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Earth Sheltered Housing; Design Concepts for Urban Ground-scrapers

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Abstract: The history of human housing portrays Earth sheltered homes as dwellings originally developed for shelter, warmth and security for the earliest human dwellers. These buildings which originated as subterranean dugouts have evolved into modern housing options over the years. Physical attributes of earth sheltered houses signifies a retreat from surrounding elements into secluded spaces bordered by earth-mass as building covering. Further studies reveal its thermal efficiency between seasons and energy conservation properties due to its thermal mass application. A review of typologies identifies various techniques of its design and construction across the globe. This paper looks at the existing construction typologies of earth sheltered housing from the traditional to modern applications. Four unique subterranean applications were studied which represented the major construction typologies. It further investigates the uniqueness in the design concepts of earth sheltered housing as models for future earth-contact housing needs based on the energy conservation and thermal performance of this category of housing. Earth contact characteristics of these types of houses makes for potential energy conservation in single unit earth sheltered homes; however, large scale concepts consequently possess the potentials for optimization of thermal and energy performance. Hence communal type concepts are presented as ideas for urban scale application of Earth sheltered housing.

Keywords: Earth Shelters, Building with Earth, Earth Homes, Underground Building, Ground Scrappers, Thermal Mass

1. Introduction

The use of earth in building construction is an age long traditional practice which has evolved into an energy conservation option for underground and earth contact home designs in modern times. The background of modern earth sheltered buildings is based on the awareness of increased energy consumption in housing [1]. Studies show that building underground provides energy savings by reducing the yearly heating and cooling loads when compared with known conventional structures. This is achieved firstly, via the reduction of heat loss due to conduction through the building envelope by the high density of the earth cover and secondly because the building is also protected from the direct solar radiation. The ground temperatures in an earth-sheltered building at very shallow depths and within normal environmental conditions, seldom reach the outdoor air temperatures in the heat of a normal summer day [2]. This condition allows the conducting of less heat into the house due to the reduced temperature differential. However, in the case of colder climates, the rate of heat loss in the earth supported structure (bermed type) during winters is less in comparison to that in above grade structures. Kumar R. (et al), indicates 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]. The combined effect of this thermal reuse which reduces dependency on active heating systems contributes in lessening the compound effects of global warming arising from housing [4]. In terms of energy conservation, thermal performance studies in earth sheltered residential homes showed reduction of energy consumption of about 40% [5, 6]. In addition to the energy conservation values which the subsurface climate of the earth provides, other significant properties of earth shelters includes the recycling and reusability of surface space above the houses by relocating functions to underground. By so doing, valuable surface space are freed for other functional uses that includes the creation of larger ground surface visual environment, open surfaces for landscaping and thus a more greener atmosphere [7].

With the single unit potential of earth sheltered houses, this paper looks into the wider scale benefits. Whereas contemporary use of earth contact housing is confined to individual homes built on single plots of land which will be affected by surrounding conventional structures, the idea of a collective housing concept is to create entire communal villages that will stay within the same conditions the micro-environment provides as a few isolated earth sheltered houses do not really reach the scale needed for sustainable development [8]. Since studies identify that single cases of earth sheltering is found to have significant advantages on thermal and energy conservation, these advantages can only increase if applied to whole communities with the adoption of communal design concepts.

2. Study of Communal Concept in Earth Shelter construction

As earlier discussed, achieving maximum benefits of energy conservation and thermal efficiency in earth contact housing, application of earth shelter concepts at urban scale with optimized conditions is essential. Rather than individual homes or small cluster of houses which will absolutely be affected by the surrounding conventional structures, design of earth shelter districts that will take advantage of the energy balance the earth's microenvironment provides, is ideal for modernized urban development of earth shelters. Optimization in terms of structural integrity, construction materials, interior finishes and planning of external environment will produce improved living environment for occupants. For centuries, traditional and modern applications of the communal concepts can be seen in several types of earth contact houses. Analyses of typology, energy and thermal principles, as well as internal living environment of communal earth shelter houses are presented.

2.1. Study of Traditional Concepts

The two major communal earth shelter concepts are the sunken/true underground design and the elevational design. Two major historical residential districts identified with these concepts are discussed below.

2.1.1. Subterranean Neighborhoods of Shanzhou District in Sanmenxia, Henan Province

Foremost amongst existing traditional styled earth sheltered housing is the subterranean neighborhood in Shanzhou District in Sanmenxia, Henan Province. These underground dwellings are believed to have existed for about 4,000 years. The district was listed by the Chinese government among the 518 intangible heritage in 2006 [9], and had made efforts in restoration of the site. Studies identified up to 10,000 homes spread all across the district with about 3,000 residents currently residing in the district. Located on the east central part of China, the Shanzhou communal design (*Yaodongs*) were buried at depths of up to 10 meters with their underground homes built around courtyards.

With its depth, the passive heating and cooling potentials attainable in earth shelter housing concepts is utilized all-round the seasons for thermal comfort. The atrium-style design not only offers ample sunlight, but also surface spaces for other activities in this farming community. Reports at the site showed that average temperatures within the homes in winter ranged over 10°C and about 20°C in summer. This is a significant value for thermal and energy conservation prospects.

2.1.2. Analysis of Design Typology of Subterranean Neighborhood Concepts

The subterranean neighborhood of Shanzhou District in Sanmenxia is primarily an Atrium design type made up of rooms built around courtyards as seen in figure 1. Each courtyard represents a family housing unit. Collective family units are arranged around shared entrance corners with about 4 or more units accessed from one entrance point.

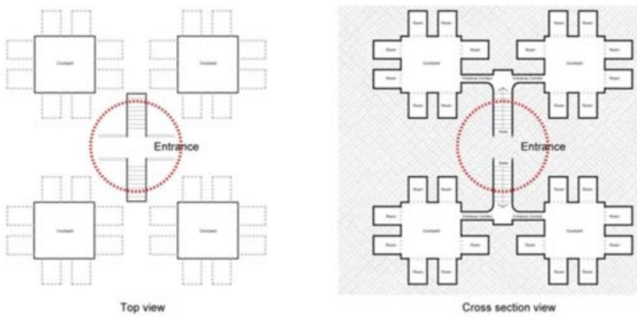


Figure 1. *Typical Layout of the Sanmenxia subterranean neighborhood courtyard design.*

(a)

(b)

Figure 2. *(a) Aerial view of Sanmenxia subterranean neighborhood, (b) Top view showing the typical entrance to collective units.*

2.1.3. Cliff Dwellings of the Kandovan Village, Iran

Another traditional subterranean community is the Kandovan Village in Iran. The famous Kandovan cliff dwellings represent a true elevational earth shelter communal housing concept. The Kandovan village is located 50km on the south-west of Tabriz city, East Atrpatakan province of Iran.

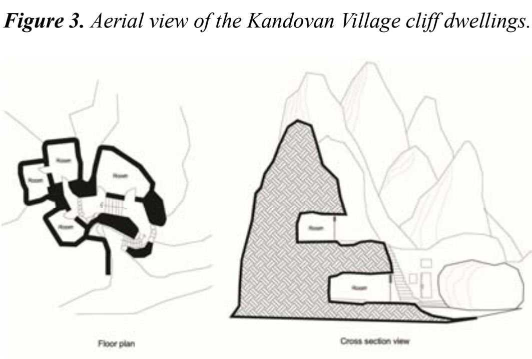
These shelters are mainly residential structures carved within the conic rocky projections going up to a maximum height of four stories. From studies, the traditional dwellers here built these houses as barns and workshops [10]. It is believed that these dwellers had fled the Mongol attacks on Hileware in the 7th century to this location that makes present day Kandvan. Progressively, they gradually excavated the conic rocky projections into what exists today as seen in figure 3. Owing to this unique architectural texture, this Kandovan village is registered in the National Heritage Society of Iran.

With wall widths that vary from 2 to 3m, the dwelling spaces maintain good insulation during the hot seasons and these functions as a good energy saving factor. Consequently, study showed very low temperature fluctuation inside the room spaces during winter, as the room temperature is higher than outside temperature and the opposite is likewise the case for the summer seasons [11].

2.1.4. Analysis of Design Typology of the Cliff Dwelling Elevational Concepts

The construction of the dwelling spaces are made up of somewhat smaller rooms with about 2m heights for each room space. Each family dwelling consists of about 2 to 3 stories with access from frontal steps arranged along the hill sides. The construction of the dwelling spaces in the Kandovan village showed evidence of the difficulties faced by the traditional builders. This is seen mainly in the room width and heights and also in the spatial arrangement of rooms which are mostly not connected to each other owing to the thick rocky walls. Though the compactness of the spaces presented good energy saving prospects, the extremely small opening (doors and windows) suggests very low ventilation and sunlight access into the spaces. However, the composition of the dwellings rationalizes the minimalist ideology of the early dwellers.

Figure 3. *Aerial view of the Kandovan Village cliff dwellings.*



(a)

(b)

Figure 4. *(a) Typical Layout and Elevational Section showing the dwelling spaces in the rocky cliffs, (b) pictorial views of the frontage and access stairways to upper dwelling rooms.*

2.2. Study of Modern Concepts

Earth shelter concepts have been utilized as energy conservation ideas in modern times. However, other factors necessitated the emergence of earth shelters as housing options in present times. The most common being the prevalent fears of atomic wars during the 1960's. Other factors include the popular awareness of fragility of the environment and ecological systems. By this process, environmentalists projected the concept of earth sheltered homes in combination with generous landscaping as ways of softening the impacts of buildings to the environment [12]. This brought about the notion of ground-scapers. The comparison of the pros and cons between aboveground and earth sheltered approaches to housing presents various forms of energy efficiency in housing. Different designs based on the two major construction typologies (sunken/true underground design and the elevational design) have been identified in use across the globe. Some of the communal earth shelter housing is presented below.

2.2.1. Earth House Estate Lättenstrasse in Dietikon, Switzerland

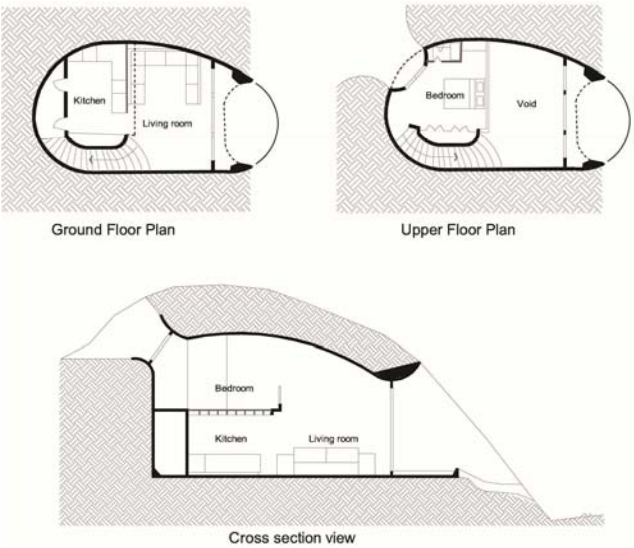
The earth sheltered estate designed by Vetsch Architektur, in Dietikon, is a stunning example of a modern communal residential settlement. The earth-covered homes are grouped around a small artificial lake. The estate consists of nine homes, which comprise of three 3-bedroom units, a 4-bedroom unit, a 5-bedroom unit, three 6-bedroom units, and a 7-bedroom unit (figure 5).

2.2.2. Analysis of Design Typology of Lättenstrasse Estate

The Lättenstrasse Estate utilized the elevational design concept for all the houses. This was done to maximize the natural lighting into the homes. By so doing, the daytime zones of the homes (sitting rooms, kitchen etc.) are situated towards the south, while the nighttime zones (bedrooms) face the north. Rooftop windows were used to get natural lighting into the middle parts where the bathrooms and the connecting stairs to the basement are located.

Figure 5. Aerial view of Earth House Estate Lättenstrasse in Dietikon, Switzerland.

(a)



(b)

Figure 6. *(a) Pictorial view of the Estate, (b) Floor plans and interior section of a typical house in the estate.*

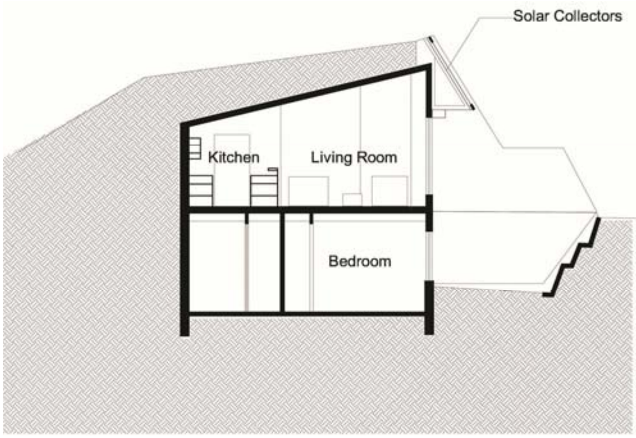
2.2.3. Seward Town Houses Minneapolis

The Seward Town homes' community symbolizes a modern earth sheltered cooperative housing project. It is one of the most city-centered earth sheltered housing neighborhood, with its location adjacent to a busy freeway and adjoining a major intersection. One of the most successful components of this location was the Architect's use of earth mass to dampen the usual freeway noise. Its energy efficiency was optimized through the application of both active and passive solar features. While the active solar system consists of interconnected forced-air flat-plate collectors placed on the roof for preheating the domestic water and storing excess heat, the south facing windows on the other hand contributed to the substantial passive solar gain that is useful in the colder seasons [12].

2.2.4. Analysis of Design Typology of the Seward Town Houses

With twelve units of housing (three 3-bedrooms and nine 2-bedroom units), the Seward community was designed with the bermed concept. The bermed construction consisted of the use of earth piled over three sides of each house, leaving only one side free for both occupants' and solar access. While the bermed front is located to the north side of the buildings and on the east and west ends, the southern front is utilized for seasonal passive solar contact (figure 7b). With its bermed structure on the northern end where the freeway is located, the houses successfully dulled the usual highway traffic noise as well as creating a characteristic landscape along the entire stretch of the community.

(a)



(b)

Figure 7. *(a) Aerial view of the neighborhood, (b) Section of a typical housing unit showing the bermed construction.*

2.3. Potentials of the Communal Earth Sheltered Building Typologies

Apart from the general characteristics of subterranean housing, collective earth sheltered housing ideas present unique potentials over the individual home options. The tendencies of achieving maximum benefits of energy conservation, thermal efficiency and energy balance for earth sheltered designs depict the communal concept as a more effective energy efficient idea. Some of the fundamental principles that may influence the optimization of earth sheltered potentials in collective housing include the following:

i. Seasonal thermal storage systems (PAHS)
ii. Thermal energy balance and energy recycling
iii. Design and construction typologies

2.3.1. Seasonal Thermal Storage Systems (PAHS)

Passive annual heat storage (PAHS) uses thermodynamic principles in conjunction with bare earth to aid the control of micro-climates. When observed in earth sheltered dwelling, it utilizes the surrounding earth to regulate its temperature throughout the year. Annually, the earth receives electromagnetic radiation from the sun (short-wave radiation) and emits it at longer wavelengths (long-wave radiation) [13]. The absorption and re-emission of radiation at the earth's surface level yields the idea for the principle of PAHS. The idea behind PAHS follows the fundamental principles of heat transfer from a warmer system to a cooler system. As is the case with the human body, if you are warmer than the surrounding air, the heat of the body will escape to the surrounding air until temperature equilibrium is attained. Likewise, if the air inside the room is warmer than the surrounding walls, heat will be drawn out of the air into the walls, thus cooling the air and warming the walls. Conversely, if the air temperature inside the room is cooler than the surrounding walls, heat will be drawn out of the walls into the air, thereby warming the air and cooling the walls. In the case of the single earth sheltered dwelling, the earth mass is utilizes to regulate temperature throughout the year. However a collection of dwellings (in a district scale) will perform better, as the number of dwellers will generate extra heat which will be collectively retained within the subterranean mass.

2.3.2. Thermal Energy Balance and Energy Recycling

Buildings absorb excess energy from the soil in contact with them especially during the colder seasons. This absorbed heat is naturally released (through the process of thermal diffusivity) into the building whenever indoor air temperature is below that of the surrounding thermal mass. This action of thermal absorption and releasing process (termed energy balance) provides essential heat energy required in earth sheltered buildings (figure 8a). In a single earth sheltered house, thermal comfort parameters indicate efficient measure which evidently influence rise in interior surface temperature and microclimate [14]. However, with the communal earth shelter option, a larger collection of buildings will be in contact with the earth (thermal mass) and also in contact with each other through the shared thermal mass. This condition will bring about the recycling of thermal energy from one home to another due to the collective earth contact (figure 8b). Hence, the soil's thermal diffusivity coefficient influences the energy balance of these earth sheltered buildings.

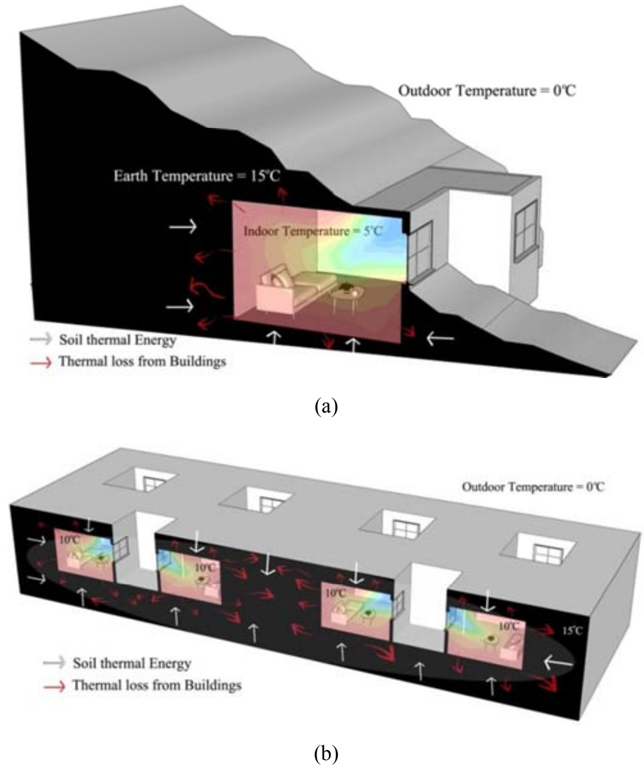


Figure 8. *(a) Thermal transfer pattern in Single earth sheltered home, (b) Thermal transfer pattern showing recycling of thermal loss in grouped earth shelter homes.*

3. Soil Thermal Diffusivity and Effusivity

The rate at which heat energy spreads within the earth affects the rate of spread of thermal energy across the soil and contact elements. Thermal diffusivity is rated as thermal conductivity divided by the density and specific heat capacity at constant pressure [15], this represents the ability of any material to conduct thermal energy relative to its ability to store thermal energy. Soil thermal diffusivity measures the rate of transfer of heat energy from the hot end to the cold end of the soil. Parameters which should be considered in the design for optimal utilization of earth thermal energy includes the soil temperature at specific depth $T(x)$ and the earth thermal diffusivity at same depth (α_x). However, the soil thermal diffusivity, α (m^2/s), depends on soil type, density and water content.

Equally, soil thermal effusivity (thermal inertia) which measures the soil's ability to exchange thermal energy with its surroundings can reflect the value of heat exchange between units in contact with the earth. When units are brought in perfect contact with the earth with temperatures T_1 and T_2, temperature at the contact surface T_m will be given by the relative effusivities of the units as in equation 1 [16].

$$T_m = T_1 + (T_2 - T_1)\frac{\boldsymbol{e}_2}{\boldsymbol{e}_2 + \boldsymbol{e}_1} \quad (1)$$

The multiplication of earth contact home units through communal earth shelter developments improves the tendencies of recycling thermal flow from the soil to the buildings and from the buildings back to the soil (vice versa).

4. Concepts for Modern Communal Earth Shelter Developments

4.1. Communal Sunken/Underground Earth Shelter Developments

Modern designs for Sunken Earth sheltered buildings combine the specific functionality of earth to building thermal effusivity with aesthetics. The figure 9 below, presents a design concept for a modern earth shelter communal housing. While the x-ray view (figure 9b) illustrates the internal living units arrangements which can be circular of rectangular. The significance of circular design presented here is for improved thermal flow. The architectural design assumes the collection of units in clusters linked by "Communal ramped access zone", through which other private atrium/yards can be accessed via vaults. The arrangement of the home units in true underground concepts presents possibilities for all the building envelope covers to be in contact with the earth. Whereby the building covers are in full contact with the earth mass, the tendencies of achieving maximum benefits of energy conservation, thermal efficiency and energy balance is optimal due to reduced losses with fewer exposed building covers to the external air.

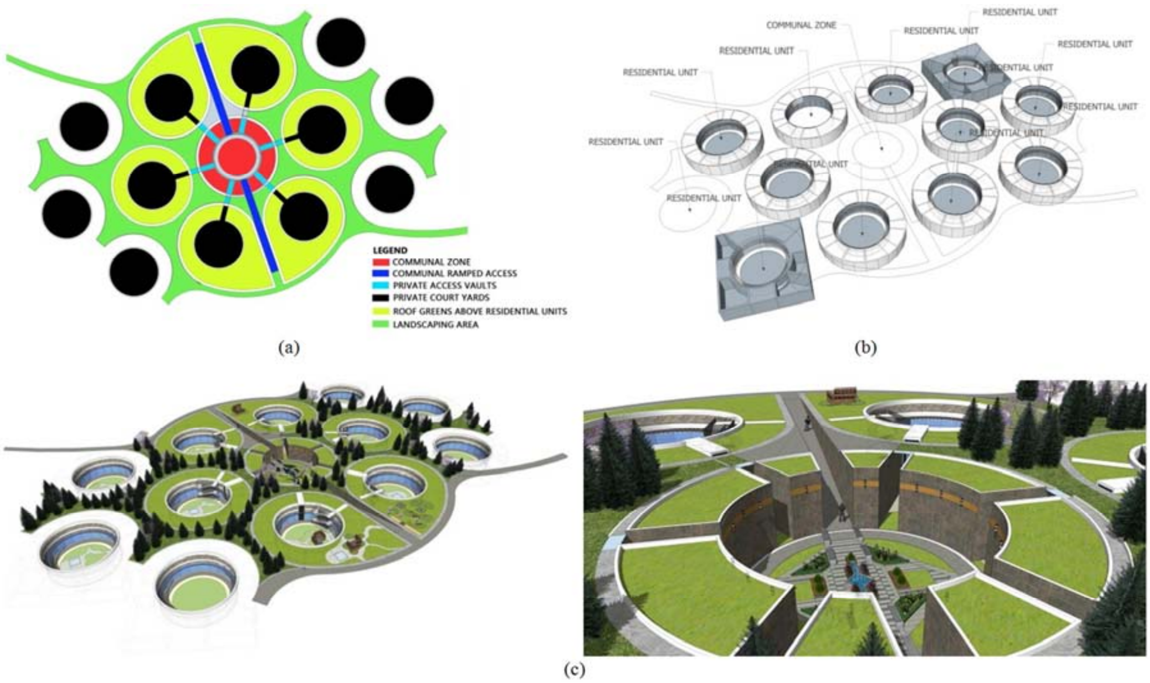


Figure 9. *(a) Layout of a modern Sunken earth sheltered communal architectural design. (b) 3D x-ray view, showing the residential units interior arrangements (circular or rectangular). (c) Aerial views of the central atriums/courtyards for each unit.*

4.2. Communal Bermed/Hillside Earth Shelter Developments

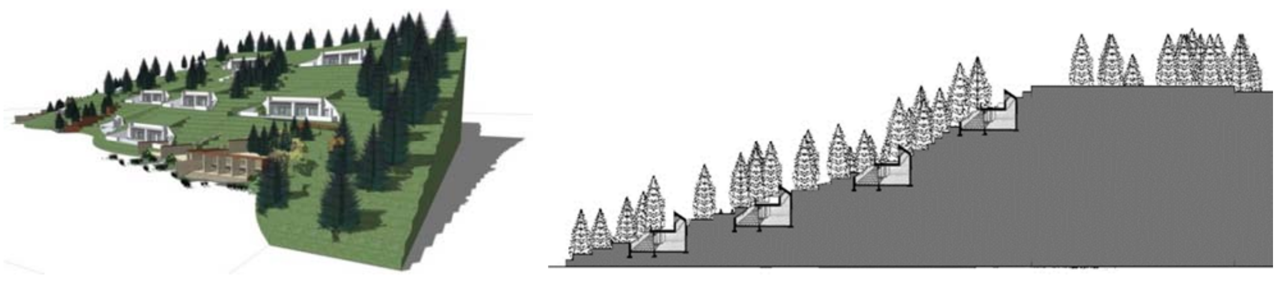


Figure 10. *Earth house district designs (a) Sunken/underground community, (b) Bermed/Hillside earth house community.*

In the case of the Bermed or Hillside communal earth sheltered housing. The design concept presented in figure 10 illustrates the arrangement of home units arranged along the slope sides of hills. The section shown in figure 10b illustrates the elevated levels of the home units which show the earth contact sides of the building covers. Whereas the Sunken/True underground earth shelter homes can achieve up to 75% or more of building envelope contact with the earth mass, the Berme/Hillside option achieves less envelope contact with the earth mass. This means that while the passive thermal gains will be limited only to the reduced contact areas, the tendency of heat loss will be higher on the exposed part of the building cover that is without earth contact. This concept may be considered lower in energy saving owing to the heat and cooling losses due to thermal transmittance factors by losses via the soil to the external air.

5. Conclusion

This paper presented communal design concepts of earth sheltered housing as models for future earth-contact housing. It centered the study on identifying communal earth shelter houses as unique alternatives in underground housing concepts with a view towards improving energy conservation and thermal performance of this category of housing. The review of the traditional and modern classes of communal housing identified various categories of subterranean neighborhood ideas with unique potentials for optimized thermal and cooling properties over the individual home options. Some of the fundamental principles that may influence the optimization of earth sheltered potentials in collective housing were identified as:

i. Seasonal thermal storage systems
ii. Thermal energy balance and energy recycling
iii. Design and construction typologies

While the passive coolness provided by the earth mass is considered a huge potential in hot seasons, in colder climates, the significant property is the reduction of heat loss due to conduction through the building walls combined with the impacts of thermal inertia in the surrounding soil. Apart from the optimization of thermal and energy conservation qualities, communal housing concepts provides unique urban living environments that redefines housing in combination with generous landscaping as ways of softening the impacts of buildings to the environment. By this approach, earth sheltered mass housing optimizes the general concept of building with earth, by creating entire ground scraping communities which enjoy dual land use by locating all housing underground and retaining the natural landscape all through the district.

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