Impact of Received Solar Radiation on Energy Potential of Ground Integrated Buildings on Slope Terrain

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Abstract: Depending on its local characteristic and other factors as climate conditions and soil thermal properties, the ground may absorb a large part of the solar radiation received by the earth's surface. To a certain depth, the ground can act as an indirect heat energy source since it is able to collect, store and transmit energy. Buildings' thermal performance can benefit from using this indirect solar energy through earth-coupling strategies. EnergyPlus' Basement Auxiliary program is a useful tool for thermal simulation of buildings with direct ground contact. However, input data such as terrain tilt or orientation is not available in this software. This limitation means that the ground heat transfer calculations offered by this program always assume that ground-integrated buildings are placed on horizontal terrains.

Through the use of a mathematical model, the authors explained how undisturbed ground temperatures under a flat terrain are different from those under slope terrain. Consequently, the authors argued that terrain inclination and orientation should be included as parameters for simulations of the ground heat transfer of buildings.

Two elements that Labs' equation uses to calculate ground temperature are solar radiation aspects as the mean annual temperature of the surface of the soil (T_m) and the annual range of the temperature wave at the soil's surface (A_s). In this paper, the authors analysed the impact of using the appropriate solar radiation values for calculating ground thermal potential of slopes, which was done by using the corresponding solar radiation data for Lisbon surface tilts from 0° to 60°, with 5° intervals and with zero Azimuth.

The resulting analysis showed that, as consequence, T_m and A_s values are affected, proving that ground temperatures below slopes are different from those registered under flat terrains. The authors demonstrated that all terrain inclinations provide higher annual ground thermal potential than equivalent flat terrain, and that between flat and sloped terrain an intermediate ground temperature zone is produced. The authors therefore concluded that for this location, 30° to 40° slopes are the best terrain inclination to achieve maximum ground thermal potential.

Keywords: Slope thermal potential; Slope-integrated architecture; Ground temperature; Energy efficiency; EnergyPlus

1. INTRODUCTION

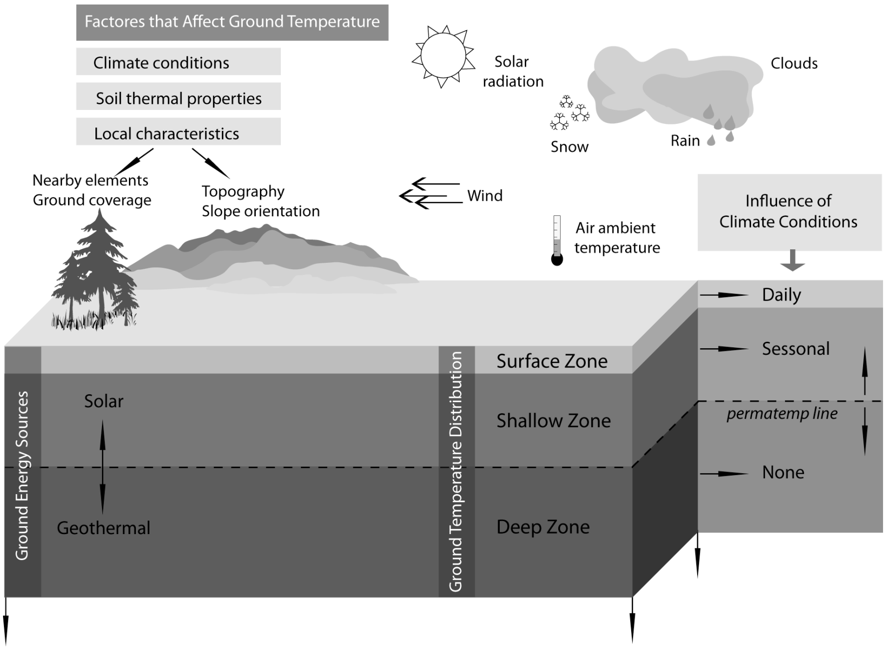

Figure 1: Ground energy sources, ground temperature distribution and factors that affect ground temperature.

The temperature distribution of the ground varies according to depth, and can be divided into three distinct zones: surface, shallow and deep as illustrated in Figure 1. The surface zone is the soil area immediately below the surface where its temperature is affected by daily weather conditions. The immediate influence of these conditions can be found up to soil depths of 0.5 to 1 m. The shallow zone is the soil area where soil temperatures are more stable and mainly affected by seasonal climactic conditions. The extent of this zone depends upon the physical properties of the soil, which can result in shallow zones set between 1 to 8 m below the surface, or which reach depths of up to 20 m. Above the *permatemp line* (Golany, 1980) that divides the shallow zone from the deep zone, the ground temperature is affected by the amount solar radiation received by the surface of the ground. Below the *permatemp line* the average annual ground temperature is similar to the mean annual ambient air temperature (Banks, 2008; Chang, 1958; Golany, 1995; Popiel, Wojtkowiak, & Biernacka, 2001) and is affected by the geothermal heat flux produced by the earth's interior (Banks, 2008; Popiel et al., 2001), making it a renewable energy source that does not depend on the sun (Brown & Garnish, 2004).

The use of ground thermal potential as can be applied to a building's heating and cooling is based on the temperature difference between the ambient air temperature and the ground temperature at a specific depth. Through direct contact with the ground, a large part of the building's structure is able to take advantage of the ground thermal potential. Although the recent increase in interest in ground thermal potential is understood to be a legacy of the Cold War Civil Defence Strategy and of the energy crisis of the 1970s, concerns about land preservation or the limited availability of urban land are currently the strongest motivations for the increasing interest in below-ground spaces. Lack of available land is normally linked to the increasing cost of land, which has been a driving force behind the recent interest in, and studies of underground spaces (Golany, 1995) such as the 're-claim[ing]' of land in Japan through the use of underground rooms (Yoshino, Matsumoto, Nagatomo, & Sakanishi, 1992) and areaways (Bu, Kato, & Takahashi, 2010). Another potential strategy for the reclamation of underground levels for construction is the maximization of the use of slope land. Ground-integrated buildings are considered ideal for sharply inclined sites (Aughenbaugh, 1980; Lee & Shon, 1988; Sterling, Carmody, & Elnicky, 1981). Since flat land often has the richest soils, ideal for agriculture (Sterling et al., 1981), slope-integrated buildings are able to maximize the use of land generally not suitable for agricultural purposes (Golany, 1992). Old hill towns are evidence that the builders of vernacular architecture understood and knew how to take advantage of ground thermal potential and slope microclimates, such as moderate ambient air temperatures and slope air flow. However, this intelligent and sustainable use of land, a common building practice for millennia in several parts of the world, has become an unfamiliar and unusual concept, particularly during the last century.

2. THE EFFECTS OF TOPOGRAPHY ON GROUND TEMPERATURES

There are several different factors that affect below ground temperature, such as soil thermal characteristics, location aspects including topography and slope orientation, and external factors relating to the climactic conditions of the site, such as solar radiation, wind velocity, precipitation values, humidity, ambient air temperature or the presence of snow (Chang, 1958). Topographical aspects such as altitude, slope orientation and steepness have a great effect on air temperature, total solar radiation and wind effects. These factors can affect daily and seasonal air temperature values and patterns and regulate the solar radiation received by the soil (Chang, 1958; Šafanda, 1999), and therefore have great influence on ground temperature (Šafanda, 1999).

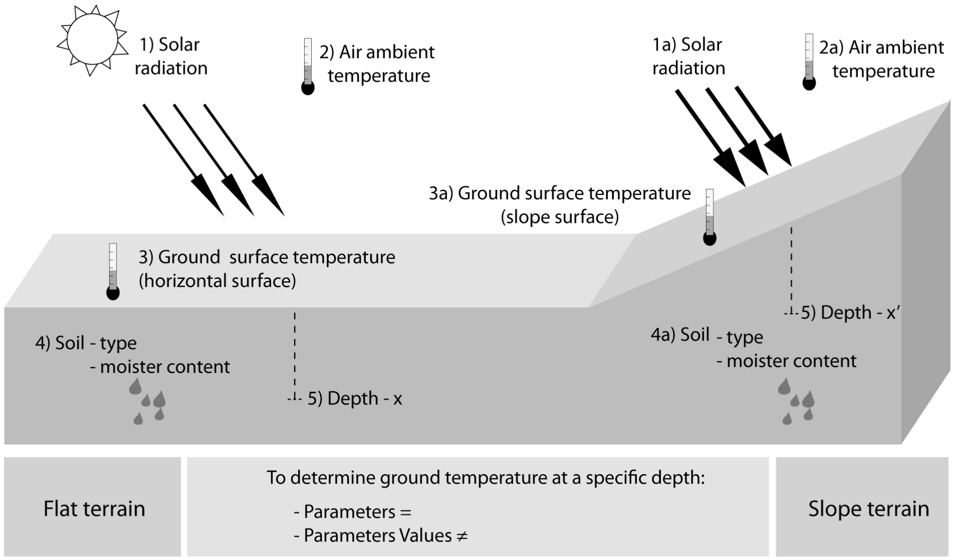

Figure 2: Topography effect on ground temperature.

These factors imply that the underground temperatures of flat and slope terrains are different. However, this has not been considered by building simulation programs such as EnergyPlus. This particular software allows for the simulation of ground heat transfer using the Basement Auxiliar program (Andolsun, Culp, Haberl, & Witte, 2011; Department of Energy, 2012). When basement outside surface temperatures are simulated with this method, the depth of the wall bellow the ground is considered, but the program lacks the ability to include values such as slope degree or orientation. This means that the simulation assumes that the ground integration is on a flat surface. Consequently, the ground temperatures are currently being calculated by applying the amount of solar radiation received by a flat terrain rather than a sloped terrain.

As summarised in Figure 2, flat and sloped terrains share the same parameters needed to calculate ground temperature at a specific depth. These parameters are solar radiation, air temperature, ground surface temperature, soil type, soil moister content and depth. However the values of the parameters for calculating the underground temperatures of a flat and a slope terrain should differ depending on the inclination of the site.

3. RESEARCH METHOD

In this paper, the authors focused on the solar radiation parameter to prove that ground temperatures below flat and slope terrains are different, and therefore prove that the thermal potential of slope terrain is also different. The authors conducted this investigation by calculating the ground temperatures at different depths under flat and slope terrains using the values received at the surface according with its inclination, with all the other parameters remaining unchanged.

3.1. Ground temperature at different depths

The annual ground temperature at different depths can be calculated through Labs' (1979) one-dimensional sinusoidal equation that is expressed in the following Equation 1 and using values from Mihalakakou et al. (1997) Equation 2 and Equation 7.

Equation 1: Ground temperature at different depths. Labs (1979)

$$T_{(x,t)} = T_m - A_s e^{-x\sqrt{\frac{\pi}{365\alpha}}} \cos\left\{\frac{2\pi}{365}\left[t - t_o - \left(\frac{x}{2}\right)\left(\sqrt{\frac{365}{\pi\alpha}}\right)\right]\right\}$$

Where:

- $T_{(x,t)}$ = ground temperature (ºC) at a depth x (m) and time t is the day of the year
- T_m = mean annual temperature of the ground (ºC)
- A_s = annual range of the temperature wave at the soil surface (°C)

- x = depth (m)
- t = day of year (days)
- *to* = phase constant of day with minimum soil surface temperature (days)
- α = soil thermal diffusivity (m^2 per day)

Equation 2: Mean annual temperature of the soil surface. Mihalakakou, et al. (1997)

$$T_m = \frac{1}{h_e}\left[h_r T_{ma} - \varepsilon \Delta R + bS_m - 0.0168 h_{sur} fb(1-r_a)\right]$$

Where:

- T_{ma} = mean air temperature at time $2\pi/w$ (°C);
- ε = emittance of the ground surface;
- ΔR = value dependent on humidity values of air over ground surface, sky temperature and soil radiative characteristics
- b = coefficient of ground surface absorptivity and illumination
- S_m = mean annual solar energy at the ground surface (W/m^2)
- h_{sur} = soil surface convective heat transfer coefficient (W/m^2K)
- f = fraction determined by ground cover and ground moisture content
- r_a = relative humidity of the air above the ground surface

Total illuminated ground surface is traduced by the following equation

Equation 3: coefficient of ground surface absorptivity and illumination

$$b = 1 - albedo$$

Fraction *f* can be calculated for bare or grass covered soils. The fraction at bare soils increases with the soil moisture content (wet soil f=1; humid soil f = 0.6-0.8; dry soil f = 0.4-0.5; arid soil f=0.l-0.2). The fraction at grass covered is estimated by multiplying a coefficient of 0.70 with the above bare soils fraction values.

The h_e and h_r values can be calculated using Equation 4 and Equation 5.

Equation 4: Mihalakakou, et al. (1997)

$$h_e = h_{sur}(1 + 0.0168af)$$

Equation 5: Mihalakakou, et al. (1997)

$$h_r = h_{sur}(1 + 0.0168ar_a f)$$

Where *a* is equal to 103.00 (Pa K-1).

Equation 6: Soil surface convective heat transfer coefficient (W/m^2K). Szokolay (2014)

$$h_{sur} = 5.8 + 4.1 \times u$$

Where *u* is the wind flow.

Equation 7: Annual range of the temperature wave at the soil surface. Mihalakakou, et al. (1997)

$$A_s = [h_r A_{sa} - bS_a \exp(i\varphi_1 - \varphi_a)]/(h_e + K_s)$$

Where:

- A_{sa} = amplitude of air temperature wave at $2\pi/w$ (°C)
- S_a = amplitude of solar radiation wave (W/m^2)
- φ_1 = phase constant (rad)
- φ_a = phase constant (rad)
- K_s = ground thermal conductivity (W/mK)

3.2. Ground temperature at different depths according with slope

The two elements that form Equation 1 ($T_{(x,t)}$), require solar radiation values. These values are the mean annual temperature of the soil surface (T_m) and the annual range of the temperature wave at the soil surface (A_s). The corresponding equation for T_m is Equation 2 and for A_s is Equation 7. The T_m equation allows for the changing of the mean annual solar radiation on the ground surface (S_m) value according with its inclination, while with the A_s equation, the annual amplitude of the solar radiation wave (S_a) value can also be changed according with the slope studied. Based on these equations, the ground temperatures in Lisbon were calculated using the corresponding T_m and A_s for tilt surfaces from 0° to 60° with 10° intervals. The T_m and A_s were found using the corresponding S_m and S_a values for each slope. These values were based on the monthly data retrieved from the online Photovoltaic Geographical information system - interactive maps (JRC) and are display in Table 1.

Table 1: Mean annual solar radiation and amplitude of the solar radiation wave at Lisbon for different slope terrains

	00°	05°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°
S_m	388.14	404.79	419.46	431.95	441.88	449.14	453.75	455.93	454.91	451.11	444.72	435.47	423.36
S_a	349.29	328.86	307.77	291.15	272.46	252.69	231.08	207.38	187.33	172.17	156.67	139.83	136.67

The remaining inputs used in the calculations are displayed in Table 2, with their values based on monthly weather data retrieved from the weather file PRT_Lisboa.085360_INETI.epw, which is produced using public data published by the Instituto de Meteorologia and distributed by EnergyPlus. The thermal properties of the soil, such as conductivity and thermal diffusivity, correspond to the median range values for limestone provided by ASHRAE (2011).

Table 2: Input values - ground temperature calculation at Lisbon

Mean air temp, °C	T_{ma}	16.29	Value dependent of humidity and air, W/m^2	Δr	63.00
Amplitude of air temp wave, °C	A_{sa}	12.00	Pa K-1	a	103.00
Phase constant, rad	φ_a	0.10	Emittance, 0 to 1	ε	0.93
Phase constant, rad	φ_1	0.28	Wind, m/s	u	4.99
Ground thermal conductivity, W/(m K)	K_s	3.1	Relative humidity,	ra	0.68
Soil thermal diffusivity, m^2/day	α	0.107	Soil absorptivity and illuminance	b	0.75
Phase constant soil surf - Day with min. soil temp, Day	t_0	40	Fraction of the soil, 0 to 1	f	0.50

4. RESULTS AND DISCUSSION

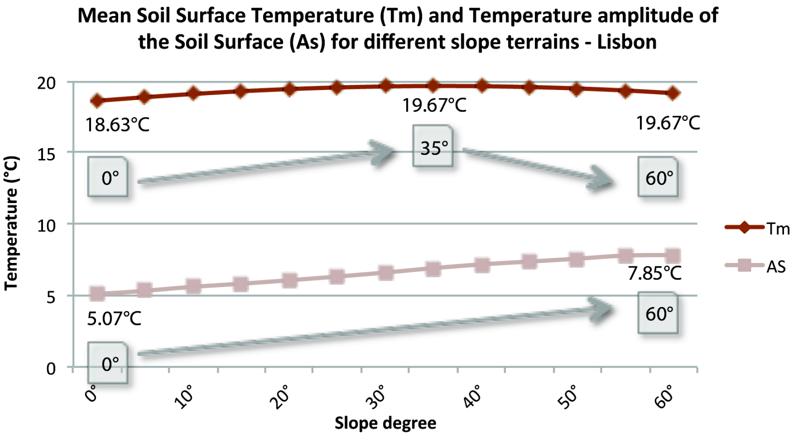

Figure 3: T_m and A_s according with slopes - Lisbon

The authors found that by changing the received mean annual solar radiation values (S_m) according with the slope, it is produced different mean soil surface temperatures (T_m). As illustrated in Figure 3, the T_m value increase from a 0° to a 35° slope, with a total range of 1.04°C, and decreases from a 35° to a 60° slope. It is also evident that the T_m value for a 15° slope is higher than for a 60° slope.

Regarding the temperature amplitude of the soil surface (A_s), the authors observed that these values are also affected by the terrain inclination. As can be seen in Figure 3 and Figure 4, by using the correspondent annual amplitude of the solar radiation wave (S_a) the A_s values increase with the steepness of the slope. The total A_s value range produced is of 2.77°C, from a 0° slope with 5.07°C to a 60° slope with 7.85°C. It should be pointed out that the steeper slopes, such as 55° and 60°, have a small difference in amplitude between then. As a result of these findings, the authors have proved that by using the corresponding mean annual solar radiation (S_m) and temperature amplitude of the soil surface (A_s), the inclination of the terrain affects both T_m and A_s values and, consequently, affects ground temperature calculations.

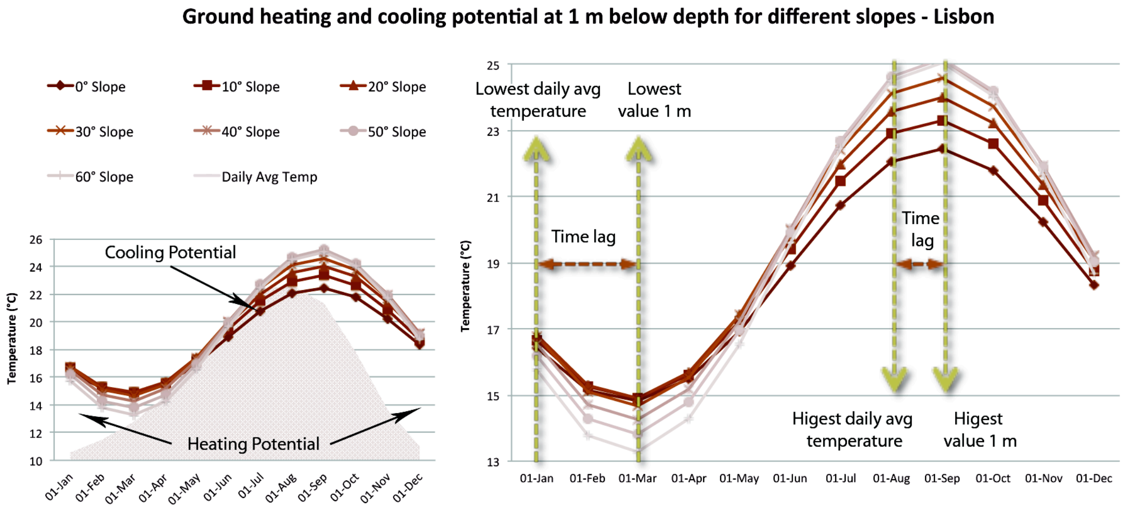

Figure 4: Ground heating and cooling potential for different depths, Lisbon – 1 m depth

The impact of using the T_m and A_s values in accordance with slope inclination on ground temperatures at a depth of 1 m can be seen in Figure 4. This graph shows that, for the same location, different slopes produce different ground temperatures values during the year, which demonstrates that ground temperature calculations need to use the appropriate solar values according with terrain inclination. Regarding the ground thermal potential, the display values show a considerable heating potential from October until March but also that the cooling potential is limited to July. This limitation exists because most slopes produce temperature values higher than the daily average temperature. During January, slopes of 20° and 30° produce the best results. In April a 20° slope is the best inclination, in July a 0° slope produces the best values and in October a 50° slope produces the best temperatures, the latter closely followed by a 40° slope. Overall, at this depth, the best annual temperatures, and therefore the greatest ground thermal potential, is provided by slopes of between 20° to 40°. Concerning the time lag, the authors found that in winter it is of around two months and in summer of one month.

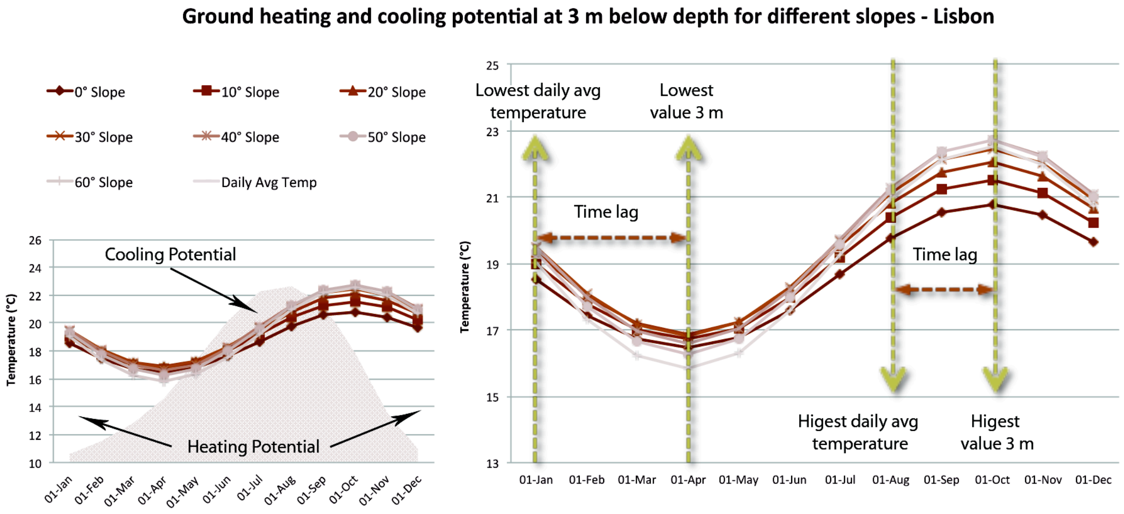

Figure 5: Ground heating and cooling potential for different depths, Lisbon – 3 m depth

Examining the values presented in Figure 5, it is clear that at a depth of 3m all terrain inclinations have a good ground heating and cooling potential. At this depth, the temperature gap between the inclinations is reduced. During January the best slopes are of 30° and 40°, in April 20°, in July 0° and in October the best slope is of 50°. The best average annual temperatures are provided by slopes of between 30° to 40°. The time lag at the coldest period is around three months, while the warmer ground temperatures are felt during October, that is, two months after the heat peak of the outside air temperature.

Sloped terrains produce different ground temperature patterns than flat terrains. These patterns are verified by comparing the ground temperature at 3 m depth below a flat terrain, against the location where the same temperature is found under different slope terrains. This verification is done for single days at the beginning of January, April, July and October and the ground temperatures are display with vertical sections.

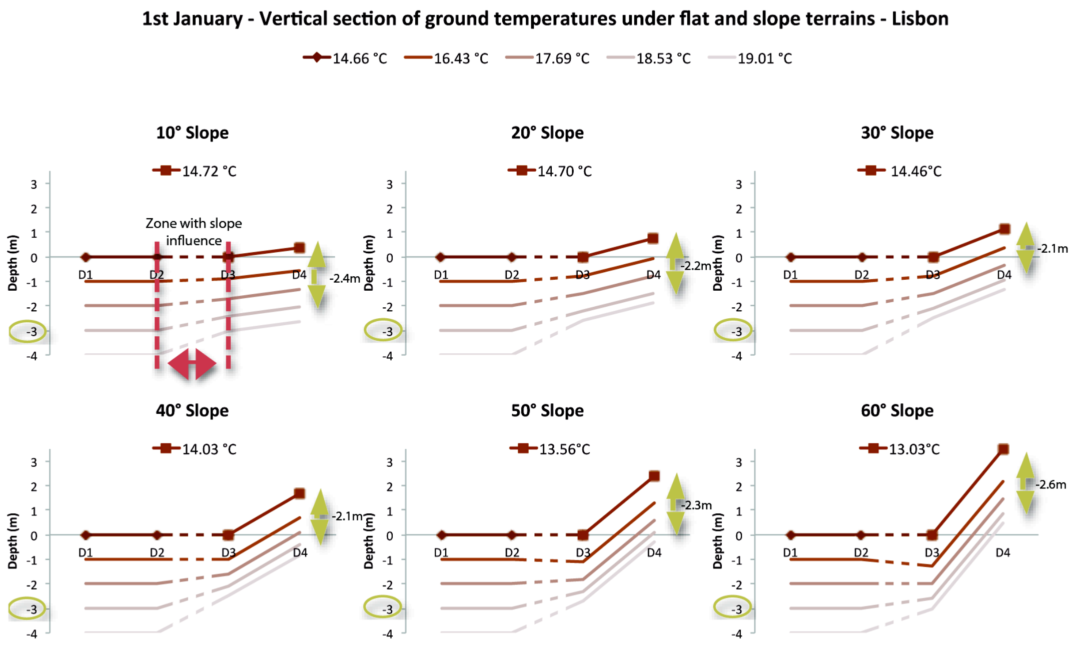

Figure 6: Ground temperature comparison between flat and slope terrains, Lisbon – 1st January

At the beginning of January a warm ground temperature of 18.53°C can be found below a flat surface at 3 m depth. Following the same temperature value, it can be seen in Figure 6 that the distance of this measurement from the surface changes with the angle of the slope. On this winter day the warmest values are closer to the ground surface below all slopes. With a 10° slope the 18.53°C is found at 2.4 m depth and it reaches its lowest depth of 2.1 m in 30° and 40° slopes. This is an indication that at this depth, all slope terrains provide better ground temperatures than a flat terrain, and that the best ground heating potential is produced with slopes between 30° and 40°. With this comparison it also becomes clear that an intermediate zone is produced between a flat and a slope area, and the slope affects the ground temperatures in this intermediate zone. Therefore ground integrated buildings in, as well as near, slope terrains can benefit from higher ground thermal potential during winter.

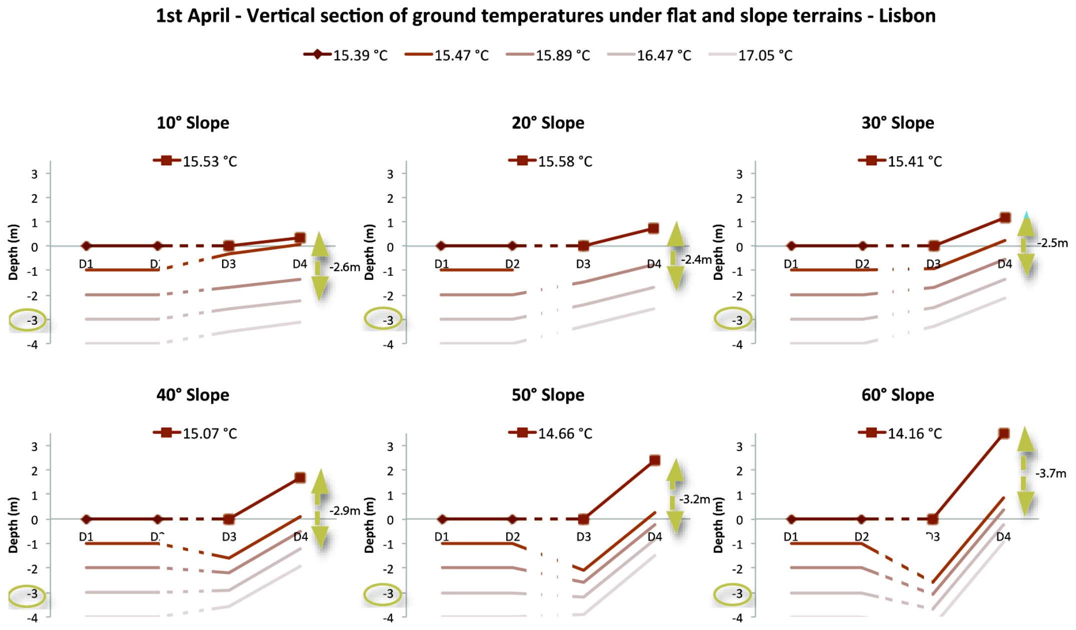

Figure.7: Ground temperature comparison between flat and slope terrains, Lisbon – 1st April

In Figure 7 it can be seen that during early spring the ground has released a great part of its energy. During this period, although the surface temperatures are warmer than their winter values, all other ground temperatures up to 4 m depth have reached their annual lowest values. As a result, slopes from 10° to 40° are able to provide better ground temperature values than a flat terrain. The 16.47°C value registers at 3 m below the flat surface moves closer to the surface below a 10° to 40° slope. Its proximity to the surface is greatest under a 20° slope where this value is located at a depth of 2.4 m. It is also confirmed that slopes higher than 50° produce worse ground temperatures, since the 16.47°C only appears at depths below 3 m. Therefore it is concluded that, in this period, slopes between 10° to 40° can increase ground heating potential and the greatest ground thermal potential is provide by a 20° slope. Slopes greater than 50° have less ground heating potential than flat terrain.

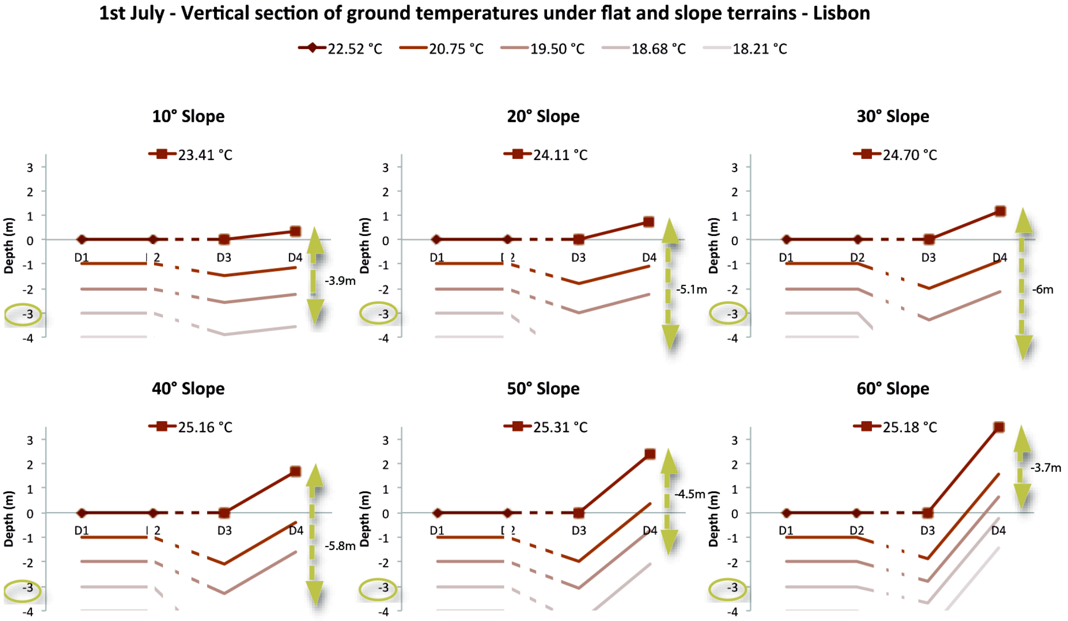

Figure 8: Ground temperature comparison between flat and slope terrains, Lisbon – 1st July

When looking at the position of ground temperature below flat and inclined areas in the beginning of July (see Figure 8), it is clear that all slopes produce higher ground temperature values than flat terrain. The temperature value of 18.68°C was registered at a depth of 3 m below a flat terrain, but appears at 3.9 m below a 10° slope, and the maximum depth for this temperature value is found under a 30° slope, where it only appears at 6 m below the surface. Although this shows that the ground cooling potential of a slope area is reduced when compared with a flat terrain, it also indicates that the annual heating potential at any slope will be greater, since during this period the ground instead bring charged with heat energy.

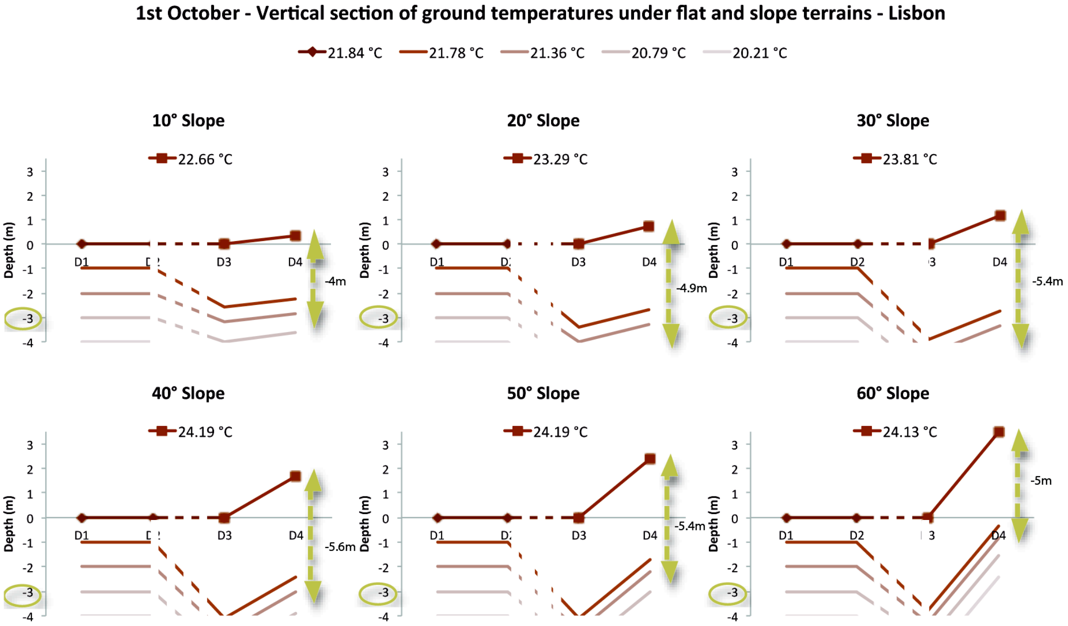

Figure 9: Ground temperature comparison between flat and slope terrains, Lisbon – 1st October

As a consequence of this heat charging observed during the summer, it is evident from Figure 9 how the ground has stored the solar energy it receives by the 1st of October and become totally charged. At the beginning of the autumn, all slope terrains have higher heating potential that a flat terrain. The 20.79°C ground temperature value found at 3 m below a flat area appears further below all slopes. Inclinations between 30° to 50° have good thermal potential, and 40° is the optimum slope during this period.

5. CONCLUSIONS

In this paper, the authors have shown that slopes affect the ground temperature by calculating the ground temperatures in Lisbon using the corresponding solar radiation values for each tilted surface. For each tilted surfaces the appropriate S_m and S_a values were used. As a consequence, the results analysis shows that T_m and A_s values are affected by terrain inclination. This relationship between slope inclination and S_m, S_a, T_m and A_s values proves that ground temperatures below slopes are different from those registered under flat terrains, demonstrating that ground temperature calculations should take the inclination of the terrain into consideration. Therefore, software packages for building thermal simulations should include terrain inclination and orientation as input parameters for calculating ground heat transfer. Between all slopes studied, altering the S_m values according with slope angle will generate a T_m result range of 1.04°C. This value increases in slopes from 0° to 35° and decreases in 35° to 60° slopes. Whereas, by altering the S_s values it is found that the A_s value range increased by up to 2.77°C: the value for a 0° slope is 5.07°C and for a 60° slope is 7.85°C, thus the higher the tilt, the greater the A_s value.

In this investigation it is found that, in Lisbon, all terrain inclinations produce higher annual ground thermal potentials than flat terrains. Regarding the seasonal behaviour, for a depth of 3 m, a 30° to 40° slope provide better temperatures at winter, spring and autumn than the other slopes studied. These are the seasonal periods when the most energy is required. For summer, both slopes provide greater temperatures than lower slopes as 0°, 10° and 20°. However this season corresponds to the annual period with lower energy needs and, therefore, any form of ground integration is an advantage. This makes 30° to 40° slopes the best angles to maximise the annual ground thermal potential. It is also observed that time lag was increased with depth, as at 1 m the coldest ground temperature values are registered two months after the outside cooling peak, while at 3 m the difference is increased to three months.

The authors demonstrated that slopes terrains produce different ground temperature patterns than flat terrains. And, furthermore, that between a flat and a slope area, an intermediate zone is produced since the slope affects are not limited to the sloped area itself. At the beginning of January, it was found that the ground temperature value at 3 m below a flat terrain appears closer to the surface under all slopes. This finding proves that in this period all slopes have higher ground heating potential than a flat terrain. It was below 30° and 40° slopes that the observed temperature values reached their deepest depth of 2.1 m. In early spring, the ground temperature value at 3 m under a flat terrain is visibly closer to the surface than those temperatures measured beneath a 10° to 40° slope, which shows that these slopes produce the best ground thermal potential. During July, all slopes produce greater ground temperature when compared with flat terrain. This indicates that the flat terrain has higher ground cooling capacity but also shows that these sloped terrains are in charging mode, which means that their heating potential during autumn and winter is greater. During early October the optimum slope is found to be 40°. Overall it is concluded that the best annual ground thermal potential is provide by slopes between 30° and 40°.

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