Simplified methods for designing thermo-active retaining walls

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Abstract. Thermo-active retaining structures are geotechnical structures employed to provide thermal energy to buildings for space heating and cooling through heat exchanger pipes embedded within the concrete structure. Consequently, the design of these structures needs to consider both the long-term energy efficiency as well as the thermo-mechanical response in terms of stability and serviceability. Transient finite element analyses can be carried out to evaluate the behaviour of thermo-active walls, where the heat exchanger pipes are explicitly modelled, thus requiring three-dimensional (3D) analyses. However, performing long-term 3D finite element analyses is computationally expensive. For this reason, in this study, new approaches are presented that allow the thermal or thermo-mechanical design of thermo-active walls to be carried out by performing two-dimensional (2D) plane strain analyses. Two methods, which are based on different design criteria, are proposed and their performance in replicating the three-dimensional behaviour is assessed. Furthermore, the factors affecting the 2D approximations for the two modelling approaches are evaluated, where particular emphasis is given to the influence of the simulated boundary condition along the exposed face of the retaining wall.

1 Introduction

Thermo-active retaining walls are employed to produce thermal energy for space heating and cooling. This is achieved by installing heat exchanger pipes within the structure, which, through the circulation of a hot or cold fluid, inject or extract energy to/from the ground, respectively. Hence, this type of structure has the dual purpose of providing both energy and stability to buildings. As such, these two aspects, i.e. energy efficiency and structural performance (both in terms of stability and serviceability), are of concern when designing thermo-active walls.

Limited field work has been carried out to characterise the thermal and thermo-mechanical behaviour of walls [1-3]. For this reason, the response of thermo-active walls has been investigated through numerical analysis to evaluate their energy efficiency (e.g. [4]) or structural response (e.g. [5]). Due to the presence of heat exchanger pipes, which lead to non-uniform temperature distributions along the width of the wall panel, these problems are inherently three-dimensional (3D). However, due to the dimensions of the analysed problem and the need to employ a coupled thermo-hydro-mechanical (THM) formulation [6], performing three-dimensional (3D) analyses is computationally expensive. Thus, thermo-active walls are often simulated in two-dimensional (2D) plane strain analyses, although no modelling procedures which ensure that the response in 2D is comparable to that obtained in 3D have been proposed in the literature.

This paper seeks to address this issue by presenting two modelling approaches that enable the estimation of

the energy efficiency (thermal design) and structural performance (thermo-mechanical design) of thermo-active walls using 2D plane strain finite element analyses. It should be noted that, although the proposed 2D approximations were established assuming that the heat exchanger pipes form U-loops, the general methodology described in this paper can be extended to include any pipe arrangement. The simulations reported herein are carried out employing the Imperial College Finite Element Program (ICFEP, [7]), which is capable of simulating fully coupled THM problems [8] and the heat transfer occurring within heat exchanger pipes through the use of one-dimensional elements [9, 10]. The validity of the proposed 2D approximations is demonstrated by simulating a thermo-active wall problem using 3D analyses and comparing the results to those obtained by the corresponding 2D analyses. The adopted sign convention is such that positive values refer to tensile axial forces, bending moment as a result of tension along the excavated side of the wall and upward vertical movements.

2 Problem description and numerical model in three-dimensional analysis

Figure 1 depicts a schematic representation of the analysed problem and Figure 2 shows the finite element (FE) mesh. The thermo-active wall, of which a single panel is modelled, is embedded entirely in London Clay. It is 20.0 m long (L), 1.0 m thick (W) and 2.0 m wide (B) and supports a 30.0 m wide and 16.0 m deep (L_{exp}) excavation. The wall is supported by horizontal slabs (see

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Figure 2), where the floor slabs and the base slab were assumed to have thicknesses of 0.3 m and 1.0 m, respectively. The mechanical boundary conditions include a restraint in the vertical direction along the bottom boundary and in the horizontal directions along the normal direction to each lateral boundary. The heat exchanger pipes (internal diameter of 27.33 mm) are located at a distance of 0.1 m from the concrete edge on the retained side, with a pipe-to-pipe spacing of 1.0 m, and reach a depth of 19.5 m. The initial ground conditions consist of a hydrostatic pore water pressure profile, with the water table located at the ground surface, a coefficient of earth pressure at rest, K_0 , of 1.0, and a saturated bulk unit weight of soil, γ , equal to 20 kN/m³. Two different conditions were assumed for the wall-air interaction along the exposed face: no heat flux takes place across this boundary (NF) and a wall face maintained at constant temperature equal to the initial temperature (T_0) of 15°C (CT), i.e. similar to those adopted in [11].

The concrete and heat exchanger pipes were modelled as linear-elastic materials, with the former having a Young’s modulus, E , of 30 GPa and a Poisson’s ratio, ν , of 0.3, while the latter have a sufficiently low stiffness such that they do not affect the response of the wall. The soil was modelled as a non-linear elasto-plastic material, with a Mohr-Coulomb failure surface ($c'=5.0$ kPa, $\varphi'=25.0^\circ$, $\psi'=12.5^\circ$) coupled with the IC.G3S non-linear elastic stiffness model [12]. The employed parameters for London Clay are adopted from [13]. The soil has a permeability of 1.0×10^{-10} m/s and the coefficient of expansion of water, α_w , is equal to 6.9×10^{-5} m/mK. All materials present the same coefficient of thermal expansion, α , of 1.2×10^{-6} . The thermal material properties are outlined in Table 1.

The rapid excavation was simulated by removing 2.0 m thick soil layers until the excavation depth was reached. During this stage, temporary props at depths of 3.0 m, 7.0 m and 11.0 m, simulated as a nodal spring with a stiffness of 100 MN/m applied to the middle of the wall panel, supported the excavation. These were removed after completion of the excavation, when the permanent slabs were constructed, modelled as springs normal to the wall surface along the whole width of the panel, simulating concrete slabs ($E=28$ GPa). Subsequently, six months of heat injection were modelled by imposing an

inlet temperature, $T_{in,3D}$, of 30°C (corresponding to a difference between the inlet and initial temperature, $\Delta T_{in,3D}$, of 15°C) and circulating water at a velocity, v , of 0.35 m/s. As shown in Figure 1, at the pipe outlet, the thermo-hydraulic boundary condition was applied [14]. Before the application of changes in temperature, the excess pore water pressures generated during excavation were allowed to dissipate in order to isolate the thermal effects from those generated during construction and the stiffness of the soil was reset to its maximum value [13]. To guarantee numerical stability in the presence of large water flow velocities within the pipes, the Petrov-Galerkin finite element method [15] was adopted. Appropriate time steps were employed to avoid the thermal and hydraulic shock problems [16, 17]. The ground surface was maintained at a constant temperature (equal to $T_0 = 15^\circ\text{C}$) throughout the analysis, while all other boundaries were considered adiabatic (apart from the exposed face, as previously described).

Table 1. Thermal material properties

Material	Thermal conductivity λ (W/mK)	Volumetric specific heat capacity ρC_p (kJ/m ³ K)
Concrete	1.60	2615
London Clay	1.79	1820
Pipe/water	0.60	4180

Fig. 1. Diagram of the problem and thermal boundary conditions

Fig. 2. Finite element mesh

Fig. 4. Comparison of heat flux with time

4 Thermo-mechanical design

The method proposed for thermo-mechanical design aims at reproducing the average thermally-induced forces per metre width of wall panel to which thermo-active walls are subjected. Indeed, further studies have shown that the method described in the previous section, while yielding a good estimate of the thermal performance, does not allow an accurate reproduction of the thermo-mechanical response. To address this limitation, the new method was developed such that only simple analyses where the heat exchange is simulated through the application of thermal boundary conditions are required, thus avoiding the use of elements simulating heat exchanger pipes, which require advanced numerical methods [15].

Figure 5 presents a schematic illustration of the proposed method. First, through a thermal simulation of the wall problem in plan view (“2D plan analyses” of exposed and embedded sections, see respectively Figure 5 (a) and (b)), an average temperature, $T_{i,2D}$, is evaluated using the following expression:

$$T_{i,2D} = \frac{L_{exp}}{L} T_{i,Av,exp} + \frac{L_{emb}}{L} T_{i,Av,emb} \quad (5)$$

where L_{exp} and L_{emb} are the exposed and embedded lengths of the wall (m), respectively, L is the total length of the wall (m) and $T_{i,Av,exp}$ and $T_{i,Av,emb}$ are the average temperatures at time instant $t = t_i$ across the width of the panel (B) where the pipes are located for the exposed and embedded sections of the wall, respectively (i.e. along line A-B in Figure 5 (a) and (b)). For the simulation of the presence of the heat exchanger pipes in this analysis, a constant temperature boundary condition is prescribed at their positions within the wall section. Assuming that the temperature along the pipes varies linearly, the temperature applied at these points is taken to be, approximately, $T_{in,3D} - \Delta T/2$ (see Figure 5 (a) and (b)), where ΔT is the temperature difference between the inlet and outlet of the pipes. This quantity should be characteristic of the heat extraction/injection rates reported for thermo-active walls in the literature (i.e. 10 to 30 W/m², see [3], [20] and [21]).

The computed variation with time of the average temperature, $T_{i,2D}$, is then applied as a boundary condition along the corresponding position of the pipes in the original geometry (i.e. along line C-D in Figure 5 (c)) in a 2D coupled THM plane strain analysis. For details on the thermo-mechanical behaviour of thermo-active walls in coupled THM analyses it is referred to [6] and [22].

For the case described in section 2, the temperature difference between the pipe inlet and outlet, ΔT , was assumed to be 1.0°C. Note that this value could have been extracted from the 3D analysis, but since the objective of the method is to avoid performing this type of analysis, an estimate is preferred here. Consequently, a constant temperature of 29.5°C (given that $T_{in,3D}=30^\circ\text{C}$) was imposed at the nodes where the pipes are located in the 3D analysis. In order to account for the different wall-air interactions, two different plan analyses of the exposed section were performed with either a NF or CT boundary condition. A period of 6 months was simulated and, for each step of the analysis, $T_{i,Av,exp}$ and $T_{i,Av,emb}$ were evaluated in order to compute $T_{i,2D}$. This was then applied as a time-dependent boundary condition along the position of the pipe (i.e. at 0.1 m from the concrete edge on the retained side) in a fully coupled plane strain THM analysis.

Fig. 5. Diagram of the modelling approach for thermo-mechanical design in 2D analyses (a) 2D plan analysis for exposed section, (b) 2D plan analysis for embedded section and (c) 2D THM analysis simulated with temperature boundary condition.

It should be noted that, in order to guarantee the same conditions prior to the commencement of the heat exchange, the construction sequence up to this stage of the analysis was identical in the 3D and 2D models. Furthermore, the mesh discretisation and dimensions for both the 2D plan analyses and the 2D THM analyses were the same as those employed in 3D in the x-y and x-z planes, respectively.

In order to demonstrate the effectiveness of the proposed method, the axial forces, bending moments and vertical wall displacements computed in 3D and 2D for the two boundary conditions considered along the exposed face of the wall are compared. These results are presented in terms of changes from the beginning of the application of temperature changes.

The profiles of changes in average axial force and bending moment per meter width of the wall are shown in Figure 6 (a) and (b), respectively. The results are reported for two different time instants, i.e. the short-term (ST) and long-term (LT), which correspond to 3 days and 6 months from the beginning of the heat exchange, respectively. The change in axial forces computed in 2D compare very well with those obtained by the 3D model, for both time instants, with maximum differences limited to ± 1.5 kN/m.

Similarly, the average bending moment is well reproduced by the 2D analysis. Indeed, in the short-term, negligible differences between the values computed in 3D are observed. In the long term, for the CT case, the maximum change in bending moment, which occurs within the exposed part of the wall, is overestimated in 2D by approximately 30 kNm/m (9%); for the NF case, the 2D analysis predicts a slightly larger negative change in bending moment at the position of the base slab (i.e. 15.0 m depth).

Figure 7 displays the variation of the thermally-induced vertical displacement at the top of the wall with time for both boundary conditions. Both the magnitude and rate of change with time are well reproduced in the 2D analysis, with differences of less than 0.5 mm (9%) when compared to the values computed in the 3D analysis.

Similar to the previously described method for thermal design, the proposed methodology to simulate the thermo-mechanical behaviour has been checked against numerous 3D analysis with varying geometric and thermal parameters, with an excellent agreement being observed in all cases [22].

It should be noted that, as previously stated, non-uniform temperatures across the width of the wall panel develop in three-dimensional analyses simulated with the presence of heat exchanger pipes. As observed by [23], this temperature difference affects the distribution of axial forces along this dimension, since it induces differential thermal expansion between different portions of wall, leading to the development of internal actions and reactions. It has been observed that the additional forces are notably larger than the average axial force shown in Figure 6 and should thus be considered during design. While a 2D plane strain analysis cannot account for such a phenomenon, an analytical procedure has been developed to provide an estimate of the generated forces [22].

Fig. 6. Variations in depth of wall forces in terms of (a) axial force and (b) bending moment

Fig. 7. Change in vertical movement of top of wall with time

5 Conclusions

This paper presents two new modelling approaches for the accurate simulation of thermo-active walls by means of two-dimensional (2D) plane strain analyses. Since thermo-active walls are employed to provide both energy and stability to buildings, the proposed approximations were determined to allow an estimation of their thermal performance and thermo-mechanical response. The

objective of these methods is to approximate the behaviour obtained by three-dimensional (3D) analyses where the presence of heat exchanger pipes is simulated explicitly, thus allowing considerable savings in computational effort by reducing the size of the problem. Given the known effect of the simulated boundary condition along the exposed face of the wall on the temperature distributions and, hence, on the response of the structure, two extreme scenarios, namely an insulated wall (NF) and a wall face maintained at a constant temperature (CT) were considered in this study.

The approximations for the thermal design were established for 2D analyses which include heat exchanger pipes. To ensure an equivalent energy input in 3D and 2D analyses, the same water flow rate has to be simulated in both problems, which is achieved by adjusting the cross-sectional area of the 2D element simulating the pipes in the 2D analysis. For walls maintained at a constant temperature, an additional correction is required to account for the increased heat transfer in 2D under such conditions. The proposed correction factor X reduces the inlet temperature applied in 2D analyses to simulate the same heat transfer rate as in the 3D problem.

For the thermo-mechanical design of thermo-active walls, a modelling procedure which consists solely of applying prescribed temperature boundary conditions, rather than modelling explicitly the existence of heat exchanger pipes, was developed. It requires an initial analysis of the problem in plan view to obtain the variation with time of the average temperature across the width of the wall panel along the position of the pipes. To account for the wall-air interaction, both the exposed and embedded sections are simulated and the average temperature is determined as the weighted average of the results obtained by the two analyses according to the excavation depth. The obtained average temperature is then applied as a time-dependent thermal boundary condition in a 2D plane strain THM analysis of the wall in cross-section.

This paper demonstrates the applicability and accuracy of the proposed modelling procedures by simulating a hypothetical thermo-active wall problem. It is shown that, by simulating the problems using 2D plane strain analyses employing the proposed design methods, very good estimates of the thermal performance and structural response of the wall are obtained. Therefore, simpler and more computationally efficient analyses can be used to evaluate the complex behaviour of this type of structures, facilitating their design.

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