Investigating the impact of earth tubes in an Earthship

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Abstract

This paper presents a sensitivity analysis that explores the impact of design and operational factors on the performance of 'earth tubes' as a 'passive' cooling and heating strategy built into an Earthship dwelling located in South Australia. Earth tubes are pipes buried underground acting as heat exchangers to deliver fresh air to the internal spaces, which is cooled in summer and warmed in winter. The results show that the air flow and temperature in the earth tubes was sensitive to how the dwelling was being operated. Through simulations, the ideal scenarios of operating the dwelling in summer and winter in this location as well as in the climate where the Earthship concept was invented, i.e. Taos, New Mexico, are reported. Lessons learned from the study will help those who consider implementing earth tubes in their buildings.

Introduction

Minimizing environmental impact from buildings and building construction processes while providing thermal comfort to the occupants are some of the main goals of green building design. Many different approaches exist to achieve this goal, one of which is the 'Earthship', invented by architect Michael Reynolds based in Taos, New Mexico, USA. An Earthship is an earth-sheltered autonomous house made substantially from reused and re-cycled materials such as earth-filled car tyres for the load bearing walls providing a significant thermal mass effect, and glass bottles and aluminium cans as 'bricks' in non-load bearing walls (Freney, Soebarto & Williamson, 2013A).

Figure 1: Earthship Ironbank (Note: earth tube inlets at bottom, centre of photo)

An equator-facing greenhouse provides passive heating, and the designs often use earth tubes for passive cooling and heating (Freney, Soebarto & Williamson, 2013B). Earth tubes are pipes buried underground which deliver fresh air to the internal spaces; cooled in summer and warmed in winter due to the heat exchange effect caused by the relatively stable ground temperature.

Freney's 'Earthship Ironbank' in South Australia's Adelaide Hills is Australia's first council-approved structure of the type. The design incorporates earth tubes, as shown in Figures 1 and 2, that comprise two pipes: 250mm diameter, 18m long, 4mm thick PVC material, and buried on average approximately 2m deep. It is noted that the design here is relevant to this particular sloping site whereas on flater sites other arrangements may be used including vertical risers to form the inlet.

The use of earth tubes to minimize heating and cooling has been investigated in numerous studies (e.g. Lee and Strand 2008, Darkwa et al. 2011). This paper focuses on investigating earth tubes as an effective strategy for passive cooling and heating in this Earthship design. While theoretically earth tubes bring fresh air cooled or warmed by the soil underground, it is hypothesized that the effectiveness of earth tubes would be affected by how the earth tubes as well as openings such as doors and windows in the house are operated.

Method

In this study, the simulated performance of the earth tubes was investigated through analysing the changes in the air temperature inside the house and in the earth tubes, as a result of changing the operational schedules of opening and closing of the earth tube's air outlet and of the different openings in the house. The simulations were conducted using the IESVE software Version 2015.2.1.0 that incorporates ApacheSim dynamic thermal calculations (IES, 2015A) and MacroFlo that simulates the flow of air through openings in the building envelope (IES, 2015B). The MacroFlo module in IES calculates the air flow rate, direction and effect based on the driving forces of wind and temperature at any particular instant. Since this software does not include a specific earth tube module, the earth tubes were modelled as unconditioned and unoccupied 'rooms' connected to the outside on one end and to the living space on the other end, and with a ground temperature profile assigned to the external surface of the 'rooms' (tubes).
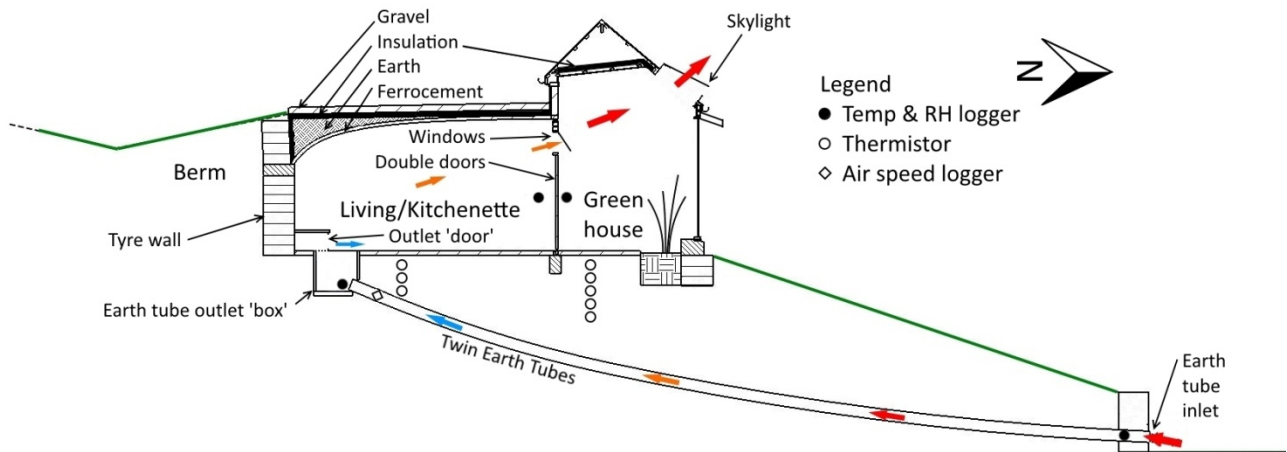
Figure 2: Cross section of the Earthship building and earth tube

The simulation model was first calibrated by comparing simulated hourly temperatures of various indoor spaces and inside the tubes with monitored indoor and earth tube temperatures near the earth tube inlets and outlets. Simulated air flow rates near the inlets and outlets were also compared to measured air flow rates at those inlets and outlets. For calibration purposes, since the available measured data were from July to October 2016, hourly weather data measured on site for the same period were inserted into the weather file for the simulation. Measured ground temperatures were also used in the simulation model, which will be discussed further in the paper.

The accuracy of the simulation model was analysed by calculating the Coefficient of Variance of the Root Mean Square Error (CV(RMSE)) between the simulated results and measured data. A CV(RMSE) of up to 20% is considered acceptable for hourly calibration although this approach was originally developed in calibrating hourly energy use (Bou-Saada & Haberl 1995, Kreider and Haberl 1994). Once the model had been calibrated to measured data, the calibrated model was used to explore the impact of varying the operation schedule of the windows, doors and other openings on the indoor temperatures. For this purpose, a typical meteorological year weather data file for Adelaide and Taos (in an EPW format) as well as monthly ground temperature data based on long term records (for the actual site in Ironbank) were used. The model was also used to analyse whether the earth tubes should be operated differently in Taos, compared to Ironbank or Adelaide, to give the best outcome.

The Earthship building model

Actual Building

This Earthship house is located in Ironbank, South Australia (35.049° South Latitude and 138.683° East Longitude, 360 meters above sea level). It is within the Climate Zone 6 (mild temperate) according to the Australian National Construction Code climate zone (ABCB 2016) or Csb (cool summer Mediterranean climate) according to Köppen classification. The temperatures in summer months (December to February) range on average from 10.5 to 22.1°C while in winter months (June to August) they vary from 4.9 to 9.9°C (BOM 2016). Mean relative humidity during summer is 42.3% and 71% during winter months. A weather station measuring hourly temperature, relative humidity, solar radiation, wind speed and direction was also installed on site 20m north of the building.

The building consists of around 22m² of a combined sleeping, living and cooking space, a 24m² north-facing greenhouse on the north side of this living space, an entry space to the east of the greenhouse and a bathroom to the west of the greenhouse (Figure 3). The main material for the southern external walls is earth-bermed uninsulated earth-filled used car tyres, earth rendered on the inside. The exterior, northern walls of the entry and bathroom curve at the top to form a vaulted roof and are constructed of ferrocement (75mm) with an insulative layer of hempcrete (100mm) and are lime-rendered on the interior and exterior. The exterior east/west walls are 'bottle walls' utilising recycled glass bottles as 'bricks' in a mortar of adobe for the entry east wall and cement mortar for the bathroom west wall. All internal walls are bottle walls in cement mortar.
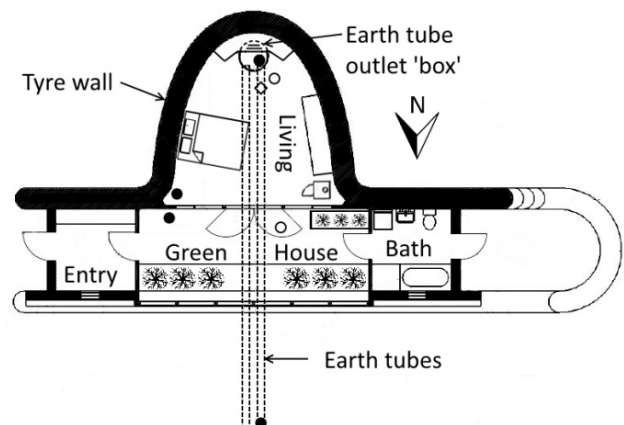

Figure 3: Floor plan of the Earthship building

The floor is made of earth (50mm) on a gravel base (75mm). The living space has a vaulted ceiling, constructed of ferrocement (75mm), covered with earth infill (400mm average), expanded polystyrene (150 mm), rubber waterproofing membrane (1 mm), and gravel (100mm). The greenhouse roof is insulated with expanded polystyrene (150mm), clad with corrugated steel on timber frames. All glazed windows and doors use double glazing in hardwood timber frames (5mm clear/10mm argon/5mm clear, U=1.68 W/m²K).

As mentioned, there are two 250 mm diameter PVC tubes, buried underground, to bring fresh air from the outside to the living space. The inlets of these tubes were about 10 meters north of the house, and around 3 meters lower than the ground floor level (Figure 2). The tubes slope upward towards the outlets which are located on the floor of the living space, 600mm from the back (south) wall. The two tubes are spaced at 300mm centre to centre.

The stack effect has been used as an integral strategy to forcing air through the earth tubes. Operable windows (0.81m²) have been placed above the doors (4.05m²) connecting the living space and the greenhouse and operable skylights (2m²) in the greenhouse can also be opened (Figure 2) to provide air flow.

The building was intended to be occupied by one or two people and during the monitoring period the building was mostly vacant. Indoor air and globe temperatures as well as relative humidity of the living space and greenhouse were monitored hourly using data loggers (Onset U30 (Onset 2016)) mounted to the walls at a height of 1200 mm above floor level (Figures 2 and 3).

Modelling the building and earth tubes

Each space in the building was modelled as separate rooms connected by doors, as indicated in Figure 3. As the building was mostly unoccupied during the study period, no internal loads (i.e. occupants, lights and equipment) were entered into the model.

Each of the earth tubes was modelled as a vacant 'room'. As the earth tubes were exposed to different ground conditions (i.e. outside, under the greenhouse and under the living space), each was modelled as three connecting cylinders with 250mm diameter, with the last part being modelled as a vertical cylinder connected to the floor of the living space. The cooling system was modelled as 'none' because there was no space cooling in the actual building. While a space combustion heater exists in the actual building, as it was not used during the study period, the heating system was also modelled as 'none'.

Building construction

The earth-filled tyre wall construction was modelled as two layers of 10mm thick rubber positioned 650mm apart, with compacted soil/clay in between these two layers and 25mm screed (render) on the internal surface. As the wall is bermed, 1000mm thick compacted clay was added to the wall as an external layer. The entire wall construction was then set to have a ground contact. The other external and internal walls, floor and roof were modelled as per the construction layers in Table 1. The floor is coupled to the ground by setting the ground contact U-value adjustment.

Earth tubes

The 'wall', 'roof' and 'floor' of the earth tube 'room' was modelled as 4mm thick PVC with 1000mm thick of soil/clay as an external layer. The entire earth tube wall/roof/floor construction was also set to have a ground contact. The thermal properties of the building construction as modelled are presented in Table 1 while a graphical representation of the model is shown in Figure 4.

To correctly estimate the earth-air heat transfer inside the earth tubes the convection heat transfer co-efficient needs to be determined. The ApacheSim software has a number of options for modelling interior convection heat transfer that apply to building surfaces but gives no specific option applicable to the earth tubes. The following procedure was therefore adopted.

Assuming that the internal surface of PVC pipes used in an earth tube installation is smooth, the Nu correlations given by De Paepe and Janssens (2003) can be used to estimate the convective heat transfer co-efficient h_c defined as,

$$h_c = \frac{N_u k}{D} \quad (1)$$

Nu is the Nusselt number, k is the thermal conductivity (W/m^2K), D is the diameter of the tube (m)

The Nusselt number for flow in a tube is given by (2) as,

$$Nu = 3.66 \text{ if } Re < 2300 \quad (2)$$

$$N_u = \frac{f/8(Re - 1000)Pr}{1 + 12.7\sqrt{(\xi/8)}(Pr^{2/3} - 1)} \quad (3)$$

Where Re is the Reynolds number, Pr is Prandtl number, and f is the friction factor for smooth pipes.

$$\text{With } f = (1.82 log Re - 1.64)^{-2} \quad (4)$$

If $2300 \leq Re < 5 \times 10^6$ for a fully developed laminar flow and $0.5 < Pr < 10^6$ for turbulent flow with smooth surfaces. The Reynolds number is related to the average air speed and the tube diameter as,

$$Re = \frac{\rho v_{air} D}{\mu} \quad (5)$$

Where v_{air} is the velocity of air in the tube (m/s), D is the diameter of the tube (m) and μ is the dynamic viscosity of the air (kg/ms).

The Prandtl number is given by:

$$Pr = \frac{\mu C_p}{k} \quad (6)$$

Cp is the specific heat of air (J/kgK) and k the thermal conductivity (W/mK).

From the measured speed of air in the earth tubes it was determined that h_c varied in the range 0.5 W/mK to approximately 4.5 W/mK, with an average value of 1.5 W/mK. As ApacheSim allows a user-specified constant convection co-efficient this value was adopted for all simulations.

Modelling the openings

As this building relies on openings to provide natural ventilation, it is critical to model them and their operations as accurately as possible. There are a number of opening types in this building modelled in MacroFlo:

1. Between the living room and green house: there are fixed glass windows as well as top hung operable windows above the doors with maximum angle of opening of 60 degrees and 'sheltered wall' as the exposure type.

2. Roof windows ('skylights') of the greenhouse: these are openable skylights with maximum angle of opening of also 60 degrees and 'exposed long wall' as the exposure type.

3. Earth tube inlets: as there was no cover on the earth tube inlets, the inlets were modelled as having 100% openable area and opened all the time.

4. Earth tube outlets: these outlets have covers and a grille but when opened the opening type was modelled as 'grille' with a coefficient of discharge of 0.25.

Modelling the ground/soil temperature

A critical element in modelling the earth tubes and the Earthship in general is the estimation of ground/soil temperatures as inputs to the model. A series of in-ground temperature sensors were installed during the construction of the building. These sensors (thermistors) were installed at varying depths under the living room, greenhouse and outside to the north of the building. Data from these sensors provided monthly temperature records from October 2015 through October 2016. These data were used to validate the ground temperature models discussed below.

Table 1: Thermal properties of construction layers in the Earthship building

| Construction layers (from outside to inside)	Thickness (mm)	Conductivity (W/mK)	Density (kg/m^3)	Specific heat (J/kgK)
Earth-filled tyre wall:				
Compacted soil/clay	1000	1.41	1900	1000
Hard rubber	10	0.15	1200	1000
Clay	650	0.7	1280	950
Hard rubber	10	0.15	1200	1000
Screed/render	25	0.41	1200	840
Exterior wall/roof vault:				
Lime render	50	0.41	1200	840
Hempcrete	100	0.07	330	1500
Ferrocement	75	0.22	1500	800
Lime render	10	0.41	1200	840
Earth tube pipe "wall/floor/roof":				
Clay	1000	0.70	1280	950
PVC	4	0.16	1004	0.025
Earth tube box (outlet):				
Clay	1000	0.70	1280	950
Concrete	100	1.13	2000	1000
Internal/external bottle brick walls:				
Screed/Render	10	0.41	1200	840
Cement mortar	100 (internal) 200 (external)	0.72	1860	800
Screed/Render	10	0.41	1200	840
Earth floor:				
Gravel	75	0.35	2080	840
Earth floor	50	1.25	1540	1260
Gravel covered vaulted roof:				
Gravel	100	0.36	1840	840
Waterproofing membrane	1	1.00	1100	1000
Expanded polystyrene	150	0.035	25	1400
Clay	400	0.70	1280	950
Cast concrete	75	1.40	2100	840
Corrugated metal roof:				
Steel	0.6	50.00	7800	480
Cavity	35			
Expanded polystyrene	150	0.035	25	1400
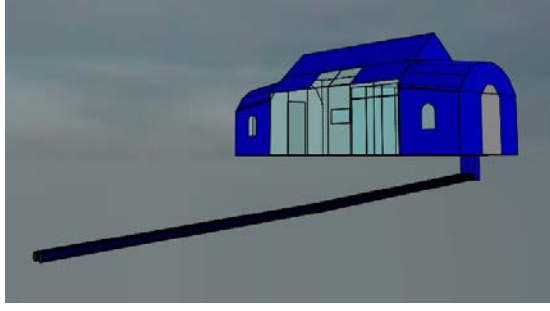
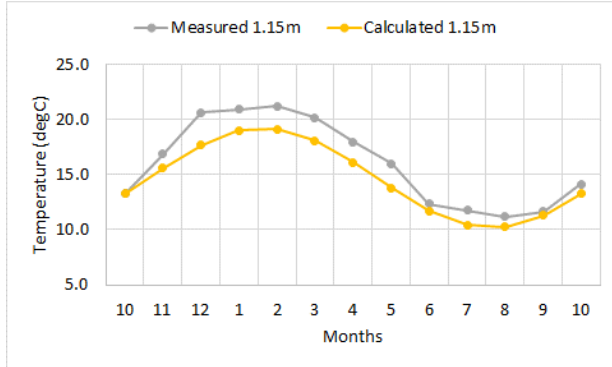*Figure 4: Graphical representation of the building as modelled in IES*

Figure 5: Measured and calculated temperatures in the ground outside the Earthship, depth 1.15m.
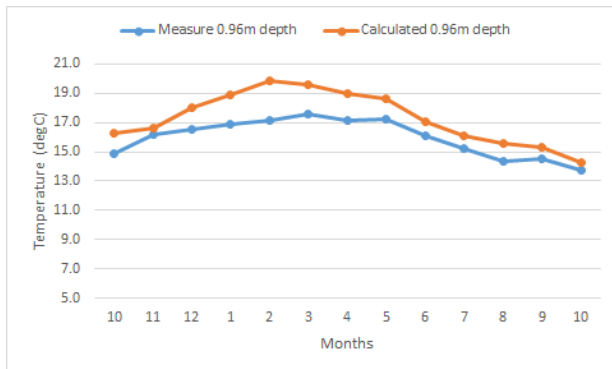

Figure 6: Measured and calculated temperatures in the ground under living room floor, depth 0.96m.

Two ground temperature models are employed to generate monthly input data. First, the annual variation of temperature with depth in undisturbed soil i.e. outside the building, has been given by Hillel (1982) as,

$$T(z,t) = T_a + A_o e^{-z/d} \sin\left[\frac{2\pi(t - t_o)}{365} - \frac{z}{d} - \frac{\pi}{2}\right]$$

Where:

T(z,t) is the soil temperature at time t and depth z
T_a is the average surface soil temperature (°C)
A_o is the annual amplitude of the surface soil temperature (°C)
t_o is the time lag (days) from the starting date
d is the damping depth (m) of the annual fluctuations given by $\sqrt{(2D_h)/\omega}$, and
D_h is the thermal diffusivity (m²/s)

A comparison of measured and calculated ground temperatures at a depth of 1.15m below the natural surface 20m to the north of the building is shown in Figure 5 (note: month 1 is January in all graphs). The ground thermal properties have not been measured so typical values for clay soil have been used. The thermal properties are assumed homogeneous and invariant over time which is not necessarily the case given that the soil moisture content will change throughout the year.

To estimate the various ground temperatures required for the simulation inputs under the building, around the earth tubes and in the earth berm, a model previously described by Williamson (1994) was used. This model employs a harmonic calculation procedure based on a 365 day annual cycle. A comparison of measured and calculated ground temperatures at a depth of 0.96m below the finished floor level under the living room is shown in Figure 6. The calculated values in this case assumes dry clay soil with a thermal conductivity of 0.25 W/mK.

The average calculated 'error' is 1.3°C, however, the closer match of measured and calculated data for the months 6 to 10 gives some confidence in the adequacy of the model. The 'error' in the preceding months can be explained by varying and unknown ground conditions as the conditions stabilise following construction. Considering the various unknowns overall the two ground temperature models appear to provide an adequate means of determining simulation input profiles.

Simulating the building

Based on the measured ground temperatures discussed above, a number of ground temperature profiles were created in IESVE, i.e. around the earth tubes outside (to the north side of the building), under the greenhouse and under the living room, as well as for the ground temperatures directly under the floor of the greenhouse and the living room. In the ApacheSim module, these ground temperature profiles were assigned as the adjacency conditions for the relevant surfaces.

The on-site weather data were converted into a weather data file in EPW format and used for the simulation. However, although 12 months of weather data were available, the initial simulations (and calibration to measured data) were conducted only for a 10-day period in September 2016 and a 10 day period in October 2016, when detailed records of the operation of the various windows, doors and vents were kept.

During September to October, the outlet of the earth tubes were mainly closed; however, as the doors of the earth tubes were not completely sealed, it was estimated that about 2 to 5% of the outlet gross area was actually opened, thus the outlet covers were simulated as having 2 to 5% openable area. The doors and windows above the doors between the living room and greenhouse as well as the skylights were slightly opened and these were modelled as having 40% and 20% openable area, respectively.

Results: Initial model

Figures 7 to 10 show the comparisons between the hourly measured and simulated indoor temperatures in the living room, green house, inside one of the earth tubes' inlet, and inside the earth tube outlet. These were the conditions when the earth tube outlets were mostly closed. The results show that the simulation model well represents the actual building and its operation during the study period. The CV(RMSE) between the predicted and measured indoor temperatures in the living space, greenhouse, earth tube inlet and earth tube outlet is 3.86%, 6.16%, 3.1% and 3.3%, respectively.
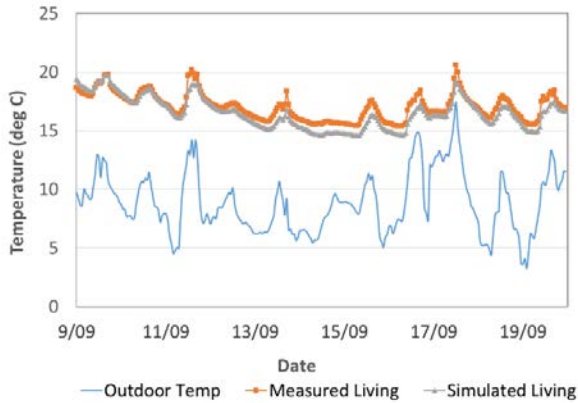
Note that there are more obvious discrepancies between the simulated and measured temperatures inside the earth tube's outlet box. It is likely that in reality the doors between the living space and the greenhouse were occasionally opened which altered the strength of the stack effect. As a result, more cool air leaking through the earth tubes' outlet doors was being drawn into the living space. In the simulation model, each of the openings (doors and windows) had a set schedule (i.e. either always 'on' or open, or always 'off' or closed), and the earth tube outlet doors had a constant value of openable area. These settings result in a less fluctuating air temperature inside the earth tube outlet, as shown in Figure 10.

Figure 7: Measured and simulated temperatures in the living space during 9-19 September
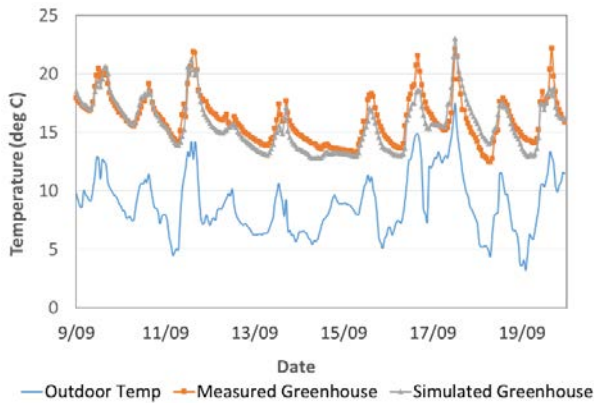

Figure 8: Measured and simulated temperatures in the greenhouse during 9-19 September
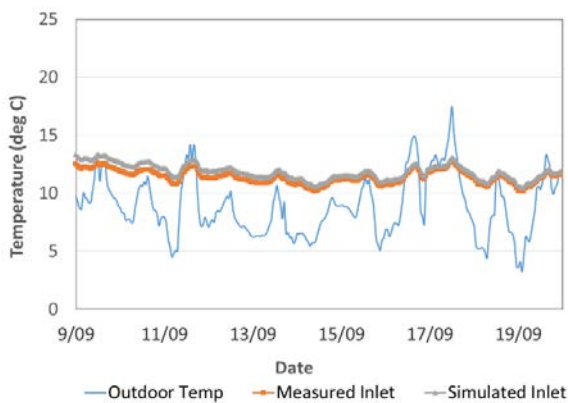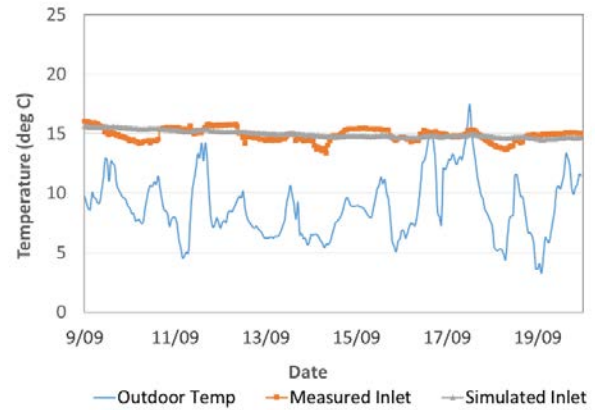

Figure 9: Measured and simulated temperatures in the earth tube inlet during 9-19 September

Figure 10: Measured and simulated temperatures in the earth tube outlet during 9-19 September
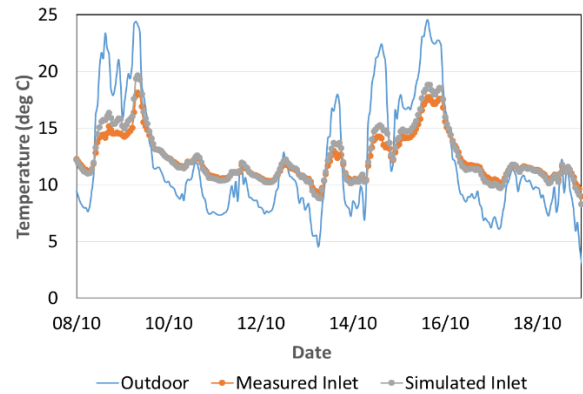

Figure 11: Measured and simulated temperatures in the earth tube inlet during 8-18 October
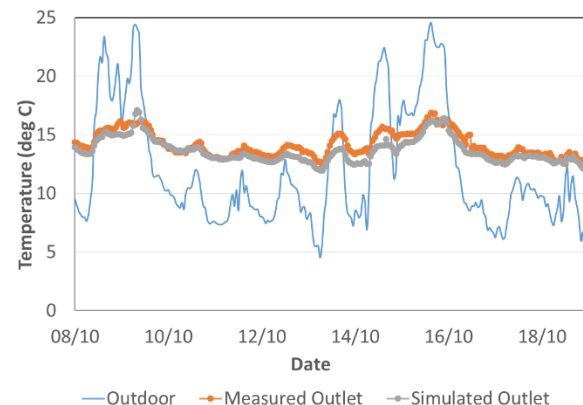

Figure 12: Measured and simulated temperatures in the earth tube outlet during 8-18 October

In October, during the majority of the time, the earth tube outlets were left opened. These were modelled in the Macroflo module as having 40% of openable area. Figures 11 and 12 show the comparison between the measured and simulated indoor temperature inside the earth tube inlets and outlets. Overall, the CV(RMSE) between the predicted and measured indoor temperatures in the living space, greenhouse, earth tube inlet and earth tube outlet is 8.61%, 9.65%, 2.94% and 3.96%, respectively.

Based on the above comparisons and as the CV(RMSE) between the predicted and measured temperatures of various spaces were within the acceptable range, the model is considered a good representation of the actual building. This calibrated model was then used for further investigation; however, it is worth noting a number of issues learned during the calibration processes.

Lessons learned from model calibration

Slope of pipes

Initially the earth tubes were assumed to be level instead of sloping down towards the north of the building. While this did not have much impact in terms of the indoor temperatures (in the living space and greenhouse) when the earth tube outlets were closed, it was found that the simulated airflow inside the earth tubes was much lower than the measured airflow. Even with the earth tube outlets being opened, the airflow inside the earth tube was still low.

The model was then fixed by changing the earth tubes to be sloping downward from the house, as in the real situation. By creating a difference in heights between the air inlets and outlets, the simulated airflow started to become closer to the measured airflow as this increased height difference enhances the stack effect.

Ground temperature

As the earth tubes are buried in the ground, it is critical that the coupling to the ground is simulated properly. In ApacheSim, this was done by assigning the adjacent external condition of the pipe surfaces to the corresponding soil temperature. Daily and monthly soil temperature profiles for different parts of the ground (i.e. outside to the north of the building, under the greenhouse, and under the living space) were created, and each part of the earth tubes was assigned to have adjacent external surfaces to correspond to these soil temperature profiles. This has resulted in a simulation model that closely reflects the actual building.

Predicting the impact of earth tubes in summer

Using the calibrated model above, the impact of earth tubes was further investigated for the summer period. Note that since summer monitored data were not available, this investigation was purely based on simulation for Adelaide, a nearby city. Also, due to space limitation, only results from the warmest period in summer in this location are reported (i.e. early to mid-February are presented here).

To investigate the impact of earth tubes and how effective they would be in cooling the building, several cases were explored, as follows:

1. Case 1: Earth tube inlets and outlets were closed and all other openings were also closed. In Figure 13 this is indicated as 'All closed'.
2. Case 2: Earth tube inlets and outlets were opened, but all other openings were closed or 'Only ET opened'.
3. Case 3: Earth tubes were opened, doors between the living space and green house opened, skylights were closed, or 'ET and doors opened, skylights closed'.
4. Case 4: Earth tube inlets and outlets were opened, and so were the doors between the living space and greenhouse and the skylights were opened. This is indicated as 'All opened'.
5. Case 5: Earth tubes were closed but all other openings were opened, or 'ET closed, others opened'.

When the doors and windows above the doors between the living space and the green house were opened, it was assumed that the opening area was only 40% of the total doors area, and when the skylights were opened, only 40% of the total skylight area was opened, to reflect that in reality, they were not totally opened.

The results show that the living space would experience the warmest indoor temperature when the earth tubes and all other openings were shut (Case 1). As the building has a considerable amount of thermal mass and the north-facing façade of the greenhouse is not shaded, the collected heat would warm up the entire living space without letting it escape. Bringing in fresh cooled air from the earth tubes would slightly lower the temperatures in the living space, however without having any outlet, the living space would remain warm (Case 2).

Opening the doors and windows above the doors between the living space and greenhouse noticeably lowered the living space temperatures as the cooled air from the earth tubes was able to remove the heat from the living space to the greenhouse; however, without allowing the heat in the greenhouse to escape, the heat from the greenhouse mixes with the air in the living space (Case 3). The effectiveness of the earth tubes to bring in fresh air depends on letting out all the warm air from the living space and the greenhouse, as shown in Case 4. In this case, the skylights in the greenhouse were opened, allowing the warm air to escape out thus lowering the temperatures in the living space by around 5° K during the day and 8° K at night.

In Case 5, the windows, doors and skylights were opened but the earth tubes were closed. This was to test the case for typical houses where earth tubes were not installed. The result showed that even though this arrangement helped to release the heat from the living space, the temperatures in the living space were higher than with the earth tubes in use. Without the earth tubes the air flow through the window above the door between living and greenhouse in a typical day was 38.3 L/sec but with the earth tubes operating this air flow increases to 46.6 L/sec. This demonstrates the effectiveness of earth tubes in providing improved ventilation and lowering the temperatures compared with just natural ventilation.
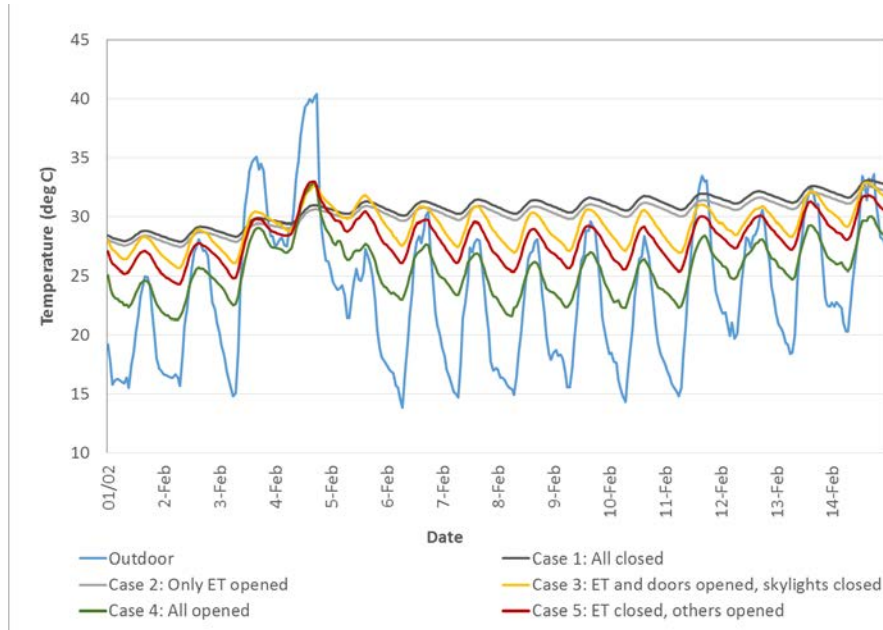
Figure 13: Testing the five cases in 2 summer weeks in Adelaide, South Australia

In other words, it is clear that using earth tubes in the summer will help to passively cool the building; however, such strategy will only work effectively if there are sufficient high level openings to let the warm air out, inducing a stack effect to draw cool air through the earth tubes, thus continuing to cool the internal space of the building.

Predicting the impact of using earth tubes in another climate

With the model calibrated to measured data at sufficient accuracy to represent the real building, as presented in the low CV(RMSE,) it can be used with some confidence to explore other possibilities. In this case, we explored the use of earth tubes (for the same Earthship building design) in Taos, New Mexico, where the Earthship was invented. Taos is located in a Warm Summer Continental Climate (Dfb). It has a warm summer and a very cold winter with the average high of 29.2ºC in July and average low of -11.8ºC occurring in January (US Climate Data 2016).

To model the building in this location the monthly ground temperatures for various positions were also calculated based on the ground temperature modelling approach discussed above, i.e. outside adjacent to the earth tubes, under the greenhouse around the earth tubes and under the greenhouse floor, under the living room around the earth tubes and under the living room floor, and adjacent to the living room walls. Daily, weekly and yearly ground temperature profiles were created in the IESVE model from these data. See Table 2.

Note also that the building orientation in Taos was turned 180 degrees so that the greenhouse would face the equator (i.e. south) in order to receive passive solar heating in winter. A number of scenarios were tested and they include:

1. Summer with earth tubes, doors and windows above doors between living room and greenhouse opened (opening area 100%, 40%, 10%), denoted as S100, S40, S10.
2. Summer with earth tubes but all openings closed, denoted as S0.
3. Winter with earth tubes, doors and windows above doors between living room and green house opened (opening area 100%, 40%, 10%), denoted as W100, W40, W10.
4. Winter with earth tubes, but all openings closed, denoted as W0.

Note that when the openings and earth tubes were indicated as opened, they were simulated as being opened all the time.

Table 2: Calculated ground temperatures for Taos, NM

Month	A	B	C	D	E	F
1	2.1	14.7	14.2	13.4	14.3	13.0
2	2.4	14.9	15.2	15.1	14.4	13.6
3	4.2	14.8	14.6	15.4	14.7	14.2
4	7.0	16.5	16.5	17.6	16.4	14.7
5	10.2	17.2	17.1	19.1	17.3	15.9
6	12.8	19.1	18.9	22.2	19.8	17.3
7	14.2	20.2	19.4	22.3	20.3	18.4
8	13.9	20.4	18.9	22.1	20.8	18.7
9	12.1	20.6	19.0	21.9	21.1	18.2
10	9.3	19.6	18.0	20.4	20.1	17.2
11	6.1	18.7	17.5	18.4	18.8	15.7
12	3.5	16.2	15.1	15.0	15.9	14.2

A = outside, 2.5m depth; B = under living room, -1m; C = under living room, -2m; D = under greenhouse, -1m; E = under greenhouse, -2m; F = berm, 1m from tyre wall, -2m.

Figures 14 to 16 show the predicted living room temperatures in the Taos location in July (summer) and January (winter). Figure 14 shows that the earth tubes would only be effective if the openings between the living room and greenhouse as well as the skylights in the greenhouse were opened (S10, S40 and S100). It is also important to note that the opening area does not need to be too large. In this study, openings as little as 10% of the total openable area (would result in the lowest living room temperatures during summer days (case S10). Opening the doors between the living room and greenhouse as well as the skylights for 40% of the total openable area or more would result in lower temperatures at nights as more internal heat would be released to the outside. What this means is, if lower night-time indoor temperatures are desired in summer, the occupants can easily open all the openings between the living room and greenhouse as well as the skylights until the desired condition is reached. However, during the day, it is not necessary to widely open these openings as doing so would result in bringing in too much warm air from the outside and from the greenhouse into the living space. Ideally just the windows above the doors would be opened (doors remain closed) to allow the stack effect to occur while isolating the warm greenhouse air from the cool living room air.

The most effective strategy for winter is the opposite of that for summer. In winter, opening the earth tubes' inlets and outlets as well as all other openings would result in the lowest indoor temperatures despite the fact that the air coming through the earth tubes was warmed by the ground (Figure 15). This is because the openings would let warm air escape and this is obviously not desired as the temperatures in the living room could be as low as -12.5°C when the outdoor was -18.4°C (Figure 16). The living room would be the warmest in winter when the earth tubes' outlets were closed (W0). This result is similar to previous monitored data in a built Earthship home in Taos (Freney, Soebarto & Williamson, 2013B).

Similar results were obtained when the earth tubes' outlets were left opened but with the doors and windows between the living room and greenhouse as well as the greenhouse' skylights being closed. However, if the doors and windows above the doors were opened during winter months, e.g. for 10% of the total openable area even though the greenhouse skylights were closed, the living room's temperatures would drop by around 7-10°C (Figure 17).

Discussions and Conclusions

This study has investigated the use of earth tubes as a strategy for passive cooling and heating in an Earthship house. Figure 2 illustrates how the earth tubes will work – they require not only the inlet to bring in fresh air and the outlet to distribute the air to the internal space, but also external outlets for the warm air from the space to be exhausted to the outside in summer. These outlets, however, need to be closed in winter.

Figure 14: Predicted living room temperatures during two summer weeks in Taos, NM
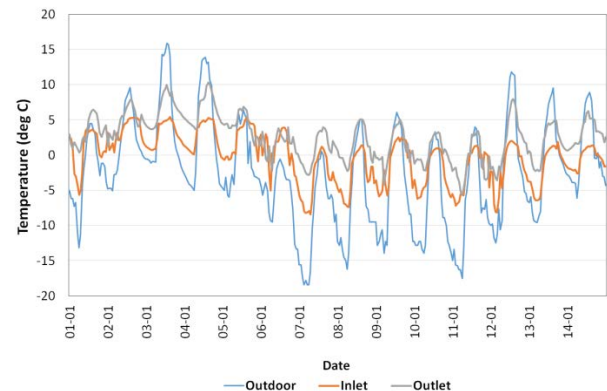

Figure 15: Predicted earth tube inlet and outlet temperatures during two winter weeks in Taos, NM
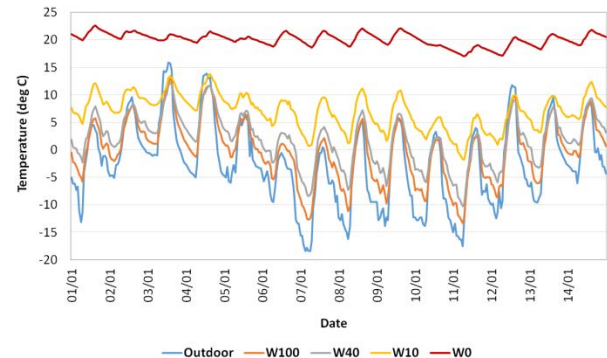

Figure 16: Predicted living room temperatures during two winter weeks in Taos, NM.
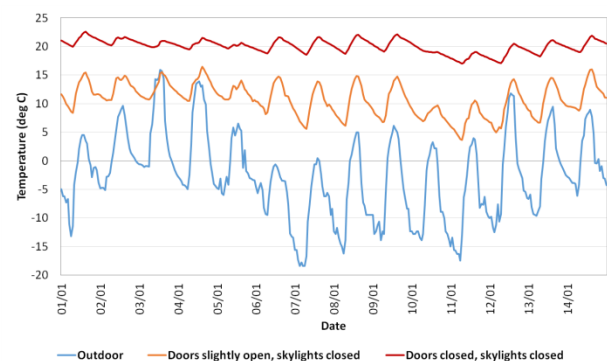

Figure 17: With doors and windows between the living room and greenhouse opened and closed.

This concept has been confirmed through a calibrated simulation model for the Earthship house in Ironbank, South Australia, and further tested in the same building design but located in Taos, New Mexico.

It was found that in order to accurately simulate the earth tubes and investigate their impacts, it is critical to calculate the temperatures of the ground adjacent to the earth tubes as well as of the ground under the floor and adjacent to the earth-bermed external walls. It is also critical to model the earth tubes as having several different zones to take into account different ground temperatures acting upon the earth tubes due to depth and proximity to different areas of the building.

The study has shown that the presence of openings between the living room and greenhouse as well as the presence of openable skylights in the greenhouse is crucial in ensuring the effectiveness of the earth tubes. To lower the temperatures in the living room during summer days, these openings need to be opened, even slightly, in order to create a stack effect to allow the warm air to rise and escape outward. It is shown that doing so can increase the airflow out through the greenhouse by 22%. Completely opening them while it is warm outside, however, is not recommended as it will bring in warm air from the outside during the day, as shown during the two hottest days in Figure 13. On the other hand, if lower indoor temperatures at night-time are desired, these openings can be opened fully.

During winter, maintaining indoor temperatures at a reasonable level, i.e. around 18°C or above, can be achieved either by completely closing the earth tubes outlets or by opening the earth tubes but closing the doors and windows above the doors between the living room and greenhouse together with closing the skylights in the greenhouse. The former strategy clearly stops the air in the earth tubes from entering the living room, which even though it is warmer than the air entering the earth tubes, its temperature is still below the desired indoor temperature as the ground temperature is below 15°C (see Table 2). The latter strategy does the same by preventing the air in the tubes from being sucked into the living room as there is practically no outlet for the air to escape. With either strategy, solar heat from the greenhouse, which radiates into the living room, is retained creating a much warmer indoor than outdoor. The result also shows that it is crucial to keep the doors and windows between the living room and greenhouse closed during winter because opening them, even as little as 10% of the total openable area, would result in lowering the living room temperatures by 7-10°C. An exception to this is during sunny winter days when the greenhouse air temperature is greater than the living room temperature and mixing of the air between these two spaces is desirable. An advantage however of maintaining the air flow at all times is that fresh air is delivered to the living room which likely produces a healthier indoor quality.

In conclusion, the study shows that having earth tubes alone will not work. Other forms of openings are needed in summer to assist in creating a stack effect to draw the cool air through the earth tubes allowing the warm air to escape. In winter, even with the earth tubes' outlets being left opened, closing the other openings will prevent the stack effect from occurring, thus the heat radiating from the greenhouse can be retained resulting in indoor conditions that are much warmer than the outside. The study has also demonstrated that the most optimum strategy in using earth tubes can be tested via simulation which may help designers design better earth tube systems and educate Earthship occupants about how to 'sail' their 'ship' most effectively.

Acknowledgement

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