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Direct and Indirect Benefits of Underground Space Use

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Abstract

This paper presents a brief but comprehensive discussion of the various advantages and disadvantages of underground facilites with a special emphasis on environmental aspects.

1. INTRODUCTION

The rapid growth of world civilization will have a significant impact on the way humans live in the future. As the global population increases and more countries demand a higher standard of living, the world must provide more food and greater energy and mineral resources to sustain this growth. The difficulty of doing this is compounded by three broad trends: the conversion of agricultural land to development uses; the increasing urbanization of the world's population; and growing concern for the maintenance and improvement of the environment, especially regarding global warming and the impact of population growth. Underground space utilization offers opportunities for helping address these trends.

By moving certain facilities and functions underground, surface land in urban areas can be used more effectively, thus freeing space for agricultural and recreational purposes. Similarly, the use of terraced earth sheltered housing on steeply sloping hillsides can help preserve precious arable flat land in mountainous regions. Using underground space also enables humans to live more comfortably in densely populated areas while improving the quality of life.

On an urban or local level, the use of underground facilities is rising to accommodate the complex demands of today's society while improving the environment. For example, both urban and rural areas are requiring improved transportation, utility, and recreational services. The state of traffic congestion in many urban areas of the world is at a critical level for the support of basic human living, and it is difficult if not impossible to add new infrastructure at ground level without causing an unacceptable deterioration of the surface environment or an unacceptable relocation of existing land uses and neighborhoods.

On a national level in countries around the world, global trends of increasing resource consumption are causing the creation and extension of mining developments and oil or gas recovery at greater depths and in more inaccessible or sensitive locations. These trends have also led to the development of improved designs for energy generation and storage systems as well as national facilities for dealing with hazardous waste (including chemical, biological, and radioactive waste), and improved high-speed national transportation systems. All these developments involve use of the underground.

This paper focuses on a brief but comprehensive discussion of the various advantages and disadvantages of underground facilites with a special emphasis on environmental aspects. The discussion is taken from *Underground Space Design* by Carmody and Sterling (1993).

2. CHOOSING TO BUILD UNDERGROUND

Given the wide range of types and sizes of underground facilities, the discussion below should be considered only as a discussion of potential factors for choosing to build a facility underground. Individual projects may only involve a few issues providing significant advantages or disadvantages. It is also important to note that one of the prime considerations in developing underground space is location. Thus, the issue is often not merely choosing between an underground facility and a surface facility on the same site, but determining whether alternate locations, types of construction, and perhaps alternate means of achieving the desired end result without construction are appropriate. For example, a high-cost option of siting a new surface structure in downtown Seoul may be compared with an underground structure also in downtown Seoul or a surface structure in a suburban area. One of the principal issues to be weighed will be the relative importance of a location in the downtown area - a decision unrelated to any specific features of the construction.

Table 1 provides in chart form the principal advantages and disadvantages generally associated with underground space use. Direct benefits of a particular project are separated from indirect societal benefits with little relevance to an individual user (unless the environmental benefits are linked to permit costs, tax incentives, etc.). Physical benefits are likewise separated from those benefits that can be expressed in actual cost benefits to a project. Although some physical benefits can be measured in terms of cost, others such as aesthetic issues must be balanced within a decision-making framework.

Following the basic structure of the chart, the nature of each listed issue is amplified in the rest of this paper. Where appropriate, several references are provided to papers or reports relevant to the issue being discussed.

3. POTENTIAL PHYSICAL BENEFITS

LOCATION

Locational advantages for underground structures include the ability to build in close proximity to existing facilities or on otherwise unbuildable sites. For some projects, such as essential utilities, the location may be predetermined, which in turn may mandate underground construction due to the utility type or surface restrictions.

Building decisions also may be affected by the status of certain locations within a city or urban area, which may translate into a premium being paid for a downtown location. For example, a higher cost for underground construction may be acceptable if it permits a downtown location for a facility that otherwise would have to be located further from the city center.

ISOLATION

Isolational advantages relate to the physical characteristics of typical underground spaces and their surrounding ground environment. The ability to isolate structures within a mass of earth provides the following specific advantages.

Climate

Thermal. In most regions of the world the temperature within the soil or rock at depths of less than 500 meters represents a moderate thermal environment compared with the extremes of surface temperatures. These moderate temperatures and the slow response of the large thermal mass of the earth provide a wide range of energy conservation and energy storage advantages:

- Conduction losses from the building envelope in cold climates are reduced.
- Heat gain through the exterior envelope from both radiation and conduction is avoided in hot climates.
- Earth-contact cooling is possible in hot climates.
- Energy requirements are reduced for tempering air infiltration.
- Peak heating and cooling loads are reduced due to large thermal inertia.

Carmody and Sterling (1983, 1985) provide more complete discussions of the energy issues involved in underground buildings.

Severe weather. Underground structures are naturally protected from hurricanes, tornadoes, thunderstorms, hail, and most other natural phenomena (Moreland 1981). The most vulnerable portions of underground structures are the surface access points for entry, light, or view. Underground structures can also resist structural damage due to floodwaters, although special isolation provisions are necessary to prevent inundation of the structure itself.

Fire. Underground structures provide a natural protection against external fires. The ground is incombustible and provides excellent thermal isolation to the structure beneath. Access points are again the most vulnerable. Brush fires are a relatively common hazard in some regions of the world such as Australia and California. Urban fires are a major concern during other calamities such as a major earthquake or during wartime.

Earthquake. Underground structures have several intrinsic advantages in resisting earthquake motions:

- The ground motions at the ground surface are amplified by the presence of surface waves.
- Structures below ground are usually designed to support significant ground loads and hence earthquake loadings may not provide massive increases in loadings.

Structures below ground are constrained to move with the ground motion, so there is not the same opportunity for amplification of ground motions by structural oscillation effects as there is aboveground.

Earthquakes will damage underground structures at fault movement locations, and special care must be taken in lightly supported blocky rock structures which could be loosened during ground movements. In general, however, experience with underground structures during earthquakes has been excellent.

Protection

Noise. Small amounts of earth cover are very effective at preventing the transmission of airborne noise. This attribute can be very important for structures located in exceptionally noisy locations such as those adjacent to freeways and major airports. Surface openings provide the major transmission path for noise to the interior.

Vibration. Major vibration sources in urban areas include road and highway traffic, trains, subways, industrial machinery, and building HVAC systems. High technology manufacturing systems require environments with increasingly stringent limits on vibration amplitudes, velocities, and accelerations. If the vibration sources are at or near the ground surface, levels of vibration will diminish rapidly with depth below ground and distance from the source. High frequency vibrations are eliminated more quickly with depth than low frequency vibrations.

Explosion. As with noise and vibration, the earth will absorb the shock and vibrational energy of an explosion. Arching of the soil across even shallow-buried structures greatly increases the peak air pressures that a structure can withstand. Once structural protection has been achieved, the access points must be designed to prevent the passage of high air overpressures.

Fallout. Radioactive fallout consists of radioactive dust particles that settle on the ground or on other surfaces following a release of radiation into the air. The majority of the types of radiation present in fallout from an atomic bomb can be absorbed by several inches of concrete, steel, or earth. A major benefit of underground structures in this regard, in addition to their heavy structures and earth cover, is the limited number of openings to the surface. All building openings and the ventilation system must be properly protected to provide adequate fallout protection (Moreland 1981; Chester et al. 1983; Chester and Zimmerman 1987; Winqvist and Mellgren 1988; Saari 1988).

Industrial accident. Explosion, fallout, and similar catastrophic protection is not solely related to military uses - many industrial facilities have a significant potential for explosions and toxic chemical release. Also, terrorists often strike non-military targets. Underground structures, especially if provided with the ability to exclude or filter contaminated outside air, can be valuable emergency shelter facilities.

Security

Limited access. The principal security advantage for underground facilities is that access points are generally limited and easily secured. This limitation of entry and exit points also seems to inhibit would-be intruders or thieves.

Inaccessibility. The structure of the facility away from surface openings is generally not directly accessible. Excavation or tunneling for unauthorized access is time consuming and can be monitored with relative ease.

Containment

Containment is the inverse function of protection. With containment, the goal is to prevent a damaging release from the facility to the surface ecosystem.

Hazardous materials. Hazardous material storage underground can take advantage of the protection, isolation, and security of the facility. Proper design and geological siting can provide very low probabilities of hazardous material leakage and of any such leakage being transported to the surface environment. Hazardous materials include both high- and low-level nuclear wastes and hazardous chemicals that are not disposed of by chemical alteration or incineration.

Hazardous processes. Containment of a hazardous (e.g., potentially explosive) process below ground can limit the effect of an explosion on the surrounding community. Several major industrial accidents over the past two decades have highlighted this concern, and protective earth berms to deflect blast waves upward are now required for some surface facilities.

PRESERVATION

Aesthetics

Visual impact. A fully or partially underground structure has less visual impact than an equivalent surface structure. This may be important in siting facilities in sensitive locations or when industrial facilities must be sited adjacent to residential areas. The increasing requirement for all utility services to be placed below ground is primarily a visual impact decision.

Interior character. An underground structure can provide an interior character quite different from that of a surface structure. Combinations of tunnels, chambers, and natural rock structures in a quiet, isolated space have inspired many religious expressions. At the other end of the spectrum the hustle, noises, and smells of a busy subway system also can provide a memorable aesthetic experience.

Environmental Advantages

Natural landscape. This is similar to the limited visual impact mentioned earlier but specifically relates to the preservation of a natural landscape in keeping with the local environment.

Ecological preservation. When natural vegetation is preserved through the use of underground structures, less damage is inflicted on the local and global ecological cycle. Plant life, animal habitat, and plant transpiration and respiration are maintained to a greater extent than with surface construction.

Rainfall retention. Results of the preserved ground surface are that percolation of rainfall to replenish groundwater supplies is encouraged and storm water run-off is reduced. This reduction in run-off permits smaller storm sewers, detention basins, and treatment facilities and also reduces the potential for flooding.

Materials

Underground structures may offer advantages in terms of preservation of the structure itself or preservation of objects stored within the structure. For example, embalmment followed by entombment has been very successful in preserving corpses from ancient civilizations. Likewise, food preservation is often enhanced by the moderate and constant temperature conditions and the ability to maintain a sealed environment that restricts the growth of insect populations and fungi.

LAYOUT

Advantages in the layout of underground facilities derive primarily from the freedom (within geological, cost, and land ownership limitations) to plan a facility or an urban system in three dimensions rather than being tied to surface facilities controlled by topographic and existing land use constraints (Fairhurst 1976). Transportation and utility tunnels in areas of rugged topography are independent from the topographic constraints. Deep subway systems need not be physically constrained by existing surface land uses (although legal obstacles often limit this freedom). Likewise, a pumped-storage scheme may use a deep underground reservoir connected by shaft to a surface reservoir when the region does not have favorable topography for a conventional dual surface reservoir scheme.

Life Cycle Cost Benefits

Direct financial benefits are calculated by estimating the life cycle cost impacts of the benefits provided by an underground facility. These benefits may be in terms of initial cost or operating cost.

Initial Cost/Land Cost Savings

The most likely initial cost saving is in a reduced cost for the land purchase necessary to carry out the project. Land or easement costs for an underground project may range from a full purchase of the site for projects that essentially usurp the surface use to a very low percentage of the land value if no impact on the existing surface use will occur and the surface owner would have little opportunity in developing a use at the depth proposed. In areas with extremely high land costs, the cost of land purchase can dominate all the initial cost decisions. For an analysis of this cost comparison see Carmody and Sterling (1993).

Construction Savings

Although underground structures typically cost more to construct than equivalent surface structures, some combinations of geological environment, scale of facility, and type of facility may provide direct savings in construction cost. An example of this is the Scandinavian experience with large oil storage caverns. Underground structures may also provide weather-independent construction which can offer some cost advantages in severe climates.

Sale of Excavated Material or Minerals

If the underground facility is excavated in a geologic material with an economic value, the sale of this material can be used to offset the excavation cost. If, as in the Kansas City, Missouri, USA, limestone mines, the excavation is part of a profitable mining operation, the space becomes a near-no-cost by-product of the mining. In Coober Pedy, Australia, the rewards are not as certain, but a resident excavating an underground home there can recoup costs if sufficient opals are found during the excavation. In most cases, however, a planned continuous supply of a mineral resource is required before a reasonable economic value can be developed. This limits the economic recovery for isolated, small projects even when the excavated material has value.

Savings in Specialized Design Features

The physical advantages of underground facilities may provide direct cost benefits when compared with a surface facility. For example, thermal isolation may reduce peak load demands for a facility's HVAC system, enabling a smaller, less expensive system to be installed (Setter, Leach & Lindstrom 1980, 1981, 1983). The same level of security and protection may be available at less cost than for an aboveground facility. The partial costs for providing low vibration, constant temperature, or clean room space may also be less underground than at the surface. For buildings that would have an expensive exterior finish aboveground, significant savings can be made below grade where such finishes are unnecessary. The architect who designed an addition to the Mutual of Omaha headquarters building in Omaha, Nebraska, USA, indicated that savings in the reduced use of the expensive facing stone used on the original building more than offset the increased costs of the construction of the underground addition (Savage 1979).

Operating Cost / Maintenance

The physical isolation of underground structures from the environmental effects that deteriorate building components can result in a low maintenance cost for underground structures. The reduced impact of temperature fluctuations, ultraviolet deterioration, freeze-thaw damage, and physical abrasion can reduce the rate of deterioration of underground structures. Other maintenance advantages may include the absence of snow removal problems in underground subways and the slow temperature change in storage facilities when equipment malfunctions.

Insurance

Physical isolation also can result in reduced insurance premiums for underground facilities. Reductions are not always available, however, even if theoretically warranted, because the insurance rating system depends either on an adequate historical loss record or a detailed risk assessment for the type of facility proposed. If a loss record is not available and the company is unwilling to distinguish a separate class of facility, no reduction may be available. The use of an insurance company with experience in insuring underground facilities along with care in planning to limit hazardous internal conditions offers the best possibility of rate reductions. For more complete discussions of insurance assessments for underground facilities, refer to de Saventhem (1977) and Muller and Taylor (1980).

Energy Use

The thermal advantages of underground structures usually translate into reduced energy costs to operate them. Although ventilation and lighting costs often increase, thermal benefits outweigh these in moderate to severe climates, particularly when a surface facility would be designed as a sealed, force-ventilated facility (Sterling and Carmody 1990). Savings in energy costs are rarely sufficient to justify building a facility underground for energy conservation reasons alone since there are also techniques for greatly reducing energy use in conventional buildings and the initial cost of an underground building may be high. The reduced operating cost and the stability of thermal conditions during energy outages become more important considerations as energy shortages develop and energy costs escalate.

Indirect Societal Benefits

These benefits can accrue on a large scale but are rarely important to an individual user.

Land Use Efficiency

The ability to place support facilities below grade and preserve the land surface for uses requiring the surface environment is an important benefit. With surface development, urban sprawl replaces farm land and recreational areas. Suburban factory development often covers large land areas with windowless buildings and parking lots. The sprawl itself requires more land area to be devoted to automobile and truck transportation because development densities are too low to support adequate urban mass transportation systems.

It is also possible to improve existing land use problems through underground construction by placing existing facilities below grade and reclaiming the surface for other uses. This is being done in some cities by moving railway lines underground and using the reclaimed land for recreational space, infrastructure facilities, or commercial development.

Transportation / Circulation Efficiency

The ability to infill buildings, provide underground connections, and improve urban densities contributes to compact development that can allow efficient transportation and circulation patterns to be developed.

Energy Conservation

Beyond the immediate financial impact to a building user or developer, energy conservation has implications for national security, economic development, and the balance of trade.

Environmental Benefits / Aesthetics

These are the regional impacts of underground construction that result in better land use. New development or redevelopment can occur but with a strong emphasis on preserving the environment.

Reduced Surface Disruption

The construction of new underground systems or facilities can be organized to disrupt the existing area less than equivalent surface construction. This is particularly true of facilities that can be excavated with only limited surface access. Cut-and-cover subway systems in urban areas have developed a reputation for very damaging interference with local businesses during their construction, but the effects can be mitigated with proper controls on excavation practices and the provision of temporary road surfaces (Walton 1978; Silver and Peters 1977). Tunneled subway system construction interferes less and may only be noticeable at station locations.

Disaster Readiness / National Security

National safety or security concerns provide the driving force for the construction of underground facilities in many countries. In Scandinavia, Switzerland, and several other countries, needed community facilities are constructed underground with the additional features necessary to provide adequate civil defense shelters. The national government provides for enhanced national security and the community obtains a needed local facility (Saari 1988; Winqvist and Mellgren 1988; Rygh 1990).

4. POTENTIAL PHYSICAL/INSTITUTIONAL DRAWBACKS

LOCATION

Locating facilities below grade requires a greater interaction with the local geological environment than for most surface construction. This geologic environment may be highly unfavorable for underground construction, and exact geologic conditions are difficult to predict prior to construction, which in turn increases project uncertainties. Some types of underground facilities are not restricted to a given area and can be located in a suitable geologic environment. However, for others such as service facilities for existing development, the geologic environment in which the construction must take place is already set. Due to their historical development on the estuaries of major river systems, many major urban areas of the world have rather unfavorable geologic conditions for underground construction.

ISOLATION

Climate

Although mostly a positive issue, the isolation of underground structures can provide thermal disadvantages for certain types of facilities. For example, it is difficult to reject excess heat production in underground facilities except through air-conditioning and/or high levels of forced ventilation. Similarly, the slow thermal response of underground structures and cool ground-contact surfaces can cause undesirable interior conditions. In warm, humid weather, non-air-conditioned buildings may experience high relative humidities and condensation. High thermal mass is also not well suited to short-term changes in desired interior conditions.

Flooding is a concern for many underground structures, and protection against the effects of surface floods, fire-fighting water, and water leakage from the ground must be provided.

Communication

Communication within underground networks and between the surface and underground spaces may be impeded. Television, radio, and mobile communication systems will not operate in isolated underground spaces without antennas, cable systems, or special distributed signal repeater systems.

Human Occupancy

Probably the most pervasive drawback to the use of underground facilities for non-service functions is that a large majority of people express a strong dislike for working in underground or windowless spaces. Coupled to this psychological resistance are concerns for whether an underground environment is healthy for long periods of occupancy. Designing facilities to provide a pleasant and healthy human environment in underground space is the central issue in this book and is examined in detail in Part II. Only an indication of the problem areas is given here.

Psychology/Physiology. For most people, the idea of working or living underground elicits a negative reaction. Negative associations with underground space generally include darkness combined with humid, stale air. Among the most powerful associations are those related to death and burial, or fear of entrapment from structural collapse. Other negative associations arise in relation to feeling lost or disoriented since normal reference points such as the ground, sky, sun, and adjacent objects and spaces cannot be seen. Also, with no direct view of the outdoors there can be a loss of connection with the natural world and no stimulation from the variety of changing weather conditions and sunlight. Physiological concerns with the underground primarily focus on the lack of natural light and poor ventilation.

Continuing concern over placing people underground indicates that some of the historic images of dark, damp environments linger in our minds even though modern technology has overcome many of these concerns. The generally negative reaction to underground space has forced designers and researchers to attempt to overcome these perceptions.

Safety. Safety issues may also represent disadvantages for underground facilities. The ability to exit an underground facility in case of an interior fire or explosion is hampered in deeper underground facilities by the limited points of connection to the surface, the need for upward travel on exit stairs, and the difficulty of venting poisonous fumes from a fire. In ground containing dangerous chemicals or gases, these may potentially seep into the underground space, causing health problems. Heavier-than-air gases from the surface may also fall into underground structures to create higher concentrations than would exist on the surface.

Safety from personal attack can also be diminished in underground structures if public areas are isolated and provide areas for attackers to wait and act unseen. This has been a substantial drawback to some underground pedestrian connections in urban areas.

Resolving safety issues requires careful design and building operation, which translates into higher costs. The removal of all psychological resistance to underground facilities is not feasible despite the major improvements possible with careful design.

PRESERVATION

Aesthetics

The fact that facilities may be mostly or completely obscured below ground is not always desirable. Facilities that must attract attention for business such as retail stores and restaurants must maintain visibility to passers-by. Office buildings are often a symbol of the size, wealth, and profile of the corporations within them. Most architects who design buildings also like to make an architectural statement with their work in terms of its exterior appearance and are reluctant to consider placing their buildings out of sight.

In the design itself, underground building presents some aesthetic problems. First, even though the bulk of a facility or building may be placed below grade, entrances and building service facilities must still be provided. Unless such entrances and service facilities are provided through adjacent surface facilities, they can become the dominant visual image of the facility. Service facilities (which are normally rather unattractive) may thus have a strong impact on the exterior appearance of the facility. A more general problem for underground facilities, which has been noted in earth sheltered residential structures and large industrially oriented underground facilities, is that the aesthetic manipulation of earth forms, vegetation, and building layout to create a harmonious design can be very difficult for an inexperienced designer or one without architectural training. Poorly designed conventional facilities maintain many similarities to the normal building forms and do not stand out. A poorly designed underground building or its surface expression can quickly become an eyesore.

Environmental Disadvantages

Underground structures disturb the geologic environment in which they are placed. Sometimes this disturbance can degrade the ground environment and the surface environment. Open-pit excavation and trenching are the most immediately damaging to the existing topsoil and vegetation conditions. Mined or tunneled construction may cause surface settlement (altering surface drainage patterns and damaging existing buildings). Water leakage into the underground structure may drain the surrounding ground, causing long-term settlement in sensitive soils and again affect surface vegetation (Jansson and Winqvist 1977).

LAYOUT

Underground structures must maintain stability in the surrounding geologic environment. In some cases the ground can be self-supporting up to certain span limitations. In cases where support is used, maximum opening sizes are limited by the increasing relative cost of supporting larger openings. Such support costs typically rise faster with clear span than for surface structures, and thus constrain the layout of underground facilities significantly by determining which opening sizes and shapes are economical. The layout must maintain the separation between adjacent openings necessary for ground stability and provide for the often substantial interior structure needed to withstand ground pressures in poor ground conditions or at great depth.

Although underground facilities may have a three-dimensional freedom not possible on the surface, the location of access points for fully underground facilities is limited by surface topography and existing surface uses, and their number is limited by the high costs of shafts.

The future expansion or adaptability of underground facilities is also a potential problem. Underground structures are usually expensive to modify and, if designed for a single use, opening sizes and arrangements may not be adaptable for a wide range of other uses.

Underground structures extending deeper than adjacent sewer services must provide for the collection and removal of sewage from the lower levels of the building using sewage lift stations.

INSTITUTIONAL

There are several broad impediments to the greater use of underground facilities - obtaining the rights to development, gaining permit approvals in unusual design circumstances, and obtaining financing approval for non-standard developments.

If the surface land is not owned, easements for the proposed underground use must be obtained. For long tunnel projects, this may involve hundreds or thousands of different landowners with different degrees of receptivity to the project and differing expectations as to the proper value of the easement. The delays and costs in solving these problems in some countries can terminate the project or lead a public agency to try to keep the tunnel entirely within public right-of-way even if this means a substantial cost increase or degradation of project performance.

The difficulty of obtaining zoning and building code permits varies substantially with the type of project and its location. It may be difficult to obtain code variances relating to safety even though existing provisions are not appropriate for the type of underground structure considered.

Finally, the geological and institutional uncertainties inherent in large underground projects discourage both public and private investors from committing their resources even if the cost/benefit analysis for the project is favorable.

Life Cycle Cost Drawbacks

These direct financial drawbacks are calculated by estimating the life cycle cost impacts of the disadvantages of an underground facility. These impacts may be in terms of initial cost or operating cost.

Initial Cost

There is often a substantial cost penalty for an underground facility compared with an equivalent surface facility. This depends on the type of facility and whether the location of the underground facility can be matched to favorable site conditions. The confined working conditions, the high ground support costs (both temporary and permanent), the limited construction access points, and the cost for excavation, transportation, and disposal of the ground removed to make the space all usually contribute to increased costs. High costs are exacerbated by the geological and institutional uncertainties, particularly when contractual practices attempt to place all financial risk on a contractor. This creates an adversarial relationship for the project that harms productivity and may result in unreasonably high legal costs. It also results in an owner paying for potential risk in the bid price even when no problems may actually occur (ITA 1988).

Operating Cost

Operating cost disadvantages relate primarily to the isolation of the facility. Personnel access to deep underground facilities may be time consuming and limited in capacity, shortening the effective working day. This effect may be particularly costly in heavily used facilities such as subway stations. It may also be difficult or time consuming to transfer large quantities of goods by elevator to an underground facility compared with the easy handling in a one-story surface facility with direct access. Deep underground facilities without ramp access for trucks thus become less suitable for operations involving high rates of material transfer.

Adequate ventilation and lighting must be provided continuously in underground facilities whereas surface facilities may require far less (for example, an underground transit station versus a surface transit station).

Maintenance or repair of an underground structure may be very expensive due to the problems of accessing the point requiring repair. An example is the high cost of locating and repairing leaks in a waterproofing membrane on an underground building. Maintenance of plant materials above an underground building may also be more expensive than maintenance of a roof on a conventional building (Setter, Leach & Lindstrom 1981).

Potential Societal Drawbacks

These disadvantages may be important for large-scale underground space use or the long-term use of underground space even though they may have negligible impact on an individual user.

Environmental Degradation

The potential environmental problems of buried structures may not emerge for several years and may only be significant if the underground is widely used. Potential problems include drainage of groundwater through leakage into the facilities or watertable drawdown pumping (Jansson and Winqvist 1977); groundwater pollution from underground storage (Fairweather 1990) or waste disposal sites (National Research Council 1990); and chemical spills within underground facilities.

Permanent Changes

Underground structures permanently alter the ground conditions at a site, and the first underground facilities constructed may significantly deter or even preclude future uses. This places a burden of forward planning for competing underground space uses to a much greater degree than is required for surface structures, which are more easily adapted and renewed (Sterling et al. 1983; Jannson and Winqvist 1977).

Embodied Energy

One energy disadvantage of many underground structures is that they often constitute a higher level of "embodied" energy expended to create the facility than does a comparable surface facility. The embodied energy includes the energy for excavation, transport, and disposal of soil and rock to form the opening and the energy required to process, manufacture, transport, and install all the material used in the construction and finishing of the facility. The excavation process and the large quantities of concrete and steel used in most underground structures yield high energy investments in these structures (Hannon et al. 1977).

5. SUMMARY

Underground facilities have a wide range of potential benefits and drawbacks. It is necesary to evaluate individual projects in the light of these issues. It is better to advocate the consideration of the use of underground facilities for various purposes than to attempt a blanket advocacy of the use of underground space.

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TABLE 1: BENEFITS AND DRAWBACKS OF UNDERGROUND FACILITIES.

MAJOR ISSUES	SUBCATEGORY	POTENTIAL BENEFITS	POTENTIAL DRAWBACKS
PHYSICAL AND INSTITUTIONAL ISSUES	LOCATION	Proximity Lack of surface space Service provision Status	Unfavorable geology Uncertain geology
	ISOLATION	Climatic thermal, severe weather, fire, earthquake Protection noise, vibration, explosion, fallout, industrial accident Security limited access, protected surfaces Containment hazardous materials, hazardous processes	Climatic thermal, flooding Communication Human issues psychological acceptability, physiological concerns, fire safety, personal safety
	PRESERVATION	Aesthetics visual impact, interior design Environmental natural landscape, ecology, run-off Materials	Aesthetics visual impact, building services, skillful design Environmental site degradation, drainage, pollution
	LAYOUT	Topographic freedom 3-dimensional planning	Ground support Span limitations Access limitations Adaptability Sewage removal
	INSTITUTIONAL		Easement acquisition Permits Building code Investment uncertainty
LIFE CYCLE COST	INITIAL COST	Land cost savings Construction savings no structural support, weather independent, scale Sale of excavated materials or minerals Savings in specialized design features	Confined work conditions Ground support Limited access Ground excavation, transportation, and disposal Cost uncertainty geological, contractual, institutional delays
	OPERATING COST	Maintenance Insurance Energy use	Equipment/materials access Personnel access Ventilation and lighting Maintenance and repair
SOCIETAL ISSUES		Land use efficiency Transportation and circulation efficiency Energy conservation Environment/aesthetics Disaster readiness National security Less construction disruption	Environmental degradation Permanent changes Embodied energy