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Earth Sheltered Housing: An Approach to Energy Conservation in Hot Arid Areas

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Abstract. The world's "energy crisis" goes far deeper than being simply a shortage of fossil fuels. The crisis is generated by the reluctance to adopt the use of innovative and less energy consuming solutions for human settlements. A striking example is the large number of new cities and other major urban and rural developments in the Arab world. Despite the enormous repertory of solutions and our knowledge of heat recovery processes, insulation techniques, simple orientation, treatment of building elevations, size of elevations, size of windows, shading devices, building materials and methods of construction, energy in these developments continues to be used wastefully in a very extensive way. This is due to the questionable performance of imported lightweight materials such as metal, timber, asbestos, plastics, rubber, glass and asphalt which are increasingly used in the hot, arid, oil-rich Arab countries. When mechanical cooling and ventilation becomes a necessity, pollution hazards and health problems are then inevitable. Energy planning can improve the quality of our life and the environment in our new developments. Conservation is an essential part of energy planning, helping to economize and reduce the negative environmental impact of any development that uses energy.

The current situation dictates the need for the adoption of technology that is essentially nonpolluting, simple in principle and socially and culturally acceptable. The compatibility of these prerequisites with the characteristic attributes of earth sheltered housing is obvious. Our ancestors adopted simple, nonenergy consuming techniques using earth and masonry as the basic construction materials for their buildings. Such building materials are ideal for a region where rainfall is low, such as in Kuwait, Saudi Arabia and Egypt. These climates favor the use of heavy-weight material which has good thermal performance and a high heat storage capacity. The use of earth can keep a building cool during the warm days and warm during the cold nights. The adoption and use of such methods and techniques present problems which are not radically different from those confornted in conventional planning practices. Legislators, government and zoning officials, banking and finance people, as well as architects, contractors and owners, must be convinced of the validity of such a statement for such technologies to be adopted.

The intent of this paper is to help reach that goal through the analysis of earth sheltered housing developments, the impact of enviomment, climate and site characteristics on their design and the subsequent impact of such developments on the overall ecological setting. It is hoped that this passive solar energy solution will prove to be an excellent approach for the creation of a pleasant environemnt suitable for the prevailing social conditions and aspirations.

Introduction

Today, earth sheltering is a novel idea for many people. Living underground, however, is hardly a twentieth century phenomenon. From prehistoric times to the present, people all over the world have built and lived below the surface of the earth.

Prehistoric cave dwellers, seeking warmth and proteciton from wild animals and severe weather, chose an existing natural earth form-the cave-that provided those needs. In fact, the existence of inhabited cave dwellings in Tunisia, Libya, China and the Loire and Cher valleys of France today provides evidence that, given the proper geology and hydrology, caves can be converted into very comfortable and extremely private spaces,

Throughout history, human beings have often turned to the earth for protection againt climatic extremes and dangers. Around AD 800 the people of Cappadocia in Turkey carved out underground chambers in spines of soft rock, partially in response to the scarcity of good timber and materials for mortar but mainly to protect the inhabitants from invaders [1, p.24].

For centuries, residents of Matmata in Tunisia and Ghirian in Libya (Fig. 1) have carved into the soft rock to create atrium houses in which several excavated rooms with 4.5 meter high, vaulted ceilings open out onto a single sunken courtyard . These houses are built below ground to protect the inhabitants from the extremes of daytime heat and nighttime cold, typical of this desert region.

In China, the courtyard type houses that dot the landscape were dug into the loose, silty soil to combat the hot summers and bitterly cold winters. The chinese provinces of Shansi, Kansu and Homan, faced with the need to preserve agricultural land and house their people, have been digging entire cities beneath the land since the 1920s. Today, more than 10 million Chinese live underground, perhaps the largest number of troglodytes ever to inhabit a single reigon [2, p.113]. Buried at depths of up to thirty feet, underground homes are built around courtyards. The atrium-style design offer ample sunlight (Fig. 2). Each home is protected from biting winds and temperature extremes. Most importantly, the buried cities offer China the opportunity to put the land to dual use since the soil provides ample crops to feed the millions of inhabitants who live below [2, p. 113].

In the American Midwest, sod houses and dugouts were also built in the 1800s in response to severe heat and cold, as well as the lack of building materials-and fuel. Sod houses are still in use today in Scandinavian countries [1, p. 24].

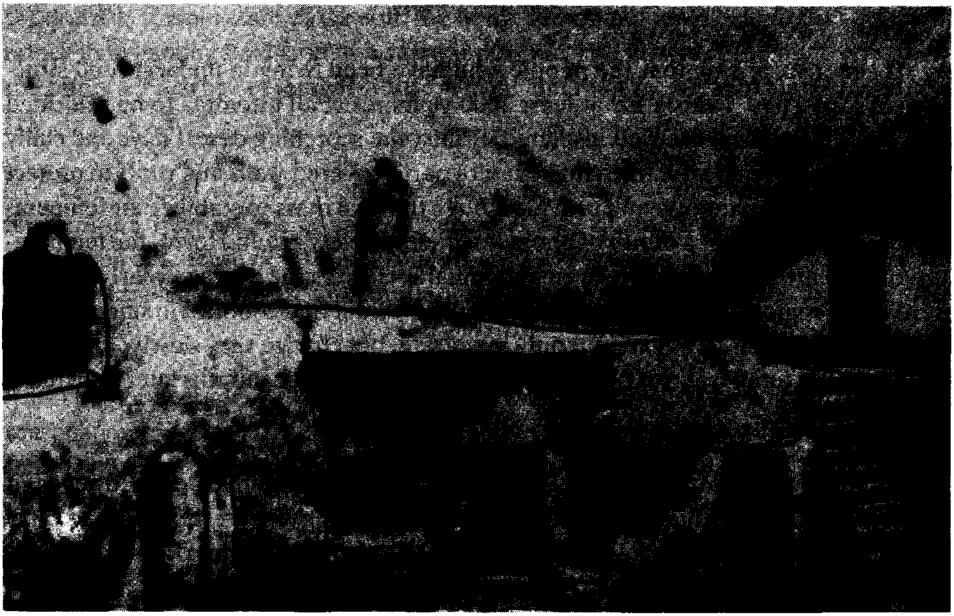

Fig. 1. Atrium houses in Matmata, Tunisia and Ghirian, Libya [9]

Fig. 2. **Underground village in northern China Drawing by Mark Heisterkamp based on a Photograph from *Architecture* Without *Architects* by Bernard Rudofsky [9, p.10].**

Heat and Cold

It is not surprising that the people who have been living in underground structures in Libya and Tunisia for at least 2000 years resist all attempts to be relocated from dwellings which are well insulated against the scorching desert days and chilly nights. Underground structures make use of earth covered walls and roofs to protect the interior from radiation and provide a huge thermal mass to stabilize air temperatures. Furthermore, at a depth of about 2.5 meters below ground level, the temperature of the earth is remarkably even and remains close to the average yearly temperature of the region, providing relative warmth in winter and coolness in summer. Soil temperatures at this depth are not only moderate, but change very slowly; maximum and minimum temperatures below ground occur up to three months later than those on the surface.

Building an underground house is not particularly complicated. However, it does have its own peculiarities: problems of weight for instance -roofs have to carry up to 2 meters of earth, problems of water proofing, and problems of insulation and cross ventilation. Wind catchers, ventilation ducts, evaporative coolers and sunken courtyards are possible solutions. Insulation of the roof and tops of walls protects the interior from the faster temperature swings near the surface, while the lower parts of walls and the floor can be exposed to the much slower temperature variations that occur at the deeper levels.

Physical Characteristics and Performance

Those unfamiliar with the basic concepts of earth sheltering assume that the excellent thermal performance and energy savings associated with underground houses result from the insulating qualities of the earth around them. In fact, although the large amounts of earth that usually cover two, three or even more sides and the roofs of most earth sheltered houses do have some insulating effect, many meters of earth would be required to equal the insulating properties of just a few inches of rigid insulation. The real energy-saving potential of earth sheltered homes is based on several physical characteristics.

Soil temperature and heat loss

Earth sheltered houses lose less heat through the walls and roof of the building than do conventional aboveground structures, which lose heat in winter and gain heat in summer. The earth surrounding an underground structure works as a temperature moderator, reducing summer heat gain and winter heat loss. Due to the relatively stable temperature of the soil, the 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 [1].

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 [1].

The Minneapolis-St. Paul area in the USA (Fig. 3) offers a comparison of the seasonal temperature fluctuaitons of the soil at different depths with the outside air temperatures. Whereas the latter swing as much as 68°C (122°F.), from -30°C (–22°F.) to 38°C (100°F.) annually, the temperature of the soil 5 to 8 m below the surface is virtually constant. Three meters below the surface, the annual soil temperature range is only 22°C (75°F.) [1] .

The slowness with which soil temperatures change creates a thermal flywheel effect that contributes significantly to the energy efficiency of earth sheltered dwell-

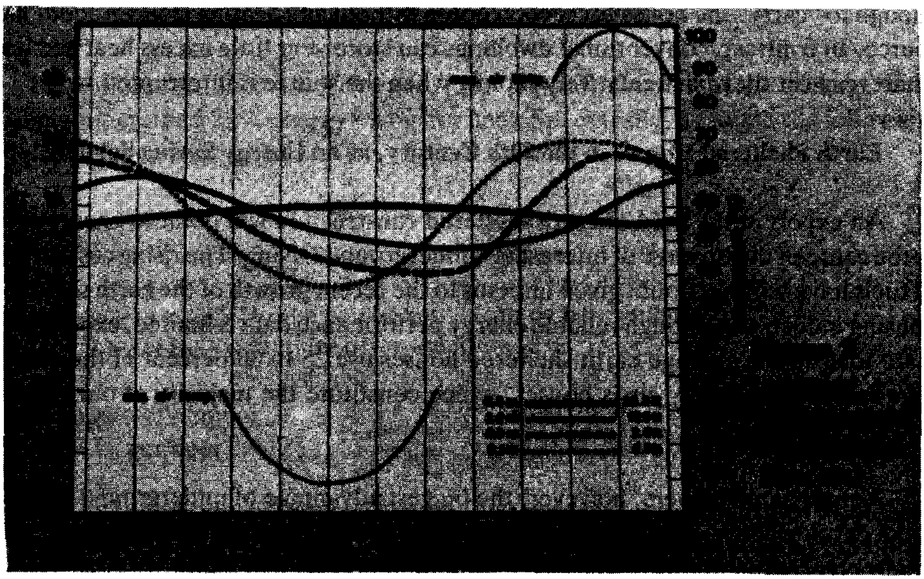

Fig. 3. Annual temperature fluctuations (air), Minneapolis, Minnesota [1]

ings. For example, in Minnesota, soil 3 m below the ground reaches its coldest temperature not in the dead of winter but in early spring, just as air temperatures begin to warm. By the same principle, this soil is warmest around November, when outside temperatues begin to drop. Hence, the periods when energy derived from fossil fuels is likely to be necessary are shorter than is the case for most conventional houses [1].

Another energy-saving characteristic of earth sheltered structures, as distinguished from aboveground structures, is the lower heat loss due to infiltration. A conventional, not well-built, aboveground house loses a certain amount of its heat through cracks around windows and doors and generally throughout the structure. This process is accelerated when the wind blows. With proper siting the soil can protect an earth sheltered house from the cold or hot wind, reduce generally infiltration considerably and lower heating or air conditioning bills.

The heat storage capacity of an earth sheltered building, due to the high thermal mass of the structure and the surrounding earth, is another important characteristic. The thermal mass of a structure is a function of the density and quantity of the building materials combined with their ability to store heat. Any building with a large thermal mass, especially a concrete shell, absorbs heat from the air or from direct solar radiation and releases it back into space at night, when there is a net heat loss. In an earth sheltered house, which also has a high thermal mass, this process can be slow enough to "carry" the house for several hours without any heating from an additional source. In contrast, conventional dwellings can store very little excess heat and lose whatever heat they have relatively rapidly when the source is interrupted.

Earth Sheitered Houses in the 20th Century, as an Energy Saving Solution,

An expert in the field of earth sheltered construction will point to energy costs as the cause of the upsurge of interest in "underground" living. The rising costs of fossil fuels have without doubt given impetus to the recent growth of the earth sheltered housing industry. Although reliable energy performance data is limited, experts estimate that on the average earth sheltered houses use 25 to 80 percent of the energy required by pre-energy cirsis houses, which constitute the majority of our present housing stock [1].

Among homeowners, however, the biggest advantage of underground housing is the extraordinary energy savings. "We pay one third of what we would have paid in a regular structure" says underground - homeowner Pat Clark, of frosty River Falls, Wisconsin [3, p. 7]. Extensive studies by Dr. Thomas Bligh of MIT, a founder of the American Underground Space Association when he was at the Unversity of

Minnesota, predicted a typical energy saving of 75% with an earth-covered house. Dr. Thomas Bligh of MIT states, "In no way can improved insulation on an above ground building begin to compete with subsurface structures from an energy-conservation standpoint" [3, p. 7].

The reason underground housing saves so much energy is not that the earth is a good insulator. In fact, as Wells notes, "earth is a lousy insulator". Urethane foam is perhaps ten to twenty times as good. But, Wells points out, "earth.. . is a great moderator of temperature change. Warm it up, and it stays warm a long time" [3, p. 7].

Earth does not react as fast, or as severely, to temperature change as air does. That means, for instance, air temperatures on the surface range from 0°F to 95°F. Four yards down the temperature of the earth will vary only from 50°F to 65°F. The earth serves as a warmer in winter and as a cooler in summer, tremendously reducing the load on home heating and air-conditioning systems. These are the reasons for the significant energy reductions in earth shelters. A good specific example of this comes from Ray Sterling, of the American Underground Space Association: "In Minnesota", he notes, "we have an air temperature range of 130°F annually = From - 30°F in winter to 100°F in summer. But the temperature of the soil, if you dig down just ten feet, swings only 20°C - from 40°F to 60°F. Even immediately below the surface you have only a 40°F annual swing, and there's practically no daily swing" [3, p. 96-100].

Lloyd Harrison, Denver, Colorado, [3, p. 99-100], found that the underground dwelling generated a 72% energy saving for heat. Specifically, he found the following rates of heat loss and gain:

	Surface house	Earth shelter
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

To estimate the amount of money an earth shelter might save, the current local rates for the preferred energy systems used for heating and cooling should be obtained. The difference between the surface and earth shelter amounts will be a general indication of expected savings [3, p. 100].

Earth sheltering is not the only means of saving energy in housing. The appropriate use of superinsulaiton and active solar and/or passive solar heating can achieve energy performance in conventional homes similar to that in earth sheltered residences. Earth sheltered homes, however, do have additional advantages: they are genrally much quieter than conventional, aboveground houses because the earth surrounding them "dampens" noise from the outside; their masonry/concrete structure – concrete is still the most commonly used structural material – is rotproof and verminproof and usually more fire resistant than other materials used in aboveground houses; and natural disasters such as tornadoes and severe storms have less effect on them because they are below ground level.

Earth sheltering makes good environmental sense too. Building into a hillside or below the earth's surface preserves an attractive landscape while still allowing access to natural light. Furthermore, sites that may be undesirable for conventional homes due to noise to traffic patterns, for example, through earth sheltering may be successfully adapted for residential use. And what is more, this mode of construction is functionally related to the concept of "working with nature" in terms of designing and planning. In fact, the overall concept of earth sheltering implies that, through design and landscaping, constructions will blend into the surrounding environment. In this way the lines and forms of earth sheltered houses tend to "complement" and "duplicate" forms found in nature.

House Types

Earth sheltered houses are not limited to any fixed design solutions. The two house design concepts illustrated in this paper are the elevational and atrium plans.

Single exposure elevational designs, particularly appropriate for colder climates, group all windows and openings on a single exposed elevation, preferably facing south in colder climates and north in hot climates, leaving the three remaining sides buried in the earth. In colder climates, energy requirements of such a structure – already low by its limited exposure – can often be reduced even further by facing its windows south which maximizes the benefits of passive solar heating (Fig. 4).

However, the three major determinants of orientation are sun, wind and outside views. Proper orientation of a house with respect to sun and wind can produce significant energy savings.

The sun is one of the most important determinants in energy efficient building design. The radiant energy from the sun can be used in both an active and passive

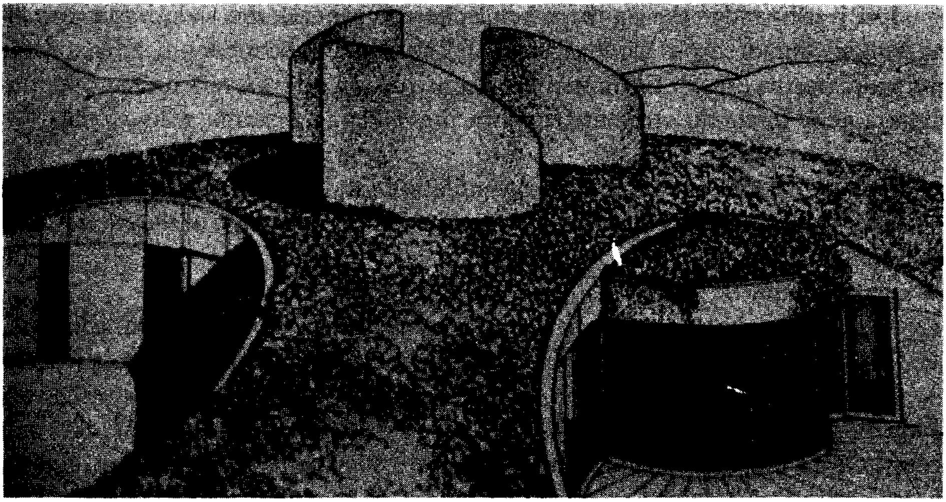

Fig. 4. Modern underground shelters [9]

manner to provide heat for a structure. Usually, the active solar collector system will be facing directly south. All passive solar collection methods are based on trapping the radiant energy of the sun which enters through the windows. The use of passive solar collection techniques in the energy efficient building is a very desirable concept since it does not involve the capital expense that an active solar collector does and can provide a substantial amount of energy.

Considering the sunlight alone, the best site orientation for any earth sheltered house (in cold climates) would place all of the window openings on the south side with the remaining three sides completely earth covered [4, p. 20]. Passive solar collection is diminished considerably with east and west facing windows and eliminated completely on the north side. It is also important to note that, while sunlight and sun-radiation are desirable in the heating season of cold weather, they are not as efficient in the cooling season of hot climates [4, p. 20].

The effect of wind on the orientation of an earth sheltered structure is a serious energy consideration. Since direct exposure to cold winter winds increases heat loss due to infiltration and 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 [4, p. 21]. Minimizing window and door openings on the north and west sides of the house will enhance its energy performance. The prevailing summer breezes are from the southeast [4, p. 21], although they can vary from site to site depending on local conditions, trees, and topography.

In Riyadh, and in the southern hemisphere in general, the undesirable prevailing winter winds are from the southeast [5]. The desirable summer breeze is from the north and northwest [5]. Earth sheltered construction offers a very unique opportunity to totally shield the structure from the prevailing undesirable winter winds.

However, to create natural cross ventilation inside the structure, some outlets such as windows or vents must be provided on the opposite side of the front wall of the building.

In a courtyard or atrium design, which is particularly appropriate for a flat site, the habitable rooms cluster around a central courtyard which provides abundant access to natural light. In its simplest from, the atrium is as aquare court with living spaces on four sides, or just three sides, leaving the fourth open for light, view and access. Other larger plans may use two or more courtyards, usually uncovered. In colder areas, they may be covered with glass. The sense of privacy provided by grouping the living space around an interior court and the flexibility it provides with regard to site orientation are among the advantages associated with this type of a plan -in contrast to most single exposure elevational plans where a southerly exposure is more or less compulsory (Figs. 1, 2, 5-7).

The architect Malcolm Wells [3, p. 3-19], thinks the atrium design has major drawbacks. He feels that the layout means "you just end up looking across at some-

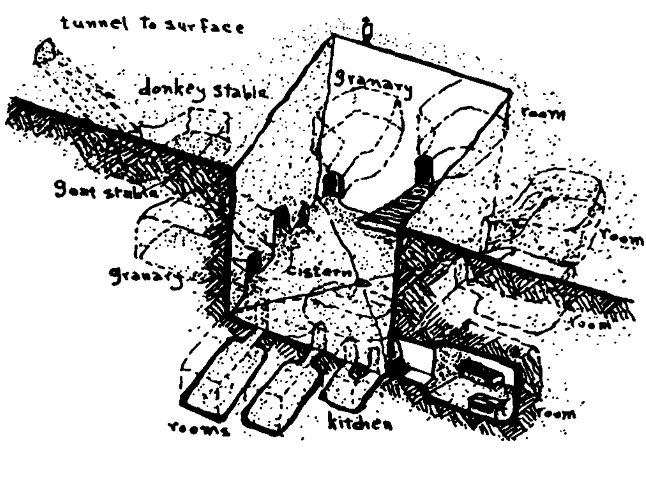

Fig. 5. **Diitic illustration of a typical Matmata, Tunisia and Gbirian, Libya dwelling with various rooms carved out of tbe earth around a 10 to 15 square meter sunken courtyard [6].**

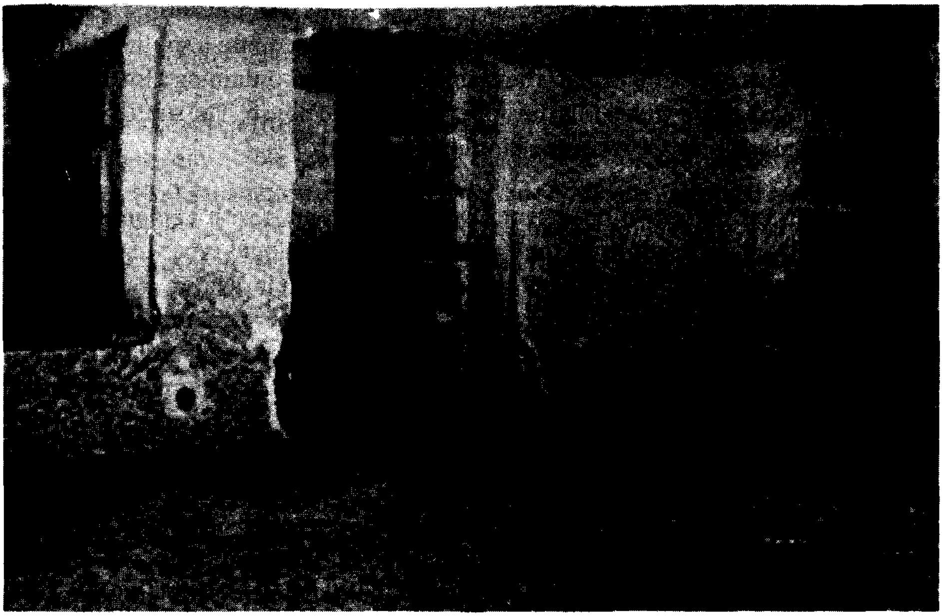

Fig. 6. Underground swelling units in Ghirian, Libya [8]

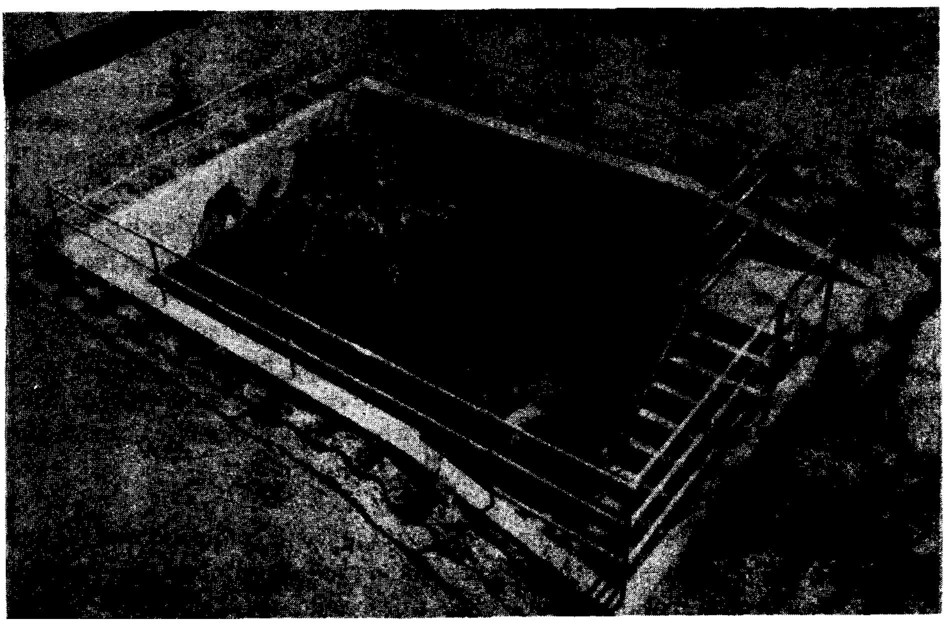

Fig. 7. **John Barnard's atrium-sheltered Ecology House has become the prototype of** the most **popular earth shelter style [3, p.18].**

one else's window". Wells prefers houses that are built into hillsides. The hillside house is more cavelike than the trium home, being recessed into a south-facing hillside. The southern exposure orients the front wall, usually containing a lot of window space, to strong sunlight which fills the upper level of the house. The sunlight can also drive solar-heating units to warm the building [3, p. 19].

Variations on these two basic types range from homes with openings in more than one wall to combinations of the "atrium" and elevational types of one of two levels, sometimes partially above and partially below ground. Naturally, the differences in amounts of earth cover influence, in turn, energy performance. In any case, although most earth sheltered houses consume less energy than conventional houses, their interior spaces feel very similar to those in homes that are completely aboveground.

Site analysis evaluation plays an important role in deciding whether an underground structure has any economic or energy advantages over a conventional one. An overall feasibility study including estimates of costs with emphasis on the energy consumption needed for construction and the maintenance and operation of the building during its service life will provide the decision maker with the necessary data to answer such questions as: Is the initial expenditure prohibitive in spite of any possible energy savings? And if not, will the additional costs of underground construction be offset by the reduced energy costs over the life of the structure? Furthermore, a special site investigation program will provide the designer with the necessary information concerning the thermal properties and strength of the soil and the water table conditions, both very decisive factors for such an underground endeavour [7].

The strength of the soil must be determined for the proposed depth of building below ground level. Excavations in a very strong soil are difficult and, in the case of rocky ground, may prove impossible, while 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. For the third case, however, the excavation may be difficult because high lateral earth pressure requires construction of heavy walls, preferably made of reinforced concrete, which implies increased capital costs and energy consumption [7].

The water table level, a very important factor in itself, combined with the area to be built and the permeability of the surrounding soil, determines the amount of water to be pumped at the construction stage, a process that may become prohibitive due to the costs involved. Prohibitive conditions also occur in cases where the water table contains a high amount of sulphite which reacts chemically with concrete and masonry. Finally, the water table level must be seriously considered in connection with possible additional lateral pressures on the walls after construction [7].

The thermal properties of the soil -if one of the above processes proves that the initial costs are reasonable -will facilitate the comparison of the energy needed for construction (soil excavation, dewatering and concrete mixing) with the energy to be saved in the long run, conditions related to the insulation efficiency of the soil. This efficiency, however, 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 (Fig. 8).

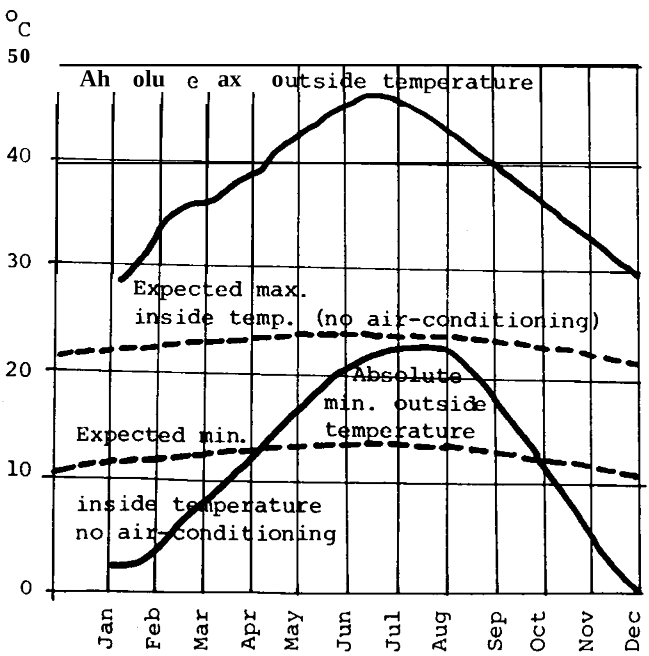

Fig. 8. Annual temperature fluctuations in Riyadh (from below zero to 48°C) and expected temperature fluctuations at 3.0 m below ground level (between 14°C and 24°C) [J].

Conclusion

We must take a serious look at the idea of the earth sheltered house as the house of the future, while at the same time carefully integrating the design with the cultural heritage and social needs of the people for whom it is being built. A developed site with earth sheltered houses will not disrupt the landscape. On the contrary, it will allow the natural beauty of the land to remain. Such low energy cost houses, noted for their "silence" and quietude, successful for centuries and functionally "inscribed" in the natural and social environment, will continue to be with us for a long time.

The Arab world must adapt its housing needs to its own environment. Earth sheltered housing, the technology for which is already available, is a positive step in that direction.

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الإسكان تحت الأرض: كوسيلة للاحتفاظ بالطاقة في المناطق الحارة الجافة

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ملخص البحث. إن أسباب مشكلة الطاقة في البلاد الحارة الجافة أكثر عمقًا وتعقيدًا عن كونها ببساطة نقص في الوقود الأحفوري والمستخرج من باطن الأرض. فالمشكلة تولدت بسبب التبديد والإسراف في استهلاك الطاقة، وعدم تبني الحلول الإبداعية والمبتكرة في التجمعات السكانية الأقل استهلاكًا للطاقة. ولذا نجد أن العديد من المدن الجديدة، وكذا المشروعات العمرانية والريفية والتي أنشئت على مقياس كبير في أرجاء العالم العربي لا تستخدم مبدأ التوفير في استهلاك الطاقة.

وبالرغم من الوفرة الزاخرة من الخبرة والمعرفة بالحلول المعمارية الجيدة وكل ما يتعلق بالسلوك الحراري لمواد البناء، وطرق ووسائل العزل الحراري داخل المباني وخارجها، وكذا أفضل وسائل التوجيه للمباني نفسها وكيفية معالجة واجهتها مناخيًا، وتحديد أفضل المقاسات والمساحات لها بالنسبة لكل توجيه مناخي، ومساحة النوافذ الزجاجية بكل واجهة، ونوعية وسائل التظليل، ومواد البناء وطرق الإنشاء، فإن الطاقة لازالت تهدر بإسراف وتبذير في هذه المشروعات العمرانية والمدن الجديدة.

وكل ذلك يرجع إلى استيراد العديد من مواد البناء الخفيفة الوزن والمشكوك في أدائها الحراري مثل المعادن المختلفة، والخشب، والأسبستوز، والبلاستيكات، والكاوتشوك، والزجاج، والأسفلت والتي زاد استعمالها بكثرة في الأقطار العربية ذات المناخ الحار الجاف.

ولـذا يجب أن يُلفت النـظر إلى أن التخطيط للطاقة وترشيدها يمكن أن يحسِّن من نوعية حياتنا الصحية والفيزيائية في بيئتنا العمرانية. وأن الانتفاع بالطاقة الطبيعية لهو جزء أساسي في عملية التخطيط لها، حيث تسـاعـد في تحقيق العامل الاقتصادي في مشروعاتنا وتقلل من التأثيرات السلبية الناتجة عن استعمال الطاقة الميكانيكية في البيئة العمرانية.

والهدف من هذا البحث هو المساعدة في الوصول إلى توضيح هذه المرئيات من خلال تحليل لبعض المشروعات الإسكانية المبنية تحت الأرضية، والتأثيرات البيئية والمناخية عليها، وكذلك تأثير ظروف الموقع وخواصه على تصميم هذه المشروعات الإسكانية وكذلك تأثيرها على حياة الإنسان نفسيًّا، وبيئيًّا وصحيًّا وفيزيائيًّا.