Analysis of the influence of soil in the thermal performance of subterranean rooms in a ground-level building in São Paulo, Brazil, via EnergyPlus

Análisis de la influencia del suelo en el desempeño térmico de las habitaciones subterráneas en una edificación de una planta unifamiliar de São Paulo, Brasil, vía EnergyPlus

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Recibido 26 de junio de 2018, Aceptado 8 de octubre de 2018

Received: June 26, 2018 Accepted: October 08, 2018

ABSTRACT

Among the several factors that interfere with the thermal performance of buildings, soil temperature is not always considered in thermal performance evaluations. However, soil temperature is a factor that influences the result of heat exchanges in the environment, especially in ground-level buildings. Thus, it is necessary to evaluate this influence due to the interaction of the soil with the building. In addition, due to the three-dimensional and transient character of the heat exchange processes involving the ground, the numerical approach becomes an important tool in the thermal performance analysis of buildings. In this respect, the software EnergyPlus emerges as an alternative to obtain such results, especially through the Basement preprocessor. Results suggest that, when the soil effect is considered in thermal analyses, the internal temperature of subterranean rooms increases up to 8.9% in the summer and decreases to 5.4% in winter. These results were obtained when compared to the initial situation, where soil influence had been neglected. Such results provide an indication of the importance of considering the soil influence on the thermal performance analyses where an accurate assessment is requested.

Keywords: Thermal performance of buildings, EnergyPlus, basement preprocessor, basement thermal analysis, soil temperature.

RESUMEN

Entre los diversos factores que interfieren en el desempeño térmico de las edificaciones, la temperatura del suelo no siempre es considerada en las evaluaciones de desempeño térmico. Sin embargo, la temperatura del suelo es un factor que influye en el resultado final de los cambios de calor de los ambientes, principalmente en edificaciones térreas. De esta forma, se hace necesario evaluar dicha influencia debido a la interacción del suelo con la fundación y paredes de una edificación. Además, en función del carácter tridimensional y transitorio de los procesos de intercambio de calor envolviendo el suelo y las paredes subterráneas, el abordaje numérico se convierte en una herramienta importante en el análisis del desempeño térmico de las edificaciones. En este sentido, EnergyPlus figura como un software de simulación de carga térmica y desempeño energético de edificaciones y surge como una alternativa para la obtención de dichos resultados, sobre todo a través del preprocesador Basement. Los resultados indican que, cuando el efecto del suelo es considerado en los análisis térmicos de edificación, la temperatura interna de las habitaciones subterráneas se eleva hasta un 8,9% en el verano, y se reduce hasta un 5,3% en el invierno. Estos resultados se han obtenido comparando la situación inicial, donde la influencia del suelo no era tomada en cuenta. Estos datos proporcionan indicaciones de la importancia de la consideración de la influencia del suelo en los análisis de desempeño térmico, donde se solicita una evaluación precisa.

Palabras clave: Rendimiento térmico de los edificios, EnergyPlus, preprocesador del sótano, análisis térmico del sótano, temperatura del suelo.

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INTRODUCTION

As constructive techniques for the upper floors of a building have improved, heat transfer through subterranean rooms has become a more significant fraction of the heat loss and of the total energy consumption of the building [1]. Labs *et al.* [2] have discovered that heat loss in non-insulated concrete walls of basements of low-rise buildings may contribute up to 60% of total losses when the upper floor is well insulated. Krarti [3] has found that the analysis of heat transfer involving the soil has a significant effect on thermal performance evaluations of ground residential and commercial buildings, contributing up to 30% of the total of the building heating and cooling loads. Choi and Krarti [4] have also verified that buildings where the insulation is optimized may represent a reduction of up to 35% in total heat loss in subterranean structures when compared to uniform insulation configurations.

Kharrufa [5] performed a thermal performance assessment at a non-thermal insulation and natural ventilation building in Baghdad to evaluate the use of underground rooms in the summer. The basement of the analyzed building consisted of brick walls, concrete block floor and concrete slab, with 2.5m depth below ground level and 1.0m above ground. The results measured for a critical summer day indicated that while the external air temperature reached the maximum value of 43 °C, the internal temperature of the upper deck registered about 40 °C and the basement temperature reached the maximum value of 35 °C. In Brazil, Costa, Roriz e Chvatal [6] compared different modeling alternatives of the parameters related to the heat transfer between the floor and the ground, and their influence in the thermal performance of a naturally ventilated single-story house, using the programs EnergyPlus/GroundDomain e EnergyPlus/Slab. The thermophysical properties of the soil were the data that had the most influence. The building was evaluated as being 57.5% less uncomfortable with the dry soil, and 25% more uncomfortable with the humid soil, in relation to an intermediate humidity level. Souza, Amparo and Gomes [7] analyzed the influence of soil thermal inertia on the thermal performance of a Brazilian residential building in light steel framing. According to the authors, soil thermal inertia plays an important

role in the thermal balance of a building since the contact with the soil can serve as a strategy of thermal inertia for cooling and/or heating. In the tested building, the surface temperatures are lower when contact with the soil occurs, reaching up to 3.5 °C difference to a naturally ventilated environment.

With projections of increasing energy consumption at the national level, energy conservation measures have become a necessity in Brazil. In the 1990s, the demand for electric power in the commercial sector alone was 9.8%, while hydroelectric generation, which is the main source of energy in the country, increased by only 5.8% [8]. In 2015, due to the unfavorable hydrological conditions in Brazil, there was a reduction of 3.2% in the available hydraulic energy, while the final consumption of electricity in the country registered a decrease of 1.8%, and the reduction of energy spent in the residential sector reached only 0.7% [9]. According to Duailibe *et al.* [10], periodic government energy auctions provide opportunities and incentives for the insertion of new electric energy generation plants, mainly thermal and wind farms projects that are usually simpler and faster to construct when compared to major hydroelectric projects. However, even with the encouragement of the use of renewable sources, the hydroelectric generation in 2015 expanded by 5.9% compared to the previous year [9]. Thus, this difference, among other measures, points to the urgency of rational energy use in buildings. Consequently, stricter energy standards are increasing building modeling requirements as a means of evaluating energy conservation projects and measures.

In this way, the need for improving the well-being of users of a building, associated with energy saving, optimization of thermal performance, and the thermal comfort of the environment has caused several studies to emerge using, as an aid, tools for numerical simulations of thermal and energy loads [11]. Also, since the soil is a heterogeneous material, the heat transfer mechanisms in it become very complex and may vary considerably as the properties of this material change. In addition, due to the three-dimensional and transient nature of numerical methods, considering the influence of the soil, a computational approach has become an important tool to aid the understanding of the process of heat transfer involving the soil.

Through the advancement of computational resources, more detailed and more realistic three-dimensional numerical models have been developed. Therefore, the use of more sophisticated modeling techniques allows the study of the interaction between the analyzed building and the external environment to be generated more efficiently. In EnergyPlus, a thermo-energy computer simulation program developed by the US Department of Energy and validated by ASHRAE 140 [12], the preprocessor capable of providing the temperature of the external face of the walls and basement floors, considering the influence of the soil, is the Basement preprocessor. This preprocessor basically uses the formulations developed by Cogil [13], but methods developed by other researchers such as Clements [1] have been modularized in EnergyPlus [14] with the purpose of making the Basement preprocessor a complete program in the analysis of the processes of heat exchange involving the soil.

The heat flow between the floor and the ground of a single-story building is one of the most influential aspects in its thermal and energy performance [6]. For this reason, basements must be conditioned to meet the same thermal comfort criteria as the other spaces on the upper floors of residences [1]. Therefore, most of the research done so far analyzes only the artificially conditioned and insulated subterranean environments and, in Brazil, where houses are usually naturally ventilated and do not have thermal insulation in walls and floors, there is a need for further studies addressing the issue. In addition, obtaining the thermophysical properties of the soil in the commercial sector has been little used due to the specific difficulties of the collection process and the appreciation of large numbers of samples [15] and, therefore, soil influence is almost always neglected in the thermal analyses of buildings.

This research is placed within this context, and its focus is on analyzing the heat exchanges between the soil, floor, and walls of a residence that has an underground part will be studied, which is not artificially conditioned and not thermally insulated, using the Basement preprocessor of the EnergyPlus software as a computational tool. This article also provides a comparative analysis evaluating the influence of the soil consideration in the thermal performance analyses and its relevance in promoting

an environment with lower energy consumption for heating and cooling.

METHODOLOGY

This section provides a general vision of the methodology adopted in the development of this article, which involves a numerical approach for evaluating the heat transfer process through the floor and subterranean walls of a single-family residence, naturally ventilated and non-insulated, via EnergyPlus (version 8.6.0). In this article, the thermal performance analyses of the model building are considered for three different situations:

- 1) disregarding the influence of the soil;
- 2) considering the influence of a saturated clayey soil;
- 3) considering the influence of a dry clayey soil.

Simulation methods in EnergyPlus

In EnergyPlus, buildings that have rooms in contact with the ground may be simulated in different manners. In this article two simulation modes are performed:

- 1) by inserting the average monthly temperatures of the soil in the object *GroundTemperature:BuildingSurface*. The guidelines for using this simulation procedure are in the *Input/Output Manual* [16];
- 2) by using the *Detailed Ground Heat Transfer* through the Basement preprocessor. The basic instructions of use of the program and the description of its input and output variables are in the *Auxiliary Programs Manual* [17].

The procedure (1) is adopted for the numerical simulation where the influence of the soil is not considered. This method is generally adopted when the user does not have the necessary input data about the building's underground rooms and the thermophysical properties of the soil surrounding the building. In this case, the method simply consists of informing the average monthly temperature of the soil surface for all surfaces that have as a boundary condition the external surface of the walls and floor in contact with the soil. Soil temperature data are usually obtained by the climatic archive used to simulate the building and do not represent the actual situation of the soil in the analyzed place. However, the use of only this data

does not provide satisfactory results in the analysis of heat losses in subterranean environments, because only a generic temperature is informed to represent the entire subterranean room that is applicable to any type of soil of the same place. This method is used in the simulations of situation 1, where the soil influence is not considered.

The procedure (2) is used in numerical simulations where the influence of the soil is considered. In this case, the program calculates the interface temperature between the floor, walls and floor slab of the building's underground rooms, which is then used as input data for the EnergyPlus to continue with the rest of the simulation. This method is used in simulations of situations 2 and 3, where the soil influence is considered. The formulation originally developed by Cogil [13] and adopted in the development of the Basement preprocessor is briefly described below.

A basement influences the ground temperature distribution in the surrounding soil. In order to obtain an accurate estimate of basement heat loss, it is necessary to model not only the foundation, but also a portion of the surrounding soil sufficient to contain this thermal disturbance. Thus, the fundamental equation governing ground coupled heat flow from buildings with no internal generation and constant thermophysical properties is given by equation (1):

$$\rho c_p \frac{\partial^2 T}{\partial t} = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (1)$$

where ρ is the density of the soil (kg/m³), C_p is the specific heat of the soil (J/kg.K), T is the soil temperature (K), t is the time (s), k is the thermal conductivity of the soil (W/m.k) and x, y, z are the north-south, east-west, and vertical coordinates.

In the mathematical method developed by Cogil [13] the ground domain analyzed in the simulation is subdivided into different three-dimensional cells composing the finite-difference numerical method grid. Each cell is attached to the adjacent cell by nodes. Thus, the implicit form of the equation (1) used in the Basement module is able to simultaneously calculate the temperature of each node of the finite-difference grid for each ground domain cell analyzed. Equation (1) may be manipulated in the

form of equation (2), which discretizes a three-dimensional explicit solution for an intermediate cell to domain boundary cells.

$$\begin{aligned} \rho c_p \frac{T_{i,j,k}^{t+\Delta t} - T_{i,j,k}^t}{\Delta t} = & \frac{1}{\Delta x} \left(k_x + \frac{T_{i+1,j,k}^t - T_{i,j,k}^t}{\delta x^+} - k_x - \frac{T_{i-1,j,k}^t - T_{i,j,k}^t}{\delta x^-} \right) + \\ & \frac{1}{\Delta y} \left(k_y + \frac{T_{i,j+1,k}^t - T_{i,j,k}^t}{\delta y^+} - k_y - \frac{T_{i,j-1,k}^t - T_{i,j,k}^t}{\delta y^-} \right) + \\ & \frac{1}{\Delta z} \left(k_z + \frac{T_{i,j,k+1}^t - T_{i,j,k}^t}{\delta z^+} - k_z - \frac{T_{i,j,k-1}^t - T_{i,j,k}^t}{\delta z^-} \right) \end{aligned} \quad (2)$$

where ρ is the density of the soil (kg/m³), C_p is the specific heat of the soil (J/kg.K), T is the soil temperature (K), $i/j/k$ are the cells faces indices, t is the time (s), Δt is time step differential, k is the thermal conductivity of the soil (W/m.k), $\Delta x/y/z$ are the distances between cell centers (m), $k_{\pm x/y/z}$ are the effective thermal conductivities at the cell face indicated (W/m.k), $\delta x/y/z$ are the cells widths (m) and x, y, z are the north-south, east-west, and vertical coordinates.

One of the most fundamental concepts in foundation heat transfer modeling is that of the effective thermal conductivity [1]. When performing an energy balance on a cell whose neighbors have differing thermal conductivities, an effective thermal conductivity must be calculated to ensure that energy is conserved in the calculation [13]. To accurately represent the heat flow through the interface of two neighbor cells with different thermal conductivity, an effective conductivity has been defined by the Cogil method. Effective conductivity, k_e (W/m.k), is the thermal conductivity of a plane layer $L_1 + L_2$ (m) thick, which has the same thermal resistance as one layer of thickness L_1 (m), which has conductivity k_1 (W/m.k), in series with the second layer of thickness L_2 (m), which has conductivity k_2 (W/m.k), given by Equation (3). In equation (3), the fact that insulation is assumed to have negligible thermal mass allows it to be modeled as a pure thermal resistance without having to redefine the finite-difference grid.

$$k_e = \frac{L_1 + L_2}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + R_{isol}} \quad (3)$$

where R_{isol} is the insulation material resistance ($m^2.K/W$).

The stability of the method is the necessary condition for the convergence to be reached. The stability criterion, λ , adopted in the Cogil method is shown below (equation (4)):

$$\lambda = \frac{k\Delta t}{\rho c_p} \left[\frac{2}{x^2} + \frac{2}{y^2} + \frac{1}{z^2} \right] < \frac{1.5}{f} \quad (4)$$

where λ is the stability criterion for f factor ADI method, k is the thermal conductivity of the soil ($W/m.k$), ρ is the density of the soil (kg/m^3), c_p is the specific heat of the soil ($J/kg.K$), Δt is the time step differential, x , y , z are the north-south, east-west, and vertical coordinates and f is the factor used to modify the conventional ADI method, $0 < f < 1$.

The finite-difference equations derived from the control volume energy balance (Equation (2)) are expressed for one time-step. In this discretization procedure, a typical interior cell is used to illustrate the procedure used to produce the tridiagonal form of the discretization equations. This example is limited to the first (1/3) fraction of the time increment (x direction implicit, y and z directions explicit), since in the other two fractions of the time increment the numerical procedure is similar. The first time increment fraction is rearranged so that the cell temperature at the first fraction ($T_{i,j,k}^t$) of the time increment is expressed in terms of the temperature of its neighbor cells at the next fraction of the time increment ($T_{i,j,k}^{t+1/3\Delta t}$) multiplied by a coefficient that considers the f-factor (equation (5)). Factor f is used

to ensure that alternating-direction implicit (ADI) methods are applied, since this method provides faster solution methods for considerably more complex problems [1].

$$\begin{aligned} -\left(\frac{\rho c_p}{\Delta t}\right) T_{i,j,k}^t = & \left\{ (3-2f) \left(\frac{k_{x-}}{\Delta x \delta x} \right) T_{i-1,j,k}^{t+\Delta t} \right. \\ & - \left(\frac{\rho c_p}{\Delta t} + (3-2f) \left(\frac{k_{x-}}{\Delta x \delta x} + \frac{k_{x+}}{\Delta x \delta x} \right) \right) T_{i,j,k}^{t+\Delta t} \\ & + (3-2f) \left(\frac{k_{x+}}{\Delta x \delta x} \right) T_{i+1,j,k}^{t+\Delta t} + f \left(\frac{k_{x-}}{\Delta y \delta y} \right) T_{i,j-1,k}^{t+\Delta t} - \\ & - f \left(\frac{k_{y-}}{\Delta y \delta y} + \frac{k_{y+}}{\Delta y \delta y} \right) T_{i,j,k}^{t+\Delta t} + f \left(\frac{k_{y+}}{\Delta y \delta y} \right) T_{i,j+1,k}^{t+\Delta t} \\ & + f \left(\frac{k_{z-}}{\Delta z \delta z} \right) T_{i,j,k-1}^{t+\Delta t} - f \left(\frac{k_{z-}}{\Delta z \delta z} + \frac{k_{z+}}{\Delta z \delta z} \right) T_{i,j,k}^{t+\Delta t} \\ & \left. + f \left(\frac{k_{z+}}{\Delta z \delta z} \right) T_{i,j,k+1}^{t+\Delta t} \right\} \end{aligned} \quad (5)$$

By this formulation the Basement program is capable of returning the average value of the soil temperature for the 12 months of the year that reached convergence.

Analyzed model

The object of study of this article is a single-family building, developed exclusively for the analysis of this research, with two floors and a total area of $114 m^2$. On the first floor there is a guest room, a dining room, a kitchen with external access, and a guest bathroom; while in the basement there is a private room, two bedrooms, and another guest bathroom (Figure 1).

Figure 1. Schematic ground plan of the study object (quotas in meters).

Both floors are 3 m high, and the underground has 2.3 m of wall under the ground (Figure 2). It is a gable roof with 50 cm eaves (Figure 3) providing partial shading of the building openings.

In Brazil, the current Brazilian standard for performance evaluations of buildings is NBR 15575, which provides criteria and requirements for evaluating the thermal performance of buildings, recommending minimum performance levels that must be met [18]. The same Brazilian standard

still recommends that computational simulations be performed in the EnergyPlus program and that, as a priority, long-stay environments are analyzed in the thermal performance evaluations [18]. Thus, only the zones of the building indicated in Figure 4 are analyzed. Zone 1 is a zone pertaining to the subterranean room located at the end of the basement, representing all the other rooms of the building that are in contact with the ground. Zone 7 belongs to the first floor of the building and is located directly above Zone 1.

Reference climate data

For performing the computational simulations, the place chosen was the city of São Paulo/SP, located at a latitude of -23.85S and longitude of -46.64W, altitude of 792 m, and belonging the Bioclimatic Zone 3, according to Brazilian standard NBR 15220 responsible for the Brazilian bioclimatic zoning and for constructive guidelines for single-family houses of social interest [19]. The EPW climatic archive, for the year 2013, is provided by the Solar and Wind Energy Resource Assessment (SWERA) project, with the National Institute for Spatial Research (INPE) and LABSOLAR, belonging to Santa Catarina Federal University [20].

According to the NBR 15575 standard guidelines, the thermal performance evaluation of a building must be performed in a typical design day, both in summer and in winter. According to the same standard, a typical summer or winter day is defined as a real day featured by the following variables: air temperature, relative air humidity, wind speed, solar radiation incident on horizontal surface for the

Figure 2. Cut AA (quotas in meters).

Figure 3. Prospects of the model.

Figure 4. Model building simulated zones.

hottest day of the year according to the average of the period of the last 10 years (summer), and incident solar radiation on the horizontal surface for the coldest day of the year according to the average of the period of the last 10 years (winter) [18]. Thus, Table 1 shows the climatic data corresponding to the typical design summer and winter days provided by the NBR 15575-1 standard for the city of São Paulo. In this article, the simulations are also performed monthly via the climatic data obtained from the EPW climatic archive, where the average values of internal and external temperature of the environment are generated.

Thermophysical properties of the soil analyzed

In one region of land surface several types of soil may be found. Each type has its own features, such as density, shape, color, consistency, and chemical formation, aside from varying their behavior according to the presence of water in soil voids [21]. More specifically, clayey soil is one of the main types of soil found in São Paulo [22] and, for this reason, it was adopted in the simulations where the influence of the soil is required in the thermal performance analyses. Table 2 shows the typical values adopted for the main thermophysical properties of the clayey soil, considering saturated and dry soils. In saturated soil conditions, the entire

void space is occupied by water while for the dry soil the entire void space is filled by air. From the thermophysical information of the soil, the soil temperatures may be obtained more accurately with the use of the Basement preprocessor.

In the analysis where the influence of the soil is disregarded, the average monthly temperatures of a generic soil obtained from the EPW climatic archive [20] of the city of São Paulo are used only as reference values in the simulation (Table 3).

Composition of the closure system of a single-family building

The internal and external closure system of the building has the same structure features mentioned in Table 4, which represents a common building envelope for Brazilian buildings. The thermophysical properties of the materials used in the closure system of the building are in Table 5.

In addition, the position of the building under study was considered at 0° of the north axis of geographic coordinates. As the windows of zones 1 and 7 are oriented to north, these environments will receive higher solar incidence. In relation to the absorption to the solar radiation of the walls, the value of the absorptance is assumed as equal to 0.5, corresponding

Table 1. Data on average summer and winter days (Bioclimatic Zone 3 - São Paulo).

Season	Daily Maximum Temperature (°C)	Daily Minimum Temperature (°C)	Daily Temperature Range (°C)	Wet Bulb Temperature (°C)	Solar Radiation (Wh/m ²)	Cloudiness (tenths)
Summer	31.9	–	9.2	21.3	5.180	6
Winter	–	6.2	10	13.4	4.418	6

Source: Norma NBR 15575-1 [18].

Table 2. Thermophysical properties of the soil.

Material		Thermophysical properties		
		k	ρ	C_p
Clayey Soil	Dry	0.25	1600	890
	Saturated	1.58	2000	1550
Note: k thermal conductivity of the soil (W/m.k); ρ density of the soil (kg/m ³); C_p specific heat of the soil (J/kg.K).				

Source: OKE [23].

Table 3. Average monthly temperature of the soil.

Soil Temperature (°C)					
Month		Month		Month	
January	20.5	May	20.1	September	15.9
February	21.5	June	18.6	October	16.5
March	21.7	July	17.2	November	17.6
April	21.5	August	16.2	December	19.1

Source: EPW climatic archive [20].

to the average color defined in the project according to the Brazilian standard NBR 15220 [19].

RESULTS AND DISCUSSION

A comparison of the results obtained between the generated simulation disregarding the soil influence

and the results of the three-dimensional analysis of the heat exchanges considering the soil, floor, and walls of the subterranean areas of the model building is considered. The results are presented in two sections:

the analysis recommended by Brazilian standard NBR 15575 [18], which provides the internal temperature results obtained for a typical summer day and a typical winter day for the three types of simulated situations: disregarding the influence of the soil, analyzing the influence of the saturated clayey soil and the influence of the dry clayey soil;

analysis of the average monthly variation of the internal and external temperature obtained from the three simulated situations. The purpose of this analysis is to verify the annual behavior of the internal environment of the building throughout one year and, then, compare it to results provided in item (1).

Table 4. Structure of the building envelope.

Envelope	Envelope Composition			
Basement walls	Cement Mortar	Brick	Cement Mortar	
First floor walls	Cement Mortar	Brick	Cement Mortar	
Basement floor	Concrete Slab	Cement Mortar	Ceramic Floor	
First floor floor	Cement Mortar	Concrete Slab	Cement Mortar	Ceramic Floor
First floor ceiling	Cement Mortar	Concrete Slab	Wooden Ceiling	
Roof	Ceramic Tile			
Windows	Reflective glass 6mm thick			
Doors	Wooden Doors			
Cover Soil	Short Grass			

Table 5. Thermophysical properties of the materials used in the building envelope.

Material	Thickness (cm)	Thermophysical properties		
		k	ρ	C_p
Cement Mortar	1.5	1.15	2100	1000
Brick	9	0.90	1600	920
Concrete Slab	10	1.75	2400	1000
Ceramic Floor	1.5	1.05	2000	920
Wooden Ceiling	1	0.20	1400	100
Ceramic Tile	1	1.05	2000	920
Wooden Doors	3.5	0.15	550	2300
Note: k thermal conductivity of the materials (W/m.k); ρ density of the materials (kg/m ³); C_p specific heat of the materials (J/kg.K).				

Source: NBR 15220 [19].

RESULTS ACHIEVED IN A TYPICAL DESIGN DAY

This step has the purpose of evaluating the external temperature of the air and the internal temperature of Zone 1 and Zone 7 (see Figure 4), representative zones of the building, for a typical summer day and for a typical winter day, through the output data generated by the simulations performed in EnergyPlus. Table 6 indicates the maximum temperature results obtained for a typical summer day and the minimum results obtained for a typical winter day.

In the summer, the lowest temperatures are obtained in the analysis where the influence of the soil is not considered while the highest temperatures were found in the analysis of a dry clayey soil. The values shown in Table 6 indicate that the temperature of the basement representative zone (Zone 1) is up to 6.8% higher in a saturated clayey soil and 8.9% higher in a dry clayey soil when compared to the results generated when the influence of the soil is neglected. For the zone pertaining to the ground floor (Zone 7) this temperature elevation is less pronounced, reaching 0.7% for a saturated clayey soil and 1.0% for a dry clayey soil.

Kharrufa [5] performed a thermal performance evaluation in a Baghdad building without thermal insulation and natural ventilation to evaluate the use of subterranean rooms during the summer period. The basement of the building analyzed was composed of brick walls, concrete block floors and concrete slab, 2.5 m depth below ground level

and 1.0 m above ground. The results measured in a critical day of summer indicated that while the external air temperature reached a maximum value of 43 °C, the internal temperature of the first floor was recorded at about 40 °C and the basement temperature reached the maximum value of 35 °C. In Table 6, the same behavior found by Kharrufa [5] may be seen where the external temperature has shown a maximum value of 31.9 °C, and the internal temperature of the first floor has varied from 25.3 to 25.8 °C. By comparing the results, it is possible to verify that the temperature of the upper level in both situations reaches values close to the external temperature while the internal temperature of the basement is always lower than the temperature of the first floor; for the Baghdad building the variation value found was 5 °C and for the São Paulo building it was 3.6 to 3.2 °C. It can be noted that for the simulations where the soil was not considered, the internal temperatures found are even lower—a fact that may suggest an incoherent interpretation of the thermal performance of a building project.

The opposite occurs in the winter, where the highest temperature values were found in the simulation where the influence of the soil is disregarded, while the dry clayey soil was responsible for generating the lowest internal temperatures. By interpreting the data provided in Table 6 it is possible to point to a decrease of 4.7% in a saturated clayey soil and of 5.4% in a dry clayey soil when compared to the results generated when the influence of the soil is not considered. In the zone pertaining to the first floor (Zone 7), this temperature decrease reached

Table 6. Maximum/minimum temperature, Maximum outdoor temperature and Minimum outdoor temperature.

Summer				
Zone	Maximum Temperature (°C)	Disregarding the soil (°C)	Considering saturated clayey soil (°C)	Considering dry clayey soil (°C)
1	31.9	23.7	25.3	25.8
7		28.7	28.9	29.0
Winter				
Zone	Minimum Temperature (°C)	Disregarding the soil (°C)	Considering saturated clayey soil (°C)	Considering dry clayey soil (°C)
1	6.7	14.9	14.2	14.1
7		10.9	10.8	10.8

the value of 0.9% both for a saturated clayey soil and for a dry clayey soil.

As for the thermal performance criterion established by NBR 15575 [18] for natural ventilation, with an air renewal rate of 1 Ren/h, in both situations, summer and winter, the ground building of São Paulo is satisfactory to the results presented for the thermal conditions in the building, presenting a superior performance level of the standard. In the superior performance standard, the maximum values obtained for the interior air temperature should be lower than the daily maximum air temperature value minus 4 °C, in the summer, and the daily minimum interior air temperature values should be higher than the minimum external temperature plus 7 °C in the winter. Thus, energy consumption in the ground floor of the building may be reduced since the results indicated that there is no need to adopt an artificial heating system in winter and a cooling system in summer. However, it can be noted that in the simulations where the influence of the soil is disregarded, the internal temperature results in the summer have lower values than in the simulations where the soil is considered. In the winter the opposite is found. Consequently, disregarding the influence of the soil may generate mistaken analyses of thermal performance where a better classification may be evaluated, when in fact, the classification might be at an inferior level of thermal comfort.

The Figure 5 graphs show the internal and external air temperature one-hour values for a typical day

in summer, for the zone pertaining to the basement (Zone 1). Once again, it can be seen that data generated by simulation where the influence of the soil is disregarded show the lowest temperatures within the three analyzed situations, while the highest temperatures are obtained for a dry clayey soil.

As well as to a typical summer day, the Figure 6 graphs show the internal and external air temperature one-hour values obtained over a typical winter day for Zone 1. In contrast to what happens in the simulation of a typical summer day, it can be seen that the data generated by the simulation where the influence of the soil is neglected bears the highest temperatures within the three situations analyzed, while the lowest temperatures are found in the dry clayey soil simulation.

Monthly results for temperature variation

The second section of results aims to show the average monthly temperature throughout the year resulting from simulations performed in EnergyPlus for the three procedures approached: disregarding the influence of the soil and considering the influence of a saturated clayey soil and of a dry clayey soil. From the graphs provided in Figure 7 and Figure 8, it is possible to observe the annual behavior of the average monthly external and internal temperature of Zones 1 and 7, respectively. As well as the results provided by the previous section (3.1), it is noted, as from Figure 7, that the disregard of the influence of the soil provides results for the Zone 1 internal temperature which are lower than the obtained results, when the influence of the soil is considered,

Figure 5. Temporal evolution of internal and external temperature for a typical summer day-Zone 1.

Figure 6. Temporal evolution of internal and external temperature for a typical winter day-Zone 1.

Figure 7. Annual evolution of the average monthly internal and external temperature-Zone 1.

Figure 8. Annual evolution of the average monthly internal and external temperature-Zone 7.

in summer months, and higher internal temperatures in winter months. In addition, in the same soil it is possible to note that the internal temperature in the simulation of a dry clayey soil becomes more elevated than for a saturated soil in summer months and contrary to what happens in winter months. For the zone pertaining to the first floor (Figure 8), the same analysis performed in Zone 1 can be considered, emphasizing the fact that these effects are noticeable in the first floor on a considerably smaller scale when compared to the internal temperature results obtained for the environment pertaining to the subterranean room. The difference in temperature between the results obtained disregarding the influence of the soil and considering the influence of the dry clayey soil causes temperature gains of up to 5.9 times higher in subterranean rooms than in the ground floor, and temperature losses of up to 5.2 times in relation to the temperatures losses obtained in a subterranean room and the ground floor.

Table 7 shows the average monthly outdoor face temperatures of a basement in contact with the ground, generated by the Basement preprocessor by Equation 5, for the two analyzed soils: dry and saturated clayey soil. Table 7 also informs the soil temperature obtained by the climatic archive [20] and adopted in the simulation where the influence of the soil is disregarded. These soil temperature presented in Table 7 are used as input data for EnergyPlus to calculate the internal temperature of the analyzed

building. It is possible to verify that the maximum temperature difference between the outside face of the floor is 0.8 °C between dry and saturated soil. In relation to the walls do not occur variations of temperature for the twelve months of the year. It is also possible to observe that in simulations where soil influence is not taken into account the soil temperature values reported by the climatic file differ considerably from the values calculated by the Basement preprocessor. In the case of the soil considered in this study, the temperatures obtained by the climatic archive are lower than the temperatures obtained considering the three-dimensional analysis of the soil effect in the building in summer period and higher in winter period. Again, disregarding the soil effect may provide misleading performance analyzes because the soil, with its high thermal capacity, maintains its temperature considerably lower than outdoor air temperature during the summer and higher than outdoor air temperature during the winter. However, the results generated by Figures 7 and 8 suggest that the consideration of the soil influence causes the internal temperature of the air in the building to be higher in the summer and lower in the winter when compared to the situation where soil influence is disregarded.

CONCLUSIONS

In this article, the influence of the soil on the thermal performance of subterranean rooms of

Table 7. Monthly outside face temperature and soil temperature.

Month	Outside Face Temperature				Soil Temperature
	Dry clayey soil		Saturated clayey soil		Disregarding the soil influence (°C)
	Walls (°C)	Floor (°C)	Walls (°C)	Floor (°C)	
January	24,0	23,9	24,0	23,4	20,5
February	24,0	23,9	24,0	23,4	21,5
March	24,0	23,9	24,0	23,4	21,7
April	15,9	16,5	15,9	17,0	21,5
May	15,9	16,1	15,9	16,3	20,1
June	15,9	16,0	15,9	16,1	18,6
July	15,9	16,0	15,9	16,0	17,2
August	15,9	16,0	15,9	16,0	16,2
September	15,9	16,1	15,9	16,2	15,9
October	24,0	23,3	24,0	22,5	16,5
November	24,0	23,7	24,0	23,0	17,6
December	24,0	23,9	24,0	23,3	19,1

a naturally ventilated ground level building in São Paulo has been assessed via EnergyPlus. For this, it was performed comparisons between the simulations where the influence of the soil is disregarded and in the situation where the three-dimensional effect of the soil heat transfer is taken into consideration.

For the summer period, results indicated internal temperatures of the subterranean room as higher, by up to 8.9% in situations where the influence of the soil was considered in relation to the situation where this parameter was neglected. For the winter, the opposite happened, where the internal temperatures decreased up to 5.4%, considering the influence of the soil in relation to the situation where the soil was not considered. In the zones pertaining to the ground floor, these effects were less noticeable when compared to the internal temperature variation of the basement, since the internal temperature of the simulation where the soil was considered increased up to 1.0% in summer and decreased up to 0.9% in winter. This data indicates that in an accurate analysis consistent with reality, both via EnergyPlus and other energetic simulation software, the soil consideration as an active medium in the process of heat transfer is necessary for the thermal comfort of the occupants and for the energy economy of the environment to be correctly weighed.

With the results raised in this article, the importance of considering the soil in the thermal performance assessments of a ground level building becomes an especially relevant factor for Brazilian buildings, which usually are not artificially conditioned and do not have thermal insulation on the subterranean walls and floor, being subject to higher heat flows through these elements. Additionally, in non-conditioned basements, the internal temperature variation reflects on credits and penalties resulting from heating and cooling caused by direct contact with the soil. Those values also influence the thermal performance of the first floor of the building, becoming of crucial importance for an accurate thermal performance assessment to be made.

ACKNOWLEDGMENTS

The authors would like to thank the CAPES Foundation for funding this research study.

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