Earth-sheltering effect on dwelling in cold climate: simulation-based and theoretical approaches

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Abstract. A number of equal but variously submerged samples of a detached residential building are assessed with the intention to trace an impact of earth-sheltering on the building energy conservation ability under cold climatic conditions. Passive House Planning Package (PHPP) is used to carry out this. Additionally, an assessment of the building thermal comfort and profitability is performed when considering two contrasted samples of it – non-deepened and deepened as much as possible. The study results support the basic understanding of earth-sheltering expediency as a type of sustainable construction and show that maximal use of earth as an additional insulating layer provides 44.4% less heat requirements (compared with the non-deepened sample). Moreover, earth-sheltering measures are able to reduce a form factor impact on energy loss by 50%. Their cost, as the study reveals, can be compensated by means of investing the saved energy expenditures for less than 20 years. Lastly, earthen insulation assists to rise an operative temperature inside the building by 0.3oC.

1. Introduction
The use of one of the most ancient ways of maintaining comfortable temperature inside dwellings consisting in adaptation natural environment – relief and landscape features – as additional protection is not already limited with creating refuges against bad weather by now. One can follow how the role of natural environment evolved out of human primitive shelters – a group of trees, ravines, earth-houses – into means to increase energy savings in buildings by specially arranged ground and vegetation around them [1]. In particular, thermal protection with earth as an established principle for both reducing energy consumption and slowing down the temperature variations inside buildings [2;3] now conforms well to the intention to meet the Passivhaus standard [4]. The latter demonstrates ability of modern earth-sheltered buildings (in contrast with earlier ones) to provide sufficient level of solar gains to light and heat the habitable underground space, which is crucial for passive houses [5]. Next, it is stated earth-sheltered buildings turned out to be cost efficient, especially in climatic zones with wide air temperature span and low humidity [6]. Taking into consideration the foregoing evidence, this study deals with examining the efficiency of earth-sheltered buildings designed in accordance with Passivhaus principles under climatic and economic conditions of the South Ural region. Such buildings have not been tested here consistently, although local natural conditions inspire their active installation into the construction practice. Thus, the purpose of the study is to assess a virtual model of a climatically localized earth-sheltered building in terms of energy efficiency, thermal comfort and profitability.
2. Materials and methods
The building modelled and estimated is a detached one-storied single-family house on inclined relief, typical for most settlements about the South Ural Mountains, with 94 m² of heated area (table 1). The building is placed on the south slope, taking into account the maximum solar radiation. Four possible variants of the building contact with ground in terms of the share of submerged constructions area are generated: 0% (a structure on pillars), 26%, 36%, 86% of earth-sheltering (figure 1, a – e).

Generalized data on temperatures and solar radiation endemic to settlements of mountainous zone of the South Ural region is used for the calculation [7]. The local climate is defined as gently continental with damp microclimate zones within hollows. The average air temperatures are for the coldest month – January – -15.7 °C, for the warmest month – July – 18.1 °C. Minimum air temperature that is taken into the calculations is -30.9 °C. Height above sea level is 540 m. Minimum solar radiation is observed in December that is 19 kWh/(m²-month), the largest – in June is 174 kWh/(m²-month).

As a rule, folds of the relief around the mountain ridges form hills, which due to slightly sloping (10° – 18°) are suitable for housing development. The average heat capacity and thermal conductivity of the soils with predominance of loams and clays in their composition are 3 MJ/m³K and 3 W/(mK), respectively. The range of monthly ground temperatures to compute heat transfer coefficients of the constructions is represented in table 2; as seen, there are very small seasonal temperature fluctuations at the deepest ground level below the floor plate.

Consisting in balancing loss through structures/ventilation and gains from the sun/inner sources the principal energy modelling method allows to determine the energy amount necessary for space heating. This amount shows a degree of the building effectiveness as a part of the heat losses uncovered by heat gains [8]. The method is implemented by means of Passive House Planning Package – a stationary simulation program verified by measurements – where the variants are consistently modeled [9].

Thermal comfort for the building indoor space is generally estimated as an average value between the sums of the interior surfaces radiation temperatures and the internal air temperature [10]. Profitableness of the thermal protection measures is considered as an investment plan: the earth-sheltering measures cost is compared with incomings from reducing the heating energy costs invested in a bank [11]. As a part of the profitability assessment, an impact of the building compactness on energy expenditures is weighed under 0% and 86% of the building envelope submerged area through the building modelling with a number of form factor values.

Table 1. Specification of the building modelled.

| Construction/system | Elements/characteristics |
|---------------------|--------------------------|
| Floor plate         | 1) 25 mm of wooden board, 2) 220 mm of concrete-slab, 3) 400 mm of cellular polystyrene; U-value – 0.10 W/(m²K); area – 125 m² |
| Walls               | 1) 20 mm of interior plaster, 2) 270 mm of concrete wall, 3) 300 mm of cellular polystyrene, 4) surface water proofer; U-value – 0.13 W/(m²K); total area – 191.7 m² |
| Roof                | 1) 13 mm of plywood, 2) 200 mm of concrete-slab, 3) 300 mm of mineral wool, 4) 6 mm of roofing cooper; U-value – 0.14 W/(m²K); area – 130 m² |
| Windows             | plastic framed (U-value – 1.60 W/(m²K)) double glazed (U-value – 2.0 W/(m²K)) with g-value of 0.7; total area – 32.6 m² |
| Ventilation, heating and hot water systems | mechanical ventilation heat recovery system with 74% efficiency; wood burning boiler to heat the room and hot water |
| Indoor temperature and internal heat sources | 20 °C; 2.7 W/m² |
Figure 1. a – general view; b – non-deepened (0%); c – deepened foundation (26%); d – deepened foundation and northern front (36%); e – deepened, except the entrance and south front (86%).

Table 2. Monthly distributed ground temperatures (°C) below the foundation depending on depths of submerging and the earth volume around/on the building (according to PHPP).

| Variants of earth-sheltering1 | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|------------------------------|----|----|----|----|----|----|----|----|----|----|----|
| 0%                           | -9.9 | -14.0 | -13.8 | -9.3 | -1.8 | 6.9 | 14.2 | 18.4 | 18.1 | 13.7 | 6.1 | -2.5 |
| 26%, 36%                     | -0.8 | -2.4 | -2.3 | -0.6 | 2.3 | 6.1 | 8.9 | 10.5 | 9.9 | 8.2 | 5.3 | 2.0 |
| 86%                          | 2.0 | 1.0 | 1.1 | 2.2 | 4.7 | 7.4 | 9.4 | 10.4 | 9.5 | 8.2 | 6.2 | 4.0 |

3. Results and conclusions

3.1. Energy modelling

The revealed tendency of direct dependence between the extent of the building submerged area and heat loss decrease is regular. This coincides with the findings of Tundrea et. al study [12] that U-values of earth-sheltered walls and floor can be reduced by 45% and 16%, respectively, comparing with the ones that are above ground, and suggests correctness of the modelling (table 3). The noticeable decrease of the loss is explained by additional thermal resistance of the upper earth layer smoothing impact of low temperatures and preventing cold air infiltration through the exterior structures, which is caused by intensive wind effect – typical of open slopes.

Contrary to the expectations, the contribution of enlarged glazed of the south front to the building heat supply is negative. The heat losses are 34% higher than the gains from the sun (table 4). Thus, enlarging a translucent part of the envelope without improving the windows design is an insufficient way to utilize solar gains in cold climates. At the same time, the application of triple-panes with low-e surface and sashes insulated in the building would have allowed to decrease the heat transfer coefficient of the installed windows by two and half times (that, for its turn, would have made the heat loss through the windows by 25% lower). Lastly, the walls heat protection with a ground ‘blanket’ offsets the impossibility of the windows implication as a solar collector that is visible from the lowering 44.4 % by the most deepened building heat consumption in comparison with the non-deepened one (table 5).
Table 3. Annual heat loss, kWh/a.

| Loss sources | U-value, W/(m²K) | Area, m² | Earth-sheltered area, m² | Variants of earth-sheltering |
|--------------|------------------|---------|--------------------------|-------------------------------|
| Floor        | 0.094            | 125.0   | 125.0*                   | 1677.0 1186.0 1086.0 972.0   |
| North        | 0.127            | 45.0    | 48.2                     | 814.0 814.0 498.0 498.0      |
| East         | 0.127            | 48.7    | 55.1                     | 881.5 881.5 883.2 550.0      |
| South        | 0.127            | 42.7    | -                        | 771.7 771.7 774.3 773.0      |
| West         | 0.127            | 53.2    | 55.1                     | 962.8 962.8 964.8 550.0      |
| North        | 1.960            | 3.2     | -                        | 895.0 895.0 0.0 0.0          |
| East         | 1.960            | 6.4     | -                        | 1791.0 1791.0 1791.0 0.0     |
| South        | 1.970            | 21.1    | -                        | 5933.0 5933.0 5933.0 5933.0  |
| West         | 1.950            | 1.9     | -                        | 533.0 533.0 533.0 0.0        |
| Front door   | 1.410            | 2.1     | -                        | 423.0 423.0 423.0 423.0      |
| Roof         | 0.143            | 129.9   | 129.9                    | 2655.0 2655.0 2655.0 1234.0  |

| Window variants (MVHR + ventilation through windows) | 1979.0 | 1979.0 | 1779.0 | 1514.0 |
| Column total | 19316.0 | 18825.0 | 17312.0 | 12446.0 |

* The loss values for the variants where earth-sheltered area appears are italic.

Table 4. Annual heat gains, kWh/a.

| Gains sources | Variants of earth-sheltering |
|---------------|-------------------------------|
|               | 0%   | 26%  | 36%  | 86%  |
| Roof from solar radiation | 335.0 | 335.0 | 335.0 | 0.0  |
| North          | 92.0  | 92.0 | 0.0  | 0.0  |
| East           | 514.0 | 514.0 | 514.0 | 0.0  |
| South          | 3903.0 | 3903.0 | 3903.0 | 3903.0 |
| West           | 135.0 | 135.0 | 135.0 | 0.0  |
| Internal heat sources (heating season duration equals 205 day/a) | 1241.0 | 1241.0 | 1241.0 | 1241.0 |
| Column total   | 6220.0 | 6220.0 | 6128.0 | 5144.0 |

Table 5. Annual space heat requirements.

| Variants of earth-sheltering |
|-----------------------------|
| 0%   | 26%  | 36%  | 86%  |
| General, kWh/a               | 13096.0 | 12605.0 | 11184.0 | 7302.0 |
| Specific, kWh/(m²a)          | 139.3   | 134.1 | 119.0 | 77.7 |

3.2. Thermal comfort

The building indoor comfort evaluation consists in a calculation of operative temperatures within the two contrasting variants – 0% and 86% of earth-sheltering – by equation (1).

\[ t_{OT} = 0.5t_i + 0.5t_r \]  

(1)

where \( t_{OT} \) – operative temperature, °C; \( t_i \) – indoor temperature, °C; \( t_r \) – radiant temperature, °C. The interior surfaces radiant temperatures are calculated systematically for all elements by equation (2).
$$t_i = \frac{\sum (A_i \times \tau_i)}{\sum A_i}$$  \hspace{1cm} (2)$$

where $A_i$ – area of an element interior surface, m$^2$; $\tau_i$ – temperature of an element interior surface, °C; while the last can be found using equation (3), in accordance with [13].

$$\tau_i = t_i - \frac{t_e - t_i}{R_i R}$$  \hspace{1cm} (3)$$

where $t_e$ – outdoor temperature, °C; $R_i$ – thermal resistance of an element interior surface, m$^2$K/W; $R$ – an element thermal resistance, m$^2$K/W.

According to the counts, the thermal acceptability of the building estimated turned out to be beyond the earth-sheltering influence, primarily due to its developed insulation layer. The difference in the operative temperatures is only 0.3 °C: 19.1 °C in the non-deepened building and 19.4 °C – in the deepened one (and their surfaces radiant temperature are 18.3 °C and 18.8 °C, correspondingly).

### 3.3. Profitability

There is a firm correlation between a form factor and space heat requirement regarding conventional buildings: the larger the form factor of the building the less efficient it is during energy operation period [14,15]. The ratio of the total external surface area ($A$) to the treated floor area (TFA) is used to simulate the form factor influence and related heat demands of the building (table 6), as it is the ratio that has a higher accuracy among other relative values to define the compactness [16]. The evidence that each iteration of the form factor increase involves the heat demands rise in the both variants (unequally, though) points to a preferable choice in favor of compact solution, even when designing earth-sheltered buildings, to reach a profitable in energy conservation terms $A$/TFA ratio.

| Thermal envelope increase (%) | A/TFA | Heat requirements for variants of earth-sheltering, kWh/(m$^2$a) |
|-----------------------------|-------|-------------------------------------------------------------|
|                             |       | 0% | 86% |
| 10                          | 5.2   | 145 | 82 |
| 20                          | 5.3   | 147 | 83 |
| 30                          | 5.4   | 149 | 84 |
| 40                          | 5.9   | 158 | 90 |
| 50                          | 6.0   | 160 | 91 |

Annual prices for heating energy for the earth-sheltering variants, under the 0.01 €/kWh of firewood local cost, are as follows (€/kWh): 0% – 131, 26% – 126, 36% – 112, 86% – 73. Hence, the last variant provides 44% heat energy savings compared with the first one. The savings as a regular annual investment could offset the energy efficiency measures cost and this can be assessed using net present value method, expression (4).

$$S \times \frac{1-(1+i)^{-n}}{i}$$  \hspace{1cm} (4)$$

where $S$ is a difference in heating energy prices (131 – 73 = 58, €/a), as well as the initial investment; $i$ – average real (less inflation) interest rate (3%); $n$ – a time lag from the moment of the first savings deposit from the sum of the heating energy costs economy is 20 years (time horizon of comparatively predictable interest rates). A gain from the savings invested equals €850, while the thermal protection with earth cost equals €810 (270 m$^3$ – excavated volume by 3 €/m$^3$ – digging cost), consequently, the savings for less than 20 years offset the cost of earth-sheltering. In addition, the earthen thermal protection will continue to act, bringing some profit, even when this period is over.
In summary, the numerical evidences of considerable heat economy and financial adequacy of the earth-sheltered dwelling prove its high potential in the cold climate as the South Ural’s is and make it a rational alternative to other ways of energy conservation. The present study has established that it is expediently to use earthen masses, extracted during the construction, for the building thermal protection. Moreover, the extent of this protection could be maximum – three fronts, a roof and a floor – as the only front with enlarged glass covered area is enough to light the space. Solar radiation coming through it from the south direction, as the modelling shows, is 100% utilized by the building heating requirement and does not overheat indoor air in the local climate, even during the summer. Following the determination of the building thermal comfort parameters, it is found that a heat-insulating layer, developed and regularly placed, enables to maintain an acceptable indoor operative temperature without additional earthen cover. Nevertheless, paying attention to a sizeable difference in the indoor and outdoor air temperatures of 51 °C, for an ordinary insulated building it is earth-sheltering that becomes an efficient measure to rise interior surfaces temperatures and to influence positively the microclimate.

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