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# SOIL THERMAL PERFORMANCE AND GEO-SPACE DESIGN

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## ABSTRACT

Geo-space is a general term used here for earth-integrated spaces at different depths and in different forms. The term is also commonly employed in Japan for space to be created deep below ground. The Japanese designers have recently introduced several innovative concepts on the usage of such deep geo-space especially for diverse infrastructure and have integrated within it the use of a "shallower" geo-space for daily multi-human activities. This paper is concerned with the shallow below-ground zone of around ten meters depth. It discusses the correlation between the thermal performance and the design form, the functions and the significant benefits of such geo-space.

## 1. INTRODUCTION

The most early shelter used by mankind as a natural form for living was the cave. It provided an ambient protective environment against the outside harsh diurnal and seasonal climate. Throughout the many millenia of using this form of shelter, man has come to recognize the significance of the soil thermal pattern and its process pattern and used it to his advantage for living, food storage, working and for the protection of his well-being.

Contemporarily, we can find three major community concentrations which are still practicing below-ground space and which have accumulated some thousands of years of experience in living this way. The largest concentration is located in the loess-type soil zone of northern China where an estimated 35-40 million people live in below-ground dwellings (*yaodong*) in rural as well as urban communities. The other are Tunisia (at the Matmata Plateau) and Cappadocia (Central Turkey).

The common denominator among these three major historical concentrations is their location in regions of arid and semi-arid climate, their lengthy accumulated historical evolution along with their distinct architectural design, and their adjustment to the harsh environment. Their arid climate region is characterized by temperature fluctuations between extreme highs by day and lows at night and by torrential, yet limited, rainfall. It seems that the need for protection against this climate, in a region where fuel resources are limited, has contributed significantly to the selection of this form of living. The author's study of these cases provided a wealth of data concerning below-ground space thermal performance, design form, interior micro-environmental considerations, and reciprocal indoor-outdoor relationships. It is our opinion, that the study of this data can benefit our modern geo-space usage.

The recent special interest in the technologically advanced countries in use of earth integrated space has been the result of efforts toward energy saving, as well as the result of a drastic rise in urban land cost, increasing space consumption and other pressing forces. Modern geo-space is now in use for habitats, educational facilities (USA), shopping centers (Japan and Canada), industries, ports (Scandinavia), agriculture production, food and grain storage (China), hospitals, museums, restaurants, and entertainment centers.

## 2. SIGNIFICANT BENEFITS

Geo-space living is an effective way to cope with the outdoor climatic conditions especially the harsh ones. Its weatherproofing provides a comfotable ambient environment in both winter and summer. It consumes less energy and reduces heat gain and

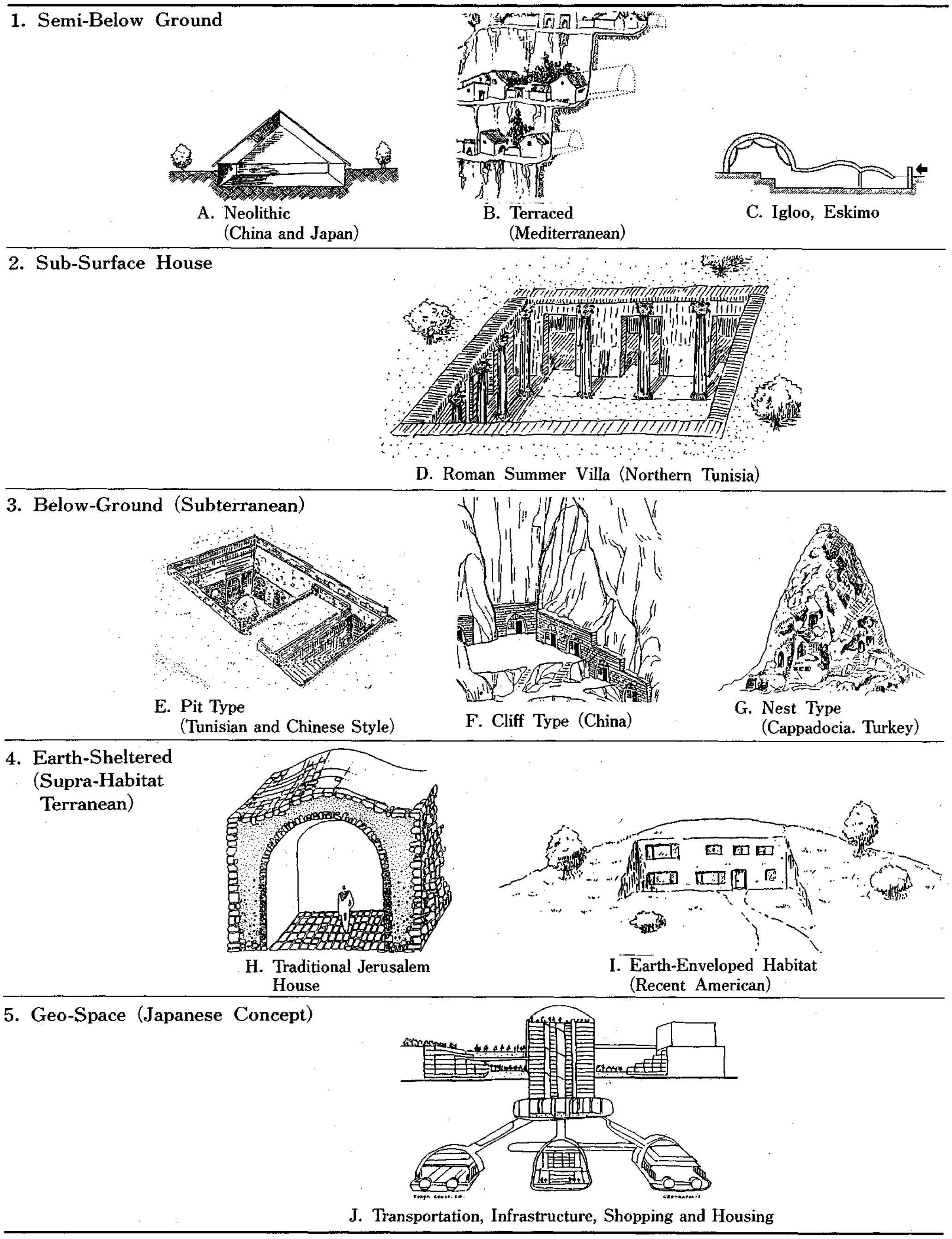


**Fig.1** Different types of earth enveloped habitats

heat loss. There are other benefits as well.

Generally, the land cost is reduced, either because of the possible dual use of it or because of construction on low-priced sloping land. In fact, land saving can be significant since it releases other above-ground space for different purposes such as playgrounds, recreation or other buildings. The insulated quietness of the geo-space habitats enables them to be built even near airports. Design and building cost can be minimal when a large production takes place or when, geologically, the lack of stratification enables the "cut and use" method of construction. Also, due to the paucity of exterior building materials utilized and the low maintenance, the price is reduced. There is no need for new roofs every 10 to 15 years and the damage

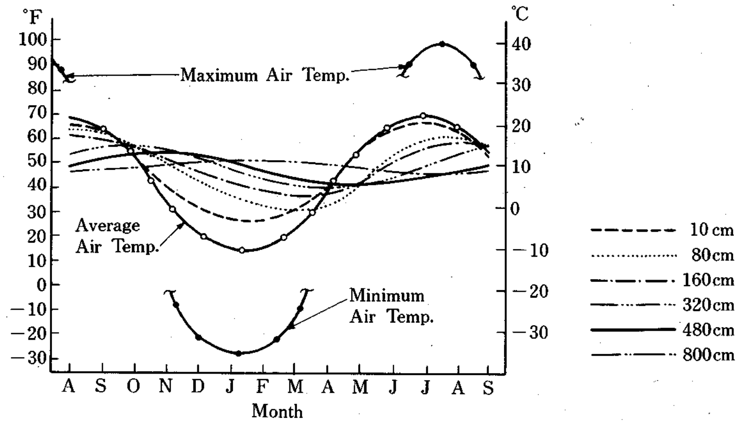


**Fig.2** Average monthly soil temperature changes at different depths.

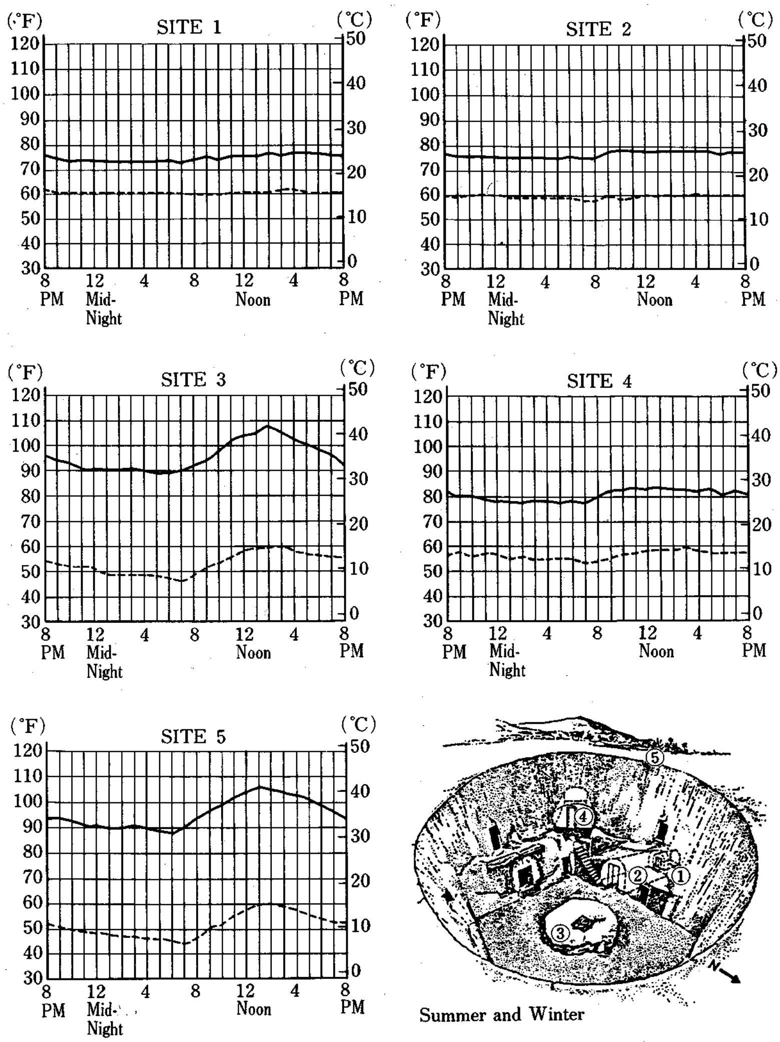


**Fig.3** Comparison of summer (solid line) and winter (broken line) dry bulb temperatures of the five sites, measured diurnally in Matmata, Tunisia

normally caused by wind, hail, rain, snow or other natural factors is minimal.

Geo-space habitat preserves the land and environment and saves plenty of space for green and open areas. It provides privacy, quiet and a relaxing environment. As such, it is ideal for creative work, such as writing, music, composition, painting and sculpture.

Geo-space habitat can be safer than the above-ground environment when it is properly designed. It is protective against storms, cyclones, tornadoes, radioactive fallout, and it is fireproof, with minimal potential for a fire to spread to neighboring houses. Accordingly, insurance is expected to be lower than for the conventional above-ground house. It can be made safer against earthquakes if protective design measures are taken. Geo-space habitats do not have problems such as water pipes freezing and cracking.

Also, geo-space offers diversified land use with special advantages. Temperature stability of geo-space is most suitable for certain industries which require seasonal or perennial thermal stability such as the film and wine industries. Our research findings point out that the minimal thermal fluctuation of geo-space helps to bring the healing of external wounds after an operation. We found that the wet and dry temperature synchronization reduced the time required in the recovery room for surgical patients by 20 percent.

Research conducted in below-ground living in Australia revealed that living in a geo-space is more tranquil and healthier than above-ground space, especially for chidren. A mother when interviewed, indicated that her children had never slept so tranquilly as they did in the geo-space habitat (Sydney A. Baggs, "The Dugout Dwelling of an Outback Opal Mining Town in Australia," in Underground Utilization, vol.Ⅳ, p.573).

Geo-space can also be used for large scale refrigeration and central food storage, especially citrus fruits and vegetables due to its coolness in summer. Such storage centers are used in Cappadocia, Turkey, in Ohya, Japan, and in Chongqing, China. In the Middle East, as well as in China and many other places of the ancient world, geo-space has been used extensively for grain storage. Grain storage pits used in China during the Tang Dynasty (7th to 10th centuries) were recently discovered in Luokou and in Luoyang city (Henan province) where more than 50% of the grain was still in good condition. Modern methods for geo-space granaries are now being researched in the USA with a potential for large-scale development.

Other effective uses of geo-space in the USA today are for educational facilities, such as libraries, schools, bookstores and the like. In universities, where space is precious and the expansion of the existing well-established library becomes essential, the nearby geo-space becomes an ideal solution without interference with the existing environment. Here too, thermal stability is an asset in preserving the book's quality. However, in the case of the library, there is a need to have stable, low relative humidity. Good examples of libraries expanded in geo-space in the USA are at the universities of Illinois, Harvard, Johns Hopkins, and Cornell, to name a few. Also, there has been a development of around one hundred modern earth integrated schools in the USA.

Similarly, a large number of offices, public gathering places, business spaces, religious centers and habitats within geo-space have been constructed within the last two decades. This new movement of earth-sheltered usage was generated in response to the energy crisis, the need to obtain ambient environment thermal conditions or environmental protection.

## 3. DESIGN EVOLUTION OF GEO-SPACE

Since the early use of the cave as shelter there have been different earth integrated spaces developed by mankind for various other uses. Accordingly, a long list of terminology has been adopted to represent these diverse forms. However, the variation of forms represents different degrees of relationship to the soil and patterns of thermal performance, adjustment to the local environmental conditions, and the availability of building materials (**Fig.1**).

However, the design of geo-space especially for living to meet our modern norms and standards, necessitates special considerations and treatment specifically in the elements of form, thermal performance, natural light, sunshine, ventilation, and accessibility. This paper focuses on the thermal performance of geo-space and the related principles of the design form.

## 4. SOIL THERMAL PROCESS

One of the strongest elements influencing geo-space usage is the thermal performance of the soil. Generally in the past, interest in the study of the soil thermal performance process was limited to a specific zone of the soil. The agronomist's interest has been in the shallow few tens of centimeters depth which effect vegetation. On the other hand, the mining engineer has been concerned with a depth of hundreds of meters and its thermal performance. Geo-space designers became interested in the zone ranging between 0~10 meters depth when modern geo-space usage became feasible (**Fig.2**). The rediscovery of this zone has wide potentials for usage and has broad economic, social and health implications.

The soil mass thermal process differs significantly from that of above-ground space. In general we can state that down to a depth of around ten meters, the soil thermal pattern depends upon the sun as the main heat supplier. As the depth increases further the effect of earth heat increases. However, the heat gain and loss and thermal behavior within the soil depends not only on the intensity of the source of thermal supply but also on the soil composition and density (rock, sandy, alluvial etc.) and the degree of water containment.

During the day, solar heat influences the soil to a shallow depth generally ranging between 5-7 centimeters. Yet, there is a continued movement of this heat to the depth of around 10 meters. The basic rules are :

* Between the soil surface and this depth there is a seasonal thermal fluctuation which decreases toward the depth and increases toward the surface. No diurnal temperature fluctuation occurs.
* Around the depth of 10 meters the temperature is seasonally stable (**Fig.3**).

In short, the soil has two distinct functions. One is as an efficient insulator of heat gain and heat loss. The second is as a thermal retainer. Our findings show that it takes one season of around three months for the air temperature to travel to a depth of around 10 meters. To obtain thermal retainment it is necessary to have the mass of the earth. Thus the summer air temperature will reach geo-space at a depth of 10 meters by the winter season and the winter air temperature will reach that depth by the summer, when it is most needed.

## 5. EARTH-ENVELOPED HABITAT PERFORMANCE

The realization of these two functions of the soil is essential for determining geo-space design and form. If insulation alone is required we would need to build the habitat above ground and envelop it with layers of earth as in the adobe houses of the southwestern USA. In fact, we can today achieve the insulation with modern thin walls of high quality insulation capability and can minimize heat gain and heat loss. Many modern American habitats of the 1970's and the 1980's have used the above-ground earth-enveloped form to achieve high insulation. In this way they missed the significant advantages of the soil mass thermal retainment of geo-space—the natural process resulting coolness in summer and warmth in winter.

## 6. JERUSALEM HOUSE

In spite of what we have said above, it is still possible to build the habitat above ground and eatablish the heat retainment process. Throughout the historical evolution of human settlement our ancestors have realized the soil's natural seasonal thermal process and have practiced it by simulation in building thick walls in the above-ground habitat. A good example of this is the traditional Jerusalem house design type.

The Jerusalem house type practiced throughout history until half a century ago is made of thick walls formed of 1~2 meters of soil. The wall is sandwiched between large stones on the outer side and small stones and mortar on the interior (**Fig.1-4H**). The outer wall receives the low winter temperature and the high humidity and forwards them through the soil to reach the inner wall by the summer and establish an indoor cool environment. Similarly, the summer's high temperature and dryness received at the outer wall is processed to reach the inner wall by the winter. In short, the interior part of the Jerusalem house is cool in the summer and warm in the winter. The thickness of the wall determines the heat gain and heat loss period and the heat retainment capacity. To a great extent this house design is a simulation of the thermal performance of the earth mass itself.

## 7. THERMAL FLUCTUATION

There is a strong correlation between the depth of the soil and temperature fluctuation. The governing rule is that the greater the depth from the soil surface, the smaller the thermal fluctuation. In general at a depth of ten meters the temperature is stable seasonally and diurnally at around 22 °C in the summer and 15 °C in the winter. Further at much greater depths the temperature increases due to heat coming from deep within the earth.

Geo-space has its own ambient microclimate independent of the outdoor air temperature fluctuation. This fact is significant especially in regions of harsh climate where the establishment of temporary or permanent settlements becomes necessary for the exploitation of natural resources.

It is, however, possible to minimize temperature fluctuation between the depth of zero and ten meters by distorting the normal thermal pattern. This can be achieved through the construction of horizontally extended insulation between the geo-space ceiling and the soil surface and beyond the geo-space size. In this case it will take the surface temperature a longer time to travel through the greater mass of soil in order to reach the walls of

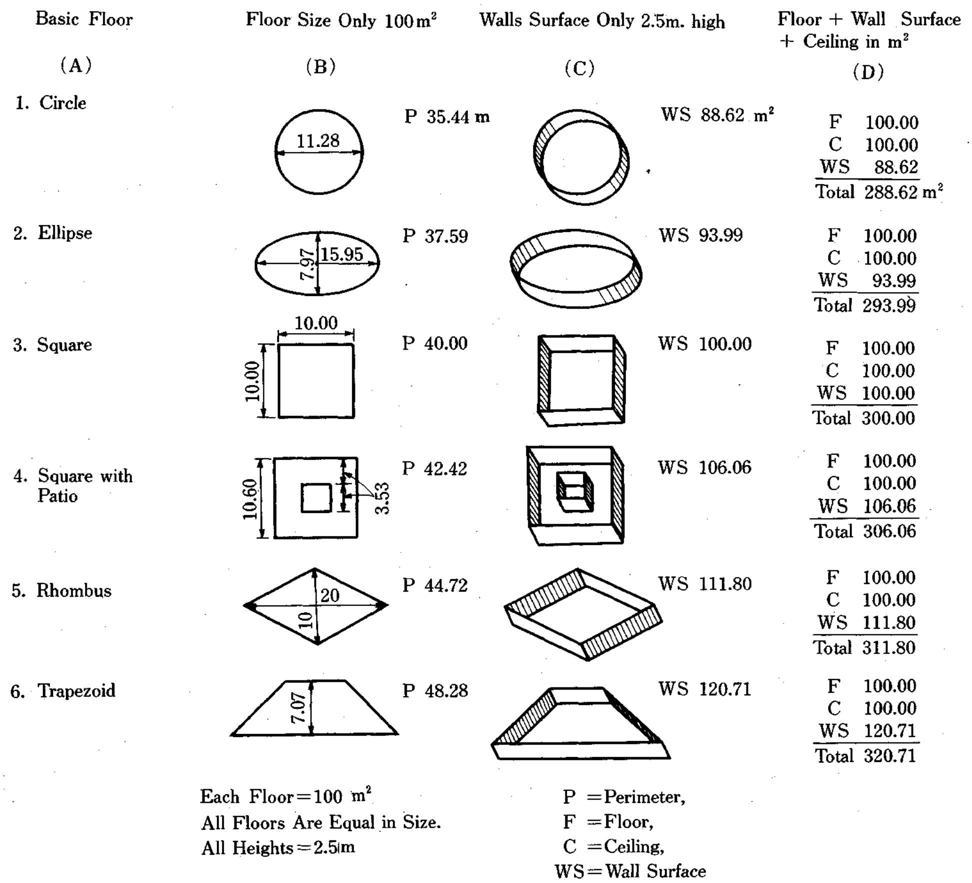


**Fig.4** A variety of design forms with equal floor area as well as equal height to the ceiling.

the geo-space. Another way is to cover the ground surface above the geo-space with buildings or dense forest.

Soil thermal fluctuation patterns can also be distorted when acceleration of the soil thermal process is desired to reach geo-space in a shorter time than usual. To achieve such reaults, the soil surface above the geo-space is to be watered in the evening causing the temperature received throughout the day at the shallow depth of around 5 cm to penetrate further deep into the soil. The watering should take place in the evening hours when the soil surface still has its maximum thermal share of the day and before soil temperature is defused into the air. In repeating this action for a few evenings, the surface temperature will reach the geo-space more quickly than it would by the normal process.

By observation of the living creatures within thier natural environment we have noticed that some creatures who live in regions of stressful climate (very hot, such as the Sahara or very cold, such as Canada or north central Asia) or where there is an extreme diurnal temperature fluctuation, have constructed their habitats within the geo-space for thermal protection. An example of these is the Jarboa.

## 8. CONDENSATION

Condensation is the release of relative humidity caused by the air contraction when the air temperature is reduced significantly. In geo-space habitat condensation can take place in the summer when the walls provide cool low temperatures, the relative humidity of the air is very high, and when air exchange is minimal or non-existent. Geo-space located in rainy summer regions, such as Japan, will most probably be subject to condensation.

To minimize or eliminate condensation it is necessary to increate ventilation and air movement. Passive air movement can be achieved through the construction of vertical airshafts where, due to the temperature differentiation between the outdoor (high) and the indoor (lower) air pressure, differentiation will take place. If a window or door opening into a patio is provided, the outer air will then move downward through the

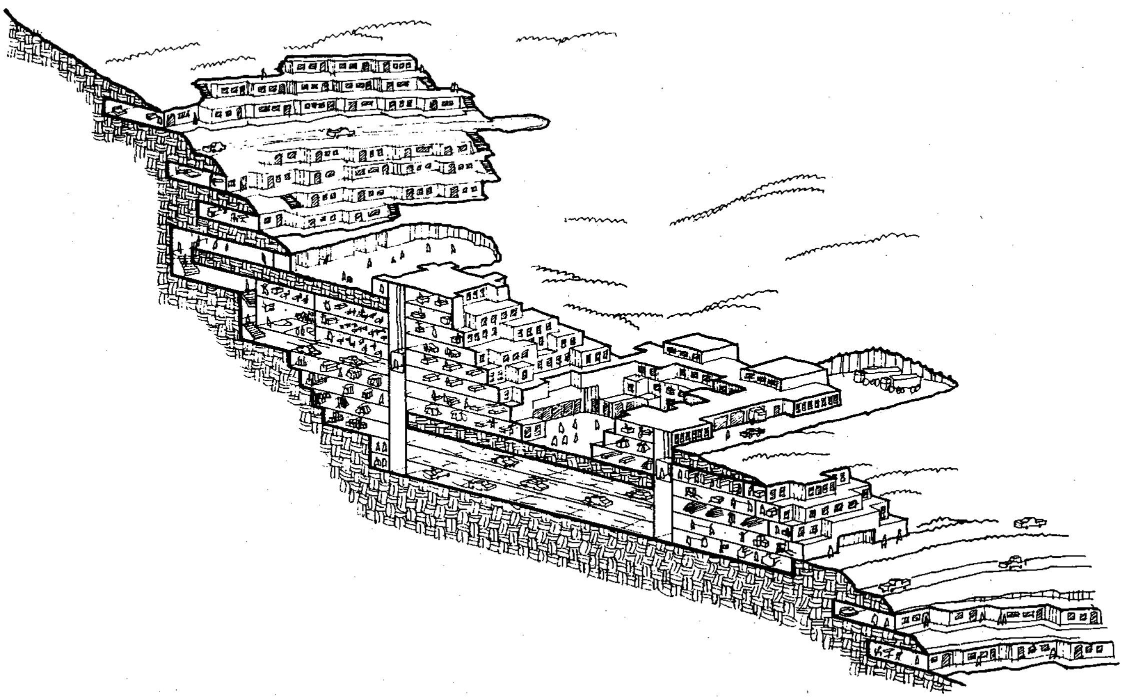

**Fig.5** Generalized cross section of a combined compact and subterranean city

shaft into the geo-space habitat.

Another ambient thermal issue associated with geo-space habitat is the differentiation in temperature between the outdoors and the indoors. As was mentioned previously, indoor winter temperature is relatively higher than that of the outdoors due to the summer heat retained by the soil and the time lag process. Our research findings in the subterranean dwellings of the Matmata plateau, Tunisia, indicate that this indoor-outdoor temperature differentiation often causes the inhabitants of the dwelling to catch cold.

## 9. THERMAL PERFORMANCE AND DESIGN FORM

Do regions of different thermal performance require different geo-space design forms? Or is a geo-space form that is applicable in the hot-dry climate such as North Africa, an ideal one in the cold-dry climate, such as central Canada?

Geo-space thermal performance observations indicate that where the summer temperature is cool and the discomfort index usually between 20~22, a cooling system is not needed. In the winter the discomfort index is around 12 which necessitates some type of heating system to be operated. Thus, regions of hot-dry climate, where cooling is needed throughout most of the year, will require maximization of the surface space (walls, ceiling and floor) since the total surface provides the cooling system of the geo-space habitat. On the other hand the major problem of the cold-dry climate region is the consumption of fuel heating during most parts of the year and therefore the habitat will require the minimization of the surface size in order to reduce energy consumption. Our research indicates that the most suitable design form for the hot-dry climate is the trapezoid and for the cold-dry climate, the circle (**Fig.4**).

## 10. CONCLUSION

In Japan, like many other countries the image of living below ground has been associated with negative connotations such as darkness, dampness, lack of ventilation, unhealthfulness, and most important, claustrophobia. All in all, people have had a strong bias and a negative attitude. This bias is a historical one when the image of below-ground housing was associated with poverty and backwardness. The design implementation of below-ground habitats had been of poor quality in most societies throughout history. Almost all the problems associated with geo-space habitat can be considered as design or as technological ones and can certainly be solved to meet our present norms and standards. The major limitation of below-ground habitat usage is the psychological factor. The problem to be challenged is a dual one, that of claustrophobia and that of socio-psychological bias. Claustrophobia is the feeling of being afraid of

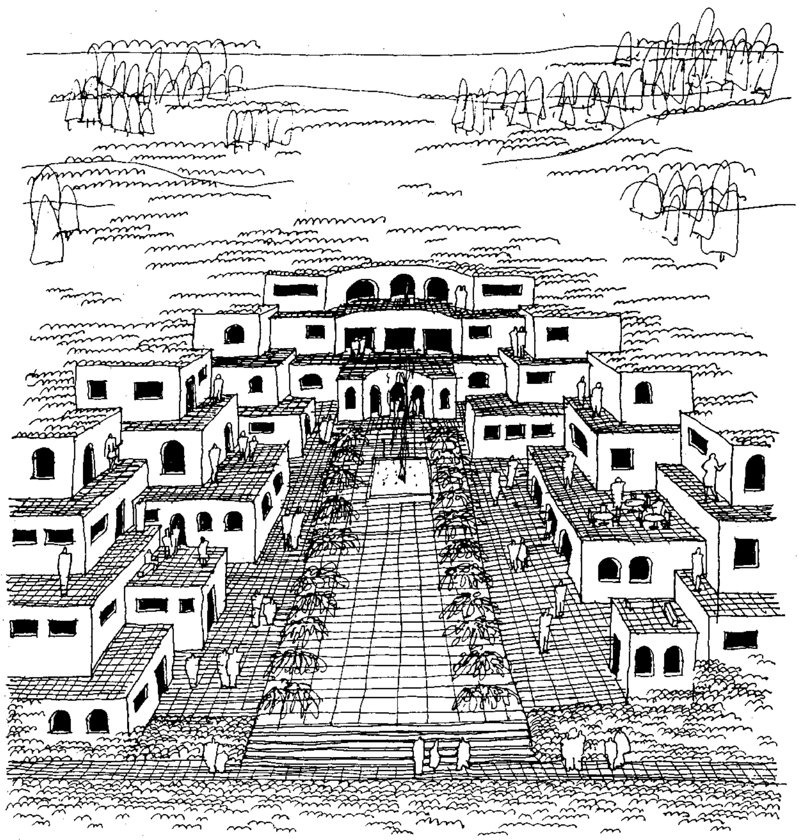

**Fig.6** Subterranean, terraced, compact housing with central open patio located on a slope overlooking the lowland or the valley. Outer walls are thick, double or earthcovered.

confined space—to which children, women and elderly persons are often sensitive. Our research leads us to offer the following design rules in order to cope with such problems.

1) Geo-space habitats should be located exclusively on the slopes and in terraced form (**Fig.5**).
2) Geo-space habitat design should be oriented toward the south, southeast or southwest and enable direct deep penetration of sunshine and maximum natural light.
3) Ascending, not descending, access to the habitat should be adopted (**Fig.6**).
4) Provide direct eye contact between indoors and the outdoor environment so that the inhabitants can feel the daily rhythm of the natural surroundings.
5) The outdoor environment should be brought into the geo-space habitat.

The problem of the negative image of the geo-space habitat is expected to be eased and resolved when modern construction of such habitat becomes commonly used by middle and upper class socio-economic groups. Also, increasing knowledge on the potentialities offered by good modern design should improve this image of the geo-space habitat.

Finally, the use of geo-space as habitat yields more favorable results in extreme climates, hot or cold, than in temperate ones. Yet, every climate type introduces its own problems to the geo-space design which need to be resolved separately. The major problem, for example, in the rainy-temperate climate zone is the humidity and with it the need to introduce an effective ventilation system along with waterproofing. Like every endeavor, the introduction of the geo-space habitat is a trade-off in which there is both a gain and a loss.

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