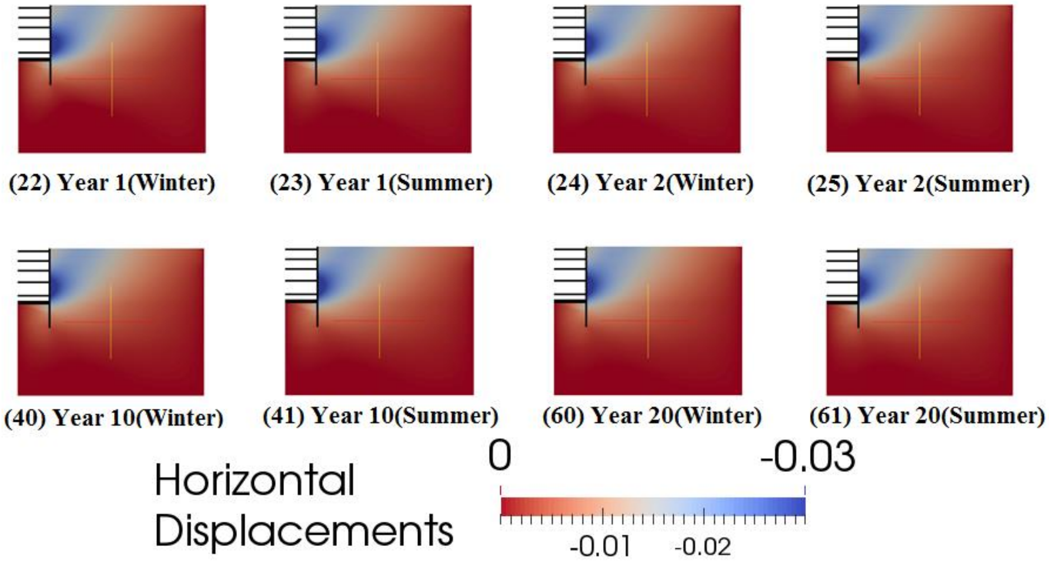


Fig. 28 - Contours of changes in horizontal displacement with No Operation of Energy Wall

Fig. 28 shows the changes in horizontal displacement with no operation of GSHP. The horizontal displacement doesn't very greatly post-construction because there is no significant changes in the total stress. The displacement relative to the final construction displacement is shown in Fig. 29 for clarity.

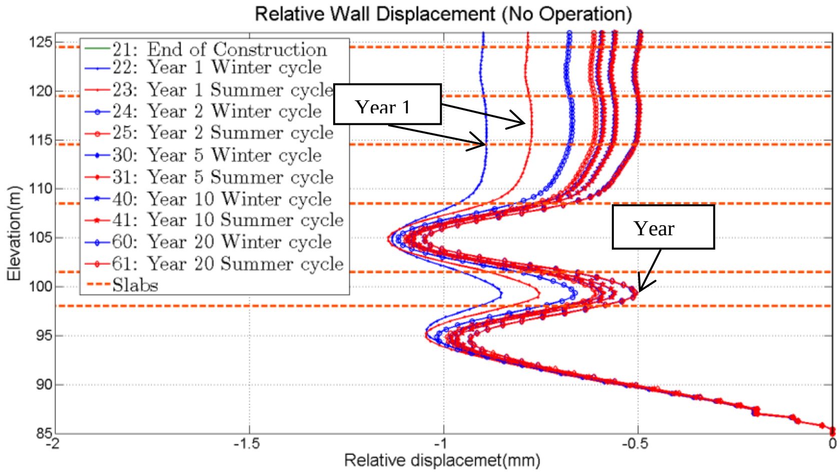


Fig. 29 - Plot of changes in relative displacement post-construction with No Operation of Energy Wall

The negative excess pore pressure below the base slab attracts water migration which causes heaving at the base slab results in soil pushing the wall below the base slab level towards the station box to replace the volume of the heave. The soil at +103m had large negative excess pore pressure developed due to the excavation. When the soil swelled, water dissipates and the effective stress is reduced, so the wall pushes back into the soil. Hence the relative displacement is getting more positive with years. The model only ran for 20 years, and it was shown previously that the excess pore pressure doesn't dissipate completely. It is expected that the displacement would continue to shift to the right until the excess pore pressure has completely dissipated. However, this movement of ~1-2mm is small compare with the original movement caused by the construction (22mm).

4.2.4 Moment

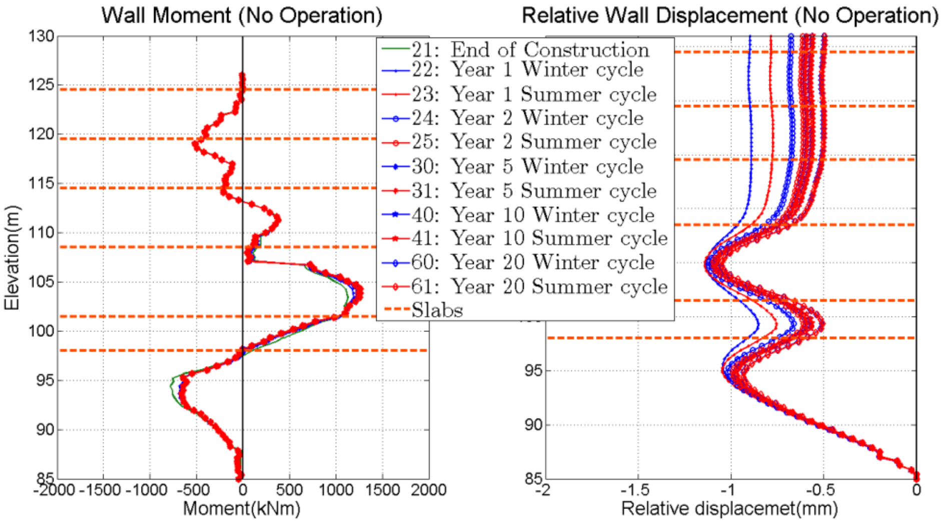


Fig. 30 - Plots of wall moment and relative horizontal displacements post-construction with No Operation of Energy Wall

Fig. 30 shows the moment distributions in the wall with no operation of GSHP. After constructions, the moment variation is very small (Fig. 30). This is because the total stresses acting on the wall are in equilibrium so the wall movement is low. There is only an increase of 100kNm at +105m and a decrease of 100kNm at +94m. These changes are due to the changes in displacement post-construction. If there are no additional loads adding to the system, the moment would be constant after swelling has completed.

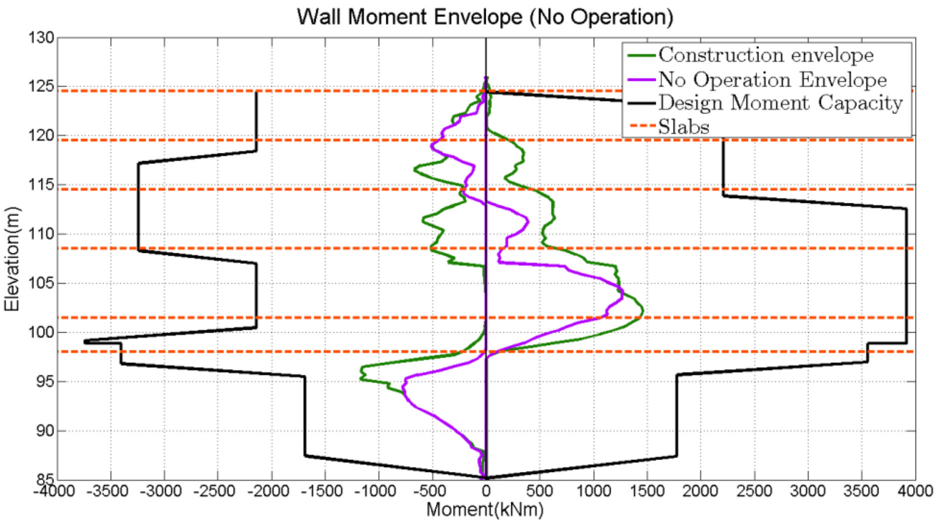


Fig. 31 - Moment envelope post-construction with No Operation of Energy Wall

Since the moment post-construction only has a small variation to the construction stage, the moment envelope is smaller than the construction moment envelope and lies well within the maximum allowable moment envelope (Fig. 31), so the wall would have good structural performance in the long term.

4.3 With Operation of Energy Wall

The thermal effects due to the operation of the wall are added in the model, so the diaphragm wall performs as an Energy wall in this phase. This is then compared with the no operation reference case described in the previous section (4.2).

4.3.1 Temperature

Initially at the final construction stage, the model was set to have a uniform temperature of 12°C everywhere. In the winter, heat needs to be extracted from the ground. Coolant of a lower temperature (2°C) than the soil is pumped through the inlet of the thermal pipe circuit to extract heat from the ground to gain thermal energy from the ground. This results in an increase in coolant temperature at the outlet of the thermal pipe circuit. The summer cycle pumps coolant of higher temperature (18°C) through the pipes, 'dumping' heat into the soil.

A step change in pipe temperature from 2°C for 6 months (Winter Cycle) to 18°C for 6 months (Summer Cycle) is used to simulate the operation of the Energy Wall. The temperature of the station is kept at 18°C throughout the year, as the energy wall is operated such that keeping this temperature constant. This is an extreme case to simulate, because of the step changes in the temperature rather than gradual changes which is more applicable to reality.

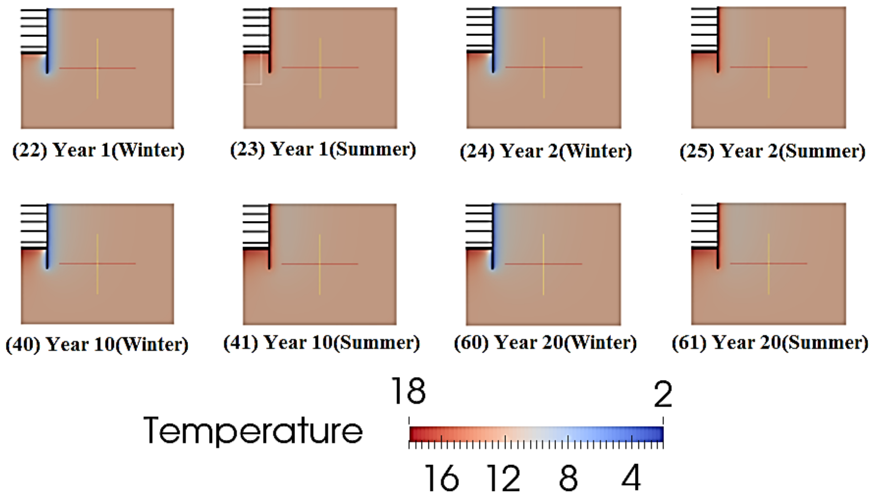


Fig. 32 - Contours of changes in temperature With Operation of Energy Wall

Fig. 32 shows the temperature contours during the operation of GSHP. The soil temperature near the wall drops/rises for winter/ summer cycle (Fig. 32). The effect of change in wall temperature on the soil reduces with increase in distance away from the wall. The zone of influence of the temperature in winter is larger than in summer due to the change in coolant temperature is higher in the winter than the summer. The soil temperature below the base slab is also influenced by the change in coolant temperature. Also, the contour shows there's a cumulative effect of cooling (slight blue in soil) the surrounding soil after 20 years of operation. This influence zone would not progress further when it reaches equilibrium with the far-field temperature. An analysis modelling for more years of operation can be used to examine the long term effect of temperature change in soil.

4.3.2 Pore Pressure

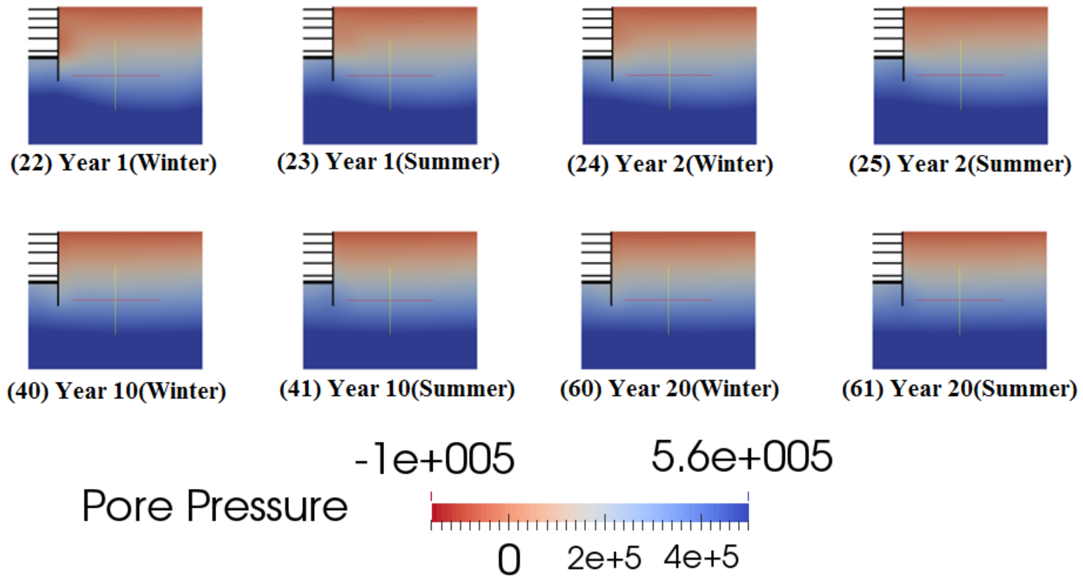


Fig. 33 - Contours of changes in pore pressure With Operation of Energy Wall

Fig. 33 shows the excess pore pressure developed from construction dissipates, but the pore pressure is affected from the operation of the wall. The pore pressure in the soil adjacent to both sides of the wall would increase and decrease in summer and winter respectively. When the soil is heated, the soil skeleton and the pore fluid expands, causing the increase in pore pressure; when the soil is cooled, the soil skeleton and pore fluid shrinks, results in a drop in pore pressure. Fig. 34 shows the pore pressure profile during operation of GSHP. The maximum difference in pore pressure between the cycles after 20years is 50kPa at +95m on the soil side (Fig. 34). The previous years have bigger difference because of the excess pore pressure from the construction phase. Also, it appears the operation of wall would delay the time for swelling in the soil. Below the base slab level, the changes in pore pressure between winter and summer in both sides is around 50kPa in the long term, so the effects are balanced out.

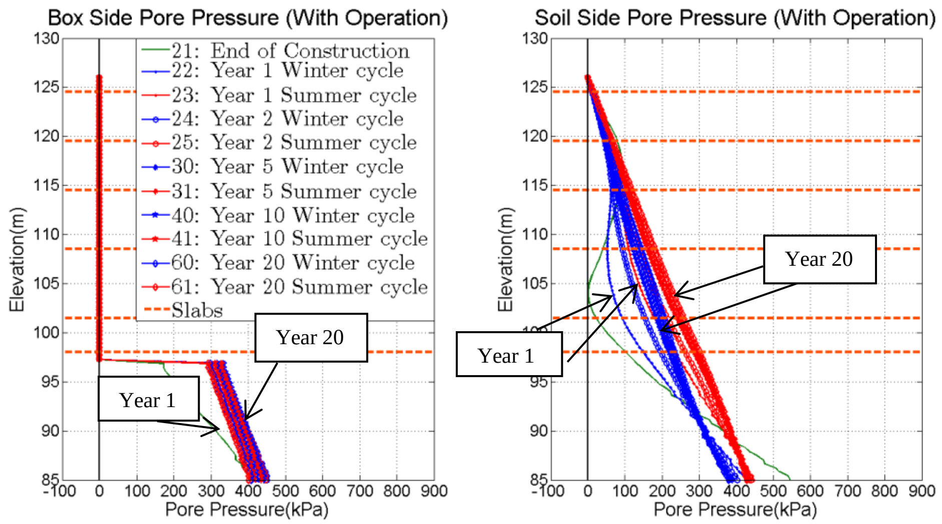


Fig. 34 - Plots of changes in pore pressure With Operation of Energy Wall, Summer(Red), Winter(Blue)

4.3.3 Total and Effective Stress

The horizontal stresses in the soil are the applied loads acting on the diaphragm wall and these changes with time after the construction has to be examined carefully. It is therefore important to analyse these changes in order to investigate the structural performance of the Energy Wall.

With no operation of the Energy Wall, the excess pore pressure dissipates without the thermal effects due to the operation. It is purely due to swelling of the soil. The total stress remains fairly constant after construction because no external loads (e.g. thermal) are applied (Fig. 26).

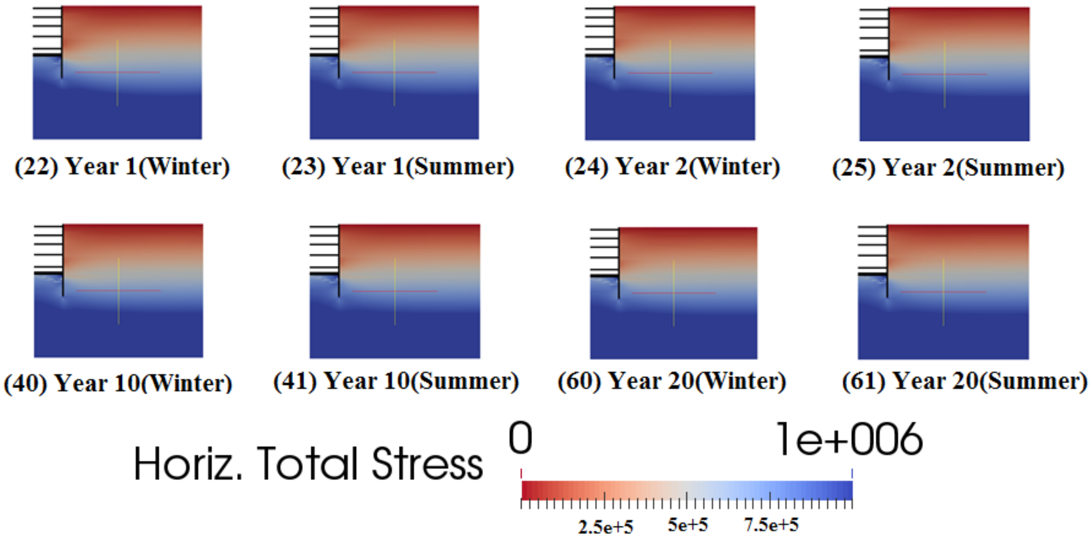


Fig. 35 - Contours of changes in horizontal total stress With Operation of Energy Wall

Fig. 35 shows the total horizontal stress changes with the operation of GSHP. The lowered total stress in year 1(22) is from the excavation stage, the total stress increases and decreases in the summer and winter cycles respectively as the years of operation progress (Fig. 35). The increment in stress is caused by the swelling of the wall and soil skeleton and pore fluid. Fig. 36 shows the total horizontal stress changes on both side of the wall during operation. In winter cycles, the soil is cooled and it shrinks resulting in a reduction in total stress. The changes in total stress between the cycles are about 25kPa (Soil Side), which is rather small, and this is caused mainly by the wall displacement which will be discussed in more detail in parametric study see section 4.4.2.

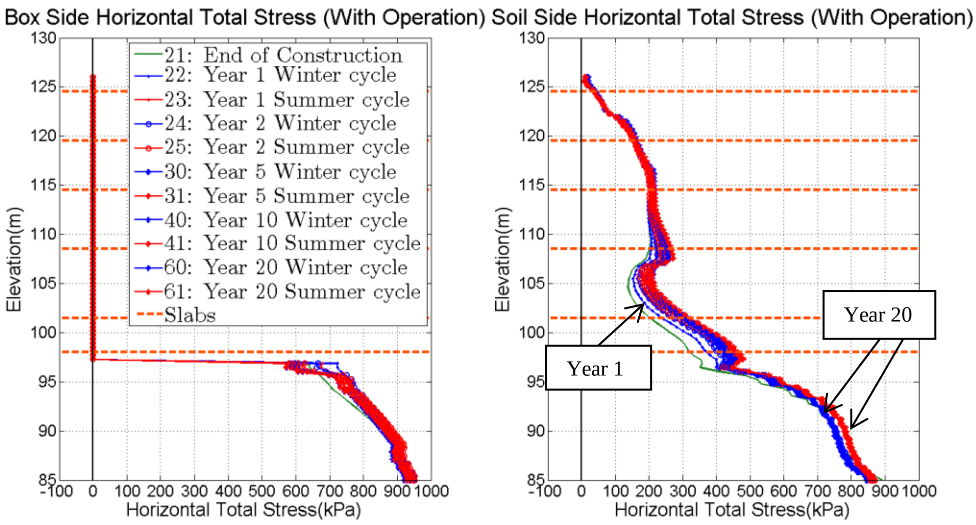


Fig. 36 - Plots of changes in horizontal total stress With Operation of Energy Wall, Summer (Red), Winter (Blue)

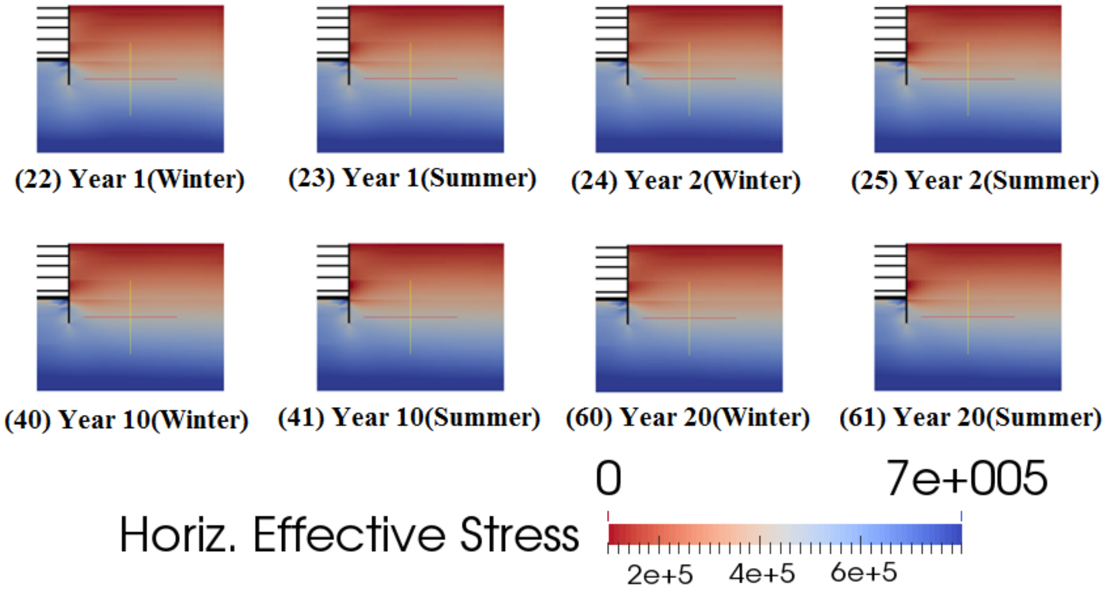


Fig. 37 - Contours of changes in horizontal effective stress With Operation of Energy Wall

Fig. 37 shows the effective stress contours in the soil with operation of GSHP. Previously during construction, the total stress has reduced but effective stress stayed the same. When the pore water is drained, the excess pore pressure dissipates and the effective stress reduces until these are equilibrated with total stress. This is seen is the first two years of operation in Fig. 37. After 10 years, the excess pore pressure has almost dissipated completely, so the long term effect of the operation on effective stress can be seen. Fig. 38 shows the horizontal effective stress on both sides of the wall with operation of GSHP. The effective stress reduces in the summer and increases in the winter(Fig. 38), this means the six months duration in each cycle allowed the dissipation excess pore pressure to occur even after an immediate change in pore pressures when temperature were varied from the summer cycle to the winter cycle. The figure shows the effective stress is negative (+105m, summer). In the model Mohr-Coloumb soil model is used, the small negative effective stress is due to the cohesion coefficient in the model. This can be improved by adopting a more advanced soil model.

In the summer, the increase in temperature causes both the soil skeleton and pore water to expand, which leads to an increase in total stress acting on the wall and pore pressure rises. The overall effect decreases the effective stress in the soil. The opposite happens in the winter cycle. The pore pressure increase is compensated by the decrease in effective stress (even when both changes are large) and hence the change in total stress is small, resulting small cyclic displacements (see section 4.3.4).

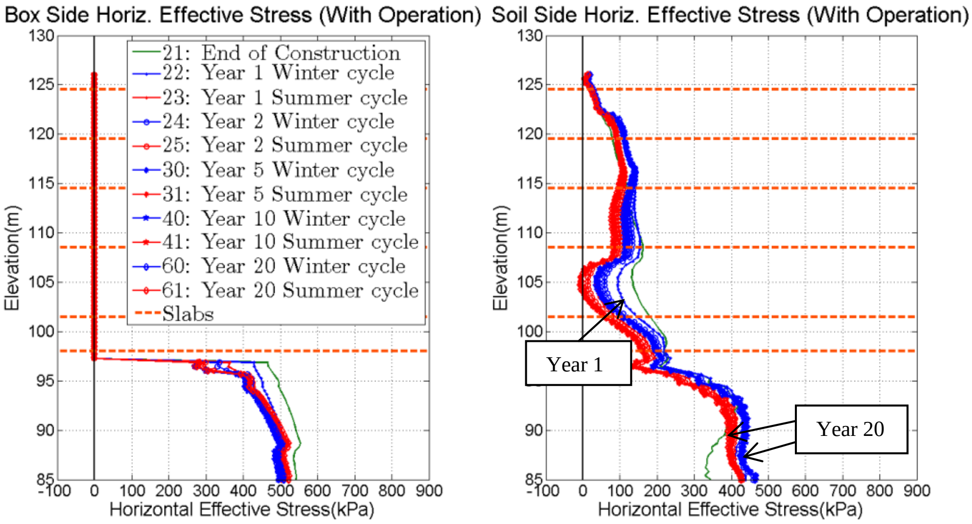


Fig. 38 - Plots of changes in horizontal effective stress With Operation of Energy Wall, Summer (Red), Winter (Blue)

4.3.4 Displacement

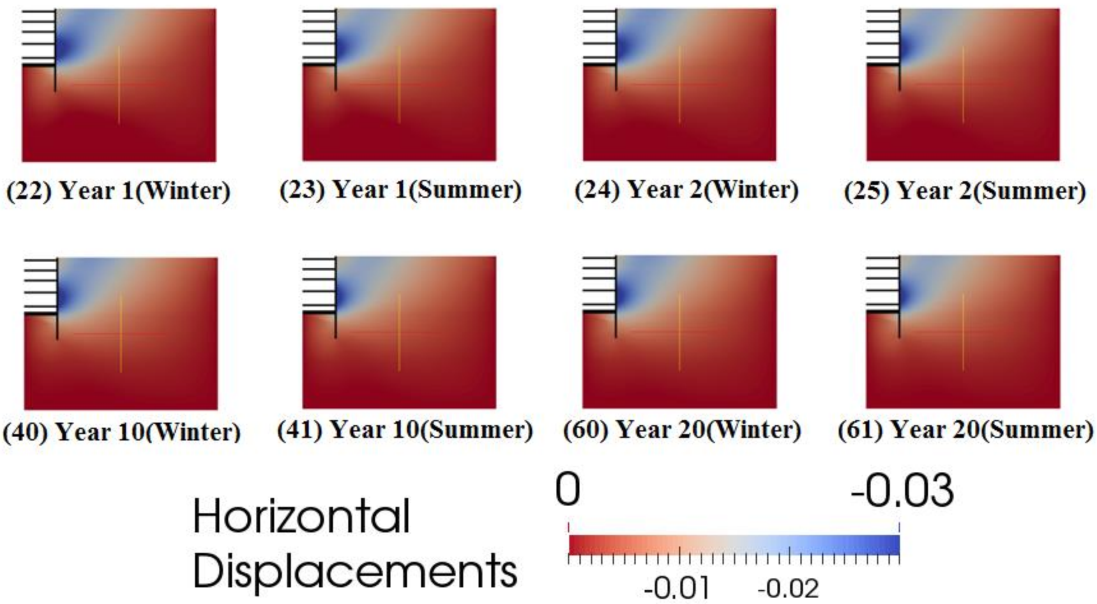


Fig. 39 - Contours of changes in horizontal displacement With Operation of Energy Wall

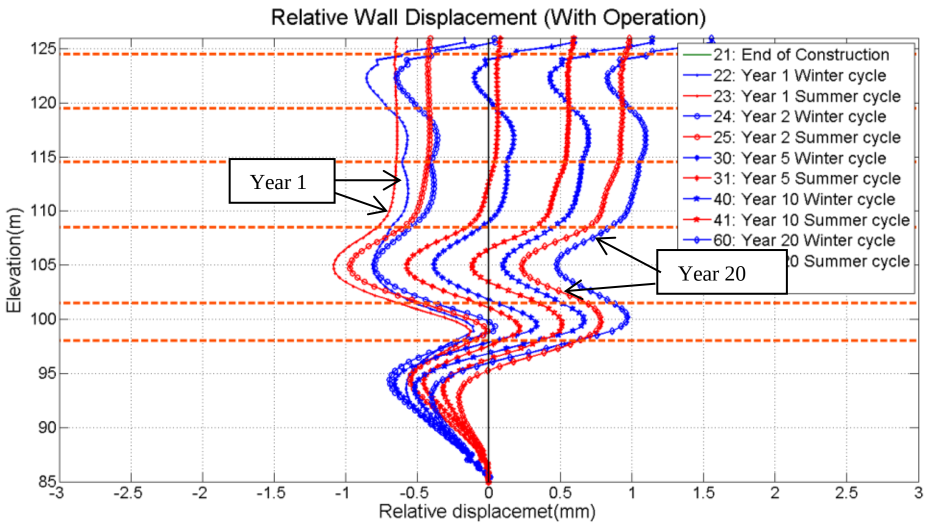


Fig. 40 - Plot of changes in relative displacement With Operation of Energy Wall, Summer (Red), Winter (Blue)

Fig. 40 shows the relative horizontal displacement of the wall during operation. The overall trend in Fig. 40 the wall shifts to the right with time, which is seen in previously with no operation, and is caused by dissipation of pore pressure. However, the operation of the wall has a greater effect on the wall movement, the relative displacements after 20 years are -0.5mm and 1mm for No Operation and With Operation of wall respectively. This is due to the cumulative effects between cycles.

In the winter, the pipe temperature is cold and the station side of the wall is hot, so this causes thermal strains in the wall and pushes the soil to the right. But, the total stress has decreased because the soil also shrinks in the winter so the effect from the wall movement isn't clear.

In the summer, the temperatures of both faces of the wall are much more similar and the wall movement is more similar across the elevation. The wall shifts to the left relative to the winter cycle because the similar temperature across the wall thickness causes the wall to bend back into the original shape.

The thermal straining effect difference between summer and winter can be seen clearly at +123m in Fig. 40. The opposite happens below the base slab, because in the summer the pipe temperature is higher than the box side face of the wall; and for winter the box side temperature is higher because of the heat transfer from the base slab of the station.

This result shows that the displacement caused during the winter cycle is not recovered by the summer cycle and will have a cumulative effect. The operation is delaying the swelling in soil due to thermally induced changes in pore pressures.

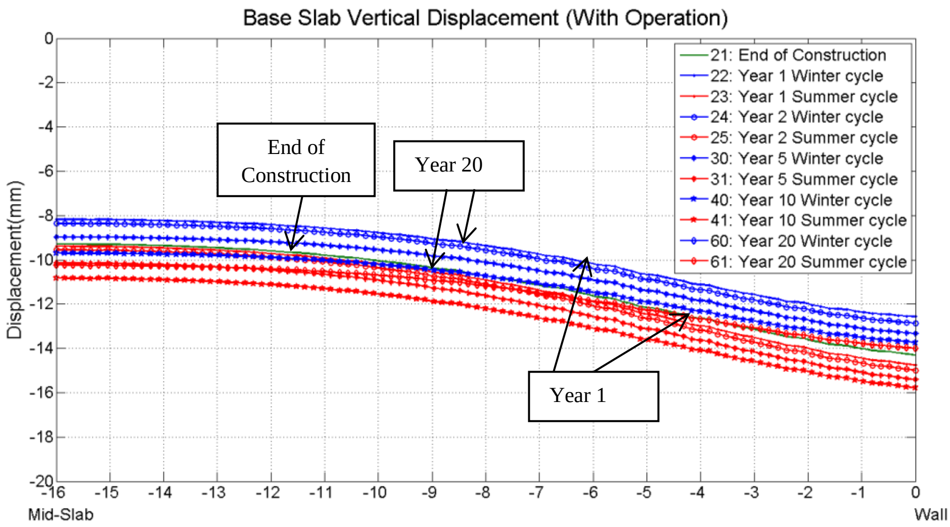


Fig. 41 - Plot of changes in base slab vertical displacement With Operation of Energy Wall, Summer (Red), Winter (Blue)

Fig. 41 shows the vertical displacement of the base slab. The vertical displacement of the base slab is caused by the soil heaving up. During excavation, the soil above the base slab level is removed, so the total vertical stress of the remaining soil is reduced by the weight of the removed soil. Due to the low permeability of the clay, the water cannot escape from the soil skeleton, so it is in undrained condition. Total stress has dropped, which means negative excess pore pressure develops as the effective stress remains the same in undrained condition. As the soil swells, the excess pore pressure dissipates, the water migrates into soil skeleton causing soil to expand and heave. The displacement at the mid-slab is at the maximum because it is not restrained, and it’s at its minimum near the wall, as the wall acts as a restraint which reduces the movement of the slab (Fig. 41).

4.3.5 Moment

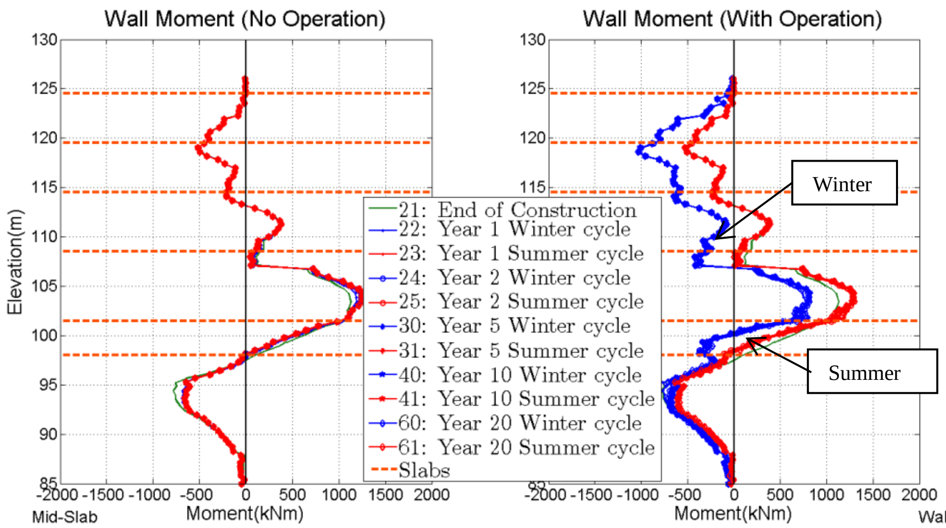


Fig. 42 - Plots of wall moment with No Operation and With Operation of Energy Wall, Summer (Red), Winter (Blue)

The moment in the wall is caused by the contributions from the lateral stresses from the soil and slabs and also the thermal stresses from the operation of the wall. The pipe circuit is modelled at the surface near the soil, so it is not at the centre of wall, so the difference in strains from the outer and inner wall is different due to thermal gradient within the wall. The differential strains induced in the wall results in bending moment in the wall.

Thermal effect due to differential strain in the wall is greater in the winter than the summer because the difference in box temperature (18^{o}C) and the coolant temperature(2^{o}C in winter and 18^{o}C in summer) is high in the winter.

As shown in Fig. 42, there is a clear difference in the bending moment between winter and summer cycles. Below the base slab level(+97m), the wall is restrained both sides by soil, so the difference between summer and winter cycles is less compared with above +97m where the wall is only restrained by soil on one side only. There is an offset of about 400kNm between the winter and summer above the base slab level. The maximum bending moment in the wall is at +104m and at base slab, where the separation between restraints (slabs) is the biggest, so it allows greater bending and the soil below base slab acts as a fixed end.

During winter, the coolant is 10^{o}C below the far-field soil temperature of 12^{o}C, so this side of the wall would shrink. The station box side temperature is always maintained at 18^{o}C, so it expands. This temperature gradient in the wall causes expansion in the box side and contraction in the soil side of the wall inducing bending moment in the wall. However, in the summer, the temperature across the wall is more uniform, so the difference in thermal strains is less. This results in a smaller increase in moment.

The induced moment is dominated by the thermal gradient across the wall and the effect of soil expansion/contraction is small. This is because the total stress does not change even though the pore pressure in the soil changes. This is examined more carefully in the next section.

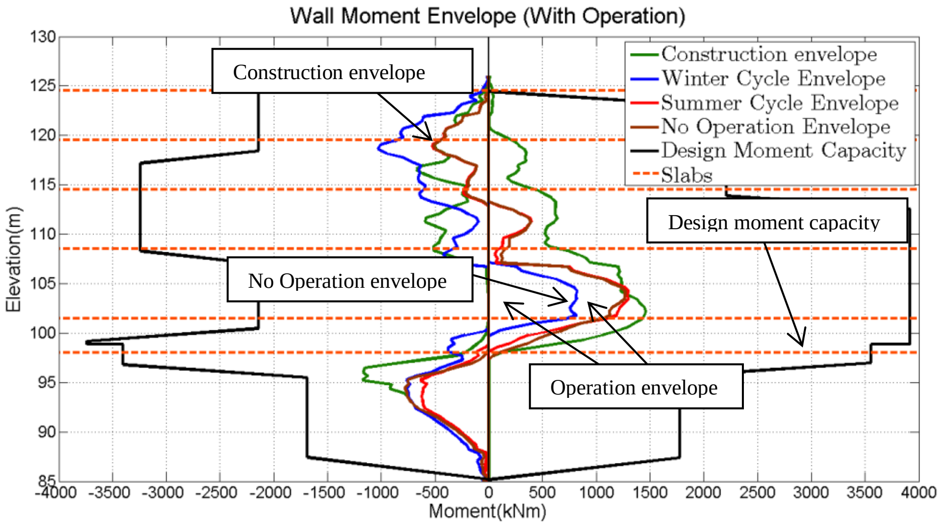


Fig. 43 - Wall moment envelope of various stages of Energy Wall

The thermal, mechanical and hydraulic effects are coupled together in the analysis, so only the overall effect contributed by the three is available. Further research is required to differentiate the effect caused by each one to see which effect has the largest effect.

The profile of maximum bending moment in the wall during different stages is shown in Fig. 43. The magnitude of positive bending moment in operation is lower than construction stage because the wall had less lateral supports during construction stage than after construction where more slabs are added and replaced the temporary props. The bending moment predicted using this FE model is well within the maximum design bending moment envelope used by Arup. So the wall would be safe from bending failure due to operation of the wall. The difference in the shape of the moment envelopes with the moment capacity may be due to a slight variation in the elevations used for props and slabs of the wall.

4.4 Parametric Studies

Parametric studies are performed to understand the mechanism in the operation response, and identifying the parameters that may potentially critical in the performance of the wall both structurally and as thermo-active foundation. Several parameters are considered in this study and their effects are investigated.

4.4.1 Permeability

Soil is a multi-phase material, the heat transfer is complex. The heat transfer mechanisms are mainly conduction and then convection. Hence the dissipation of excess pore pressure and the heat transfer are both affected with this change. In this study, 0.2, 1.0 and 5 times of normal permeability are used for comparison.

Temperature

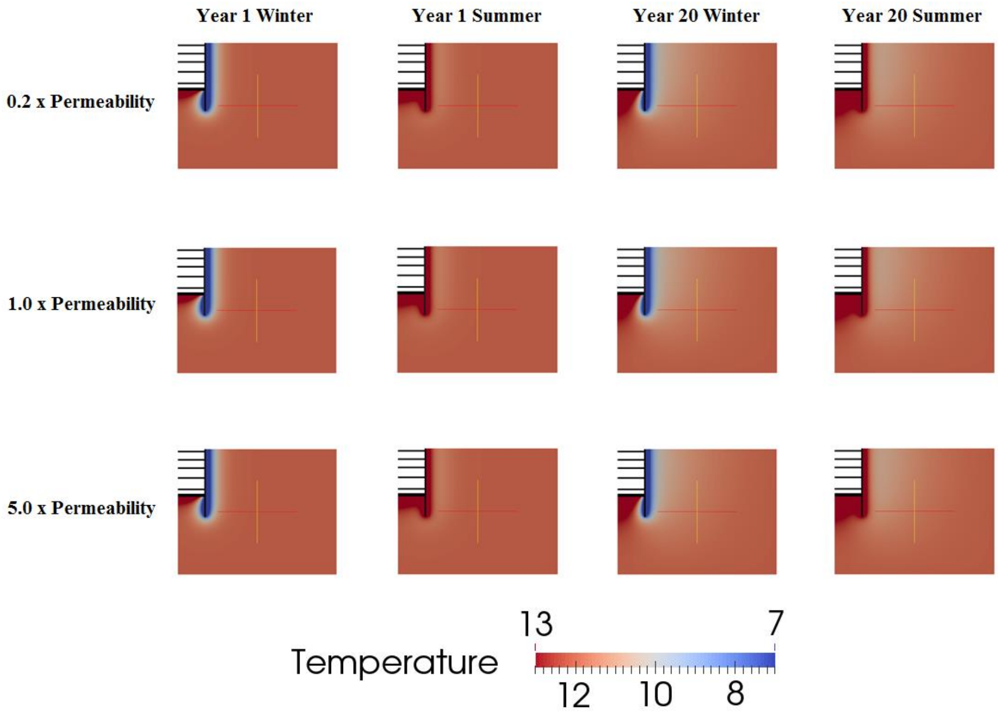


Fig. 44 - Contours of changes in temperature distribution by varying permeability in soil

At first it is thought that changing the permeability in the soil would affect the heat flow because the water would carry the heat energy from the wall and disperse into the soil increasing conduction and convection. Fig. 44 shows the temperature distribution in soil for short term (Year 1) and long term (Year 20) operation of energy wall. It shows that varying the permeability has negligible effect in the short term operation, and has little effect in the long term. Only a little increase in the influence zone with increasing permeability can be seen in long term summer cycles and has no effect on long term winter cycles. This means the heat transfer in soil is mainly by conduction in soil particles.

Pore Pressure

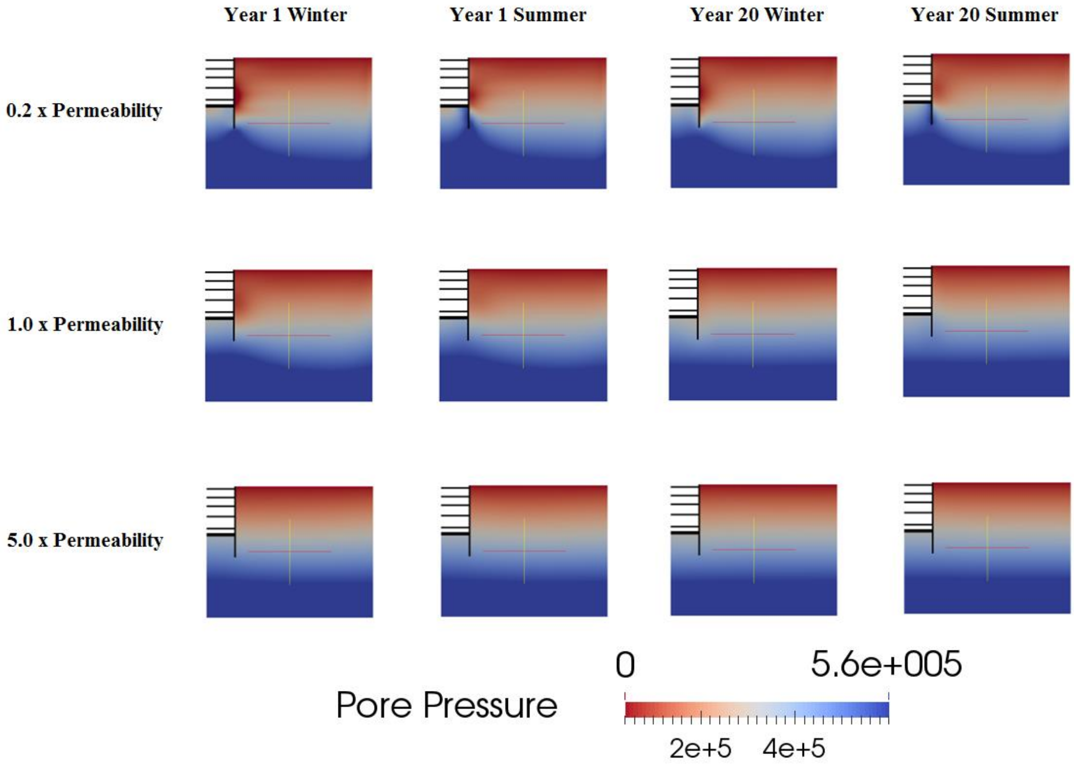


Fig. 45 - Contours of changes in pore pressure distribution by varying permeability in soil

Changing the permeability has a clear effect on pore pressure distribution in Fig. 45.In normal permeability, the excess pore pressure developed from excavation first get dissipated before the effect of the operation of the energy wall becomes apparent in Year 20. With the reduced permeability, the pore fluid migrates slowly within the soil skeleton, so the excess pore pressure doesn't dissipate after 20 years. In this set of contours the thermal effect on pore pressure can be seen more evidently than in normal condition (the pore pressure increase and decrease with temperature). With 5 times the permeability, no excess pore pressure is seen in the model, even at the first stage of operation, this shows the excess pore pressure has dissipated during the installation of permanent slabs. However, the dissipation does seem faster than expected given the permeability is of order of 10^{-10}m/s. The analysis makes physical sense, but further verification is required for the dissipation of pore pressure modelled.

Total and effective stress

Fig. 46and Fig. 47 show the total horizontal contours and profile at the soil side of the wall respectively. The total horizontal stress varies more between each cycle with decrease in permeability (Fig. 46). This is because when permeability decreases the pore fluid is trapped within the soil skeleton, so the thermal expansion of the entrapped fluid induces stress upon the soil skeleton. The extra pore pressure with low permeability changes the total horizontal stress the soil experiences. The total stress difference between cycles for 0.2, 1.0 and 5.0 times permeability are 50kPa, 25kPa and 10kPa respectively (Fig. 47). Hence assessment of field permeability is important.

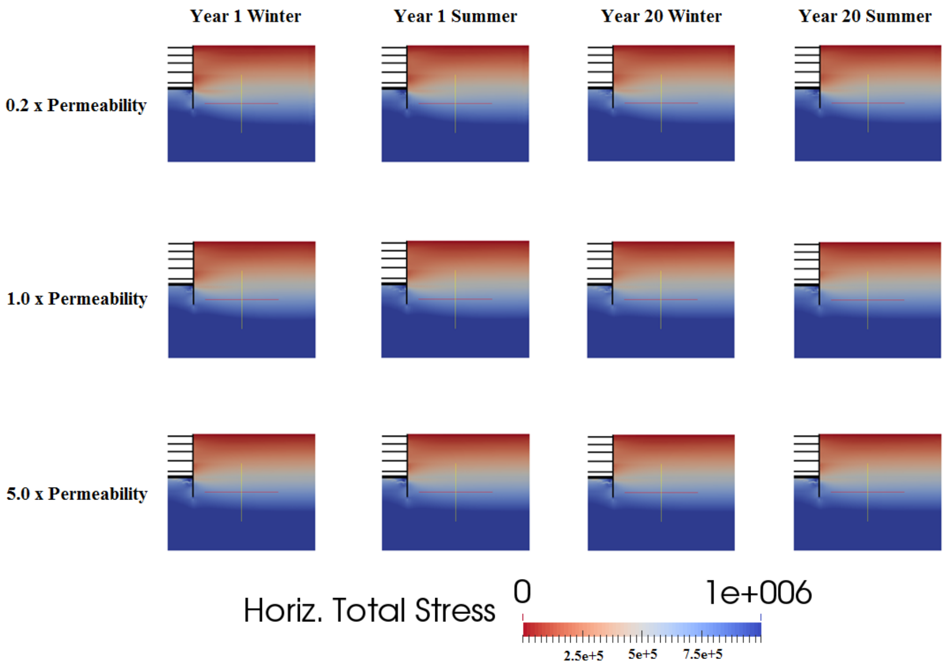


Fig. 46 - Contours of changes in horizontal total stress distribution by varying permeability in soil

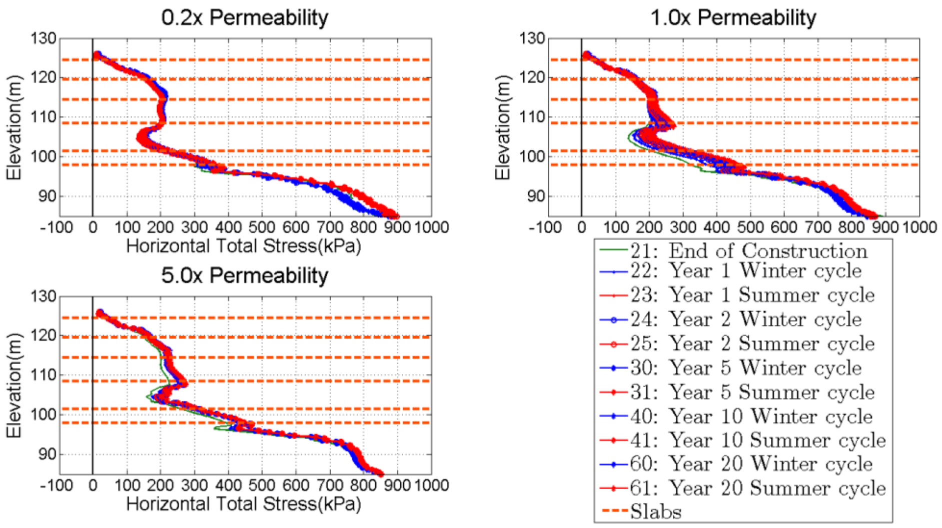


Fig. 47 - Plot of changes in total stress with variation in permeability in soil

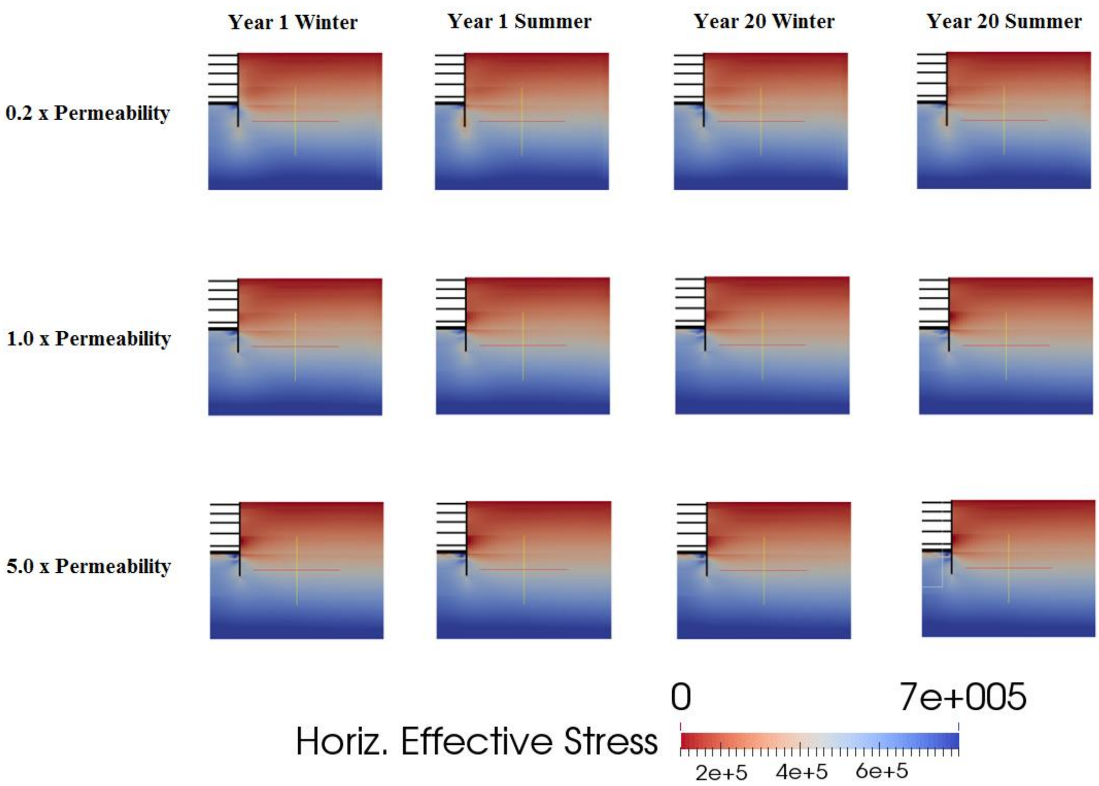


Fig. 48 - Contours of changes in horizontal effective stress distribution by varying permeability in soil

The effective stress had little variation in 0.2 times permeability throughout the 20years of operation (Fig. 48), because the rate of dissipation in excess pore pressure is slow, so the effective stress remains constant. In the 5 times permeability case, the effective stresses are similar for its summer cycles and winter cycles. The soil is allowed to consolidate within each cycle so the thermal induced changes in effective stress are seen straight after each cycle.

Displacement

Fig. 49 and Fig. 50 show the horizontal displacement contours and the wall relative displacement respectively. In low permeability, relative displacement is relatively constant above the base slab level, and has greater variations at the base slab level (Fig. 50). This is because the soil movement is related to the migration of pore fluid. The volume change in soil is caused by the addition or loss of pore fluid from the soil skeleton, the soil is therefore restricted from expansion/shrinkage in between cycles. The 5 times permeability plot can be viewed as the long term effect of operating the energy wall. The negative excess pore pressure developed in excavation gets dissipated, so pore fluid is drained from the soil skeleton results in soil swelling. However, the increasing permeability helps heat transfer, so a larger volume of soil adjacent to the wall is affected by the temperature change. That means the temperature gradient across the wall in the winter is greater, causing thermal straining in the wall. This has a push-back effect on soil, which overcomes the swelling of soil.

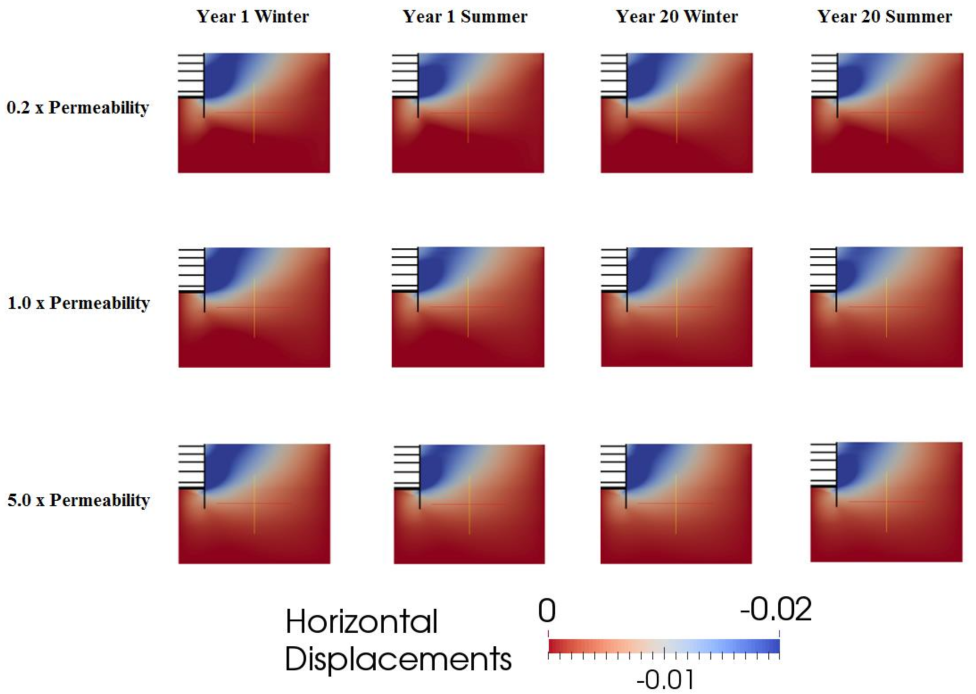


Fig. 49 - Contours of changes in horizontal displacement by varying permeability in soil

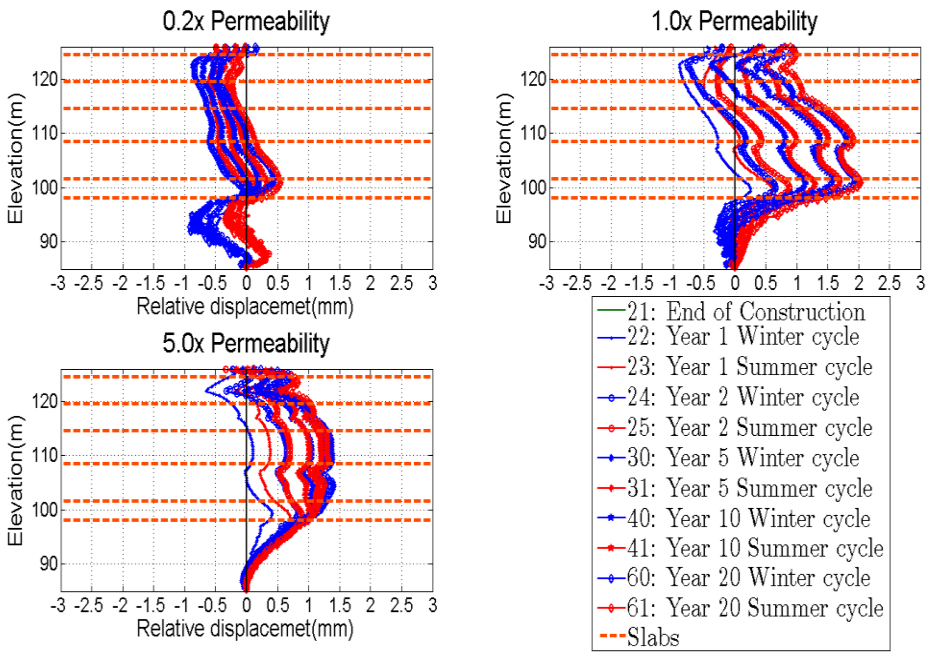


Fig. 50 - Plot of changes in wall relative displacement with variation in permeability in soil

Moment

From Fig. 51, the moment distribution along the wall increases with permeability because greater movement is seen in the more permeable model. The magnitude of the increase is about 50-100kNm, but this would not compromise the structure(within moment envelope, see section 4.3.5). That means the permeability would not affect the structural performance by the operation of this energy wall.

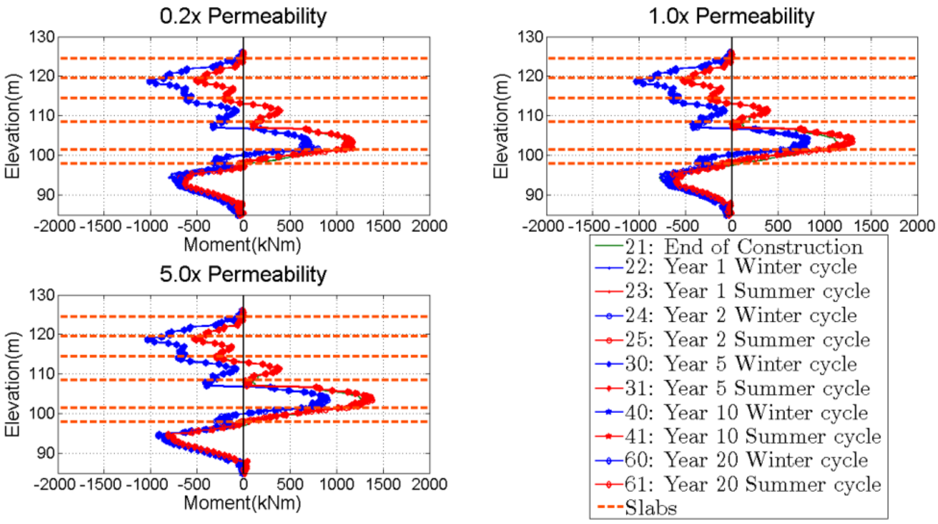


Fig. 51 - Plot of changes in wall moment with variation in permeability in soil

4.4.2 Thermal expansion coefficient of concrete

Displacements and therefore moments are affected by the thermal expansion coefficient of the material, because thermal strain of a material is dependent on it. The bending moment changed when there is a temperature difference in the wall(e.g. winter). These factors potentially impair the structural performance of the diaphragm wall. Hence it is important to check the effect by varying the thermal expansion of the concrete.

Temperature

Fig. 52 shows the temperature distributions with different thermal expansion coefficient in concrete. The thermal expansion coefficient doesn't affect the heat transfer, so the temperature distributions are the same as 4.3.1. During the winter cycle, the adjacent soil cools and in the summer the soil heats up. In the long term, the operation of the wall has a cooling effect on the surrounding soil.

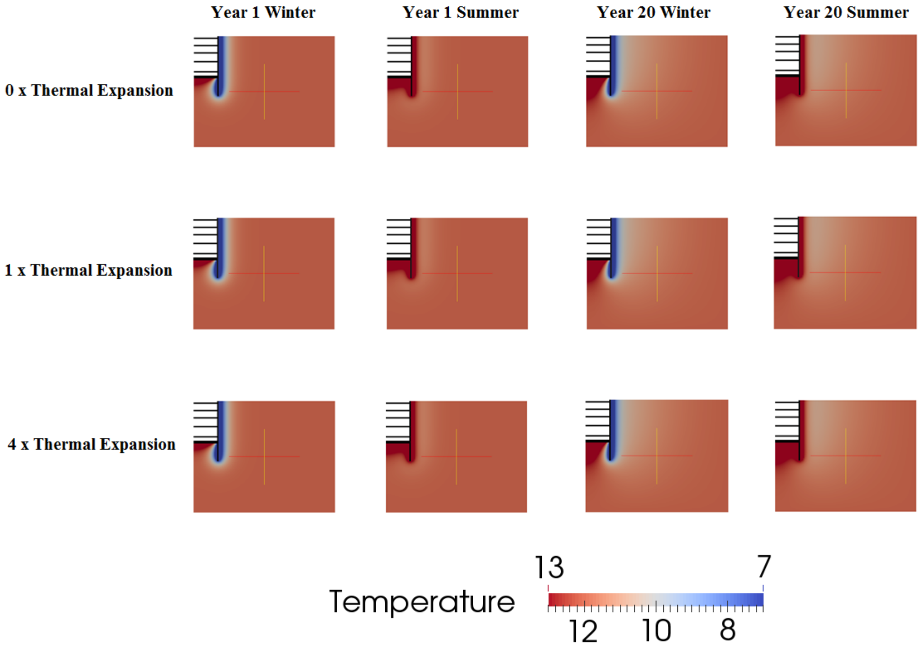


Fig. 52 - Contours of changes in temperature distribution by varying thermal expansion coefficient in concrete

Pore Pressure

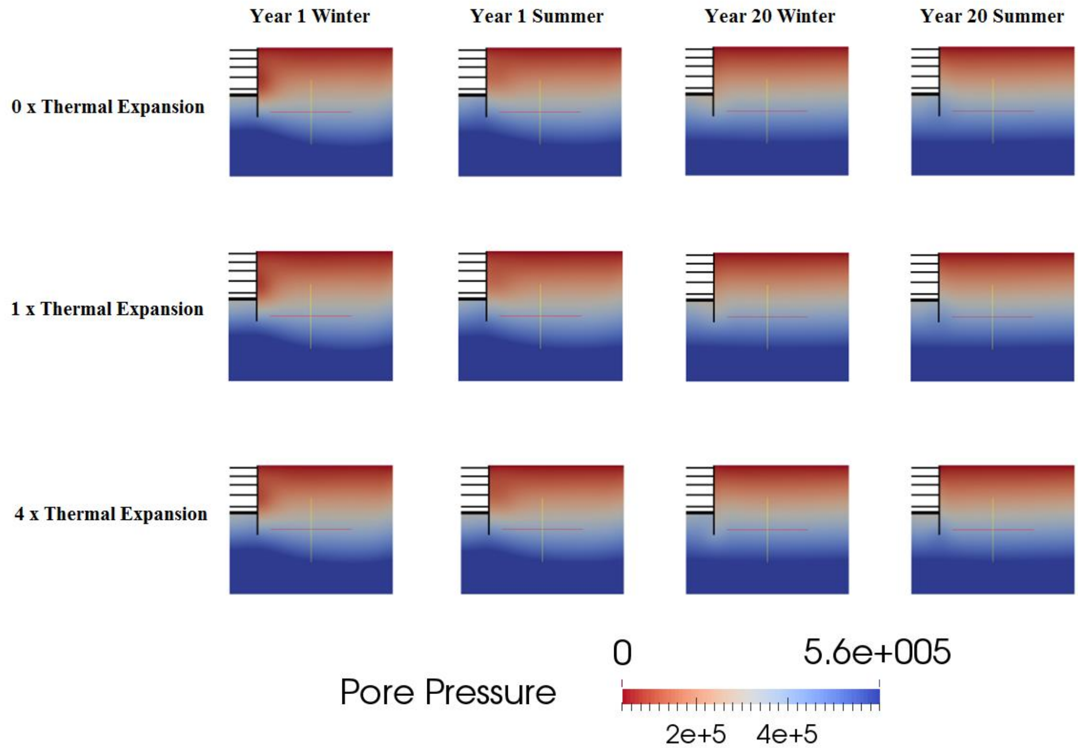


Fig. 53 - Contours of changes in pore pressure distribution by varying thermal expansion coefficient in concrete

Total and Effective Stress

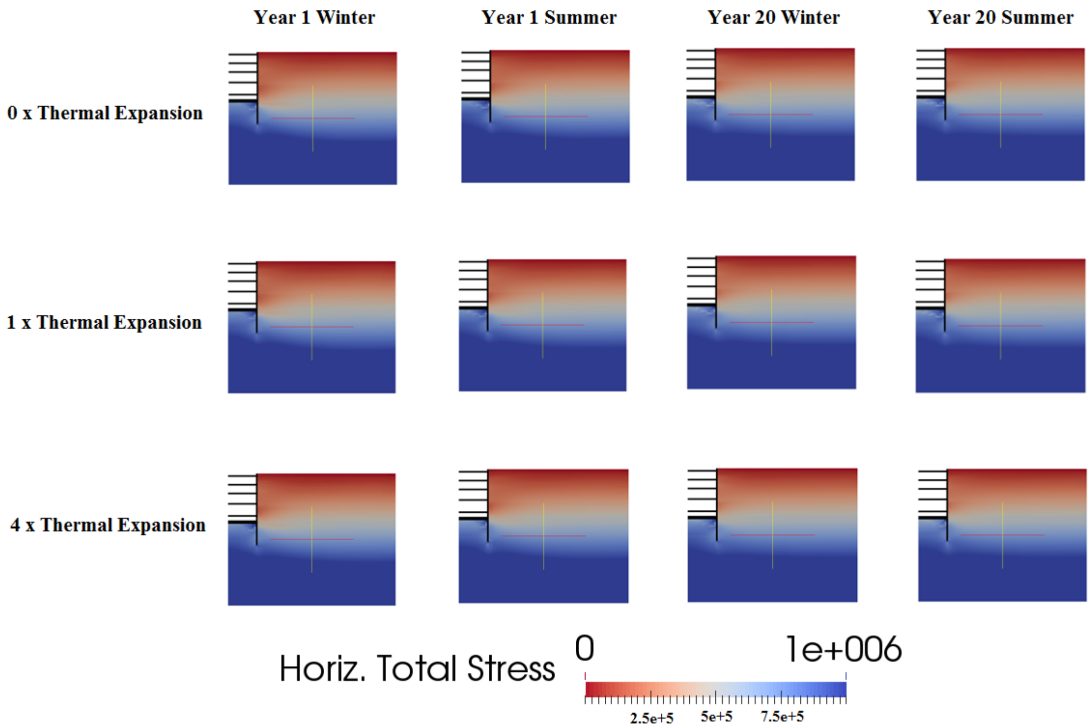


Fig. 54 - Contours of changes in horizontal total stress by varying thermal expansion coefficient in concrete

Fig. 53 and Fig. 54 show the pore pressure and total horizontal stress contours. When there is no thermal expansion in concrete, the change in total stress is caused purely by the thermally induced pore pressure in the soil. For 4 times thermal expansion, the total stress above the base slab increases in the winter cycles; this change occur when the wall expands into the soil. The maximum change in total stress occurs below the base slab level because that's where the maximum temperature difference across the wall is. The length of wall below the base slab is 12m. Although it is bounded by soil on both side, but the stresses occur on both sides are balanced out. This means if the wall expands/contracts it would be have the largest displacement between summer/winter cycles.

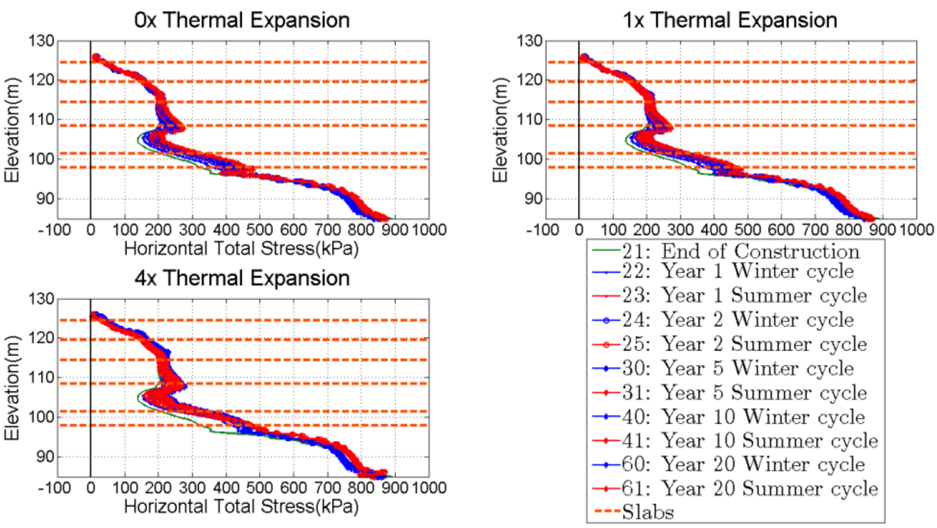


Fig. 55 - Plot of changes in horizontal total stress with variation in thermal expansion coefficient in concrete

The effective stress in the summer is lower for 0 expansion than 4x expansion because the pore pressure is higher for 0 expansion and the total stress is almost the same. The opposite happens for the winter cycle.

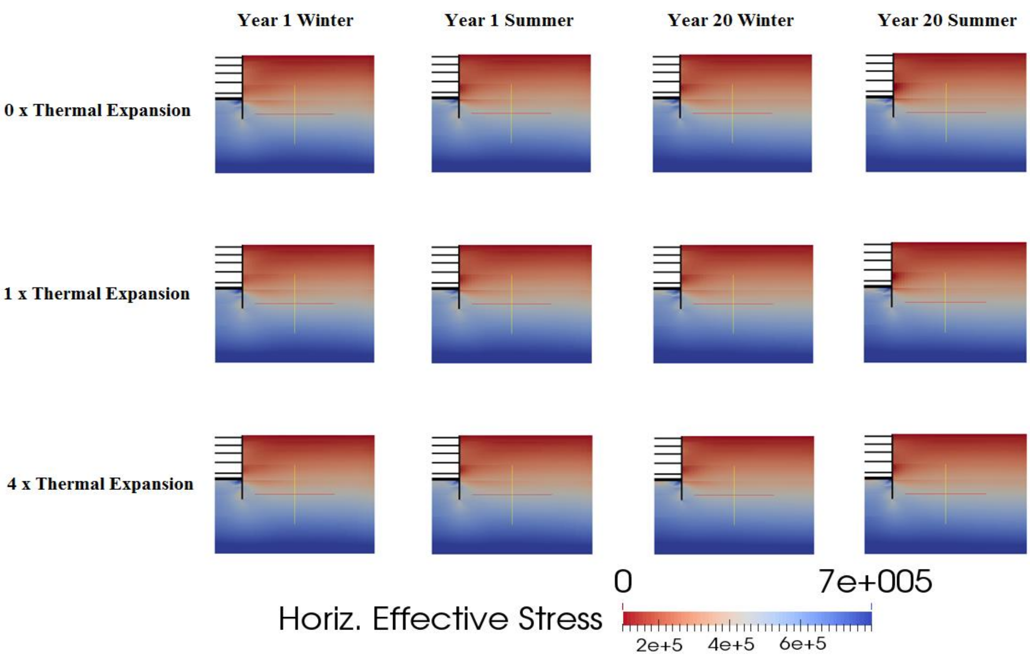


Fig. 56 - Contours of changes in horizontal effective stress by varying thermal expansion coefficient in concrete

Displacement

Fig. 58 shows the displacement of the wall with different thermal expansion coefficient in concrete. The displacement with 0 expansion of concrete is caused by the thermal expansion of soil, this change in displacement is uniform and doesn't induce curvature. The wall movement increases with expansion coefficient, the difference in temperature across the wall induces thermal strains. The induced thermal strains increase with thermal expansion coefficient, and results in induced curvature in the wall.

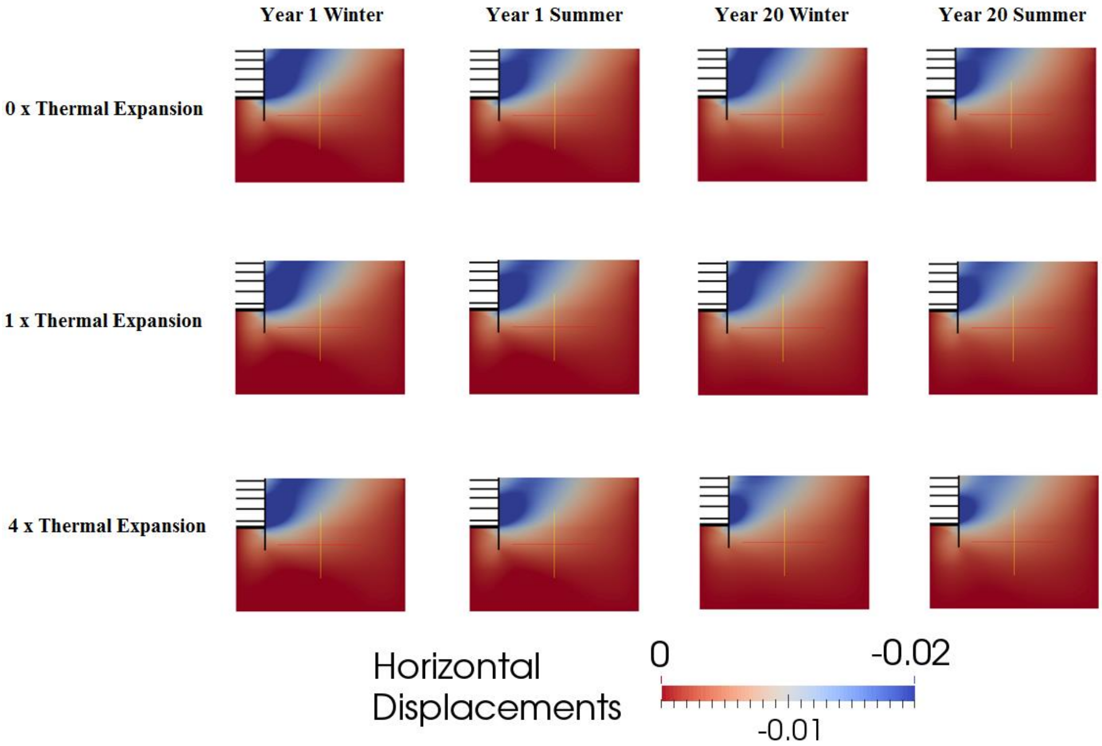


Fig. 58 - Contours of changes in horizontal displacement by varying thermal expansion coefficient in concrete

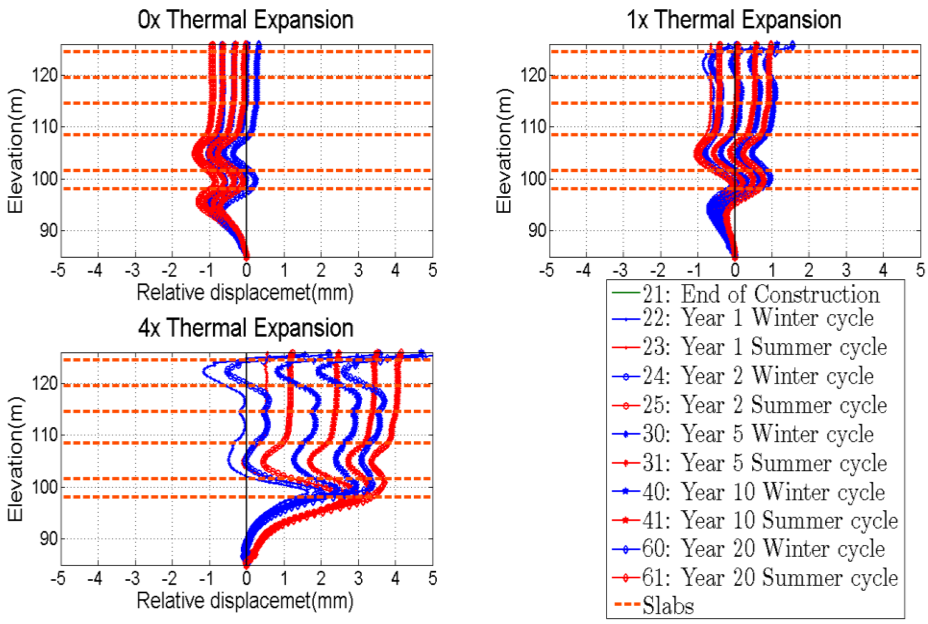


Fig. 58 - Plot of changes in wall relative displacement with variation in thermal expansion coefficient in concrete

Moment

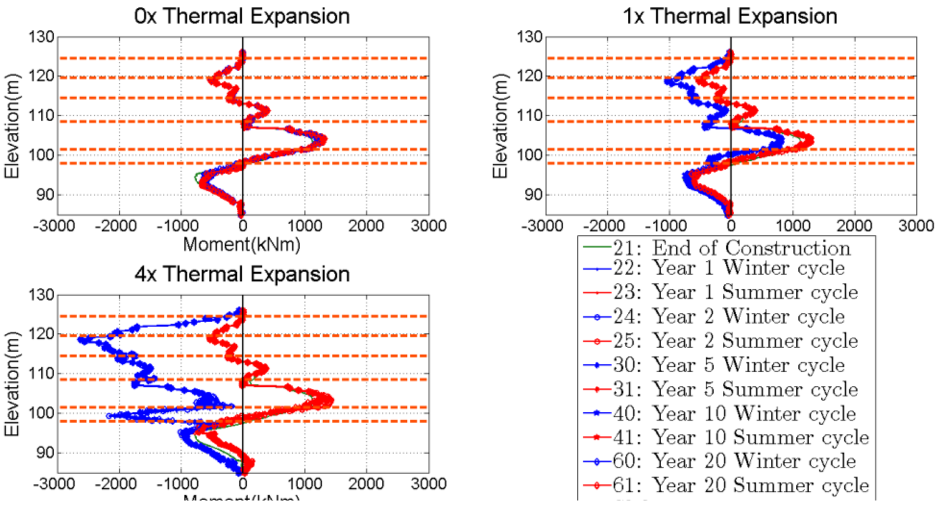


Fig. 59 - Plot of changes in wall moment with variation in thermal expansion coefficient in concrete

Fig. 59 shows the moment distributions in the wall with different thermal expansion coefficients. It can be seen in Fig. 59, the expansion of soil causes negligible bending strains in the wall. Therefore the thermal expansion of soil would not affect the structural performance in the operation phase of the energy wall. More importantly, the bending strain is governed by the thermal expansion of concrete in the wall. The summer cycles are independent of the expansion coefficient due to the temperature difference across the wall is small during summer. Both sides of the wall are around 18^{o}C, so the induced thermal strains are small. In winter, the temperature difference is the largest, results in large increase in curvature and therefore moment. The thermal expansion coefficient of concrete can be controlled by the type of binding material(e.g. cement), aggregates used when it is casted, so it can be considered in the design stage of the energy wall.

4.4.3 Thermal conductivity

Thermal conductivity is one of the most significant thermal properties of soil because it is one of the main heat transfer mechanisms in soil. This may affect both the structural performance and the performance of the energy wall.

Temperature

In Fig. 60, the temperature distribution is strongly affected by the thermal conductivity of the soil. The zone of influence gets larger with increasing thermal conductivity. So in the winter, more surrounding soil is cooled and the opposite is seen in the summer. It should also be noted that below the base slab, more soil is cooled in the winter due to the operation of the wall in the models with higher thermal conductivity. The cumulative cooling effect of operating wall occurs in all the models, so this effect is independent to the thermal conductivity of soil. It is likely to be affected more by the rate of heat extraction from soil, i.e. the coolant temperature, but further analysis is required for validation.

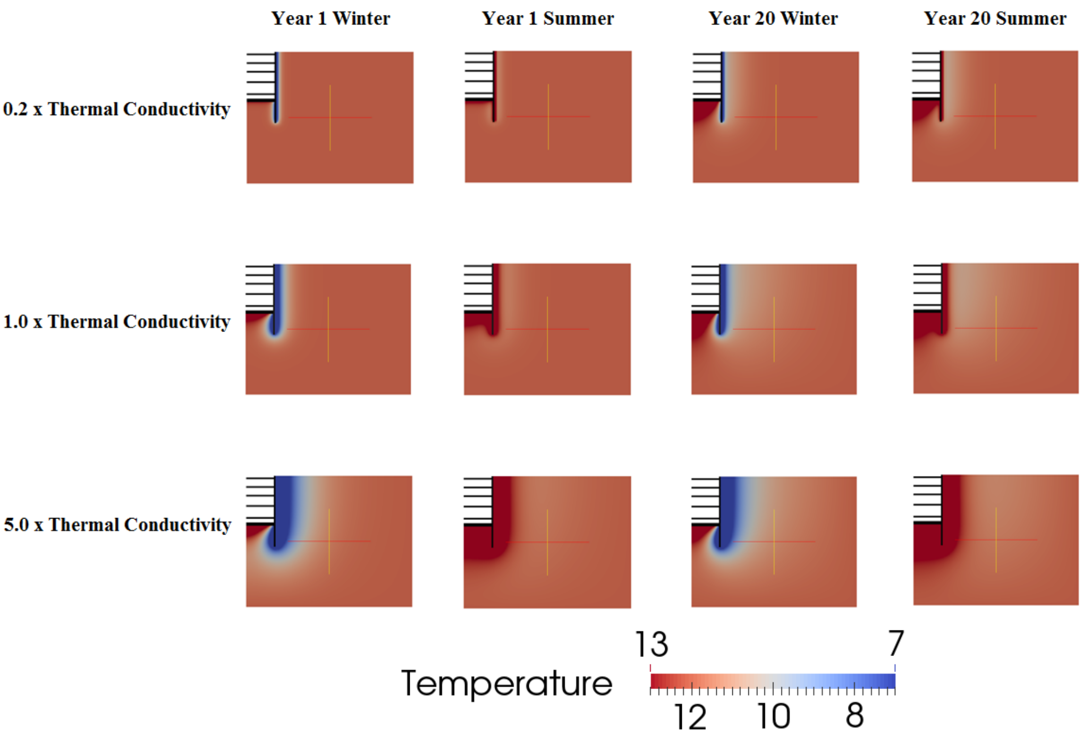


Fig. 60 - Contours of changes in temperature distribution by varying thermal conductivity in soil

Pore Pressure

It is apparent in Fig. 61 that the pore pressure is affected by the thermal conductivity. In winter more negative excess pore pressure is generated by cooling a larger volume of soil with increase in conductivity, this is because more soil is cooled so more soil skeleton and pore fluid contracts. This results in a larger negative excess pore pressure to develop. More excess pore pressure is developed in the summer because of the greater influence zone of increased temperature in soil.

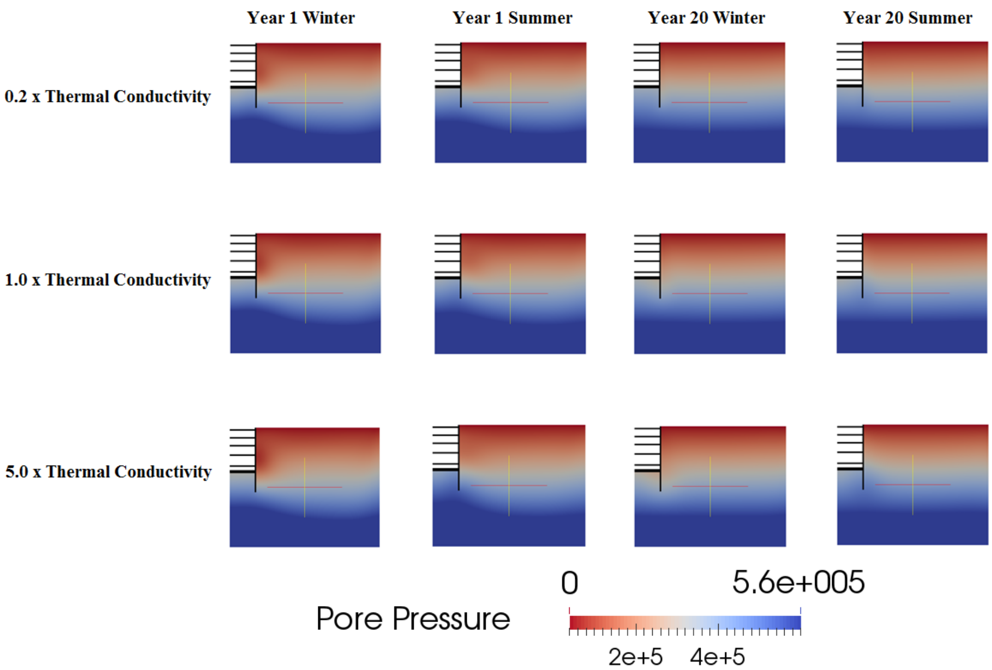


Fig. 61 - Contours of changes in pore pressure distribution by varying thermal conductivity in soil

Total and effective stress

There are no additional applied loads applied on wall after constructions are completed, only the thermal loads from wall movement and the expansion in the soil. With higher conductivity, more soil is influenced by temperature change as seen previously. The total stress in the summer increases more with the higher conductivity because more soil is influenced so the pore pressure rises. Fig. 63 shows the relative displacement with different thermal conductivity in soil. With 5 times conductivity, the total stress difference between cycles increased from 30kPa to 60kPa, and for 0.2 times conductivity, the stress difference is 15kPa. This suggests the total stress difference is maybe 2.5 times the factor of increase in conductivity, but more models with different conductivity need to be analysed to verify the statement.

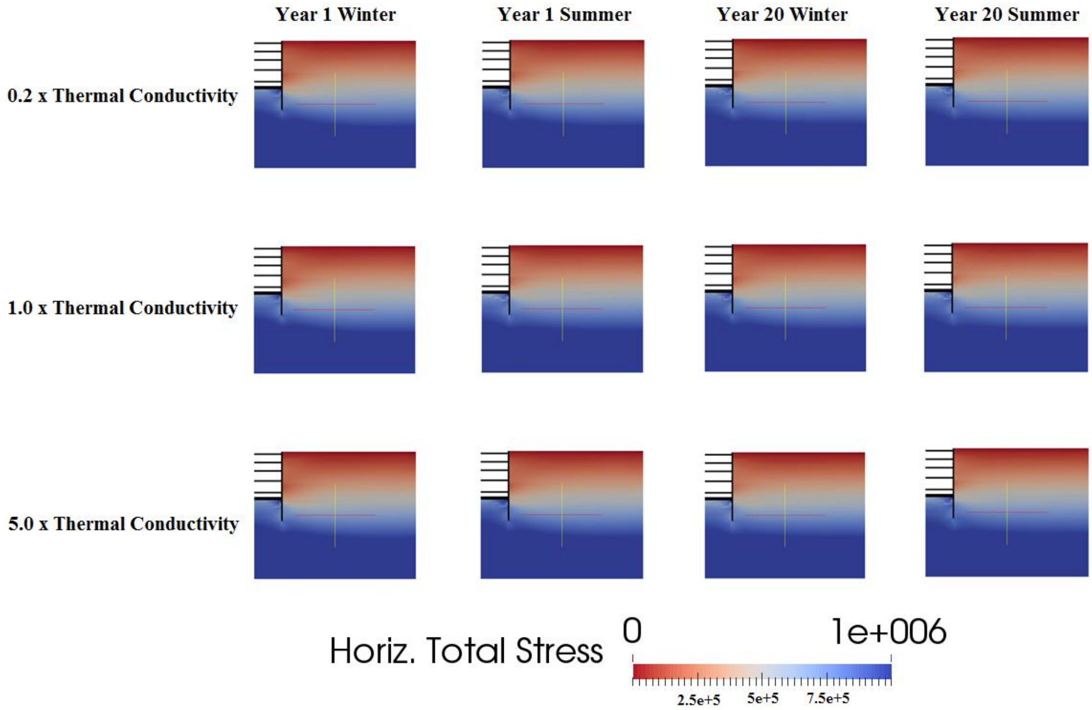


Fig. 62 - Contours of changes in horizontal total stress by varying thermal conductivity in soil

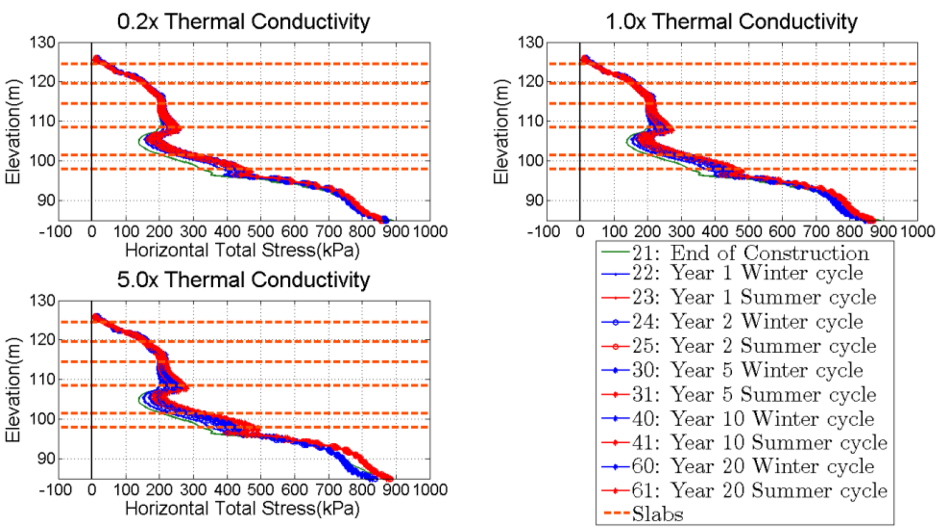


Fig. 63 - Plot of changes in total horizontal stress with variation in thermal conductivity in soil

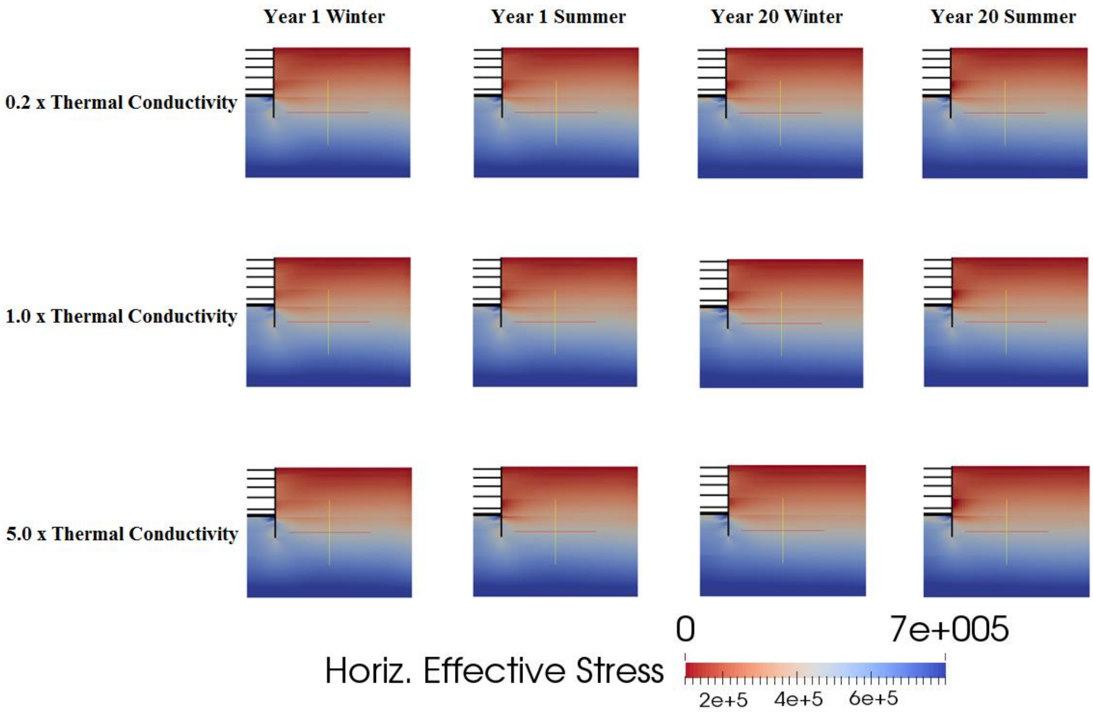


Fig. 64 - Contours of changes in horizontal effective stress by varying thermal conductivity in soil

Fig. 64 shows the effective horizontal stress with different thermal conductivity in the soil. The effective stress difference between cycles also increases with increase in conductivity. The pore pressure increase/decrease with temperature and the effective stress increase/decrease correspondingly after consolidation. The 6 months cycle allow soil to consolidate partially, the sum of the pore pressure and effective stress results in the total stress.

Displacement

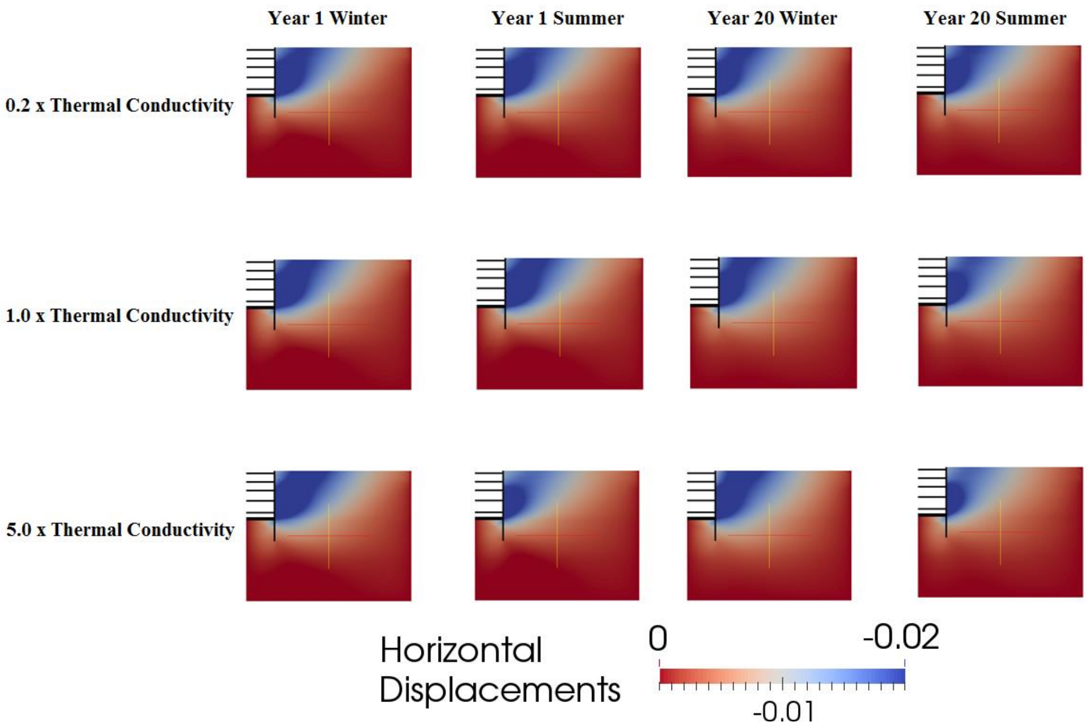


Fig. 65 - Contours of changes in horizontal displacement by varying thermal conductivity in soil

Fig. 65 and Fig. 66 show the horizontal displacement contours and plots for different thermal conductivity in the soil. With the increase in conductivity, the relative displacement shifts to the right for winter cycles (Fig. 66). The zone of influence for the long term cooling effect in soil means more soil is cooler, so more soil suffers from shrinkage when the winter cycle begins. The total stress acting from the soil decreases, so the wall is allowed to displace further into the soil side than when the conductivity is lower. However, the conductivity has smaller effect on the summer cycles displacements in comparison because the soil swells back into its original position. More soil is affected by the increase in soil temperature when the conductivity is high, so more soil expansion causing the wall to move to the left. However, the cooling effect had more influence so the overall curves shifted to the right.

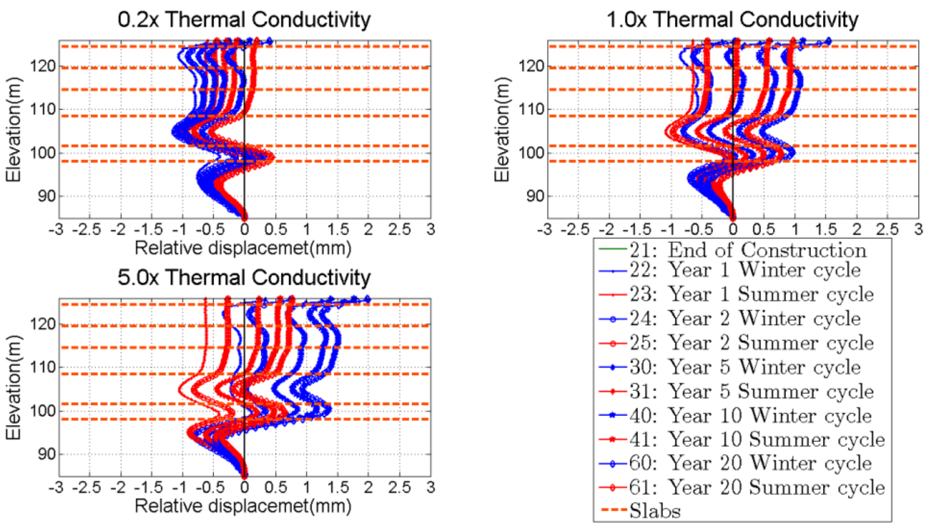


Fig. 66 - Plot of changes in relative displacement with variation in thermal conductivity in soil

Moment

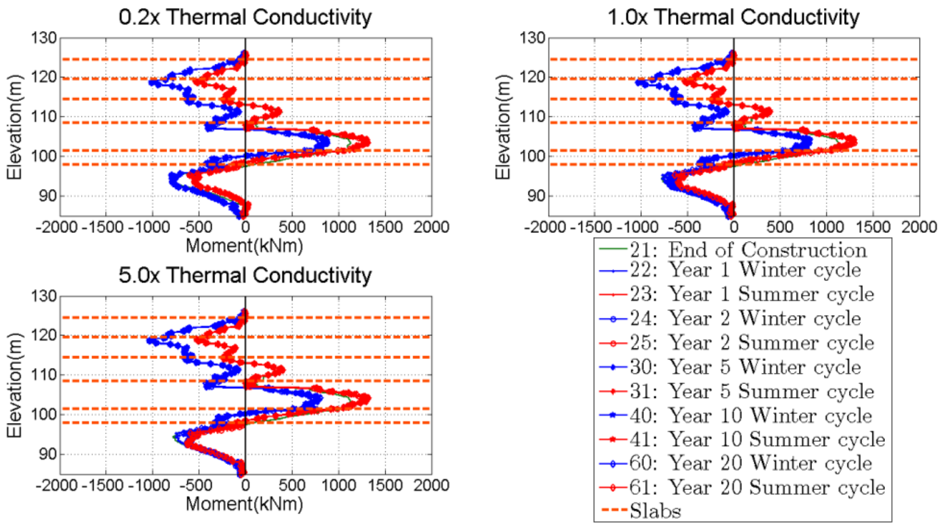


Fig. 67 - Plot of changes in moment with variation in thermal conductivity in soil

Although the difference in total stress and displacement have increased with conductivity, but these have little influence on the moment (Fig. 67). This is because the moment changes are dominated by the temperature gradient in the wall, so the soil effect is negligible. The moment envelope of the normal thermal conductivity lies well within the design moment capacity, and the new moment wouldn't exceed the limit. The thermal conductivity has little effect on the moment and therefore the structural performance isn't impaired.

5 Conclusion

The construction phase of the model was matched with the field data and the mechanism of the wall construction and subsequent long-term effects was understood.

With no operation of GSHP, the pore pressure returns to almost hydrostatic after 5 year, the total horizontal stress has little variation. The wall gradually moves back into the soil with time and the moment distribution of the wall is has negligible changes from the moment distribution immediately after construction.

During winter, cold coolant is injected in absorber pipes. Soil shrinkage and decrease in earth pressures are seen. The large temperature difference between the station box and the absorber pipes induces large bending moments in the wall.

During summer cycle, the injected coolant is warmer than soil. Temperature increase causes expansion in pore fluid and soil skeleton, increasing pore pressure, total stress and effective stress. The earth pressure together with the thermal straining of the wall causes the wall to displace inducing curvatures in the wall which results in bending moments on the wall. The induced bending moments in summers are less than winters because the temperatures of both sides of the wall are uniform. The summer cycle bending moment envelope is similar to the construction bending moment envelope.

The total stress stays constant with operation of the wall, and there's a difference of 50kPa in pore pressure between cycles. The operation of the wall has a cooling effect to the surrounding soil where the average temperature in the soil decreases. This will affect the power output of the energy wall, but the scale of the effect needs to be further investigated.

Permeability affects the dissipation rate of excess pore pressure. Higher permeability would reduce the total stress in the soil. However, it has negligible effects on the bending moments.

Thermal expansion coefficient of concrete has significant effect on displacements and bending moments of the wall, and the thermal expansion/contraction in soil is negligible.

The zone of influence of the operation increases with thermal conductivity in soil, so the long term cooling effect is larger. It leads to a small change in bending moments of the wall.

The pore pressure, total stress and effective stress in the soil are influenced by the operation of the energy wall. Their collective effects cause displacements of the diaphragm wall resulting in bending moments on the wall. However, their effects are negligible in comparison to the thermal expansion/contraction of the wall itself.

6 Suggestions for Further Work

- Anisotropic permeability can be applied to model for a more realistic analysis. This could be done by setting the vertical permeability as a fraction of the horizontal permeability and keeping the mean of the vertical and the horizontal permeability as a constant.
- The temperature variations in the top surface soil can be included in the model
- Long term behaviour of the Energy wall can be assessed by running a model for a longer time frame (e.g. 50years, 100years).
- The vertical displacement of the soil due to the operation can be analysed to assess the potential damage on surrounding buildings that might be caused by the operation of the wall.
- The operation phase of model can be calibrated against actual data when the energy wall at Dean Street is operated if monitoring devices are available and installed.
- Several other factors can be considered for parametric study, specific heat capacity of soil, the coolant temperature used in cycles

7 Reference

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8 Appendix

8.1 Risk Assessment Retrospective

This project is computer based and doesn’t require experiments. The initial risk assessment only looked at the hazards superficially, such as awareness of plugging charger to power plug, water spillages on electronic equipment. However, other sources of injury became more apparent with the increased computer usage. For prolong use of computer for research, reading references, analysis may cause eye strains and headaches, so allocated resting time at regular intervals is required. Also, Repetitive Strain Injury (RSI) should not be underestimated with the substantial increase in mouse usage. Both long and short term effects of the activities required for the project needs to be considered for a more thorough preparation to the project.

8.2 Project Programme