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Computational Evaluation of the Thermal Performance of Underground Bunkers: The Case of Albania

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ABSTRACT

The present paper studies the thermal and energy performance and potential adaptive reuse of the lost underground bunkers of Kukës, Albania. The approach is exemplified using a 150-m long cross-section of the underground network selected for the parametric computational simulations. Data regarding local climate, design typology, and building materials is used to generate a finite-element simulation model of the underground tunnels. Different scenarios including insulation of the outer walls, occupancy patterns, and ventilation regimes are tested. The results show that indoor air temperature ranges from 15-18°C during winter and 23- 28°C during summer. During January, the temperatures are higher by 3-5 °C in comparison to the same structure and scenarios located above ground, whilst during July they are 5-8 °C lower. Insulation does not affect the heat flux through the outer walls. The average energy consumption oscillates around 55 KWh.m^{-2}.a^{-1} for base case and 98-230 KWh.m^{-2}.a^{-1} for design scenarios. The results establish the same building consumes 44-145% more energy when located above ground as opposed to underground.

KEYWORDS

Thermal performance simulation, scenarios, energy, underground nuclear bunker, adaptive reuse

INTRODUCTION

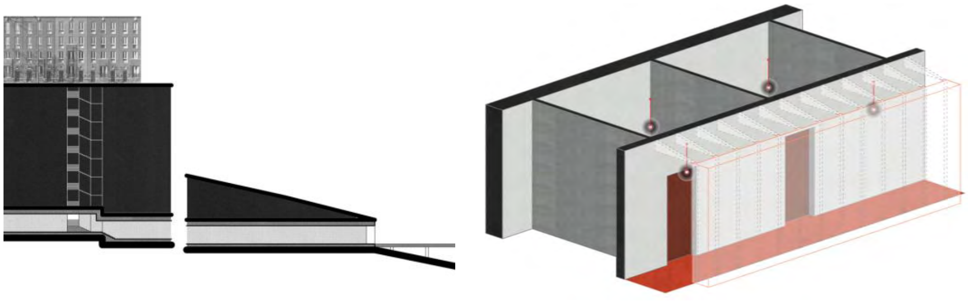

a) b)

Figure 1. a) Partial section of the underground network of tunnels for Kukës, b) Close-up partial axonometric drawing of the inner construction of the tunnels.

Whilst above ground thermal comfort can be reached only via additional services, earth sheltered buildings are known for their temperature stability (Kajtar et al. 2015) and they gain benefit from the soil's quasi-stationary temperature to achieve energy conservation (Alkaff et al. 2016). Because of the high thermal inertia of the soil, the temperature fluctuations at the surface of the ground are diminished as the depth of the ground increases (Florides and Kalogirou, 2005): the temperature of the soil changes with amplitude of 0.6 °C in the depth of 8 m and 0.2 °C in the depth of 10 m (Kajtar et al. 2015). After the depth reaches more than 20 m, the temperature becomes practically constant (Popiel et al. 2001). Popiel has concluded with the formula shown in Equation 1, where x is the depth below the ground surface, T is the temperature, k is the heat conductivity of the ground, and q the heat flux, that the heat flux of the soil is practically constant (2001). Florides depicts that due to the solar radiation and soil's relative capacity there is a 5-hour time lag a day regarding temperature distribution (2005). This explains why after reaching a specific depth the soil's temperature is always higher than the air temperature during winter and lower during summer.

$$q = -k\frac{\partial T}{\partial x} \qquad (1)\ \text{(Popiel et al. 2001)}$$

This knowledge has been practiced since ancient times: Samos, Greece, Cappadoccia in Turkey, and the Hypogeum belong to the 6th century BC, 1900-1200 BC, and 4000 BC respectively (Nývlt et al. 2016; Debertolis et al. 2015). Living underground has become today a widely spread trend in countries such as China, Japan, and Korea where residents find comfort from the increasingly high economic pressure of living in apartments. In these countries, underground urban planning is a field study of its own (Zhao et al. 2016; Li et al. 2016) and some insist it should be an integral part of any National Regulation Plan (Tan et al., 2018). The studies on the computational evaluation of either thermal or energy performance for such spaces are fewer in number. Zhu has carried out thermal simulations on a sample of atrium plan earth sheltered buildings concluding that the buildings constitute a step forward towards low energy building design (Zhu and Tong, 2017). Another thermal performance simulation and evaluation study has been carried out by Ip, but the building in question has only one wall in contact with the earth (Ip and Miller, 2009). Tan has investigated the thermal comfort conditions in underground spaces in four major Chinese cities characterized by different climate conditions in order to assess the influence of the specific climatic variables (Tan et al. 2018). Tan however also recognizes his study as only qualitative and evaluates a building energy modeling would provide more solid data since qualitative analyzes often depend on real life restrictions (Tan et al. 2018).

In Albania, a special kind of underground shelters can be observed: nuclear bunker tunnels. A similar design typology is the subway, but it differs in many ways such as scenario, and traffic network which greatly influence the thermal and energy performance of the construction. The tunnels of Kukës are part of the ex-secret military establishments of Albania. This network is 2400 m long and composed of 30 galleries. Each gallery is composed of a corridor with a row of rooms on one side; an outer concrete shell envelops rooms and corridors, whilst the indoor walls were built with bricks. The tunnels have corridors which are 270 cm high and 120 cm wide, and rooms of an average of 3.4x3.4m. The network is located from 319 m to 336 m above the sea level (the different levels are connected by staircases), whilst the ground level of the city of Kukës is located 350 m above the sea level (Poliba, 2017; Municipality of Kukës, 1973). The outer walls of the tunnels are composed of 40 cm thick reinforced concrete. The inner walls are composed of bricks and amount to 27 cm thickness. These capillaries, which were constructed in several cities during the communist period and never used to fulfill the purpose for which they were built (refuge in case of war), constitute a large underground network of concrete leftover space. Therefore, the question on the efficiency with which they can fulfill their original purpose i.e. that of sheltering, comes out naturally. This study assesses the thermal performance and evaluates the adaptive reuse efficiency of the underground shelters via computational simulation modelling using the case study of the tunnel network found in the city of Kukës as a starting point. Whereas previous studies have provided significant insight on different topics related to underground structures, there is a lack of quantitative studies providing close examination of thermal performance and energy consumption evaluation. Thermal and energy performance evaluation has not been explored yet on this typology of shelter in Albania or elsewhere, and the number of similar studies worldwide is limited. Furthermore, this paper suggests and tests alternatives for low energy consumption adaptive reuse functions appropriate for the design typology, and space quality of the tunnels.

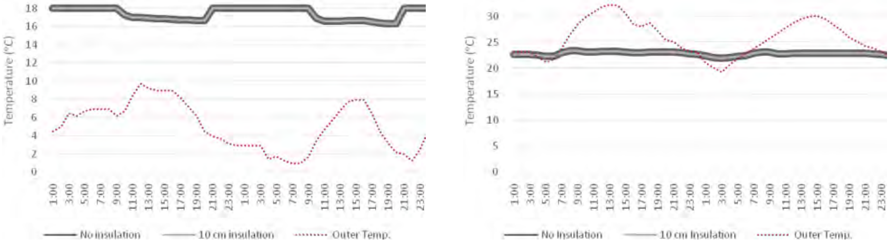
METHODS

Initial simulation models were generated based on collected geometry and construction data. Assumptions were made based on in situ observations and historical documents. The simulations are conducted with Design Builder, a software tool used to perform building energy, lighting, and comfort performance. The software has been developed to simplify the process of building, modelling, and simulation for maximum productivity allowing users to rapidly compare the function and performance of building designs, different scenarios, and deliver results quickly. Meteonorm software was used to generate the local weather file for the city of Kukës. A 150 m tunnel section that serves as an extension of the existing hospital of the city, directly connected to it by its basement, is used for the simulations. A digital performance simulation model of the underground tunnel section is generated including the modelling, occupancy patterns, air humidity, and ventilation regimes. A set of five sample scenarios are established for the parametric study. The first scenario (S1) corresponds to the existing conditions. A second scenario (S2) is defined involving thermal insulation. Three additional scenarios (S3-S5) address the thermal performance of different potential reuse activities: laboratory (S3), hospital (S4), and museum (S5). Two simultaneous sets of simulations for scenarios S3-S5 are conducted to verify energy reduction potential of underground buildings with comparison to above ground buildings: S3-S5 when the building is located at 325 m above the sea level (the actual level of the tunnels), and S3.2-S5.2 when the building is located at 350 m above the sea level (the level of the city). Table 1 illustrates the data on scenarios S3-S5 and S3.2-S5.2. The thermal transmittance of the materials is as follows: 0.27, and 0.29 for inner and outer walls respectively, whilst without insulation these values are 1.42, and 2.31.

Table 1. Data pertaining to chosen scenarios for the study of activity impact on the underground tunnels' thermal load.

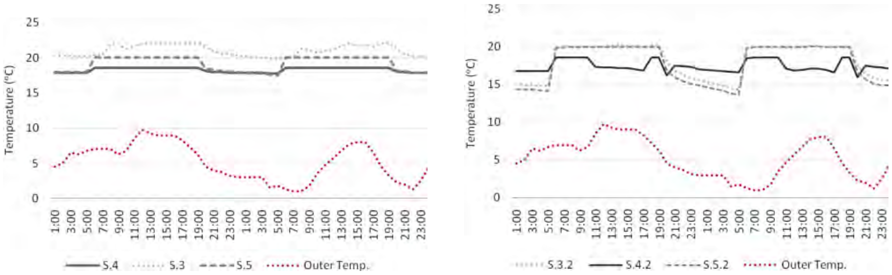
Code	Activity	Schedule	Density (people/m²)	Gain (W/m²)	Radiant fraction	Heating (20°C)	Cooling (20°C)
S3; S3.2	Laboratory	12/24 h	0.11	8.73	0.2	20	23
S4; S4.2	Hospital	24/24 h	0.10	3.58	0.2	18	25
S5; S5.2	Museum	varying	0.15	3.50	0.2	20	24

RESULTS



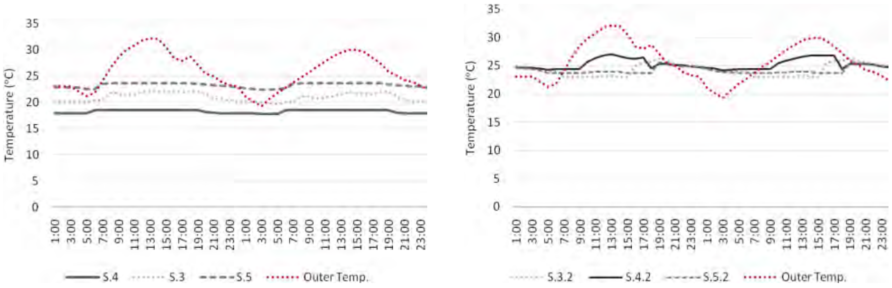
a) b)

Figure 2. Simulated indoor temperatures (whole building) for S1 (base case without insulation) and S2 (base case with insulation) together with the external temperature data from the weather file. a) 15th and 16th of January, 2016, b) 15th and 16th of July, 2016.



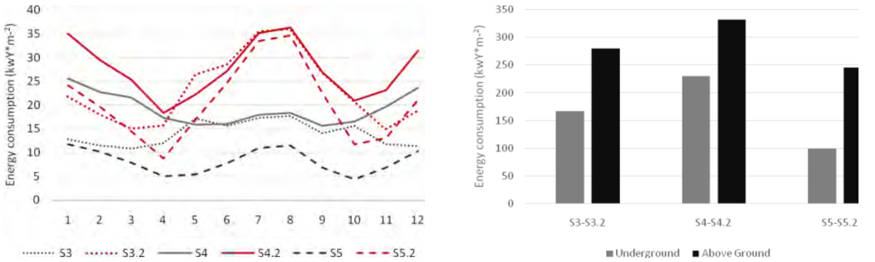
a) b)

Figure 3. Comparison of the simulated indoor temperatures (whole building) of the scenarios together with the external temperature data from the weather file for the 15th and 16th of January, 2016, a) S3-S5 (underground), b) S3.2-S5.2 (above ground).



a) b)

Figure 4. Comparison of the simulated indoor temperatures (whole building) of the scenarios together with the external temperature data from the weather file for the 15th and 16th of July, 2016, a) S3-S5 (underground), b) S3.2-S5.2 (above ground).



a) b)

Figure 5. a) Comparison of simulated monthly energy demand (kWh.m^{-2}) for S3-S5 and S3.2-S5.2, b) Simulated annual energy demand (kWh.m^{-2}.a^{-1}) for S1-S5.

Figure 2 illustrates the thermal performance of base case scenarios with and without insulation, S1-S2. Figures 3 and 4 provide an overview of the thermal performance in the selected scenarios (S3-S5; S3.2-S5.2) based on two reference days in January and July. Figure

5 summarizes comparative information regarding undergrounds' monthly energy use for the selected activities (S3-S5; S3.2-S5.2), as well as yearly overall energy consumption for S1-S5.

DISCUSSIONS

After comparing the theoretical background presented in the *Introduction* section and the results from the graphs in the *Results* section, conclusions are as follows:

i. The theoretical background assesses the heat flux of the soil in the depth where the tunnels are located, 25 m underground, is almost constant and allows the spaces enveloped in it to remain cool during summer and warm during winter. This fact is proven by the graphs shown in Figure 2 where the graph lines for 10 cm and no thermal insulation temperature performance are overlapping, thus demonstrating the effect of thermal insulation on the thermal performance of the building is negligible. During January, the time lag phenomenon described in the *Introduction* can be observed: the temperature alternates between the earth and the ground, when above ground the temperatures are high, they are lower underground and vice versa. The time lag is of approximately 10 hours. However, this phenomenon cannot be observed during July because the temperatures are constantly high and do not vary.

ii. Figures 3a and 4a compare the temperature performance of scenarios S3-S5 during two days in January and July. During January, all temperatures show an increment during the day, and cooling down after 18:00. The hospital's temperatures are more constant and 2-3^{o}C lower. The laboratory's and museum's temperatures vary considerably during the 12/24 hours of activity, most likely due to the nature of the activities held which require more physical interaction and movement from the people involved. During July, the temperature variation lines are considerably more constant and closer in value to one another. The average temperatures during July are 23.1^{o}C, 24.2^{o}C, and 23.3^{o}C for S3, S4, and S5 respectively. The average temperatures during January are 21^{o}C, 18.3^{o}C, and 19.1^{o}C for S3, S4, and S5 respectively. Figures 3b and 4b compare the temperature performance of the activity scenarios when located above ground: S3.2-S5.2. During January, the temperatures are lower by 3-5^{o}C in comparison to the same scenarios located underground, whilst during July they are 5-8^{o}C higher.

iii. The performance of the three scenarios regarding energy consumption varies. The average energy consumption per month is 14, 19.2, and 8.24 kWh m-2.a-1 for S3, S4, and S5 respectively. Regarding yearly energy consumption, the hospital's energy consumption results are 38% higher than the laboratory's, and 135% higher than the museum's. The results establish the same building consumes 44-145% more energy when located above ground as opposed to underground.

CONCLUSIONS

The case study of underground shelters poses an invitation for different research topics, however, the majority of information on them is provided by theoretical or qualitative studies. This paper is preoccupied with providing quantitative data on underground spaces, specifically nuclear shelters situated in the city of Kukës, Albania. The focus is on indoor thermal performance and energy consumption evaluation conducted via simulation software in order to assess the feasibility of adaptive reuse. Using the example of thermal simulation of a tunnel section, we explore the process and the recent results from the data collection. Hence, a building simulation model can be applied toward the assessment of the buildings' performance and prediction of the consequences of alternative options for its renovation, reuse, and adaptation. Different scenarios are tested in order to assess the thermal performance of adaptive reuse alternatives for activities of 12/24 h, 24/24 h, and indefinite occupancy hours such as laboratories, hospital extensions, and museums respectively. The study concludes that a preferable scenario for adaptive reuse would be an activity held only 12/24 h, resulting in less energy consumption. In the present specific case, the 150 m section rooms can be proficiently repurposed as laboratory sectors that could serve to the hospital situated above ground. Although simulation and evaluation through software may face limitations due to the inability to make comparison with real life situations, the study represents an effective and well documented first step towards energy efficiency and possible adaptive reuse of abandoned underground or earth sheltered bunkers.

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