Chapter 5

Earth Shelters; A Review of Energy Conservation Properties in Earth Sheltered Housing

Akubue Jideofor Anselm

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/51873

1. Introduction

Earth sheltering is an age long traditional practice. In modern times its benefits has prompted new definitions for its practice. With the potential thermal conservation qualities and physical characteristics of earth as a building mass, earth shelters can now be defined as structures built with the use of earth mass against building walls as external thermal mass, which reduces heat loss and maintains a steady indoor air temperature throughout the seasons. The popularity of earth sheltering was advanced mostly by research in energy conservation in residential housing. Originally conceived as dwellings developed by the utilization of caves within the traditional context, its evolution through technologies led to the construction of customized earth dwellings all across the globe. These structures in the past were built by people not schooled in any kind of formal architectural design or with identifiable building techniques rather they depended on the cover the very structure of the earth could provide them for purposes of shelter, warmth and security. Investigations into the traditional earth sheltered dwellings also identified sunken earth houses with characteristics that suggested potentials in passive building insulation which utilizes ground thermal inertia.

In the view of some researchers on earth supported housing, building underground provides energy savings by reducing the yearly heating and cooling loads in comparison with known conventional structures. Not only is the temperature difference between the exterior and interior reduced, but mostly because the building is also protected from the direct solar radiation [1].

One significant value of earth-sheltered housing and the reason for its evaluation is its potential energy savings when compared to conventional aboveground housing. This potential is based on several unique physical characteristics. The first of these characteristics is in the reduction of heat loss due to conduction through the building envelope because of the high density of the earth. According to [2], in an earth sheltered building even at very shallow depths and given normal environmental conditions, the ground temperatures seldom reaches the outdoor air temperatures in the heat of a normal summer day. This condition allows the conducting of less heat into the house due to the reduced temperature differential.

In the case of colder climates, it was noticed that during winters the rate of heat loss in bermed (earth supported) structure was less in comparison to that in on-grade structures. This indicates through results that the floor surface temperature increased by 3° C for a 2.0m deep bermed structure due to lower heat transfer from the building components to the ground, thus suggesting the presence of passive heat supply from the ground even at the extreme cold temperatures of winter [3]. This evidently contributes as a factor for energy saving in earth shelter buildings in cold climates.

Other characteristics include the reduction of air infiltration within the dwelling which is mainly surrounded by earth walls with very little surface area exposed to the outside air. These characteristics have been investigated in previous studies and the analysis on each location provides results and findings in terms of climatic effects, design styles and residential activities of the dwellers that bring about the unique energy saving value of these buildings.

Single unit earth sheltered houses are unique energy conservation ideas based on their earth contact characteristics as mentioned above. In order to achieve the maximum benefits from earth sheltered housing, its application could be examined also at an entirely community scale rather than simply at the scale of individual houses. One of the biggest challenges to the overall performance of earth sheltered housing would be the built conventional surroundings. While contemporary use of earth sheltering is confined to individual homes built on single plots of land or a small cluster of houses which will absolutely be affected by the surrounding conventional structures around, the traditional use encompassed entire communal design or villages that will stay within the same conditions the micro-environment provides. This communal development option is identified to be most effective as isolated pockets of earth sheltered houses do not really reach the scale needed for sustainable development [4]. Earth sheltered mass-housing may thence become the general concept for design and building with earth whereby entire communities are created, enjoying dual land use by locating all housing underground [5]. If a single case of earth sheltering is found to have significant advantages, these advantages can only increase in magnitude if applied to whole communities.

2. Fundamentals of Earth sheltered housing

The values of energy conservation in earth shelters are dependent on certain principles. These principles which form the ground rules for the design and construction of earth sheltered dwellings have been existent since prehistoric periods. Earth sheltered homes were primarily developed for shelter, warmth and security for the earliest human dwellers.

Most of the recorded cases of these shelters are found extensively in areas like Asia and Northern Africa. In one of the earliest cases in Japan was discovered the oldest human habitation in a layer of earth about 600,000 years old in Kamitakamori, Miyagi Prefecture. Archaeologists from the Tohoku Paleolithic Institute, Tohoku Fukushi University and other institutes believed that the finding may be one of the oldest in the world. There are only a few remains of human dwelling structures from the early Paleolithic period in the world, as early humans such as the Peking-man lived in caves. Researchers believed the dwellings were built by primitive man who appeared some 1.6 million years ago and likely reached Japan 600,000 years ago at the latest, according to the archaeologists. The buildings could have been used as a place to rest, a lookout for hunting, a place to store hunting tools or to conduct religious rites.

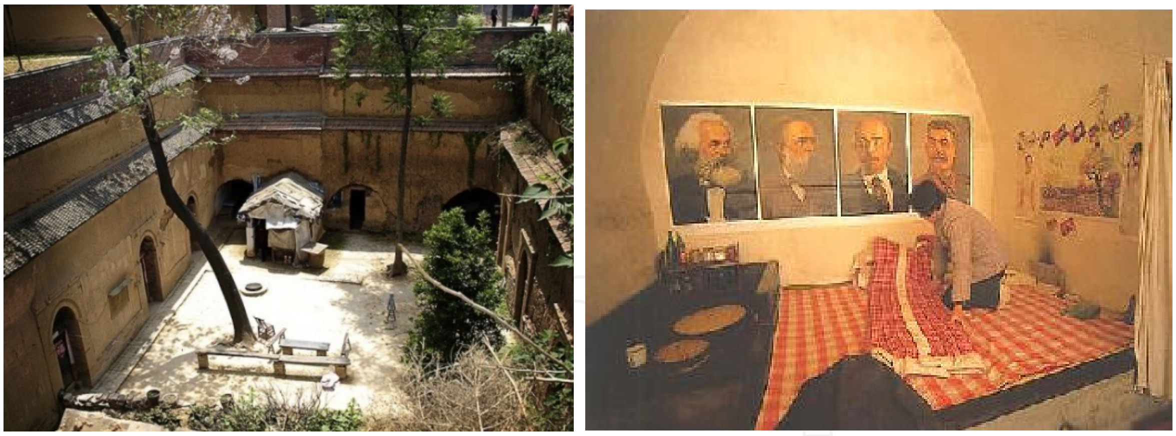
In Tunisia, residents of Matmata were discovered to have lived in manmade caves for centuries (Figure 1). Here rooms were carved into the soft rock to create atrium houses that had several excavated rooms with up to 4 to 10 meter high and vaulted ceilings opening out onto a single sunken courtyard. The original objective for going below the ground in this case was to protect the inhabitants from the extremes of daytime North African heat and nighttime cold, typical of this desert region.

Figure 1. Aerial view of a typical Matmata earth shelter dwelling. Image by Tore Kjeilen

However through the years, more modern earth sheltered dwellings were revealed as studies on the earliest forms of human settlements progressed. In China, modern earth shelters habitats were discovered with histories that dated back to before 2000 B.C. This type of habitats were commonly called cave dwellings as they were strictly home units hewed out of the mountains. It is believed that underground housing preceded above ground housing in this area. Studies on these existing Chinese earth habitats presented analytical data on the climatic and topographical relationships to the unique design elements utilized to attain living comfort by the cave shelter dwellers. Such analysis as the rain, wind, sun and seasonal weather conditions that exist in these areas where these dwellings were located possibly necessitated the advantage of its existence in these locations [6]. Analysis on each location also provided results and findings in terms of climatic effects, design styles and residential activities of the dwellers. In the North-west of China, variety of these structures evolved, ranging from the cave dwelling units to the more advanced subterranean types. In the case of the traditional subterranean homes in China (called '*yao dong*'), rooms were dug into loose, silty soil to primarily combat the hot summers and bitterly cold winters. In the early 20th century the provinces of Shanxi, Jiansu and Henan still had traditional dwellers that faced with the need to preserve agricultural land and housing for their people, dug entire cities beneath their lands. Today, it is still believed that more than 10 million Chinese live underground, perhaps the largest number of troglodytes ever to inhabit a single region. The Shanxi homes (Figure 2, 3 and 4) were buried at depths of up to 10 meters with their underground homes built around courtyards. This atrium-style design offer ample sunlight as well as surface spaces for other activities.

Research conducted in [6] also provided analytical data on climatic and topographical relationships to the structural design styles with single unit design solution, multi unit designs and finally urban planning initiatives on how to achieve a sunken city that exists beneath rather than above ground level as seen in Figure 2 below. Also fascinating in discovery included methods and techniques of ventilating the building units naturally. Such natural ventilation techniques are viewed today as ideas that advanced the notion of passive aeration of interiors which ultimately is a cost and energy efficient alternative to the whole process of earth sheltered housing.

Figure 2. Aerial view of an earth shelter neighborhood in *Lian Jiazhuang*, Shanxi Province, North-western China



(a) (b)

Figure 3. (a) Courtyard view of an Atrium type subterranean earth shelter dwelling in *Lian Jiazhuang*, Shanxi Province. (b) Interior view of a typical room space. Image by Kevin Poh.

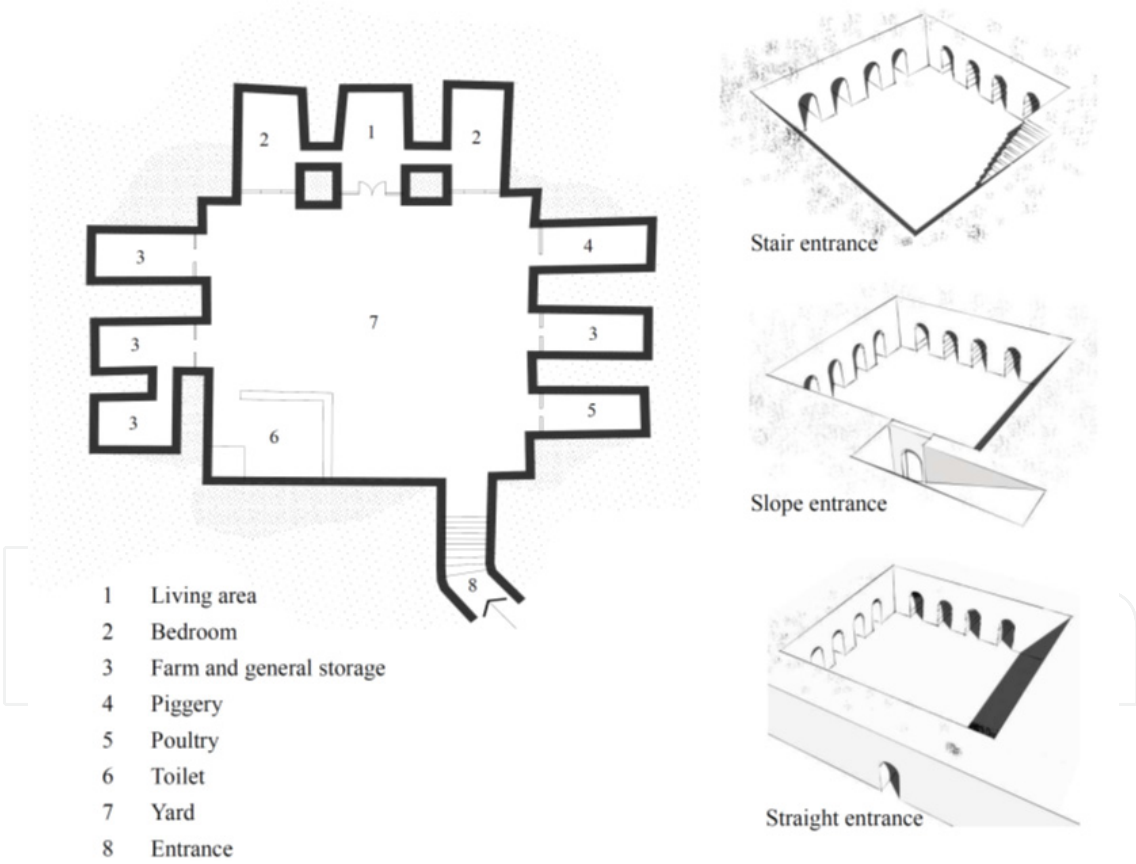


Figure 4. A typical earth shelter home layout in North-western China

With the challenges of global warming and fossil energy reduction, energy saving ideas has become an essential element in building designs and occupation. Since energy conservation is the practice of saving energy use without compromising occupant thermal comfort [7], building below the ground thence presents certain fundamentals that with the aid of research can significantly influence energy conservation efforts in modern housing. From reviews of the basic background of traditional earth sheltered housing, the fundamental objectives for building below the ground and significant energy conservation principles are listed as follows:

1. Indoor temperature enhancement based on the natural principles of annual heat storage (PAHS) whereby the earth collects free solar heat all summer and cools passively while heating the earth around it, and keeping warm in winter by retrieving the stored heat from the soil in winters. This dual function presents a scenario that makes the practice of earth sheltered housing effective in both hot and cold climates.
2. Huge temperature differential between the ground temperatures and the outdoor air temperatures. In this case the normal ground temperature seldom reaches the outdoor air temperatures in the heat of a normal hot day, thereby conducting less heat into the house due to the reduced temperature difference.
3. Building protection from the direct solar radiation, thereby elimination the challenge of direct thermal load due to heat radiation through the building envelope.

Apart from the energy values which the subsurface climate of the earth provides, the other significant characters beneficial to earth shelters includes the major goal of recycling surface space by relocating functions to underground, by this earth shelters liberates valuable surface space for other functional uses and improves ground surface visual environment, open surfaces for landscaping and thus a more greener atmosphere.

3. Modern construction techniques and design typology

The structural make up of a typical earth shelter house is made up of the supporting members and the compacted backfills in which case strength and composition can determine the ability to withstand overhead loads of moisture, dead and live loads, the distribution of which depend on the compaction strength of the backfill or supports.

However in modern designs, the supports are the parts of the house that brace against the side walls of soil and overlaying roof members that are made of backfills as in the case of underground homes. The design method and material choice will determine the resistance to failure of these structural members. In the traditional construction scenario where the earth-soil is used as building material; its strength is determined by the soil stability, which goes to improve the resistance to wind and in most cases rain erosion.

3.1. Earth shelter structural integrity

The structural make up of earth homes is mainly made up of the supporting members and the compacted backfills. As earlier mentioned, the strength and composition of the material used as backfill can determine the ability to withstand overhead loads. The supports are the parts of the house that brace against the side walls of soil and overlaying roof members that are made of backfills. The building design method and material choice will determine the resistance to failure of these structural members. In the case where the earth-soil is used as building material, its strength is determined by the soil stability, which goes to improved the resistance to wind and rain erosion. In most earth shelter construction the significant structural areas are the soil, walls and roof area. Apart from serving as a building material, the soil-walls of the shelter trench are regarded as the most valuable structural member of the Earth house structure. It provides the necessary support a normal wall gives in an ordinary house design. Nevertheless, not all soil types are efficient in use for earth sheltered house construction. From studies it is identified that the best soils are granular, such as sand and gravel. These soils compact well for bearing the weight of the construction materials and are very permeable, which means they allow water to drain quickly. The poorest soils are cohesive, like clay, which may expand when wet and has poor permeability. Soil tests, offered through professional testing services, can determine load-bearing capability of soils and possible settlements that may occur after construction. Study in [6] revealed certain traditional considerations for deciding the depth, thickness of mass and curvature of the support ceilings (vault) of the Chinese earth homes which can also be applied in modern day construction of earth shelters (figure 5).

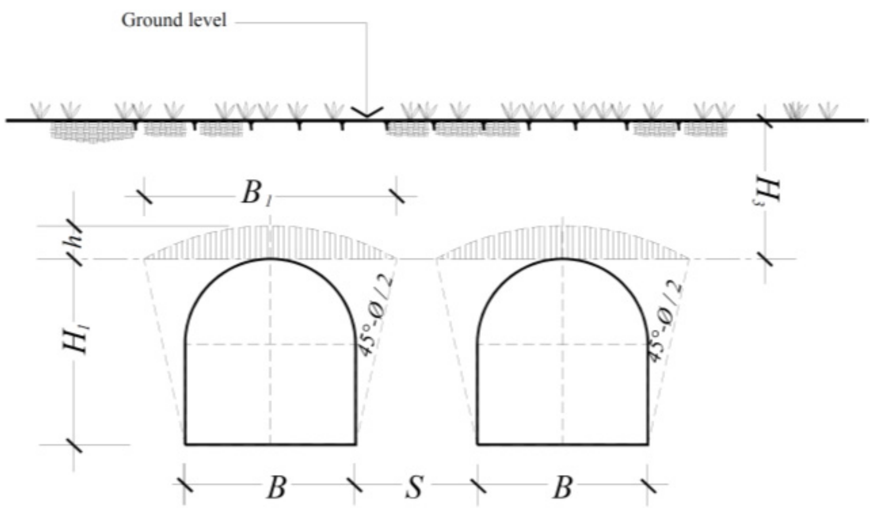


Figure 5. Structural consideration for a typical room space excavation in the Shanxi traditional earth shelters

$h = 1 \sim 2$, $Ø = 18°$.

$½ B_1 = ½ B + H_1 \, t\, g \, (45° - Ø/2)$

$= 3.5/2 + 3 \, t\, g \, (45° - 18°/2)$

$½ B_1 = 1.75 + 2.19 = 3.94 \; m$

Then S = Thickness of Earth thermal mass wall

H_3 = Extent of depth clearance

Assuming B (room span) = 3.5m and H_1 (room height) = 3m

H_3 = Depth from ground surface to ceiling. This should be greater than *h*

The Dotted/shaded area indicates possible fault lines due to the pressure from the overlaying earth mass

Varieties of techniques have been used in the past for earth shelter wall construction. The construction materials for the walls of each type of structure will vary, depending on characteristics of the site, climate, soils, and design. However, general guidelines show that houses more deeply buried require stronger, more durable structural walls. Walls must provide a good surface for waterproofing and insulation to withstand the pressure and moisture of the surrounding ground. When soil is wet or frozen, the pressure on the walls and floors increases as pressure also increases with depth.

For the traditional earth supported homes built in the Chinese and Arid (dessert) climatic regions, there usually is no use for supporting walls as the naturally compressed soil structure already serves the function. However through recent research on improving the state of earth homes for most other climatic regions, the walls of Earth homes can be made of various materials ranging from Compressed Earth bricks to Concrete, while providing cavities and drainage patterns to aid damp proofing. In most earth home designs, the roof is usually the most challenging part of the entire structure. With recent ideas in ecology, the roof of earth shelters assume interesting landscaping functions. Especially for earth supported shelters which already posses the natural materials of earthen walls and members, the roof can also be finished to assume a natural finish too. Since the basic idea of this study is to discover techniques to achieve high performance as possible, the basic structural form for constructing the earth shelter roof is as follows:

1. A frame strong enough to support the dead load brought by the soil overlay, rain, snow and ice loads where applicable.
2. A solid deck built over the frame and a waterproof membrane installed on the deck prior to final earth cover.
3. Treated soil backfill placed on the membrane (as the roof layer) and covered with a fine thick layer of soil. The roof will either grow a vegetation of its own or become a life garden depending on the appropriate type of maintenance.

Reinforced concrete is the most commonly used structural material in earth shelter construction. Products like Grancrete and Hycrete are becoming more readily available. They claim to be environmentally friendly and either reduce or eliminate the need for additional waterproofing. However, these are new products and have not been extensively used in earth shelter construction.

Some other unconventional approaches are also utilized in earth shelter construction. These techniques utilize recycled material of various forms and applications. One of such approaches is referred to as an Earth ship (figure 6). These houses are built to be self-contained and independent; their design allows occupants to grow food inside and to maintain their own water and solar electrical systems [8]. Some builders believe they have proven the design's ability to tap into the constant temperature of the earth and store additional energy from the sun in winter. These Earth ships carry out their environmentally conscious theme by employing unusual building materials in the form of recycled automobile tires filled with compacted earth for thermal mass and structure. While the tires form the major structural frames for the building, aluminum or tin cans are used for filling minor walls that are not load-bearing. Foam insulation can be applied to exposed exterior or interior walls and covered with stucco. Interior walls are also dry-walled giving it a conventional look.

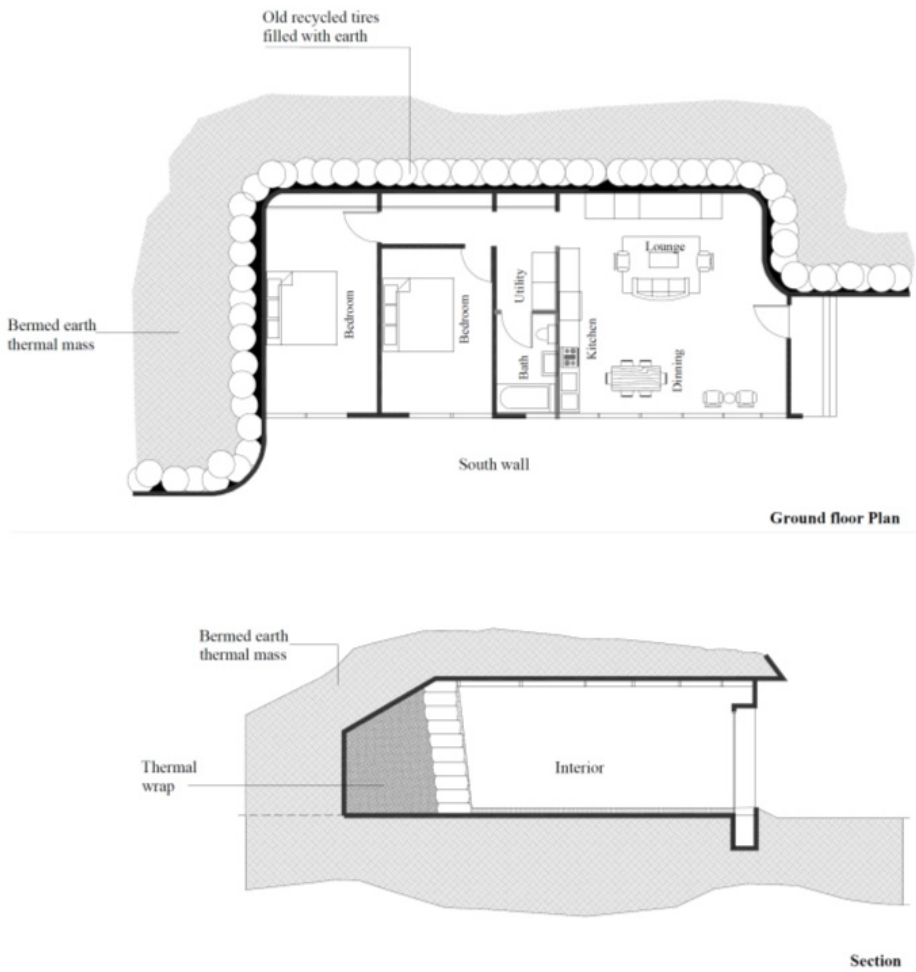


Figure 6. An Earth Ship design, using recycled materials

3.2. Earth shelter construction typology

Earth sheltered houses are often constructed with energy conservation and savings in mind. Though techniques of earth shelter construction have not yet become common knowledge, study into the most efficient application of the earth shelter principles reveals classifications of the major typologies that are utilized in the construction of earth houses. These major construction concepts are the Bermed or banked with earth type and the Envelope or True underground type. The energy conservation values of these typologies also vary depending on climate and physical challenges indigenous to each typology (table 1).

a. **Bermed earth shelter:** In this type of construction, earth is piled up against exterior walls and heaped to incline downwards away from the house. The roof may, or may not be, fully earth covered, and windows/openings may occur on one or more sides of the shelter. Due to the building being above ground, fewer moisture problems are associated with earth berming in comparison to the fully underground construction. Other variations of bermed construction are the elevational and in-hill construction (figure 7). This type of construction is particularly appropriate for colder climates. With regards to energy efficiency in colder climates, all the living spaces may be arranged on the side of the house facing the equator. This provides maximum solar radiation to the most frequently used spaces like bedrooms, living rooms, and kitchen spaces [9]. Rooms that do not require natural daylight and extensive heating such as the bathroom, storage and utility rooms are typically located on the opposite in-hill side of the shelter. The compact configuration of this construction provides it with a greater ratio of earth cover to exposed wall thereby improving its energy performance benefits through the earth-contact principles. However the case for both climates, the three major determinants for the building orientation remains the sun, wind and outside views. Proper orientation with respect to solar path and wind is significant for energy savings.

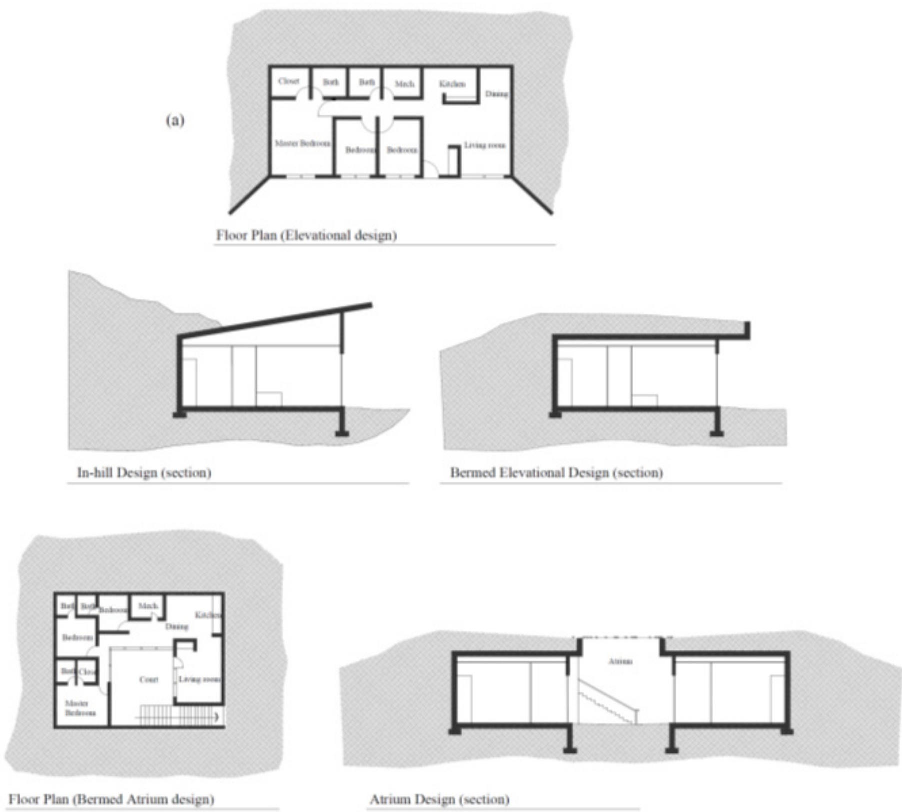


Figure 7. (a) Elevational (beremed) and in-hill designs, (b) Atrium (bermed) design

b. **Envelope or True underground earth shelter:** In the true underground construction, the house is built completely below ground on a flat site, with the major living spaces surrounding a central outdoor courtyard or atrium. The windows and glass doors that are on the exposed walls facing the atrium provide light, solar heat, outside views, and access via a stairway from the ground level. The atrium effect offers the potential for natural ventilation. In the view of some researchers, this concept reduces the energy conservation properties in colder climates mostly due to the reduced solar exposure within the courtyard or atrium opening [9]. However recent studies in the area of soil temperature analysis with respect to energy conservation in earth shelters, provides information on the prospect of efficient underground earth shelter design. Such studies as in [10], provides mathematical method for predicting the long-term annual pattern of soil temperature variations as a function of depth and time for different soils and soil properties that are stable over time and depth. The likes of these studies were utilized by John Hait's [11] in his book on Passive Annual Heat Storage (PAHS) to advance the ideas of earth shelter housing. With the development of modern passive solar building design, during the 1970s and 1980s a number of techniques are developed to enabled thermally and moisture-protected soil to be used as an effective seasonal storage medium for space heating, with direct conduction as the heat return method. Other variations of the true underground typology are the Atrium/courtyard concept and the Penetrational type where earth covers the entire house, except where it is retained for windows and doors for cross-ventilation opportunities and access to natural light from more than one side of the house (figure 8).

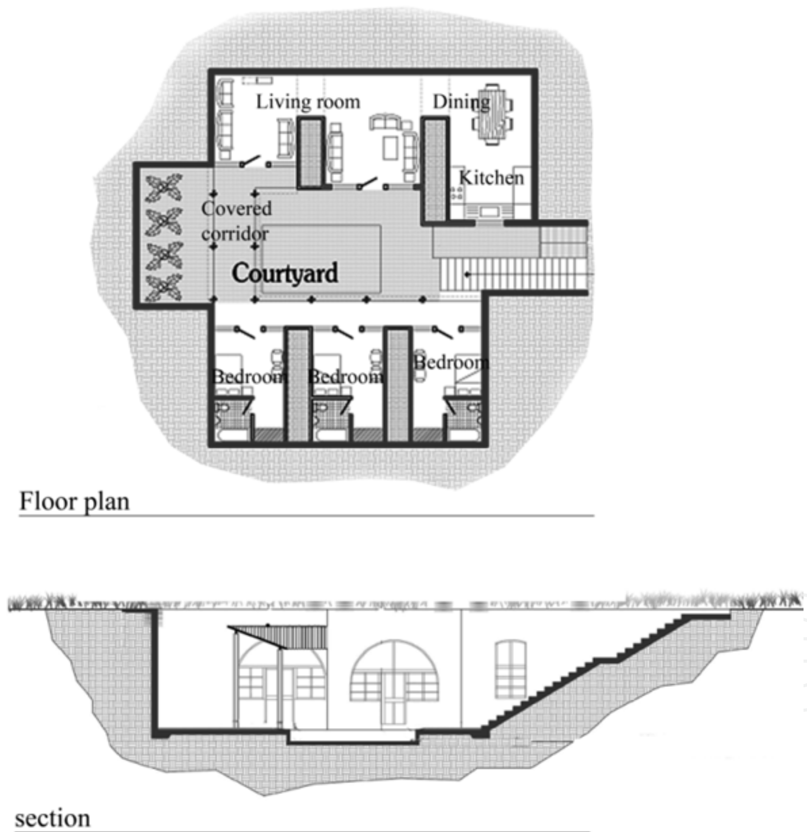


Figure 8. Underground earth shelter design

One of the most significant earth sheltered buildings in modern times is the Aloni House (figure 9). It was built in Antiparos Island in Greece and won the Greek Piranesi Award in 2009. The building epitomizes all that a modern time earth shelter represents. It combines all the design types mentioned above within a unique terrain. It also provided courtyard spaces with its landscape appearing to drift naturally into the courtyard thereby allowing for free solar penetration to the desired areas.

<table>
<tr><th>Factor</th><th colspan="4">Earth shelter building type</th></tr>
<tr><td></td><td colspan="2">Bermed</td><td colspan="2">Envelope/true underground</td></tr>
<tr><td>Passive solar potential</td><td colspan="2">Excellent</td><td colspan="2">Less effective</td></tr>
<tr><td>Thermal stability</td><td colspan="2">Less effective</td><td colspan="2">Excellent</td></tr>
<tr><td>Natural lighting potential</td><td colspan="2">Effective</td><td colspan="2">Less effective</td></tr>
<tr><td>Wind protection</td><td colspan="2">Less effective</td><td colspan="2">Excellent</td></tr>
<tr><td>Noise protection</td><td colspan="2">Less effective</td><td colspan="2">Excellent</td></tr>
<tr><td>Visual convenience</td><td colspan="2">Excellent (one directional view)</td><td colspan="2">Poor (allows only open sky view)</td></tr>
<tr><td>Appropriate Climate</td><td colspan="2">Effective for temperate</td><td colspan="2">Most effective for tropical</td></tr>
<tr><td rowspan="2">Structural cost</td><td>Modern design</td><td>Vernacular design</td><td>Modern design</td><td>Vernacular design</td></tr>
<tr><td>Intermediate</td><td>Less expensive</td><td>Most expensive</td><td>Least expensive</td></tr>
</table>

Table 1. Comparing efficiency values of the earth shelter building typology

Figure 9. Images of the Aloni House. (a) view from the hill top, (b) view from the top of the house, (c) opening leading to the courtyard, (d) the central courtyard, (e) interior view of the living room, (f) interior view from the kitchen. (Images by Julia Klimi)

4. Evaluation of energy conservation principles in earth shelter schemes

The most significant value of earth shelters and the basis for the exploitation of earth in energy saving building initiatives is its energy preservation potential. This is based on several unique physical characteristics of earth. As stated earlier, the dependability of earth in energy conservation designs is related to the natural principles of annual heat storage; huge temperature differential between the ground temperatures and the outdoor air temperatures and the insulation properties from direct solar radiation. In the cold climates, the significant property is the reduction of heat loss due to conduction through the building envelope. The amount of heat lost in this manner is a function of the thermal transmission coefficient (R-factor) of the envelope and the temperature difference between the inside of the envelope and the outside. While the R-factor for earth is substantially lower than that of other insulating materials, the large amount of earth inherent in earth sheltering can provide an overall R-factor comparable with more highly insulated structures [12].

According to investigations in [12], the temperature differential for conventional above ground structures is the difference between the outside air temperature and the interior temperature maintained for the comfort of its inhabitant. Under extreme conditions, this differential can be as much as 32°C. However, since the daily and seasonal fluctuations of temperature below the surface of the ground never equals that of the air above, therefore the deeper the temperature is taken, the less severe will be the variation. This reduced temperature differential results from the thermal storage capabilities of the soil which moderate extremes of temperature and create seasonal intervals, wherein energy from one season is transferred to the next season as in the principle of PAHS.

4.1. Solar radiation and energy conservation in earth sheltered houses

It is common knowledge that the sun is one of the most significant determinants in energy efficient building design. The radiant energy from the sun can be used as both active and passive heat generators for a building. Generally in colder climates, the active solar receptor system is oriented directly to the south, whereas all passive solar collection methods are based on trapping the radiant energy of the sun which enters through the openings on the building envelope. In the case of earth sheltered houses, the best site orientation (in cold climates) is the south-side orientation which maximizes the presence of all of the window openings whereas the remaining sides of the building are completely earth covered. The use of passive solar collection in combination with other energy conservation values is a very desirable energy efficient concept in buildings since it does not involve the capital expense that an active solar collector does. Conversely, it is important to note that, while solar radiation is desirable in the heating season of cold climates, they are not as efficient in the cooling season of hotter climates. The effect of wind on the orientation of an earth sheltered structure is a serious energy consideration [13]. Since direct exposure to cold winter winds increases heat loss due to infiltration which consequently creates a wind chill effect, it is desirable to protect a building as much as possible from this exposure. In the north hemisphere the prevailing winter winds are from the northwest. Minimizing window and door openings on the north and west sides of the house in this region will enhance energy performance.

4.2. Effects of seasonal thermal storage systems on energy conservation in earth sheltered houses

A seasonal storage system can broadly be defined as one which stores energy in one season and delivers that energy in another season. Naturally for seasonal storage systems that function as solar thermal collectors, this means that energy is collected in periods of high radiation as is the case in summer seasons and delivered in winter seasons during periods of low radiation. However to further improve the efficiency of any of the seasonal thermal storage systems, very effective above-ground insulation or super insulation of the building structure is required to minimize heat-loss from the building, thereby improving the amount of heat that needs to be stored and used for space heating.

There are three major types of seasonal (annualized) storage systems that are classified as effective or beneficial to earth shelter buildings. These are:

4.2.1. Low temperature systems:

This system utilizes the earth (soil) adjoining the building as a low-temperature seasonal heat store, thereby reaching temperatures similar to average annual air temperature while drawing upon the already stored heat for space heating. These systems can also be seen as an extension to the building design itself as the design involves some simple but significant differences when compared to conventional above ground buildings.

4.2.2. Warm temperature inter-seasonal heat system:

This also uses soil to store heat, but utilizes active solar collection mechanisms in summer to heat up thermal banks (earth mass) in advance of the heating season. Warm temperature heat stores are generated from low-temperature stores in that solar collectors are used to capture surplus heat in summer and actively raise the temperature of large mass of soil so that heat extraction is made cheaper in winter.

4.2.3. Passive annual heat storage system (PAHS):

With the development of modern passive solar building design, during the 1970s and 1980s a number of techniques were developed that enabled thermally induced and moisture-protected soil to be used as an effective seasonal storage medium for space heating, with direct conduction as the heat return method. The concept of Passive Annual Heat Storage (PAHS) is such that solar heat is directly captured by the structure's spaces and surfaces in summer and then passively transferred through its floors, walls and roof into adjoining thermally-buffered soil by conduction. It is then passively returned to the building's spaces through conduction and radiation as those spaces cool in winter. This idea was originally introduced by John Hait [11]. It includes extensive use of natural heat flow methods, and the arrangement of building materials to direct this passive energy from the earth to the building, all without using equipment. PAHS is believed to be one of the most significant ideas for energy conservation in earth sheltered buildings.

Concept of passive annual heat storage system (PAHS):

Globally, the earth receives electromagnetic radiation from the sun which is typically defined as short-wave radiation and emits it at longer wavelengths known typically as long-wave radiation. Figure 10 below shows an analysis of the earth's shortwave and long-wave energy fluxes produced with details from [14]. This absorption and re-emission of radiation at the earth's surface level which forms a part of the heat transfer in the earth's planetary domain yields the idea for the principle of PAHS. When averaged globally and annually, about 49% of the solar radiation striking the earth and its atmosphere is absorbed at the surface (meaning that the atmosphere absorbs 20% of the incoming radiation and the remaining 31% is reflected back to space). This absorbed 49% of the solar radiation presents a premise for energy efficiency in building design. The concept of earth shelter design focuses fundamentally on the utilization of the absorbed/retained heat from this annual absorption and re-emission of radiation for indoor thermal environment control.

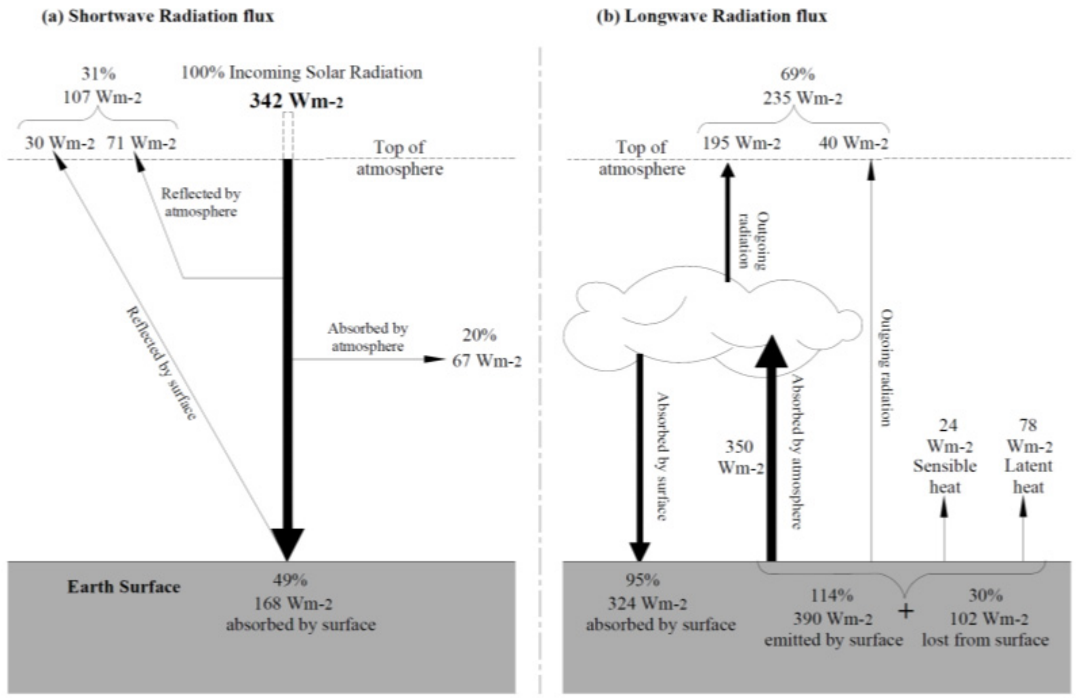


Figure 10. Earth's energy budget diagram showing the short-wave (a) and long-wave (b) energy fluxes

4.3. Analysis of soil thermal performance in earth shelter designs

The thermal property of an earth-shelter soil is an essential factor in determining its performance against other conventional above-grond houses. Due to the relatively stable temperature of the soil, the earth shelter house in summer loses heat to the cool earth rather than gaining heat from the surrounding air, and in winter the relatively warm soil offers a much better temperature environment than the subzero air temperatures. This concept is clearly confirmed by examination of the daily and yearly soil temperature fluctuations at various depths. Daily fluctuations are virtually eliminated even at a depth of 20 cm of soil. At greater depths, soil temperature responds only to seasonal changes, and the temperature change occurs after considerable delay [15]. A reasonable level of soil study is necessary in order to facilitate the comparison of the energy needed for construction (soil excavation, dewatering and concrete works) with the energy to be saved in the long run, conditions related to the insulation efficiency of the soil [16]. However the expected efficiency varies with the soil type and its water content which in some cases may have a marked effect on the thermal properties of the soil. The figure below (Figure 11) presents a typical relationship between the annual air temperatures and corresponding temperature fluctuation below the ground surface.

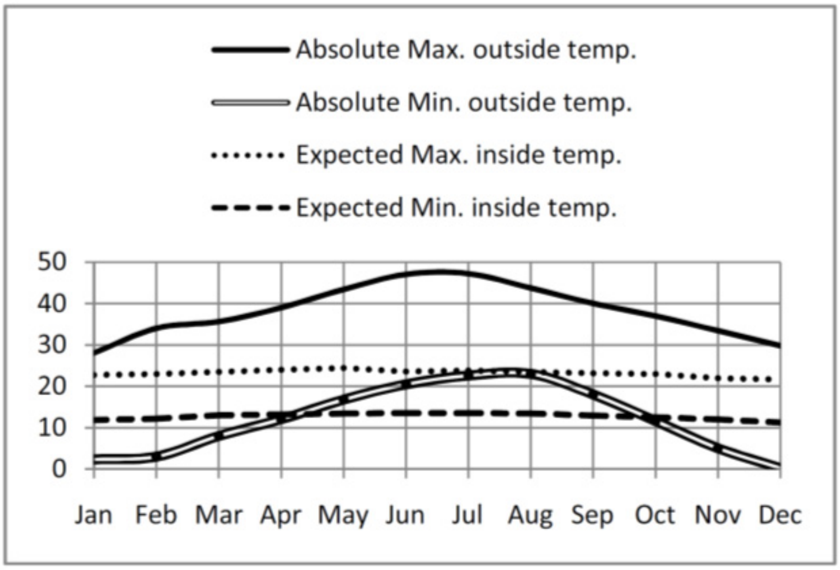


Figure 11. Annual temperature fluctuations in Riyadh from below zero to 48 ◦C and expected temperature fluctuation at 3.0m below ground level between 14◦C and 24◦C. (Data taken from [16])

In earth shelter houses, the overlaying thick earthen layer around much of the building effectively eliminates possibilities of infiltration through the building skin (as is the case in conventional above-ground houses). This can contribute significantly in reducing energy loss due to infiltration, except only through the exposed portions of the structure. Apart from the reduction of infiltration, studies identified that the application of thermal coupling of the earth-soil to the building wall places significant values to the thermal conditions of the earth shelter environment in winters. This process allows for improved thermal storage through the soil into the building walls. Since majority of modern earth shelters are built with concrete which possesses a large thermal storage capacity which can absorb the excess energy from the earth-soil, this absorbed heat is naturally released back into the building whenever the indoor air temperature is below that of the thermal mass. This thermal absorption and releasing process can provide essential heat energy required in the house for days without mechanical heating. The effect of this process is presented below (figure 12) in a thermal investigation study of a berm-type earth sheltered house in Missouri (US) covering a 4 day assessment period under a 6-hourly measurement interval [12].

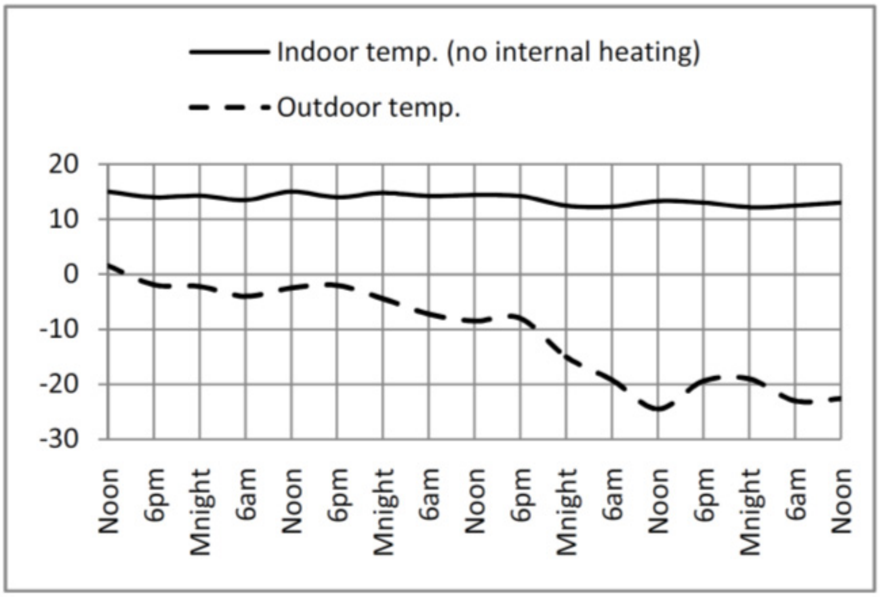


Figure 12. Temperature stability graph of an earth sheltered house in Missouri (Data taken from [12])

Determining the thermal performance of the soil for earth shelter construction involves assessing the long-term subsurface environment and above-ground temperature data. Consequently, this requires accurate environmental information on the boundary conditions, one of which is the temperature of the surrounding soil. For instance, in the case of a single basement study, a change in the mean annual ground temperature from 10◦C to 6 ◦C caused a 36% increase in heat loss [17]. Therefore, accurate data regarding diurnal and annual variation of soil temperatures at various depths is necessary to accurately predict the thermal performance of earth sheltered structures.

Study shows that actual data on soil temperatures is not usually abundant. However research has facilitated the evaluation of the underground climate in order to assess the suitability of earth sheltered structures. Algorithms for this calculation of the soil temperatures at various depths have already been developed based on existing field measurements in different regions of the world and by this, the annual pattern of soil temperatures at any depth can be accurately considered as a 'sine' wave about the annual average of the ground surface temperature. Accordingly, a mathematical method was developed to predict the long-term annual pattern of soil temperature variations as a function of depth and time for different soils and soil properties that are stable over time and depth [10]. This method is sufficiently accurate in the case certain thermal and physical characteristics are accurately estimated. The equation for estimating subsurface temperatures as a function of depth and day of the year is as follows (with the unit of cosine expressed in rad):

$$T_{(x,t)} = T_m - A_s e^{-x}\sqrt{\pi / 365\alpha}\ \cos\ \left\{\frac{2\pi}{365}\left[t - t_0 - \left(\frac{x}{2}\right)\left(\sqrt{\frac{365}{\pi\alpha}}\right)\right]\right\} \tag{1}$$

Where:

$\boldsymbol{T}_{(x,t)}$ = subsurface temperature at depth x(m) on day t of the year (◦C),
$\boldsymbol{T}_m$ = mean annual ground temperature (equal to steady state) (◦C), as the annual temperature amplitude at the surface (x = 0) (◦C),
x = subsurface depth (m),
t = the time of the year (days) where January 1 = 1 (numbers),
t_0 = constant, corresponding to the day of minimum surface temperature (days),
α = the thermal diffusivity of the soil (m^2/day)

Through this equation, the resulting temperature profile at different depths can now be graphed and compared with the annual average air temperatures. Following the evaluation of the subsurface climate, the calculated soil temperatures can then be used to calculate the heat flux through the building surfaces. The energy efficiency of a wall in contact with the earth at varying depths can thus be investigated for local climatic conditions. This can be done by simulating the heat transfer through a subsurface wall at varying depths using a computer program, and comparing the results with an above-ground wall using the same method. This procedure is a typical preliminary assessment method with minimal input required. The expected results from the simulations provides preliminary insight into the magnitude of reduction of heat flow that the building soil climate can provide in comparison to the above-grade climate and the analysis also provides a faster approach for determining the optimum depth placement for an earth sheltered building.

Although this theory seems rightly beneficial to the energy conservation concepts in earth shelter house construction, it is also right to consider other detrimental factors like the soil's heat and cooling losses due to normal thermal transmittance factors. Earth shelters are subjected to heat and cooling losses partly via the soil to the external air, via the soil to the groundwater below or directly to the groundwater. The quantity of loss is calculable in this case and the equation is generated in [18] as follows:

$$QT\ =\ Atotal\frac{\left(v_i - vOT\right)}{RAL} + \frac{v_i - vGW}{RGW}\left[W\right] \tag{2}$$

Where:

$\boldsymbol{\vartheta}OT$ = mean outside temperature
≈ 0 to -5°C ≈ ($\boldsymbol{\vartheta}$e + 15K)
$\mathbf{R}OT$ = $\mathbf{R}i$ + $\mathbf{R}\lambda A$ + $\mathbf{R}\lambda B$ + $\mathbf{R}e$ = equivalent resistance to thermal transmission room-outside air.
$\mathbf{R}\lambda A$ = equivalent resistance of the soil to thermal conductivity.
$\mathbf{R}\lambda B$ = resistance of building component to thermal conductivity.

$\mathbf{R}GW = \mathbf{R}i + \mathbf{R}\lambda B + \mathbf{R}\lambda s$ = equivalent resistance to thermal transmission room-groundwater.
$\mathbf{R}\lambda s = T/\lambda s$ = thermal conductivity resistance of soil to groundwater.
D = depth of groundwater
λs = thermal conductivity coefficient of soil
≈ 1.2 W/mK
$\boldsymbol{\vartheta}GW$= groundwater temperature = 10°C.

4.4. Energy conservation values in earth shelter design

Earth is a great moderator of temperature change. When warmed up, it can stay warm a long time without losing much of its heat [9]. Earth does not react as fast to temperature change as air does. This means that for instance if air surface temperatures ranges from -15°C to 35°C through the year (winter through summer), then about 3 meters below, the temperature of the earth will vary only between 10°C to 15°C. This short range in difference explains the ability of earth to maintain stable temperatures throughout the year. This is a significant energy conservation tendency in the case of reducing the load on home heating and air-conditioning systems. With regards to total operating cost (excluding estimates from heat-recovery systems), energy savings of up to 60% to 70% may be realized in residential scale structures within mid-temperate zones. Instances of this were presented in [19] from the energy cost studies undertaken in [20]. In this study, a conventional 135 sq m (9m x 15m) single level residence with a hypothetical subsurface structure of the same dimension was compared. With the use of climate data and energy rates of Denver metropolis in Colorado, the study establish that the underground house provides a 72% energy savings over the surface dwelling (Table 2, 3 and 4).

Measured unit	**Conventional surface house**	**Earth shelter house**
Heat loss in winter (B.T.U. per hour)	39,927	12,720
Heat gain in summer (B.T.U. per hour)	44,650	0

Table 2. Evaluation of rates of heat loss and gain in a typical above ground house and an earth sheltered house [20]

Measured unit	Conventional surface house	Earth shelter house
Winter:		
Gas (m^3)	2,656.9 m^3 ($65.80)	871.5 m^3 ($27.60)
Oil (gal.)	710 ($129.90)	233 ($42.60)
electricity (kwh)	23,157 ($428.80)	7,596 ($191.10)
Summer		
Electricity (kwh)	3,962 ($98.40)	0

Table 3. Evaluation of annual energy consumption cost in a typical above ground house and an earth sheltered house [20]

Building type	Gas	Oil	Electricity
Above ground design (AGD)	($395)	($459)	($758)
Earth sheltered design (ESD)	($120)	($135)	($283)
Cost conservation comparison between ESD and AGD	30%	29%	37%

Table 4. Evaluation of annual cost of environmental control requirements in a typical above ground house and an earth sheltered house [20]

5. Soil suitability analysis for earth sheltered building construction

As already discussed earlier, not all soil types are efficient in use for earth sheltered building construction. The choice of construction site is mainly determined by the soil type available in a given geographical area for issues of safety against landslides and other moisture originated hazards. Some types of soil are more suitable than others in the construction of sub-grade buildings. The strength of the soil must be determined for the proposed depth of building below ground level. Though may be desirous, excavations in a very strong soil may be difficult and in the case of rocky ground, may prove impossible. On the other hand, in very weak soils the excavations are easy. In the first two cases, the capital cost and the energy expenditures involved in construction need careful examination [21]. For the third case, however, the excavation may be difficult because high lateral earth pressure requires construction of heavy walls (retaining walls), preferably made of reinforced concrete, which implies increased capital costs and energy consumption. In modern earth sheltered home construction, compaction and permeability values are the most essential standards considered in the backfill process when building a berm or elevational type construction. This is mostly due to the dangers of soil drainage. It has been noted earlier that soil-water content has distinctive effect on the thermal properties of the soil hence may affect the overall energy performance of earth-homes. Choosing a site where the water will naturally drain away from the building is the best way to avoid water pressure against underground walls. In order to improve the energy performance of the earth-soil in temperate, humid or arid tropical scenarios, drainage systems must be designed to draw water away from the structure to reduce the frequency and length of time the water remains in contact with the building's exterior. Survey has identified that ideal sites are those of hilly or mountainous terrain. The partially buried (bermed-elevational) earth-sheltered home is identified as most suitable for maximizing passive-solar heating in cold climates, however since water tends to drain down the hill toward the building and off the roof toward the back of the home, it is advisable to build in highly water-permeable soils and to install water drainage systems around the perimeter of the buried walls. Hydrology discusses infiltration as the rate at which water passes into the soil. This is also affected by the ratio of macro to micro-pores of the soil in question. The more macro-pores a soil has the easier it is for water to soak into it and drain away. Soils with coarse particles like sand or gravel or nutty or block soil structures have a high proportion of macro-pores and as a result have high infiltration rates. Soils such as clays have a high proportion of micro-pores and therefore have low infiltration rates. Figure 14 below illustrates different infiltration rates based on soil structure and texture [22].

Through the analysis below, it could be said that a good earth home design site with natural drainage also requires permeable soils. The most permeable soils as identified above are the granular type which consists of a fair amount of sand or gravel while soils with high clay content are less permeable as they expand and contract as moisture levels fluctuate. Nonetheless, it is advisable to perform percolation tests on the construction site's soil to determine the earth shelter soil permeability before construction.

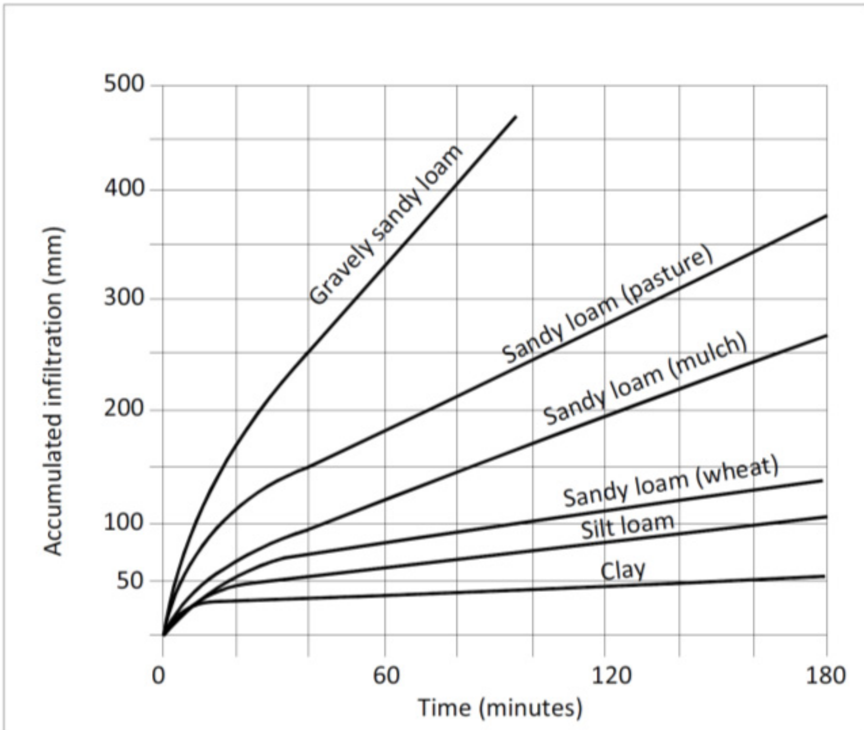


Figure 13. Infiltration curves for different soil textures

6. Thermal Integrity Analysis of earth sheltered houses

Thermal integrity factor (TIF) is a combined system for evaluating and comparing the energy performance values of building types. It is expressed in units which allow for direct comparison among such criterion as heating, ventilating, and air conditioning systems as well as the effect of various climatic conditions on different housing types. The standard unit for measuring thermal integrity values is Btu/ft^2 per degree day of the provided space condition. A TIF of 7.5 Btu/ft^2 per heating degree day is considered as representative of a baseline-factor for moderately insulated houses [23], while values in the ranges of 0.6 to 1.1 Btu/ft^2 per heating degree day are predicted for super-insulated houses [24]. Early indication of the performance of earth sheltered buildings against the conventional above-ground ones were recorded as far back as the late 1970s and 80s. Measurements were conducted on existing earth sheltered houses in some US cities. In one of the houses located in South Dakota which was monitored during 1978 and 1979, it consumed about 28,000 Btu/ft^2 for 8144 heating degree days, which yields a TIF of 3.5 Btu/ft^2 per heating degree day. The report on this house went on to note that typical above-ground framed homes in the same location generally required about 10 to 12 Btu/ft^2 per heating-degree day. This displays a

70% difference in the TIF of these two homes in the same location. Figure 13 below shows the comparative energy consumption for the above-ground and earth sheltered homes. In some other cases, earth sheltered houses display TIFs of 0 (zero) Btu/ft^2 per heating degree day. Below (table 5) are the results of the TIFs for five different buildings in Minnesota all of which recorded TIFs of less than 4.0 [25].

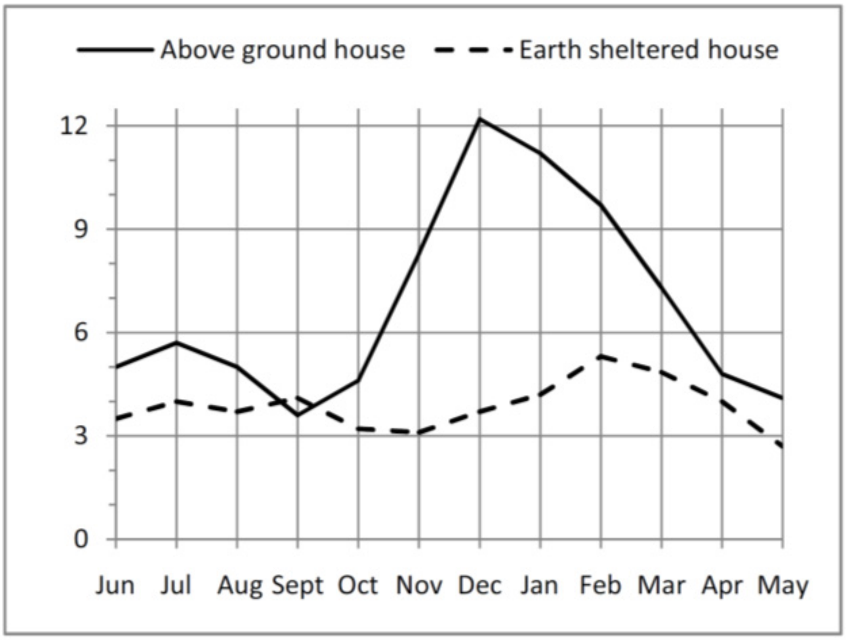


Figure 14. Comparison of monthly total energy usage in conventional above-ground and earth sheltered homes (taken from [12])

House	June 1980	July 1980	Aug. 1980	Sept. 1980	Oct. 1980	Nov. 1980	Dec. 1980	Jan. 1981	Feb. 1981
Burnsville	*nil*	*nil*	*nil*	0.65	0.84	*nil*	*nil*	*nil*	2.03
Camden	0	0	0	0	0.89	1.20	2.65	1.92	*nil*
Seward	0	0	0	0	0	2.14	3.60	2.53	3.19
Wild River	0	0	0	0	0.19	2.05	1.08	0.91	1.27
Willmar	*nil*	*nil*	*nil*	2.28	2.34	1.23	2.72	2.01	*nil*

'*nil*' = No data taken.

Table 5. Monthly thermal integrity factor for five Minnesota earth-sheltered residences

7. Conclusion

In this study, the following factors were analyzed in the hope of throwing light into the common questions that arise in the discourse of earth sheltered housing:

a. Energy conservation elements for earth shelter housing,
b. Thermal integrity values,
c. Techniques for maximizing the thermal loads necessary for comfort conditions in passively heated or passively cooled earth shelters,

d. Soil suitability, depth of placement and design techniques that optimizes structural integrity in earth sheltered house construction.

This study also presented some of the valuable analysis and results in earth shelter building evaluations as premise for assessing the potentials of passively heated earth sheltered houses. This is achieved through a review of previous performance assessments of monitored conditions in existing earth sheltered buildings. Through this review, thermal integrity factors (TIF) of existing earth sheltered homes were identified, which when compared with other housing types, perform significantly better than conventional above-ground dwellings. It also looked at both summer and winter impacts of earth shelter house types utilizing the passive approach under the different climate conditions. This study identified that the thermal integrity value of passively heated earth sheltered house is comparable with other energy-efficient approaches such as super-insulated and passive solar constructions which are much better in energy conservation performance than the conventional above-ground constructions. It further presents the criteria for identifying the appropriate soil type (sub-grade materials) needed in building earth sheltered houses with passive thermal approach. These are categorized under thermal inertia properties, bearing capacity and drainage properties. Based on the available information to date, it can be said that earth sheltered houses maintain heating energy consumption that is lesser by up to 75%. This claim appears to be substantiated as earth sheltered house compared to conventional above-ground house presents a lesser calculated or monitored TIF.

Having looked through the benefits and potentials of earth and the overall understanding of its potential for energy conservation through earth-sheltered construction, it is hoped that this review contributes to the information available so far on means of assessing the performance of earth shelters and associated thermal properties that affects it. It is then possible for designers and planners in different regions to have access to a simple framework for assessing its efficiency at the initial planning stages. The resulting outputs can then be used for the heat transfer and energy conservation analysis within the building units. Results from this analysis will provides insight into the degree of passive heating and cooling or reduction in heat flow that the soil climate can provide as compared to the surface climate as well as suggesting parameters for depth placement of earth shelter buildings for more efficient results.

Author details

Akubue Jideofor Anselm
Architecture Department, University of Nigeria, Nigeria

8. References

[1] Carpenter P, (1994) Sod It: An Introduction to Earth Sheltered Development in England and Wales, Coventry University, Coventry,.
[2] Carmody J, Sterling R, (1984) Design considerations for underground buildings, Underground Space 8: 352-362.

[3] Kumar R, Sachdevab S, Kaushik S.C, (2007) Dynamic earth-contact building: A sustainable low-energy technology, Building and Environment 42: 2450-2460.
[4] Dodd J, (1993) Earth sheltered settlements, a sustainable alternative, in: Proceedings of the Earth Shelter Conference, Coventry University 3: 26-36.
[5] Moreland F.L, (1975) An alternative to suburbia, in: Proceedings of the Conference on Alternatives in Energy Conservation: The Use of Earth-covered Buildings, National Science Foundation, Fort Worth, TX,.
[6] Golany G. S, (1983) Earth Sheltered Habitat (History, Architecture and Urban Design), Van Nostrand Reinhold Company Inc., New York.
[7] Rahman M.M, Rasul M.G, Khan M.M.K, (2010) Energy conservation measures in an institutional building in sub-tropical climate in Australia. Applied Energy 87: 2994-3004
[8] Reynolds M, (1991) Earth-ship Systems and Components, Solar Survival Press
[9] Wells M. B, (1975) To Build without Destroying the Earth. Alternatives in Energy Conservation: The Use of Earth Covered Buildings. Washington, D.C. U.S. Government Printing office. Pp. 211-232
[10] Labs K, (1979) Underground building climate, Solar Age 4: 10 44-50.
[11] Hait J, (1983) Passive Annual Heat Storage: Improving the Design of Earth Shelters, Rocky Mountain Research Center
[12] Wendt R. L, (1982) Earth-Sheltered Housing: An Evaluation of Energy-Conservation Potential. U.S. Department Of Energy, Oak Ridge Operations, TN. pp. 8-18,
[13] Minnesota University (1979). The Underground Space Center, Earth Sheltered Housing Design. Minneapolis, Minnesota: Van Nostrand Reinhold Company. pp. 20
[14] Bonan G, (2002) Ecological Climatology: Concepts and Applications, Cambridge Press, United Kingdom
[15] US Department of Housing and Urban Development, (1980). "Earth Sheltered Housing" Code, Zoning, and Financing Issues
[16] Khair-El-Din A. M, (1991) Earth Sheltered Housing: An Approach to Energy Conservation in Hot Arid Areas Architecture and Planning Riyadh. 3:3-18
[17] Mitalas G.P, (1982) Basement Heat Loss Studies, DBR/NRC, Ottawa.
[18] Klaus D, (2003) Advanced Building Systems: A Technical Guide for Architects and Engineers, Published for Architecture Basel, Boston, Berlin. pp. 50.
[19] Labs K, (1975) The Architectural Use of Underground Space: Issues and Application. Master's Thesis/Washington University, May, Mechanicsville PA. pp. 121
[20] Harrison L, (1975) Is it time to go Underground? The Navy Civil Engineer, Fall. pp. 28-29
[21] Henna A. M, (1980) Building Underground Alternatives. Miami published research for the Energy Conservation Conference, Florida.
[22] McLaren R. G, Cameron K. C, (1990) Soil science. An introduction to Properties and Management of New Zealand Soils. Oxford university press, Auckland.
[23] Lewis D, Fuller W, (1979). Solar Age, p. 31
[24] Shurcliff W. A, (1980). Super-insulated Houses and Double-Envelope Houses, A Preliminary Survey of Principles and Practice, 2nd Ed., Cambridge, Mass. p. 6.05.
[25] Goldberg L. F, Lane C. A, (1981). A Preliminary Experimental Energy Performance Assessment of Five Houses in the MHFA Earth-sheltered Housing Demonstration Program, University of Minnesota, Minneapolis. pp. 10.