Comparison of shallow basement thermal performance for different regions of Morocco using a three-dimensional heat transfer analysis

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Abstract: A three-dimensional numerical model was built to estimate the heat transfer between the soil and a shallow basement in four different climates (cold, temperate, semi-arid and arid climates) for, respectively, conditioned and unconditioned cases. The governing heat transfer equation in soil and basement was solved by the finite difference method using the alternating-direction implicit scheme (ADI). The air temperature for the case of conditioned shallow basement was maintained constant while it was computed for the case of unconditioned cellar using energy balance equation. The effects of the basement geometry, soil types and climatic conditions on the thermal behavior of the conditioned and unconditioned shallow basement were carried out. The heat losses and isotherms analysis showed that the heat flux is more significant through the walls than the basement floor and occurred mainly in the walls-floor edges. Furthermore, lowering the thermal diffusivity of the soil leads to a decrease in the shallow basement heating load. Our results show that the shallow basement as expected is more beneficial in hot climates than in cold ones. It was also brought to light that the basement thermal load is dependent on the soil type in temperate climates.

ABOUT THE AUTHOR

Our group’s key research activities aim at studying the effect of passive systems for air refreshment (and heating) in buildings in Marrakech region. The project focuses on the building envelope in order to point out the synergy between an adapted envelope to Marrakech climate and the use of passive systems for cooling and heating. Specifically, four existing residential buildings with some passive systems for cooling and heating are monitored and simulated. The response of these systems is calculated by means of dynamic transient software (TRNSYS). Buried and semi buried buildings were used through the history of mankind building for their thermal comfort. The ground high thermal inertia and its insulating properties considered as a potential passive system for air conditioning was also studied in this project. The contact of shallow basement envelop with the ground contributes to reduction of heating and cooling thermal loads and helps in reducing domestic energy consumption.

PUBLIC INTEREST STATEMENT

Energy consumption in building sector accounts for approximately 25% of the annual energy use in Morocco (AMEE, 2014). Buried building can reduce the consumed energy by electric air conditioning systems. This energy saving increases as a function of the building walls contact with the ground. This is due to the high thermal inertia of soil and its insulating properties. The thermal performances of shallow basement in different climates were done. It has been found that the soil thermal inertia plays a major role in maintaining the internal thermal comfort by stabilizing the indoor air temperature to an acceptable level in summer (26°C) and in winter (13.5°C) while the outdoor air temperature fluctuates between a maximum of 43.25°C in summer and a minimum of 2.5°C in winter. It has been also concluded that the shallow basement is highly beneficial in semi-arid and arid climates and less beneficial in the cold climate.
1. Introduction

Energy consumption in residential buildings in Mediterranean area is increasing due to the standardization of the construction that moves away from traditional bioclimatic architecture. This trend means that dwellings are less able to control the internal environment to comfortable conditions and thus, air conditioning systems are needed. In Morocco, energy consumption in the residential building sector accounts for approximately 18% of the annual energy use (AMEE, 2014). This attracted the interest of many researchers to reduce energy consumption by using passive techniques such as new material insulation, architecture and use of soil inertia. Accordingly, the use of soil inertia has a promising potential in building’s energy saving.

The use of building totally or partially buried deep in the soil for thermal comfort is a technique that goes back to the antiquity and dates back to over 5 000 years ago when in some cultures whole towns were built under the ground. The examples are the town of Matmata in Tunisia, the Goreme Valley in Turkey and the Henan Province in Shanxi (Alkaff, Sim, & Ervina Efzan, 2016; Al-Temeemi & Harris, 2004). This is highly significant because about over 33% or 50% (depending on climatic conditions) of the continents are affected by hot-dry climate and only 12% of the continents are under temperate climate (Staniec & Nowak, 2009).

Soil is a good moderator of temperature given its thermal properties. The great heat capacity and high thermal inertia allow a damping of above-ground temperature fluctuations with soil depth. In fact, Kusuda and Archenbach (1965) have reported that the temperature fluctuations at the surface of the ground are diminished at an exponential rate as the depth of the ground increases. They have also demonstrated that soil temperature depends significantly on averaged yearly ambient temperature and on the water table temperature. Therefore, external temperature fluctuations have less effect on deep soil and below 8 meters the soil temperature is nearly independent of external fluctuations (Badache, Eslami-Nejad, Ouzzane, Aidoun, & Lamarche, 2016). Radiative heat is also reduced since the buildings are less exposed to direct solar radiation (Carpenter, 1994).

Most studies have shown that the greater the percentage of the facade is in contact with the earth the better the passive annual heating and cooling gains are (Anselm, 2008, 2012; Carmody & Sterling, 1984; Kumar, Sachdeva, & Kaushik, 2007). Soil in contact with houses can affect 11% to 80% of the yearly energy balance depending on soil type and basement depth (Staniec & Nowak, 2011). Comparison studies have shown that a house buried about 0.5 meters within the soil can reduce energy consumption by about 25% (Staniec & Nowak, 2009). Deru and Kirkpatrick (2001) deduced that the heat transfer from the basement walls is more dependent on the ground surface conditions in comparison to basement floors, which are closely coupled to the conditions in the deep ground below the building. Indeed, the heat flow through a subterranean wall could be reduced by up to 51.6% compared to a thermally superior above-grad wall in a Kuwait hot arid climate (Al-Temeemi & Harris, 2003).

Commercial energy codes were also used by many researchers. Some of these works did not include the interaction between the building and the surrounding ground since the thermal precision was not always obtained from some codes (Barbaresi, Torreggiani, Benni, & Tassinari, 2014). Andolsun, Culp, Haberl, and Witte (2012) have studied the effect of ground coupling on energy requirements of slab-on-grade code houses in four climates of the US. They quantified the differences between the slab-on-grade heat transfer models of DOE-2 and Energy Plus programs.
Their results indicated a necessity of improvement in Energy Plus (the Slab model, GCS) to avoid erroneous results in residential energy code compliance calculations.

The heat transfer through the ground coupled building envelope with basement in a hot-humid climate was also considered by Andolsun, Culp, Haberl, and Witte (2011). They quantified the differences between DOE-2 and Energy Plus basement ground coupled heat transfer. The significant differences between the two commonly used energy simulation tools underlined the urgent necessity for the development of a truth standard for basement heat transfer modeling. Barbaresi et al. (2014) defined a method to assess reliability in energy simulations for underground cellar modeling. Their results were generated by Energy Plus simulations and compared to case-study recorded data. The authors concluded that their results could be reliable to assess the cellar suitability for wine-aging, but the same results could not be acceptable in other research with different objectives. El-Darwish and Gomaa (2017) proposed a retrofit strategy to improve the energy efficiency of a higher educational building located in a hot arid climate of Egypt by using a Simulation Software Design Builder via Energy Plus. However, their study was limited to a classroom sample and then they did not take into account the ground coupled heat transfer through concrete floor slabs. Valdiserri, Biserni, Tosi, and Garai (2015) have applied retrofit strategies to a tertiary building located in two different climatic zones, Bologna and Rome (Italy). The building, with a basement which was not taken into account in their study, was analyzed by TRNSYS energy simulation tool.

Two recent studies of the passive techniques integration into a residential building have been conducted by using TRNSYS program in a hot semi-arid climate of Marrakech region (Morocco). Mastouri, Benhamou, Hamdi, and Mouyal (2017) have investigated the effect of combining thermal insulation with high thermal inertia on building’s thermal performance and Sobhy, Brakez, and Benhamou (2017) have analyzed the thermal behavior and energy savings of a residential building by considering different insulation strategies. The adjacent ground temperature was calculated by the type77 based on Kusuda correlation that maintains the surrounding soil undisturbed. However, the authors did not take into account the important interaction between the building envelope and the surrounding soil.

Many analytical methods were used to evaluate the heat transfer between the ground and buildings. Among these methods, Krarti, Claridge, and Kreider (1988a) have developed a semi-analytical method called inter-zones temperature profile estimation (ITPE). It was used to calculate the approximate analytical solutions for the three-dimensional heat transfer between slab-on-grade floors and rectangular basements under steady-periodic conditions (Krarti, Claridge, & Kreider, 1990). Al-Anzi and Krarti (2004) have developed a novel local/global (L–G) analysis technique to solve transient ground-coupled heat transfer problems. This novel approach combines analytical and numerical techniques to obtain heat transfer solutions for building a foundation with significant localized thermal bridges. They showed that this method can reduce the computational time by up to 90% as compared to other methods without loss of accuracy. Amjad, Abdelbaki, and Zrikem (2003) generated a two-dimensional transfer function coefficients (TFC) for a slab-on-grade floor. Later, TFC has been derived successfully for shallow basement and earth-sheltered building.

Deru and Kirkpatrick (2001) used the two-dimensional finite elements to study the effects of moisture on the heat transfer from two basic types of building foundations, a slab-on-grade and a basement.

Most studies of heat transfer between soil and shallow basement done in Mediterranean climate zones were limited to two-dimensional configurations (Amjad et al., 2003; Boukhattem, Bendou, Hamdi, & Rousse, 2012). However, Walton (1987) revealed that the results of two- and three-dimensional cases can differ by as much as 50% for the basement. Krarti et al. (1990) had concluded, for the rectangular ground-structures, that the heat flow is of one-dimensional nature in the center area of floors, two-dimensional natures along the walls and three-dimensional
nature near the corners. For this problem, Mitalas (1987) had attempted to account for three-dimensional effects by means of corner correction factors.

Bahnfelt, Cogil, and Yuill (1998); Bahnfelt and Pedersen (1990) developed a detailed three-dimensional finite difference model for heat conduction from slab-on-grade floors and basements, including a detailed ground surface energy balance. The only available 3D analytical expression is the steady-state solution derived by Delsante, Stokes, and Walsh (1983) for a rectangular slab-on-ground with the assumption of a linear temperature distribution along the base (wall/ground interface) of the external walls.

The main objective of this paper is to carry out a comparison of shallow basement thermal performance for different Moroccan climatic zones using a three-dimensional heat transfer analysis. The approach considers the two cases of conditioned and unconditioned shallow basement. In the case of conditioned shallow basement, assuming that the internal cellar temperature is maintained constant at 20°C, computation concerns the temperature isotherms around the basement, three-dimensional effects on the lost heat flux from the basement to the surrounding and the geometry effect of the basement floor shapes on the heat losses. In the case of unconditioned shallow basement, computation concerns the variation of the internal cellar temperature in comparison to the external air temperature in semi-arid climate, the effect of six climates on the internal air temperature and the effects of soil types on thermal loads. The paper also examines the relevance of shallow basement for different climates such as cold, temperate, semi-arid and arid.

2. Mathematical model and boundary conditions

2.1. Shallow basement configuration

The computational domain is composed of the shallow basement (walls and floor) and the perturbed surrounding soil. This building is supposed to be located in an open space. The conduction and convection heat transfer effects are symmetric. The effects due to the asymmetry of solar radiation on basement heat transfer are negligible (Bahnfelt et al., 1998). For this purpose, the computational domain was reduced to a quarter of shallow basement and surrounding perturbed soil considering the existence of two vertical symmetrical plans.

The quarter of the studied shallow basement surrounded by soil is drawn in Figure 1. The basement dimensions, soil surface, far-field distance and the lower boundary of the domain are illustrated.

The shallow basement has a rectangular shape with a width of 2b, a length of 2a and a depth of c. The basement ceiling is assumed to be adiabatic. The walls and the floor are assumed to have identical thermal conductivity and diffusivity.

Figure 1. Quarter of the Shallow basement configuration.
2.2. Mathematical model

The unsteady three-dimensional heat transfer equation governing the heat transfer by conduction in the two walls, floor and soil can be written as follows:

\[
\rho C_p \frac{\partial T}{\partial t} = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]

(1)

This equation is discretized by the finite-difference method and solved using alternating-direction implicit schema (ADI). A non-uniform mesh in three directions, constructed using a geometrical progression, was adopted in order to have a finer mesh in the vicinity of interface soil-building. This is illustrated in Figure 2 which represents the spatial discretization of the computational domain for a fixed y. For this grid, an hourly time step was used.

2.3. Boundary conditions

The Boundary conditions of the studied problem are detailed below:

- At planes of symmetry:

For \(-L_{ff} \leq y \leq 0\) and \(-H \leq z \leq 0\)

\[
\left. \frac{\partial T_{int}}{\partial x} \right|_{x=-0} = 0
\]

(2)

For \(-L_{ff} \leq x \leq 0\) and \(-H \leq z \leq 0\)

\[
\left. \frac{\partial T_{int}}{\partial y} \right|_{y=0} = 0
\]

(3)

- Far from building

For \(-L_{ff} \leq y \leq 0\) and \(-H \leq z \leq 0\)

\[
\left. \frac{\partial T_s}{\partial x} \right|_{x=-L_{ff}} = 0
\]

(4)
For \(-L_{ff} \leq x \leq 0 \) and \(-H \leq z \leq 0\)

\[
\frac{\partial T_s}{\partial y}(x, y, z, t) \bigg|_{y=-L_{ff}} = 0
\] (5)

\(L_{ff}\) is the far-field distance for which the effect of the shallow basement on the ground becomes negligible (limit of surrounding perturbed soil). Beyond this distance, the soil temperature \((T_s)\) becomes constant. The value of the far-field distance is determined in section (2.8).

- At basement internal sides interfaces (wall-air)

Temperature and heat flux continuity lead to:

For \(-b \leq y \leq 0\) and \(-c \leq z \leq 0\)

\[-\lambda_w \frac{\partial T_w}{\partial x}(x, y, z, t) \bigg|_{x=-\alpha} = h_c(T_w(-a, y, z, t) - T_{int})\] (6)

For \(-a \leq x \leq 0\) and \(-c \leq z \leq 0\)

\[-\lambda_w \frac{\partial T_w}{\partial y}(x, y, z, t) \bigg|_{y=-b} = h_c(T_w(x, -b, z, t) - T_{int})\] (7)

For \(-a \leq x \leq 0\) and \(-b \leq y \leq 0\)

\[-\lambda_w \frac{\partial T_w}{\partial z}(x, y, z, t) \bigg|_{z=-c} = h_c(T_w(x, y, -c, t) - T_{int})\] (8)

\(h_c\) is the heat transfer coefficient at the two sides of the wall and floor. It is supposed constant and taken equal to 8.30 W/m\(^2\)K (Amjad et al., 2003; Boukhattem et al., 2012).

- At basement external sides interfaces (wall-soil)

There is a perfect contact between walls and ground, hence the continuity of both temperature and flux:

For \(-b - e_w \leq y \leq 0\) and \(-c - e_f \leq z \leq 0\)

\[\lambda_w \frac{\partial T_w}{\partial x}(x, y, z, t) \bigg|_{x=-\alpha - (e_w)} = -\lambda_s \frac{\partial T_s}{\partial x}(x, y, z, t) \bigg|_{x=-\alpha - (e_w)}\] (9)

For \(-a - e_w \leq x \leq 0\) and \(-c - e_f \leq z \leq 0\)

\[\frac{\partial T_s}{\partial x}(x, y, z, t) \bigg|_{x=-L_{ff}} = 0\] (10)

For \(-a - e_w \leq x \leq 0\) and \(-b - e_w \leq y \leq 0\)

\[\lambda_w \frac{\partial T_w}{\partial x}(x, y, z, t) \bigg|_{x=-\alpha - (e_w)} \lambda_w \frac{\partial T_w}{\partial x}(x, y, z, t) \bigg|_{z=-\alpha - (e_f)}\] (11)

- Deep ground temperature

According to Badache et al. (2016), the ground temperatures are essentially constant throughout the year for depths below 6 m, and equal to the average annual air temperature (Kusuda & Archenbach, 1965). This approximation has been adopted in the present work where the ground temperature is taken equal to the average annual air temperature at a depth of \(H_{dg} = 14\ m\).
2.4. Moroccan region meteorological and soil data

2.4.1. Meteorological data

The four different climates considered in this study were defined based on the analysis of climatic data recorded over the period 1999–2008 (10 years) by 37 weather stations located in six territorial zones. A Typical Meteorological Year (MTY) file is therefore established for each zone.

The concerning four different climates are represented by the following cities located in the six different zones:

Cold climate: Ifrane (zone 4)

Temperate climate: Agadir (zone 1), Tangier (zone 2) and Fez (zone 3)

Semi-arid climate: Marrakech (zone 5)

Arid climate: Errachidia (zone 6)

Figure 3 shows the monthly average external air temperature $T_{\text{amb}}$ extracted from the six zones TMY files. The relevant climatic parameters needed in the present study are reported in Table 1.

![Figure 3. Monthly average external air temperature in the six Moroccan zones.](image)

Table 1. Climate characteristics of the six zones.

|                | Agadir | Fez  | Ifrane | Marrakech | Errachidia | Tangier |
|----------------|--------|------|--------|-----------|------------|---------|
| Minimal external air temperature (°C) | 5.30   | 0.50 | −5.75  | 2.55      | −0.90      | 4.30    |
| Maximal external air temperature (°C)  | 38.95  | 41.45| 32.80  | 43.25     | 40.85      | 34.20   |
| Average external air temperature (°C)  | 18.71  | 17.90| 11.44  | 19.39     | 19.53      | 17.47   |
| $T_{\text{shift}}$ (day)                | 46     | 12   | 12     | 12        | 12         | 12      |
| Coldest day                                | 15-Feb | 11-Jan| 11-Jan | 11-Jan    | 11-Jan     | 12-Jan  |
| Hottest day                                | 21-July| 22-July| 29-July| 29-July   | 29-July    | 21-July |
This study is performed using the Typical Meteorological Year files (TMY) for the concerned six zones (Meteonorm, 2017).

2.4.2. Soil surface temperature
According to Kusuda and Archenbach (1965), and Labs (1982), the soil surface temperature variations are assumed to be a sinusoidal function of time and can be determined knowing the mean ground surface temperature for the year $T_{\text{mean}}$ (approximated by average external air temperature), the amplitude of the ground surface temperature for the year $T_{\text{amp}}$ (taken as maximum external air temperature minus mean external air temperature) (Mazarron & Canas, 2008), current day of the year $t_{\text{now}}$ and the day of the year corresponding to the minimum surface temperature $t_{\text{shift}}$. The soil surface temperature $T_{ss}$ is then expressed as follows:

$$T_{ss} = T_{\text{mean}} - T_{\text{amp}} \cdot \cos\left(\frac{2\pi}{365} \cdot \left(t_{\text{now}} - t_{\text{shift}}\right)\right)$$

This correlation is the most commonly used by authors dealing with soil-building heat transfer (Mastouri et al., 2017). It is also implemented in the computational software (TRNSYS, 2010).

The soil surface temperature evolution for one year period, as calculated from Equation 12 using the metrological data reported in Table 1, is presented in Figure 4 for the six zones.

2.5. Soil properties
As the type of soil varies from one location to another, in order to analyze the effect of soil type, it is important to consider soils with various relevant properties. Therefore, five types of soil were considered: standard sand and clay according to (PN-EN-ISO:13,370) and three types of medium sand according to Ickiewicz (1988), differing in their moisture content (Table 2).

2.6. Total lost heat transfer rate from the basement to the ground
The unsteady three-dimensional heat transfer equation governing the heat transfer in the computational domain is solved to calculate the temperature distribution in the soil, wall and floor. The total lost heat transfer rate from the basement to the ground is the algebraic sum of the lost heat transfer rate from the floor and the two walls to the ground. It is calculated as follows:

$$\frac{\partial T_s}{\partial y} |_{y=-L_s} = 0$$ (13)
\[
Q_{w1} = \sum \sum h_i \Delta S_{w1k} = (T_{int} - T_{wi})
\]
\[
Q_{w2} = \sum \sum h_j \Delta S_{w2k} = (T_{int} - T_{w2i})
\]
\[
Q_{f} = \sum \sum h_i \Delta S_{fj} = (T_{int} - T_{fi})
\]

\[ (14) \]

\(\Delta S_{wik}\) and \(T_{wik}\) are respectively the surface element surrounding a node \((w1k)\) in the first wall and the temperature in the same node. A similar notation is used for the wall \((w2)\) and the floor \((f)\). The lost heat fluxes for each basement component (walls and floor) are calculated as the corresponding lost heat transfer rate divided by the surface of the component.

### 2.7. Code validation

The established code was used to simulate the same case as Krarti et al. (1990) who considered a basement configuration consisting of a first wall \((18 \, m \times 2 \, m)\), a second wall \((6 \, m \times 2 \, m)\) and a floor \((18 \, m \times 6 \, m)\). The monthly average lost heat flux for the two walls, as calculated by Krarti et al. (1990) and the established code in the present work are compared in Figure 5(a,b). The parameters used for the simulated cases are resumed in Table 3.

Figure 5 shows a good agreement between the results predicted by the present code and those predicted by Krarti et al. (1990). Indeed, the relative difference does not exceed 8% for wall 1 (a) and 1.3% for wall 2 (b).

### Table 2. Properties of soil types used in the study.

| Soil type   | Standard sand | Standard clay | Medium Sand 12.54% | Medium Sand 4.38% | Medium Sand 0.27% |
|-------------|---------------|---------------|--------------------|-------------------|-------------------|
| Thermal conductivity \(W.m^{-1}.K^{-1}\) | 2.00          | 1.50          | 1.15               | 0.77              | 0.32              |
| Thermal diffusivity \(10^{-6} \, m^2.s^{-1}\) | 1.10          | 0.50          | 0.61               | 0.54              | 0.26              |
| Volumetric heat capacity \(10^6 \, J.m^{-3}.K^{-1}\) | 2.00          | 1.50          | 1.15               | 0.77              | 0.32              |
| Moisture content, \(\phi\), % | 12.54         | 4.38          | 0.27               |                   |                   |

### Table 3. The parameters used for the simulated validation cases.

| Lff  | hdg | Tdg  | Tint | Tss  | Hs   | hw   | hf   | \(\alpha_s\) | \(\lambda_s\) |
|------|-----|------|------|------|------|------|------|--------------|--------------|
| 15 m | 5 m | 10°C | 18°C | 8 + 7cos(\(\omega t\)) (°C) | 1 W/m²K | 1 W/m²K | 0.5 W/m²K | 6.45 x 10^-7 m²/s | 1 W/m.K     |

Figure 5. Comparison between the results obtained by current study and those obtained by M. Krarti: (a) Wall 1 \((18 \, m \times 2 \, m)\) and (b) Wall 2 \((6 \, m \times 2 \, m)\).
2.8. Mesh sensitivity
Grid independence of solution was checked by varying the number of grid points from (20x16x18) to (50x48x48). The obtained results for the annual lost heat transfer rate from the basement to surrounding, using different values of the number of grid points (mesh), are reported in Table 4. Beyond the mesh value (46x44x44), no change in results was observed. Therefore, the mesh (38x36x36) was adopted for all the simulations carried out in the present study, as it provides good results with less computational time.

2.9. Far-field distance
It is recognized that, at a large distance from the external walls, the effect of the heat transfer from the shallow basement to the ground temperature distribution becomes negligible (Adjali, Davies, Rees, & Littler, 2000). To determine the minimal distance, set as far-field distance for which an adiabatic boundary condition is assumed, several simulations were realized by varying the distance \(L_{ff}\) in Equation (4) and (5). Figure 6 shows the variation of the calculated average annual lost heat flux as a function of \(L_{ff}\). The results indicate that \(q_{av-a}\) tends to be constant for \(L_{ff}\) values beyond 8 m. Indeed, the relative variation of \(q_{av-a}\) between \(L_{ff} = 8\) m and \(L_{ff} = 10\) m does not exceed 0.2%. Thus, the far-field distance value used in the subsequent simulations is set to \(L_{ff} = 8\) m. This value is comparable to the ones set by other authors (\(L_{ff} = 10\) m (Adjali et al., 2000) and \(L_{ff} = 6\) m (Deru & Kirkpatrick, 2001)). However, these authors did not explain the reasons for the choice of a particular value of \(L_{ff}\).

3. Results and interpretation
The developed code is applied to analyze the effects of soil type and climate on basement performance. The aim of the study is to assess the relevance of shallow basement in different climates such as cold, temperate, semi-arid and arid climates. The Marrakech zone, representing a semi-arid climate, has been given special attention as the outdoor temperature can reach 43.25°C in summer while the deep soil temperature remains around 20°C. The results are carried out for shallow basement dimensions: \(b = 4\) m, \(a = 6\) m, \(c = 2\) m, \(e_{w} = 0.3\) m, \(e_{f} = 0.4\) m.

Two simulation approaches were considered: conditioned and unconditioned shallow basement. In the first approach, two cases were analyzed. In the first case, a fixed soil and climate of Marrakech zone (semi-arid climate) were considered and the internal temperature is maintained constant and equal to 20°C. The calculated lost heat fluxes permit to assess the effects of geometrical parameters. Then, in the second case, the internal temperature is assigned to remain in the set comfort temperature range.

| Mesh (x y z)     | (20x16x18) | (26x24x26) | (32x30x32) | (38x36x36) | (46x44x44) | (50x48x48) |
|------------------|------------|------------|------------|------------|------------|------------|
| Annual lost heat flux (W/m²) | 5.27       | 5.62       | 5.75       | 5.75       | 5.76       | 5.76       |

Figure 6. Variation of the average annual lost heat flux (qav-a) with \(L_{ff}\) values.
(20°C to 26°C) according to AMEE standards (AMEE, 2014). In this case, the calculated thermal loads permit to assess the effect of soil type and climate. In the second approach (unconditioned shallow basement), the effect of climate and soil type on internal temperature are analyzed.

This study is performed using the Typical Meteorological Year files (TMY) for the concerned regions. For soil properties, five types of soil were considered: standard sand and clay according to PN-EN-ISO:13,370 and three types of medium sand according to Ickiewicz (1988), differing in their moisture content (Table 2).

3.1. Conditioned shallow basement
The main objective of this section is to evaluate the effects of the soil types and cellar geometry on the lost heat flux from the building to the ground. The cooling and heating thermal loads were also calculated for different soil types and climates.

3.1.1. Isotherms
The calculation of lost heat flux is based on knowledge of temperature distribution in the domain. It is interesting to analyze the temperature isotherms around the basement. To this purpose, the case of a cellar located in Marrakech region (semi-arid climate) with soil type “standard clay” is considered. The internal cellar temperature is maintained at 20°C.

3.1.1.1. Isotherms in the central vertical plane. Figure 7(a,b) illustrates the daily average temperature distribution around the conditioned basement in the central vertical plane (y = 0 m) for two typical days in winter and summer periods (the coldest and hottest days of Marrakech TMY).

It can be noticed that the isotherms extend radially from the wall and the floor, leading to heat flow paths patterns in forms of circular arcs normal to these isotherms (Figure 7(a,b)). At deep ground, these isotherms approach horizontal lines and heat flow paths become almost vertical. This is due to the fact that, in deep ground, building effect and climatic conditions are damped. It can also be observed that intense thermal stratification occurs in the above part of the interface ground-wall, and many isotherms converge at the point of connection between the soil surface and the basement wall. This indicates an intensification of exchanged heat flux at this point. It is remarked that the 20°C isotherm which corresponds here to the double point defined according to Krarti, Claridge, and Kreider.
as the mathematical median of the three boundary temperatures \((T_{int}, T_{ss}, T_{dg})\) divides the surrounding ground into a warm zone and a cold zone. The upper part which represents the warm zone in summer period receives heat from the soil surface while the lower part loses heat to the deep ground. These effects are reversed in winter period. Across the isotherm surface corresponding to the double point, change in direction of heat flow occurs. On one side of the double point, the region loses heat but on the other side, it gains heat. The same conclusions on temperature distribution in the surrounding ground of a basement were drawn by Krarti et al. (1988b).

3.1.1.2. Isotherms in the horizontal plane including the basement floor. Figure 8(a,b) display the daily average temperature distribution in the horizontal plane \((z = -c)\) including the basement floor for two typical days in winter and summer periods (the coldest and hottest days of Marrakech TMY). Figure 8(a,b) show that, as expected, isotherms are perpendicular to the vertical symmetrical planes, as adiabatic conditions are assumed there. The isotherms are distributed in the form of circular arcs and concentrated around the edge of the floor due to the significant gradient of temperature in this area. This pattern is due to the presence of the walls and the damping effect of the central zone floor which remains almost undisturbed.

3.1.2. Lost heat flux
In order to analyze the lost heat flux from the basement to the surrounding and the contribution of each component (walls and floor), the case of a cellar located in Marrakech zone (semi-arid climate) with soil type “standard clay” is considered. The internal cellar temperature is maintained at 20°C.

Figure 9 presents the monthly average external air temperature, the lost heat flux from the basement to the ground and the contribution of each component (walls and floor).

During the year, the basement loses heat for the period extending from December to April, while it gains heat for the period extending from May to November. The phase lag between external air temperature and lost heat flux from the basement to the ground is about 1 month. The lost heat transfer rate from the basement to the ground and phase lag are mainly controlled by the walls as the maximum lost heat flux from the floor does not exceed 0.53 W/m\(^2\) while this maximum reaches 20 W/m\(^2\) for the walls. Indeed, the contribution of the lost heat transfer rate from the floor to the total lost heat transfer rate from the basement is very low (3%) compared to the contribution of the walls (57% Wall 1 and 40% Wall 2). This dominance was also reported by Bahnfleth et al. (1998) (13% across the floor and 73% across the walls) and Deru and Kirkpatrick (2001) who found that the lost heat flux from the floor to the ground is closely dependent on deep ground condition. The dominance of the heat transfer from the walls in the studied case

![Figure 8. daily average temperature distribution in the horizontal plane (z = -c m) including the basement floor for two typical days: (a) coldest day (31 January), (b) hottest day (1 August).](image-url)
Marrakech) is accentuated by the fact that the deep ground temperature is similar to the temperature maintained in the building (20°C).

3.1.3. Edge and tridimensional effects

Many authors who carried out studies on heat transfer exchange between basement and surrounding soil considered that heat transfer phenomenon was bidimensional and therefore assuming that along the third axis, the temperature was uniform and the corresponding heat flux null. The tridimensional approach adopted in the present study is used to analyze the edge effects and to show that, in fact, the heat transfer problem is tridimensional. For this purpose, the daily average lost heat flux at several lines along the x-axis from the center to the edge was calculated for the floor \((z = -c)\) and for the wall \((y = -b)\) at different periods of time.

From Figure 10(a,b), it can be seen that the lost heat flux is constant at the center of the floor and wall and increases progressively as it approaches the edges. This behavior is due to edge effects, which causes the corner zone of the floor and the wall to be influenced more by the ambient temperature than the central zone. The fact that the calculated lost heat flux along the wall and floor lines varies from the center to corners proves that the heat transfer from the basement to the ground should be considered tridimensional. The same conclusions were drawn by Bahnfleth et al. (1998) and Krarti et al. (1988b).

3.1.4. Geometry effect of shallow basement

Due to the edge effects and large difference between the contributions of the wall and the floor surfaces to the total lost heat transfer rate from the basement to the ground, it is expected that for a fixed basement depth, geometry of the basement floor (related to values of \(a\) and \(b\)) may have an effect on the heat loss from the basement to the ground.

For a fixed depth \((c = 2\ m)\), a given floor area may be generated by different values of \(a\) and \(b\) leading to shapes from square to narrow rectangles which have different perimeters. Discrete
values of \(a\) (6, 12, 25, 50 m) have been considered to generate a list of square areas \(A = 36, 144, 625, 900, 2500\ m^2\). For each area, three values of \(a\) and \(b\) are considered leading to three different floor shapes characterized by their values of perimeter \(P\). The values of considered dimensional parameters are summarized in Table 5.

The annual average lost heat flux has been calculated for each shape. Attempts to find a relationship between the annual average lost heat flux and the floor shape characterized by the values of \(A\) and \(P\), has led to the functional relationship shown in Equation 15 and presented in Figure 11.

\[
\text{Heat loss} = 7.25\frac{A}{P}^{-0.625}
\]

Thus, the annual lost heat flux from the basement to the ground depends on the ratio \(A/P = (a\cdot b)/(2\times(a + b))\) which takes into account the effect of the floor geometry. A relationship similar to Equation 15 was established by Bahnfleth and Pedersen (1990) in the case of a slab-on-grade floor.

### 3.2. Unconditioned shallow basement

The effect of the climate on the internal temperature of an unconditioned cellar was evaluated in this section. This temperature is calculated by the energy balance (Equation 16) for two extreme soil types.

#### 3.2.1. Air basement energy conservation

When air is considered as an ideal gas and its temperature uniform in the studied cellar, the energy conservation law for the internal medium of the shallow basement is given by:

\[
\rho_a C_{pa} V \frac{dT_{int}}{dt} = m_i C_{pa} (T_{ext} - T_{int}) + Q_{total}
\]

where \(m_i\) is the air change flow rate. Its value is evaluated as equal to 0.3 V/h according to (Ashrae Standard, 2013).

\(Q_{total}\) is the total lost heat transfer rate from the basement to the ground determined from Equation 13. Equation 13 coupled to Equation 16, is solved for \(T_{int}\).

#### 3.2.2. Internal and external temperatures evolution

In order to analyze the evolution of the internal cellar temperature compared to the external air temperature in semi-arid climate, the case of Marrakech TMY and standard clay soil were considered. The calculated interior air temperature evolution for 1 year is plotted in Figure 12. The external air temperature is also reported.

The shallow basement has a damping effect on external air temperature fluctuation. Indeed, the daily maximum difference for the external temperature may reach 17°C, while this difference is reduced to 1°C in the shallow basement. The maximal and minimal temperatures reached in the basement are also reduced as compared to external air temperature. Thus, during summer period the interior temperature remains less than 26°C while the external temperature may reach 43.25°C; during winter period the interior temperature remains superior to 13.5°C while the minimal external temperature may reach 2.5°C.

The soil inertia results in a phase lag between indoor and outdoor temperatures evolution. This is shown in Figure 13 in which the evolutions of the monthly averages of external and internal air temperatures are reported.

The phase lag between the external and internal air temperatures evolutions is about one month.

#### 3.2.3. Climate effect on internal air temperature

In order to analyze the effect of climate on the internal air temperature, the TMY of the six Moroccan zones that represent four different climates (cold, temperate, semi-arid and arid climates) are
Table 5. Dimensional parameters a, b, P and A.

| Area (m²) | 36  | 144 | 625 | 900  | 2500 |
|-----------|-----|-----|-----|------|------|
| a (m)     | 6   | 12  | 25  | 30   | 50   |
| b (m)     | 6   | 12  | 25  | 30   | 50   |
| P (m)     | 24  | 48  | 100 | 120  | 200  |
| a (m)     | 12  | 24  | 50  | 60   | 100  |
| b (m)     | 12  | 6   | 12.5| 15   | 25   |
| P (m)     | 48  | 60  | 125 | 150  | 250  |
| a (m)     | 25  | 50  | 100 | 150  | 250  |
| b (m)     | 25  | 120 | 120 | 150  | 250  |
| P (m)     | 100 | 200 | 200 | 250  | 320  |
Figure 11. Annual average lost heat flux as a function of the geometry of the shallow basement.

\[ y = 7.2552x^{0.625} \]
\[ R^2 = 0.9855 \]

- 36 m²
- 144 m²
- 625 m²
- 900 m²
- 2500 m²

Figure 12. Variation of external and internal temperatures for a basement located in Marrakech.

Figure 13. Monthly average of internal and external air temperature in Marrakech city.
considered in the cases of the two extreme soil types shown in Table 2 (standard sand and standard clay). The results are reported in Figure 14(a,b).

The results in Figure 14 show that:

The effects of climate and soil on the interior air temperature evolution are uncoupled.

In all cases (for all soils and climates considered) the maximal temperature in the basement does not exceed 26°C. As the thermal comfort temperature range is (20–26°C), there is no need for cooling for shallow basements located in the six zones.

For Ifrane climatic zone (cold climate), the internal basement air temperature remains inferior to 20°C throughout the year, and therefore heating of basement is required all the time for shallow basements located in this climatic zone.

Figure 14. Evolution of the basement internal air temperature for the six Moroccan zones. The two extreme soil types are considered: (a) Standard Sand, (b) Medium Sand.
3.2.4. Thermal loads of the shallow basement

3.2.4.1. Effects of soil types on thermal loads. In order to study the effect of soil type on heat transfer exchange between the basement and surrounding soil, annual thermal loads for heating and cooling were calculated with heating and cooling set points established to 20°C and 26°C, respectively. According to the analysis of the basement internal temperature evolution carried out in the previous section, the maximal temperature in the basement does not exceed 26°C for all soils and climates considered. Therefore, the thermal load reduces to heating, as the cooling load is null. The five soil types (Table 2) were considered and the Typical Meteorological Year (TMY) of Marrakech zone (semi-arid climate) was assumed for climate conditions. The results are presented in Figure 15 where annual heating load is reported as a function of soil properties (thermal conductivity, volumetric heat capacity and thermal diffusivity).

Analysis of annual heating load trends with respect to soil properties shows that the annual heating load follows the trend of the thermal diffusivity. Thus, when thermal diffusivity decreases by about 74% from standard sand to medium sand ($\phi = 0.27\%$), the heating thermal load decreases by up to 40%. This trend shows that the thermal diffusivity, which determines the rate of equalization of temperature in the soil and therefore the amount of energy stored in it, affects directly the basement’s energy balance. The same trend was found by Staniec and Nowak (2011) for completely buried buildings.

3.2.4.2. Climate conditions effects on thermal loads. In order to analyze the influence of climatic conditions on the thermal load of the shallow basement, a comparison between annual thermal loads in the various Moroccan zones that represent four different climates (cold, temperate, semi-arid and arid climates) was made. For each climatic zone, the two extreme soil types are considered to have an interval of thermal loads for each climate. The results are reported in Figure 16 together with the thresholds of thermal loads for residential buildings required in the Moroccan thermal regulation (Meteonorm, 2017).

To evaluate the thermal comfort of the shallow basement, the calculated thermal loads were compared to the limits required by the AMEE for the six zones (Meteonorm, 2017). The results of Figure 16 indicate that:

- The shallow basement is suitable for the semi-arid climate (Marrakech) and arid climate (Errachidia), as the calculated thermal loads meet the AMEE requirements regardless of soil types.
- For the cold climate type (Ifrane), the thermal loads exceed the required limit. As shown in the previous section (Figure 14), the internal basement air temperature for Ifrane climate, remains inferior to 20°C throughout the year, and therefore heating of basement is required all the time for shallow basements located in this climatic zone.

![Figure 15. The effect of the thermal properties of soils on the heating load of the basement.](image-url)
For temperate climates (Agadir, Tangier, and Fez), the calculated thermal loads may be great or lower than the required limit set by AMEE depending on the soil type.

4. Conclusion

In this work, a comparison between different Moroccan region climates on shallow basement thermal performance was executed. A three-dimensional numerical study has been conducted to evaluate the heat losses, respectively, in a conditioned basement and the internal air temperature in an unconditioned basement. The objective was to highlight the beneficial effect of the ground inertia on the internal thermal comfort in four different regions of Morocco. The effects of the basement geometry, soil type, and climatic conditions on the thermal behavior of the shallow basement were analyzed.

The heat losses and isothermal lines analysis showed that the heat flux is more significant through the basement walls than its floor and occurred mainly in the walls-floor edges. Consequently, the lost heat flux depends on the area and perimeter of the shallow basement floor. A functional relationship between the annual averaged lost heat flux and the basement floor’s shape, characterized by its area and perimeter, was found.

In an unconditioned semi-buried building, soil inertia plays a major role in maintaining the internal thermal comfort by stabilizing the indoor air temperature to an acceptable level in summer (26°C) and in winter (13.5°C) while the outdoor air temperature fluctuates between a maximum of 43.25°C in summer and a minimum of 2.5°C in winter.

Concerning the effect of soil type, the results indicated that when the thermal diffusivity decreases by about 74% from standard sand to medium sand (ϕ = 0.27%), the shallow basement heating load decreases by up to 40%.

Finally, it was stated that the shallow basement is highly beneficial in semi-arid and arid climates (Marrakech and Errachidia) and less beneficial in the cold climate (Ifrane). Furthermore, our results show that the basement thermal load is dependent on the soil type in temperate climate (Agadir, Tangier, and Fez).

Nomenclature

| Symbol | Description                                      | Unit |
|--------|--------------------------------------------------|------|
| A      | Area of the floor basement                       | m²   |
| a      | Half-length of the shallow basement              | m    |
| b      | Half-width of the shallow basement               | m    |
| c      | Depth of the shallow basement                    | m    |
| Cp     | Thermal capacity                                 | J.kg⁻¹.K⁻¹ |
| dS     | Internal elementary surface of the wall          | m²   |
| e      | Thickness                                        | m    |
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