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The Effects of Different Land Covers on Foundation Heat Exchangers Design in Chinese Rural Areas

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Abstract

The Ground Source Heat Pump (GSHP) system is extensively applied all around world for building heating and cooling. A new system type which uses foundation heat exchangers (FHXs) to reduce system capital cost has been suggested. This paper aims at studying the effects of different land covers on FHXs design lengths; consequently these affect the system capital cost. The FHXs are more applicable to rural areas since it requires enough space for laying the heat exchangers. In Chinese rural area, FHXs buried at 8 locations in 4 different cli-mates are investigated. In each location, the FHX design lengths under bare soil, concrete and vegetation are simulated. It is found that, in warm climates, land cover type has little effect on the results. In other climates, the FHX design length under bare soil and results under concrete are respectively 5.8%-18.1% and 15.9%-38.3% longer than the results under vegetation cover.

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Keywords: Ground-source heat pump system; Foundation heat exchanger design; Ground Temperatures; Land cover

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1. Introduction

With the rapid economic development, severe environmental issue occurs, clean and renewable energy application and energy conservations are becoming more critical nowadays. In China, the building energy consumption accounts for about 34% of the total energy consumption[1]. Chinese government upgraded the building energy efficiency rate so as to reach the energy saving target of 50% in building designs by 2020[2]. The Ground

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Source Heat Pump (GSHP) system is highly efficient approach for building heating and cooling. However, the high system capital cost, which is related to borehole drillings or horizontal trenches excavations, limits its application.

A new type of GSHP system uses foundation heat exchangers (FHXs) is suggested so as to reduce the system capital cost. When the house is being built, the FHXs are buried in the excavations made for the basement or footing to save the excavation fee. The FHXs are more applicable to rural areas since it requires larger space for laying the heat exchangers. Moreover, the houses where the GSHP system installs at are usually built based on high insulation stand-ard, so as to meet the demand of energy saving, as well as to reduce the required FHXs lengths. The feasibility of this new GSHP system was investigated in 10 U.S. locations in 3 climate zones by Spitler et al.[3].

The land cover is also found to be a crucial factor which affects the horizontal ground heat exchanger (HGHX) performances[4]. The land cover affects the solar radiation, convection, and other heat transfer process at the Earth surface; it is an important factor for determining the ground temperatures. Herb et al.[5] developed a model for predicting ground temperatures under different land covers, such as bare soil, asphalt, and grass cover. The results show that at the surface, asphalt gives the highest daily maximum and daily amplitude; bare soil gives surface temperatures which are between the results for asphalt and grass cover surfaces; grass cover gives the lowest surface temperatures which is about 10 °C lower than results for asphalt. Xu and Spitler[6] developed a numerical model to estimate ground temperatures, which considers effects of moisture transfer, snow accumulation and melting, soil freezing and thawing, the effects of land covers was not included. The FHX is a type of HGHX which is buried near the house foundations. The variation of the ground temperature due to land cover differences will eventually affects the sizing of the FHXs for the system. Therefore, Gao et al.[7] presented a HGHX with a rain garden on the land covers, which is beneficial for reducing the heat exchanger length required for the GSHP system.

This paper aims at studying the effects of different land covers on FHXs design in Chinese rural area. 8 locations which belong to 4 different climates in China are chosen for the case study purpose. For each locations, a 2-story house was built and GSHP system with FHXs are designed for three different land covers: bare soil, concrete and vegetation cover. Eventually, the effects of different land covers on FHXs design will be investigated so as to suggest most preferable land cover to be used to optimize the GSHP system performance.

2. Methods

To study the effects of different land covers on FHXs design. A FHX simulation tool, which uses building heating and cooling loads, ground temperatures and ground thermal properties as inputs to size the FHXs, has been developed by Xing et al.[8] and used here. The heating and cooling loads are calculated based on a 2-story house with high insulation envelope. 8 Chinese sites which belongs to 4 climates are selected for the case study; these 4 climates are warm climate, cold climate, hot summer and cold winter climate and hot summer and warm winter climate. The soil is assumed as 60% saturated clay loam with thermal conductivity of 1.08 W/m·K and volumetric heat capacity of 2.479 MJ/m3·K.

2.1. Building heating and cooling loads

This study establishes a prototype house located based on the Chinese building standard and uses software Energy Plus to calculate hourly building loads for the 8 sites. The FHX design tool uses monthly loads as inputs. For each site, Cullin and Spitler[9] method is used to convert the hourly loads to monthly loads by applying monthly constant loads over the whole month and monthly peak loads at end of the month.

2.2. House description

The prototype house is modeled in the Energy Plus Environment[10]. It has a structural area of 195.2m^2 and 6.6m height. The building envelope employs multilayer composite construction, two 0.15m thick concrete-block layers and one 0.01m thick insulation layer between them. The indoor temperature is maintained at 24.5°C in cooling and 21.7°C in heating. For this study, the building envelopes R value and the glass U value are selected based on high insulation standard level.

2.3. Location

8 sites are chosen in 4 different climates--cold climate, hot summer and cold winter climate, hot summer and warm winter climate, and warm climate. Typical Meteorological Year (TMY) weather data are used as inputs to the Energy Plus house model. The detail information is presented in Table 1.

Table 1. 8 parametric study sites in China.

Site: province	Site: city	Chinese climate classification	TMY weather files
Guizhou	Guiyang	Warm climate	Guizhou.Guiyang.578160_CSWD
Yunnan	Kunming		Yunnan.Kunming.567780_CSWD
Guangxi	Baise	Hot summer and warm winter climate	Guangxi.Zhuang.Baise.592110_CSWD
Guangdong	Guangzhou		Guangdong.Guangzhou.592870_CSWD
Zhejiang	Hangzhou	Hot summer and cold winter climate	Zhejiang.Hangzhou.584570_CSWD
Hubei	Wuhan		Hubei.Wuhan.574940_CSWD
Shandong	Jinan	Cold climate	Shandong.Jinan.548230_CSWD
Gansu	Lanzhou		Gansu.Lanzhou.528890_CSWD

2.4. Ground temperatures under different land covers

A numerical model has been developed[11,12,13] and used to estimate the ground temperatures under various land covers -- short grass, tall grass, bare soil, concrete and asphalt. It is a 1D explicit finite volume model, utilizing a full surface heat balance coupled with weather files. Although the numerical model estimates ground temperature accurately, the time-efficiency analytical model is more preferable for engineering applications. Thus, the simulated soil temperatures by the numerical model are fitted to a simplified analytical model, which represents the ground temperatures in a two-harmonic function as follow:

$$T_s(z,t) = T_{s,avg} - \sum_{n=1}^{2} e^{-z\sqrt{\frac{n\pi}{\alpha t_p}}} T_{s,amplitude,n} \cos\left[\frac{2\pi n}{t_p}(t - PL_n) - z\sqrt{\frac{n\pi}{\alpha t_p}}\right] \tag{1}$$

This function depends on annual average undisturbed ground temperature, $T_{s,avg}$, two annual amplitudes of surface temperature variations, $T_{s,amplitude,n}$, and two phase angles, PL_n.Xing and Spilter procedure was validated for grass-cover ground temperature estimations using 3-8 years of measured results at 19 SCAN sites in United States, the estimation errors are within 1.4°C-2.4°C. Concrete covered soil and bare soil temperature estimations given by Xing and Spitler procedure has been validated using 2 years measured results at St. Cloud, Minnesota[14], with an estimation error less than 2.0°C.

2.5. Simulation of foundation heat exchangers

The developed FHXs simulation tool is based on analytical method, so as to simulate the GSHP system performance - FHXs run with an indoor water to water heat pump. Each FHX pipe is treated as a line source or sink, with the soil treated as a semi-infinite source domain. The heat interactions between FHXs has been considered in the model. The simulation tool was validated against measured data collected from an experimental house located in Oak Ridge, Tennessee equipped with GSHP system using FHXs. The simulated results, for exam-ple, the heat pump entering fluid temperature give estimation errors for one year period which are less than 1.9°C.

Since the FHXs are buried near the house foundations, their lengths are limited to the house perimeters. For some sites, an auxiliary horizontal ground heat exchanger (HGHX) will be added to the GSHP system with FHXs if needed. The layouts of the FHX and the auxiliary HGHX are shown in the Figure 1.a and Figure 1.b. Figure 1.b is the typical FHX and HGHX configuration which is used in this paper. There are six FHXs buried at 4 different depths: 0.7m, 1.0m, 1.3m, and 1.6m. Based on these above parameters, the simulation tool will be it-eratively run until it eventually find out the FHX and auxiliary HGHX lengths (if needed) which meets the building heat and cooling needs.

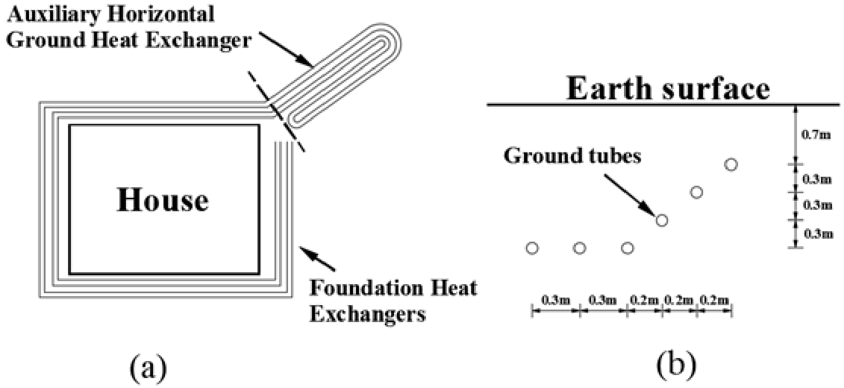

Fig. 1. The typical FHX and auxiliary HGHX configurations.

3. Results

Table 2 shows the designed FHX lengths and auxiliary HGHX lengths for the GSHP system installed at houses of the 8 sites presented in Table 1. The FHX~~s~~ length is limited by the house perimeter, which is less or equals to 52m. In this study, except for at 2 sites in the warm climates: Kunming and Guiyang which only needs FHXs, all the other 6 sites requires both FHXs and auxiliary HGHXs. In warm climate, the FHX lengths are quite similar under the three land covers. In other climates, the whole ground tube length (including FHX length and auxiliary HGHX length) is the shortest when the ground is covered by vegetation, and the result~~s~~ under concrete is the longest. If the ground is covered by concrete rather than by the vegetation, this increases the design FHXs by 15.9%-38.3%; if the ground is bare soil, this increases FHX lengths by 5.8%-18.1%.

Table 2. The results of single ground tube design lengths.

Site	Climate zone	Length of FHX			Length of auxiliary HGHX		
		Concrete [m]	Bare Soil [m]	Vegetation [m]	Concrete [m]	Bare Soil [m]	Vegetation [m]
Guiyang	warm climate	52	50	47	-	-	-
Kunming		23	23	25	-	-	-
Baise	Hot summer and warm winter		52		78	59	42
Guangzhou					60	46	34
Hangzhou	Hot summer and cold winter		52		24	13	8
Wuhan					45	34	22
Jinan	Cold climate		52		28	21	17
Lanzhou					62	39	40

Different land covers not only affect design FHX lengths, but also affects the required auxiliary HGHXs for the system. If less HGHXs is needed, the excavation fee for the system will be reduced as well. 6 of the 8 sites requires auxiliary HGHXs, Table 3 presents the excavation areas demanded for HGHXs for the 6 sites. The area for vegetation covered sites are used as base results; "Φ" stands for the auxiliary HGHX excavation area increasing percentage using a different land cover such as concrete or bare soil. The increasing percentage of bare soil $\Phi_{bare\ soil}$ ranges from 23.5%-64.5%, except Lanzhou where the FHX length under two covers are quite similar. It is observed that the effect of different land covers is more apparent in hot summer climates. The increasing percentage of concrete $\Phi_{concerete}$ ranges from 55.0%-200.0%.

Table 3. The FHX and auxiliary HGHX excavation areas under different land covers.

Site	Climate zone	$A_{vegetation}$ [m^2]	$A_{bare\ soil}$ [m^2]	$A_{concrete}$ [m^2]	$\Phi_{bare\ soil}$ [%]	$\Phi_{concrete}$ [%]
Baise	Hot summer and warm winter	63.0	88.5	117.0	40.5	85.7
Guangzhou		51.0	69.0	90.0	35.3	76.5
Hangzhou	Hot summer and cold winter	12.0	19.5	36.0	62.5	200.0
Wuhan		33.0	51.0	67.5	54.5	104.5
Jinan	Cold climate	25.5	31.5	42.0	23.5	64.7
Lanzhou		60.0	58.5	93.0	-2.5	55.0

4. Discussion

This study find that different land covers affect the ground temperatures and eventually vary the design FHX and auxiliary HGHX lengths. Using the Xing and Spitler procedures, the ground temperatures at 1.3m in Wuhan under the three land covers for a year period are calculated and presented in Figure 2. The results show that, in heating season, the ground temperature under vegetation is highest, and result under concrete is the lowest; in cooling season, it is the opposite.

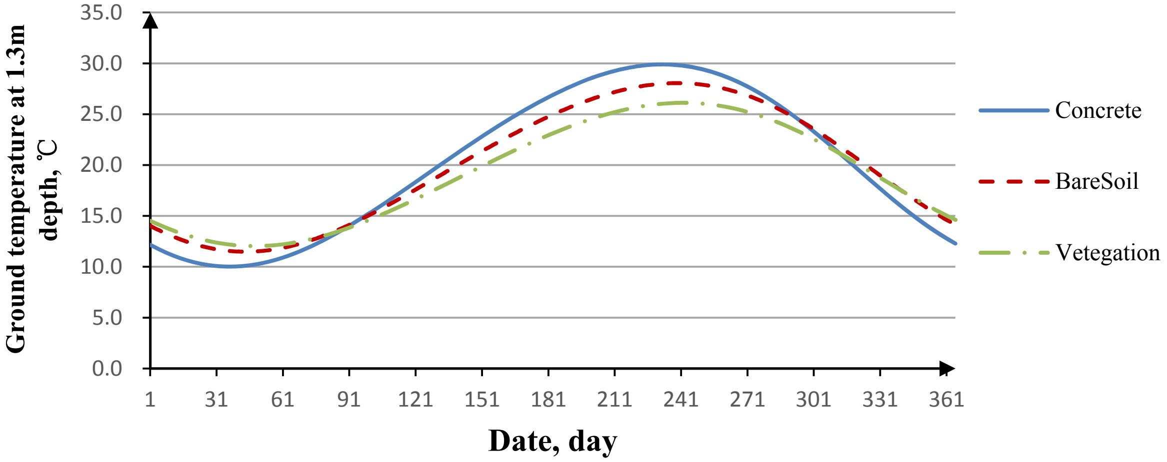

Fig. 2. Ground temperature distributions at 1.3m depth in Wuhan.

Table 4 presented the building loads, average ground temperature, heat exchange difference and building loads per meter FHX for 8 sites for different land covers. These results are plotted in Figures 3, 4 and 5. In Figure 3, it plotted the heat exchange temperature differences and FHX design length. The square bars stand for the heat exchange temperature difference under different land covers for 8 sites, the triangular dots line are the corresponding FHX design lengths under these land covers.

For each site, it is observed that the FHX lengths are inversely proportional to the heat transfer temperature differences. The vegetation increases the temperature differences and reduces the FHX lengths in each site, except for at Kunming in warm climate and Lanzhou in cold climate where the heat temperature differences are similar for bare soil and vegetation cover land. Overall, for each one site, the vegetation covered site which has the highest heat exchange temperature difference needs shorter FHXs compared to the concrete covered site.

Table 4. The determinate parameters for FHX and auxiliary HGHX design lengths.

Site	Land covers	Building loads [kW]	Average ground temperature [°C]	Heat exchange temperature difference [°C]	Building loads per meter FHX [W/m]
Baise	Bare soil	4.7	29.5	5.5	42.3
	Concrete		30.2	4.8	36.1
	Vegetation		27.7	7.3	50.0
Guangzhou	Bare soil	4.5	28.9	6.1	45.5
	Concrete		30.2	4.8	39.8
	Vegetation		27.3	7.7	51.9
Huangzhou	Bare soil	4.6	25.5	9.5	70.8
	Concrete		27.7	7.3	60.6
	Vegetation		24.1	10.9	76.7
Wuhan	Bare soil	5.0	27.5	7.5	58.6
	Concrete		29.3	5.7	52.0
	Vegetation		25.5	9.5	68.1
Guiyang	Bare soil	7.3	11.1	11.1	146.2
	Concrete		9.7	9.7	137.9
	Vegetation		12.6	12.6	155.5
Kunming	Bare soil	5.4	16.1	16.1	234.2
	Concrete		15.7	15.7	234.2
	Vegetation		14.3	14.3	215.5
Jinan	Bare soil	10.1	8.9	8.9	138.5
	Concrete		7.0	7.0	126.4
	Vegetation		10.2	10.2	146.5
Lanzhou	Bare soil	9.8	7.1	7.1	107.7
	Concrete		3.7	3.7	86.0
	Vegetation		7.0	7.0	106.5

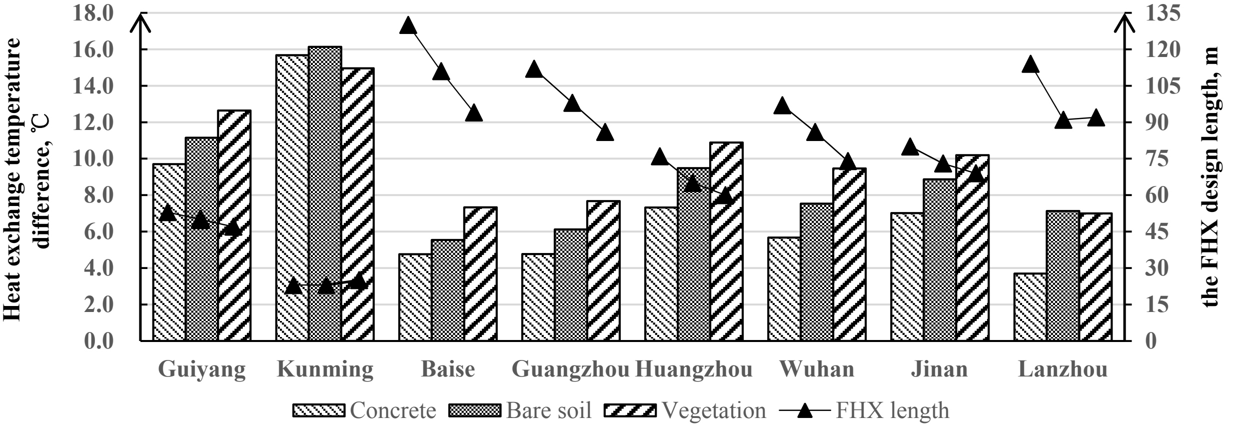

Fig 3. Ground temperature distributions range in eight Chinese sites

The GSHP system is initially run with a heat exchanger fluid temperature which equals to ground temperatures plotted in Figure 4. Take Kunming for example, for vegetation cover site, the average ground temperature is about 16°C. In winter, as the FHXs extract heat from the ground, the fluid temperature decreases continuously. The GSHP system efficiency drops accordingly. For satisfactory and high efficiency GSHP system performances, the heat exchanger exiting fluid temperature (heat pump entering fluid temperature is limited within 0°C-35°C. The temperature difference is the difference of the ground temperature and the limit of the heat exchanger exiting fluid temperature: 0°C or 35°C depends on the GSHP system is designed based on heating or cooling condition. Either way, if the temperature difference is larger, which means that during the operation period, the system is run with a more preferable fluid temperature and higher efficiency, which eventually requires shorter FHXs.

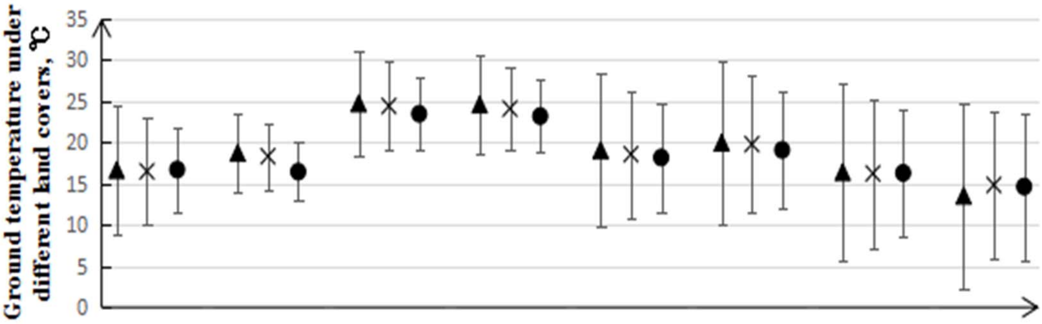

Fig. 4. Ground temperature distributions range in eight Chinese sites.

Figure 5 plotted building loads per meter FHX against the heat exchange temperature difference for 8 sites in 4 climates: warm climate, hot summer and warm winter climate, hot summer and cold winter climate and cold climate. For all the climates, the heat exchange temperature differences under all covers are within 3.7°C-16.1°C, the corresponding building loads per meter FHX are within 36.1W/m-234.2W/m. The building loads per meter FHX is closely related to system efficiency, the higher value is preferred. As you may see, the 8 sites are grouped according to the climates they belong to; for each climate, the heat exchange temperature increases, the building loads per meter FHX increases linearly, system efficiency increases, which reduces the required FHX length. For different climates, with the same heat exchange temperature differences, the increasing rate is different, warm climate is the highest, cold climate in the middle and hot summer climate is the lowest. In all, it is found that the warm climate with the higher heat exchange temperature difference and higher increasing rate performs better than the other two climates, the system is less preferable for cold climate and least preferable for hot summer climate.

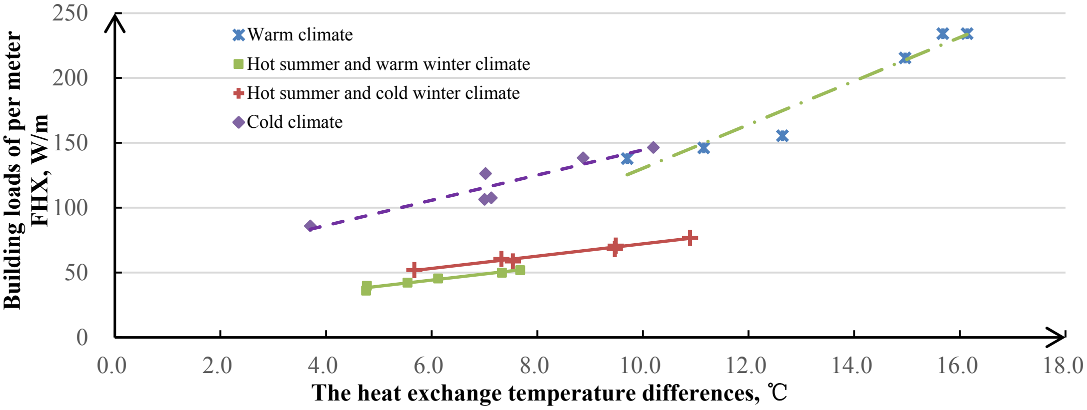

Fig. 5. Per meter FHX's building loads and the heat exchange temperature differences.

5. Conclusions

Different land covers influence FHX design lengths by affecting the ground temperature distributions at shallow depths. Under vegetation cover, the ground temperature which equals to heat exchanger fluid temperature at the initial condition are at more preferable range, which is further away from the heat pump entering fluid temperature limit 0°C and 35°C. The system is run at a higher efficiency rate, thus, for all the 8 sites, vegetation covered site which has the needs shorter FHXs compared to the concrete covered sites or bare soil sites. This effect is little in warm climate but prominent in other climate. Compared with vegetation, the bare soil increases FHX length by 5.8%-18.1%, the concrete cover increasing by 15.9%-38.3%.

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