US Army Corps
of Engineers
Construction Engineering
Research Laboratory

USA-CERL

TECHNICAL REPORT M-85/11
April 1985
Underground Construction for Military Facilities

AD-A155 212

LITERATURE SURVEY OF UNDERGROUND CONSTRUCTION METHODS FOR APPLICATION TO HARDENED FACILITIES

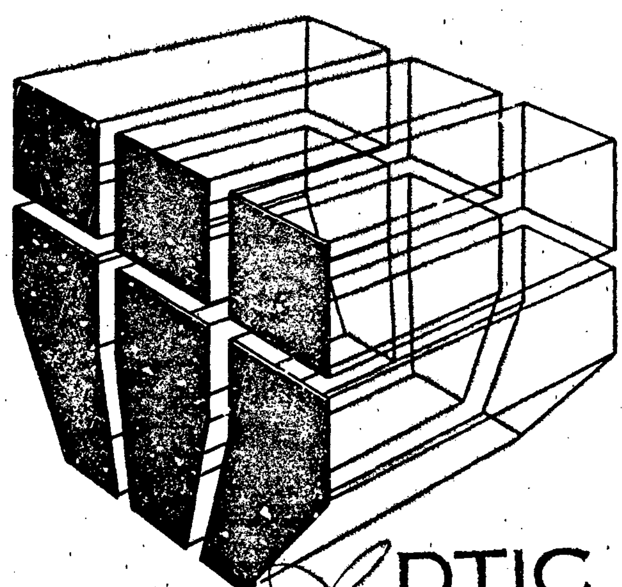
20000814023

by
A. Kao

This report is a survey of current literature dealing with underground construction practices and will provide the Army with information for comparing the advantages and disadvantages for methods for constructing hardened facilities. Current procedures and problems in underground construction were evaluated in the areas of cut and cover methods, deep shafts, tunneling, ground water control, security and survivability, costs, and energy savings.

An example building was then taken for underground siting to compare the applicability of the alternative construction techniques described in the literature. The example related the choice of construction method to security/survivability potential and ground water control methods.

The study showed that underground buildings can be more economical than conventional aboveground buildings over a 20- to 30-year life cycle because of energy savings. Since adequate technology is available to construct hardened underground facilities under virtually any ground conditions, the main constraint in construction projects remains economic viability rather than technical feasibility.



UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CERL TR M-85/11	2. GOVT ACCESSION NO. AD A155 212	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) LITERATURE SURVEY OF UNDERGROUND CONSTRUCTION METHODS FOR APPLICATION TO HARDENED FACILITIES		5. TYPE OF REPORT & PERIOD COVERED FINAL 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) A. Kao		8. CONTRACT OR GRANT NUMBER(s) DACA88-84-M-0157 SWRI Project Number 06-7933
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Construction Engr Research Laboratory P.O. Box 4005 Champaign, IL 61820-1305		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 4A162731AT41-A-071
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE April 1985 13. NUMBER OF PAGES 49
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Copies are obtainable from the National Technical Information Service
Springfield, VA 22161

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

literature surveys
underground structures
construction
hardened structures

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This survey of current literature dealing with underground construction practices will provide the Army with information for comparing the advantages and disadvantages of methods for construction hardened facilities. Current procedures and problems in underground construction were evaluated in the areas of cut and cover methods, deep shafts, tunneling, ground water control, security and survivability, costs, and energy savings.

An example building was then taken for underground siting to compare the

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

BLOCK 20. (Continued)

applicability of the alternative construction techniques described in the literature. The example related the choice of construction method to security/survivability potential and ground water control methods.

The study showed that underground buildings can be more economical than conventional aboveground buildings over a 20- to 30-year life cycle because of enery savings. Since adequate technology is available to construct hardened underground facilities under virtually any ground conditions, the main constant in construction projects remains economic viability rather than technical feasibility.

FOREWORD

This research was performed for the Directorate of Engineering and Construction, Office of the Chief of Engineers (OCE) by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (USA-CERL). The work was done under Project 4A162731AT41, "Military Facilities Engineering Technology"; Task Area A, "Facilities Planning and Design"; Work Unit 071, "Underground Construction for Military Facilities." This work was performed in part by the Southwest Research Institute under DACA88-84-M-0157, SWRI Project Number 06-7933. The OCE Technical Monitor was Mr. R. Wight, DAEN-ECE-T.

Dr. A. Kao was the USA-CERL Principal Investigator. Dr. R. Quattrone is Chief of USA-CERL-EM. COL Paul J. Theuer is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

CONTENTS

TABLES

FIGURES

LITERATURE SURVEY OF UNDERGROUND CONSTRUC⁻ION METHODS FOR APPLICATION TO HARDENED FACILITIES

1 INTRODUCTION

Background

Many Department of Defense hardened structures such as those found at munitions storage facilities are constructed aboveground, some with earth cover. An example of such a structure is the standard storage igloo. These facilities are often quite old, and the set of requirements on which they were designed and built differ from those considered important today. These facilities were based mainly on safety, with less attention given to security, survivability, and operational and environmental considerations.

In Europe, where security and survivability are important in facility design and construction, many NATO military facilities are built either underground or in the sides of mountains. Many of the installations are tunneled into rock in the mountainsides which is relatively fault-free and is not prone to flooding during construction. Often, the rock is so strong that the tunnel walls do not have to be lined.

The Scandinavian countries have built many underground or mountainside structures for civil defense. The mountainous terrain provides a very hardened personnel shelter compared to what could be built aboveground.

In the United States, under the direction of the Federal Emergency Management Agency, much work, including a great deal by the Corps of Engineers, has been done recently to design underground or earth-covered key worker shelters. The earth covering provides both overpressure hardening and radiation and thermal protection.

Several options are available for hardened facility construction. Typically, aboveground structures are made of thick reinforced concrete and can provide only limited protection. The structure can be shallow-buried, using the cut and cover construction method. This removes the structure from the surface, so it is not directly exposed to threats; however, it is still vulnerable to penetrating weapons and bombs. Tunneling down (shaft) or into mountainsides can provide a very safe environment, but multiple entrances must be provided. Also, the local geology is an important factor. Deep excavation is another option which has excellent security and survivability potential, but which requires multiple entrances. Problems encountered with deep excavations include shoring, water table, and bedrock level.

Because of the many options available and the numerous design and construction decisions they present, the Army needs information that will allow these various construction methods to be identified and compared.

Objective

The objective of this study was to obtain information on the costs, energy considerations, and security/survivability potential provided by current underground construction technology.

Approach

Computer literature searches were performed to obtain information on underground buildings and construction practices. Current procedures and problems in underground construction were evaluated in the areas of cut and cover methods, deep shafts, tunneling, ground water control, security and survivability, costs, and energy savings. An example facility was then considered for various forms of underground construction (cut and cover, deep shaft, and tunneling) to illustrate application of the information obtained.

Mode of Technology Transfer

It is recommended that the information obtained in this study be transferred through an Engineer Technical Letter.

2 LITERATURE REVIEW

Overview

Useful references on underground construction technology were identified from journals and government reports. Report subjects included methods of excavation, tunneling, underground structure lining, waterproofing practices, security, survivability, and cost and energy considerations. Much of the literature presented application of different construction methods to specific structures, such as civil defense shelters, subways, tunnels, schools, and libraries.

The papers surveyed discuss underground construction methods used in the United States and 11 other countries. Table 1 lists the reports that discuss underground construction in foreign countries. Each article is designated by country and reference number. This reference number corresponds to the complete list of references found in the appendix.

The literature collected provides an overview of the most current developments. Figure 1 shows the distribution of reports by year published. Clearly, it shows that the majority of reports have been published since 1977. The appendix provides a more detailed discussion of the literature review, including databases searched, keywords used, and journals referenced.

Underground Construction Methods

Cut and Cover

Cut and cover is the most commonly used underground construction method. This is essentially an open excavation in which the structure is supported by retaining walls while it is built and then backfill placed above the completed facility. Rajagopalan provides an excellent discussion of the basis for designing a cut and cover excavation [19].* His paper cites extensive use of the cut and cover technique for underground railway construction in India.

Structures buried at relatively shallow depths are generally well suited for cut and cover techniques, offering a fairly low-cost excavation approach. The major drawback of cut and cover methods is the large work area required. When construction space is limited, as is often the case in congested urban areas, less disruptive construction techniques are often necessary [125]. The designer must make a decision based not only on construction costs, but also on the relative merits of other types of construction, such as tunneling, which may greatly reduce surface traffic interference.

Conventionally braced excavation support systems consist of a web of walers, rakers, posts, and lateral support lacing. The waler is a horizontal member used to support formwork studs and a raker is a sloping brace. A major problem with this system is that the support structure often conflicts with the excavation and placement of the permanent structure. Excavations which use tieback systems do not conflict with the construction area. Reference 4 gives a review of currently used tieback systems. Tiebacks can be expensive since different anchor types are required for various soil

*Numbers in brackets refer to references listed in the appendix.

Table 1

Foreign Reports

Country	Report Reference No.*
India	10, 12, 34, 70
England	11, 53, 73, 95, 100
Canada	15, 16, 112
Germany	14, 17, 27, 28, 44, 59, 67, 89, 99, 105, 124, 132
China	25, 33, 126, 128
USSR	26, 72, 92, 101, 102
Austria	27
Norway	58, 104
Sweden	69, 86
Switzerland	79
Japan	114, 125, 127, 138

*See the appendix.

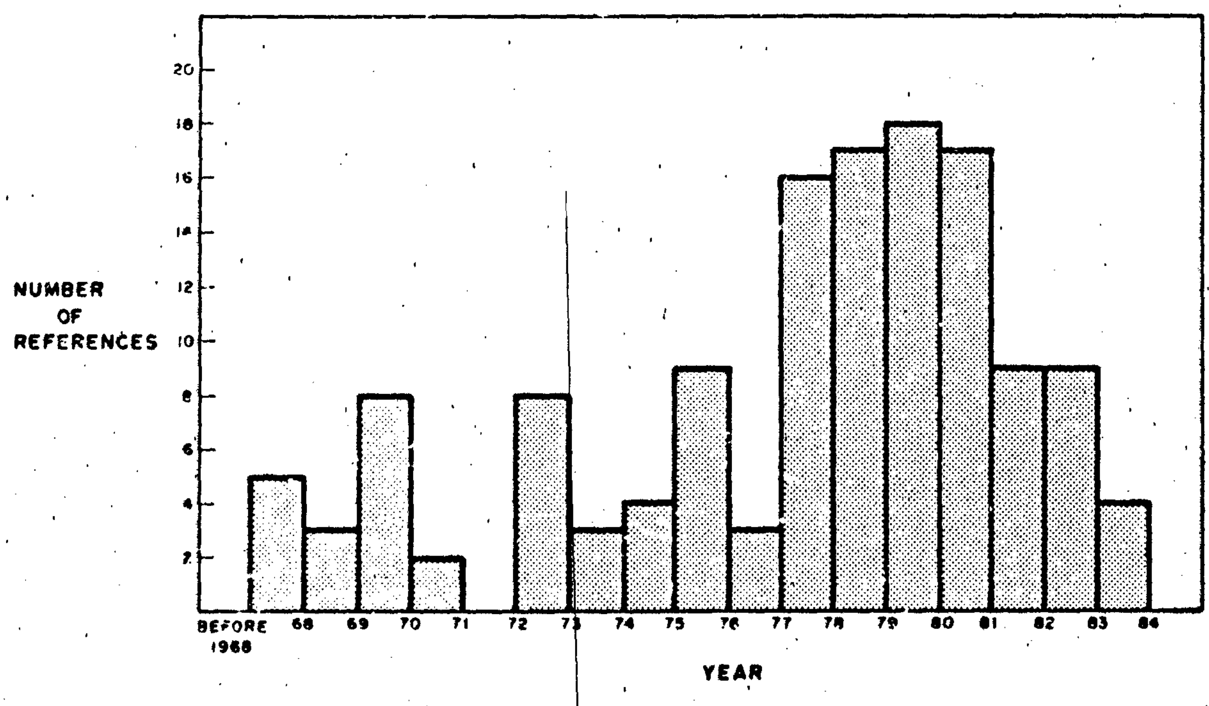


Figure 1. Distribution of references by year published.

conditions. For a given site with varying soil conditions, the contractor must be able to produce these different anchor types as different soil conditions are encountered.

Rock anchors typically exhibit a high capacity for load and are used both as tiebacks and tiedowns (to resist buoyancy). These are especially good where limiting long-term creep is desirable. The high capacity is an important consideration when excavation is deep and high water table pressures will be encountered.

Augered earth and bell anchors are the most common anchors used for cohesive soils. They are generally the least expensive, but require considerable redundancy in design due to a number of unknown factors. Casing-type anchors are used in both loose and dense granular materials.

Not all excavation support walls need to be temporary. A common technique is to use the excavation support structure as all or part of the final permanent structural support or wall. References 2 and 127 give examples of this use of excavation support. Slurry walls or secant walls are often used for this purpose. A slurry wall is constructed by digging a trench, while keeping it full with a dense cementitious liquid (slurry) that holds the sides in place. When the desired depth is reached, the cast-in-place wall is poured by pumping the concrete to the trench bottom which forces out the slurry. A secant wall is a continuous line of cast-in-place concrete piles. Page 18 discusses construction of a secant pile wall.

Reference 2 provides a detailed design analysis of a concrete diaphragm wall formed by turning a slurry wall trench into a permanent member of the structure. This reference recommends placing precast panels in a slurry-constructed trench. Bentonite grout provides the necessary waterproofing. Bentonite is a clay with a high absorption capacity, because it can expand greatly with wetting.

Most large underground construction projects use a combination of support methods. A good example is the recent construction of underground railway stations in Japan [125]. The excavation area was large and deep (230 m long, 40 m wide, and 20 to 33 m deep). Cut and cover excavation techniques were used combined with cast-in-place diaphragm slurry walls, cast-in-place pile walls (staggered secant piles), and tieback anchors.

Reference 125 provides a good discussion of the reverse construction procedure, also known as top-down construction [see also reference 127]. Typically, this consists of the top roof slab being constructed first, with piles or caissons constructed below. The subsequent excavation allows construction of the lower floors. As is typical for nonstandard underground construction techniques, this approach is generally only used when it is desirable to minimize area disruption. A unique approach to this top-down construction is pipe jacking [42]. Pipe jacking is when large diameter pipes are driven by jacks horizontally under the surface that is to be left undisturbed (such as a street). The soil is removed from the pipe. The pipes then have reinforced concrete placed in them to form the roof of the area to be excavated for the structure.

Methods for providing very large excavated pits for deep cut and cover construction have recently received much attention. This is a direct result of interest generated during the late 1970s in concepts for buried nuclear power plants [15, 18, and 124]. Reference 18 discusses cut and cover techniques studied for plants in Germany. For such deep excavated pits, Germany has generally used slurry trenches and freezing techniques. Waterproof bentonite or ice walls have already been built to depths greater than 100 m [18].

Much information can be obtained from case studies of these underground power plant construction projects. In Reference 15, a tradeoff study was performed to determine if a specific underground power station should be buried in a deep rock cavern or in a cut and cover exacavation. Scandinavian countries have been using rock caverns extensively and have developed design and construction experience. Near-surface rock formations are common in this region and are ideally suited for construction of large underground caverns.

In addition to various technical aspects of excavation and construction methods for cut and cover, Reference 16 presents an excellent discussion on field control as a critical factor in underground construction. A large underground hydropower project in Canada was designed with a reduction in the standard conservatism in underground construction based on a commitment to increased field control. One interesting example of construction savings on this project was the use of careful, controlled blasting to form rock pillars for support rather than forming concrete columns. Reference 146 provides a good text on blasting operations in excavation.

One factor to consider in cut and cover construction is the large volume of earthmoving required. Design engineers must consider hauling procedures when choosing underground construction concepts. Reference 135 discusses large wheel loaders and their use in open excavation and notes some recent trends in efficient earth-moving patterns.

Deep Shaft

Deep shaft structures are located deep within the earth (> 50 ft [15 m]). Shafts sunk into the ground provide access and ventilation to a tunneled or excavated space. Derricks and other equipment are borrowed from the oil and mining industries, which make frequent use of shafting. The construction of deep shafts involves a production phase and a support phase.

Production Phase. The production phase includes dismembering the earth and transporting muck out of the hole. Auger drilling is the most economical means of creating a large-diameter hole in soft soils (up to 200 ft [60 m] deep). Rotary drilling is the most efficient drilling technique for deeper holes (greater than 150 ft [45 m]) [9]. Drill and blast methods are used for rocky ground.

Removal of debris is generally a slower process than boring or blasting and so determines the rate of advance. Drilling mud is circulated within the shaft to remove cuttings. Recent research has focused on creating chemical additives that will make the circulating fluid more viscous to better adhere to cuttings, yet still be able to flow freely. Air-assist reverse circulation techniques have been studied to increase mucking rates and efficiency [96]. For shafts not using a slurry process, cranes may be used to remove muck up to a depth of 60 ft (18 m) [22], while an alternative method of mechanical hauling, such as raise boring, must be used for greater depths.

Raise boring and shrink raising are recently developed construction techniques [97,16] that permit a shaft to be dug from the bottom up. A pilot hole is constructed first to provide a small access shaft to the shaft bottom. In rocky ground, an upward excavation is then made by percussion drilling and blasting, allowing the muck to fall and accumulate at the shaft bottom. The muck is left to be slooped out after the excavation. This is called shrink raising. In softer soil, raise boring proceeds by assembling a cutting head at the base of the shaft and backreaming upward. Muck is removed through a tunnel at the base of the shaft.

Support Phase. A lining may be installed for ground support during the support phase of deep shafting. Steel, ribbed linings are used in temporary shafts. However, they are unsuitable for permanent shafts because they tend to be expensive and easily damaged. Unreinforced concrete linings are used in permanent shafts. In lining a tunnel with concrete, the shaft walls are secured with rock bolts and a mesh [49]. A multi-deck scaffold is then used for all sinking, lining, and formwork handling operations. Formwork rings on the scaffolding are progressively lowered into position by winches. The space between the forms and the earth is then filled with concrete passed down from the surface through flexible hoses.

Reference 9 gives a comprehensive review of shafting techniques, equipment, and costs. This paper offers a fine technical discussion of the many considerations of shafting, with an emphasis on large-diameter hole drilling. Additional papers identified during the literature search on deep shaft structures include a report of a 1200-ft (360-m)-deep repository for nuclear wastes [81] and a hydroelectric plant in Ontario [15].

Tunneling

Tunneled structures can be constructed either as branches extending from a deep shaft (as in a tunnel), or as passages to an excavated space within a hill or mountain. Tunnels are most commonly used to produce transportation routes through mountains or under bodies of water. Because the equipment used is very capital-intensive (a boring machine, for example, can cost millions of dollars), tunneling is best suited for long underground passages. Tunneling is also characterized by a production phase and a support phase.

Production Phase. The production phase, which is composed of earthbreaking and mucking, is different for rock conditions than for soil or soft ground. In rock, earthbreaking techniques include drilling and blasting, continuous drilling and blasting, boring, reaming, flame jetting, and laser cutting.

Drilling and blasting is commonly used in hard rock. This is done by a jumbo, which consists of a number of drills, or drifters, mounted on a mobile carriage for drilling tunnels in rock. The jumbo, positioned at the face of the tunnel, bores a large number of holes (each about 40 mm diameter by 4 m deep) with a rotary drill on the end of a boom. The holes are located strategically at the face loaded with explosives, and detonated sequentially to create both a passage with a minimum of overbreak and debris small enough to be hauled away with available equipment [95]. Controlled blasting techniques are also used to form rock into structural supports in underground excavations [16].

A continuous drill and blast technique has been proposed to overcome some of the shortcomings of conventional drill and blast, such as a start and stop production phase and the possible hazards of detonating large amounts of explosives [94]. Using a shielded jumbo, small charges are placed in drilled holes and fired as a spiraled cut continually progresses forward. The smaller explosive charge permits less overbreak and removes the need for evacuating personnel during blasting.

Research into boring techniques continues to produce cutterheads capable of handling harder rock (up to 43,000 psi [30.229 million kg/m^2]) [30]. Among the advantages of tunnel boring are less overbreak, lower costs for backfilling, and a safer, more continuous operation than drilling and blasting. Boring is limited by excessively hard veins of rock or large boulders. Reference 29 examines cutting fundamentals along with the capabilities and applicability of currently manufactured boring machines.

A ream concept of tunnel excavation [12] considers firing 10-lb (4-kg) concrete projectiles at the tunnel face with velocities of more than 5000 ft/sec (1500 m/sec). Thirty times the weight of the projectile can be dislocated from the face with each shot (the launcher may release up to one shot per minute). While Reference 12 cites that potentially more rapid and less expensive earthbreaking can be achieved with projectiles than with boring techniques, the safety of a launcher capable of delivering these intense impacts may be questionable for use commercially.

Flame jetting and laser cutting are proposed methods of breaking rock by means of thermally induced stresses. Flame-jet tunneling [35] uses torch-like burners to cause rock spalling. Potential environmental hazards may evolve from using this approach (intense heat and fumes, noise, dust, etc.). Rock failure caused by laser radiation has also been studied [24], but holds little promise for use in earthbreaking because of the excessive amounts of laser energy required to dislodge the rock. However, lasers have been used in tunneling to guide boring machines. Laser-directed equipment has produced accurately driven tunnels and eliminated the need for many manual surveying practices.

Soft-ground tunneling methods are used for soils of gravel, sand, salt, and clay. Shield tunneling, blade-shield tunneling, and pipe jacking are alternative excavation techniques for these conditions. Shield tunneling [20] advances as a tubular shell as the face of the tunnel is thrust forward with hydraulic cylinders. Muck pushed into the shield is then mechanically broken up and removed under the shield's protection. Hard rocks and boulders impede the progress of shield-driven tunnels. A recently developed variation of shield tunneling [28] is blade-shield tunneling. The blade shield consists of an array of cutting blades, each having a heading cylinder. Leading blades slicing into the earth are hinged to trailing blades which protect the supported tunnel until a liner can be placed.

Pipe jacking has been used in China [33] to construct a 102-in. (2591-mm)-diameter tunnel more than 1900 ft (510 m) long. In this example, a steel pipe (102-in. [2591-mm]-diameter) was shoved through the ground by hydraulic jacks grouped into stations spaced along the length of the pipe. A bentonite slurry was injected for lubrication at points along the pipe. Muck was removed by manually spraying the tunnel face with water jets; since the ground was sand and clay, a slurry was formed which pumps then ca. 'ed to the surface for disposal.

Another aspect of the production phase is mucking, or the removal of the bulk generated by earthbreaking. In both rock and soft ground tunneling, "...muck haulage is the weak link in today's high-speed tunneling systems" [22], because earthbreaking techniques can generate cuttings faster than they can be removed. Research in mucking techniques has concentrated on systems that can remove cuttings quickly, yet minimize interference with support functions (e.g., lining installation). There are three principal methods of mucking in tunnels: (1) using train cars, (2) creating a muck slurry, or (3) using belt conveyors. While belt conveyors can move material more quickly than train cars over a short distance, rail haulage has the following advantages: (1) the system is developed, (2) California switches allow continuous extension, and (3) it is generally more economical than conveyors or hydraulic pumping due to its flexible haulage rate [22].

<u>Support Phase</u>. The support phase of tunneling is the installation of a liner for ground support. Several alternative lining methods have been applied in tunnels, including rock bolts, slipforms, steel liners, precast concrete linings, and shotcrete.

In rock conditions, steel rock bolts of about 1-in. (25.4-mm) diameter by 5-ft (1.5-m) long are driven into the walls of an underground space to provide support. The bolts are inserted into holes drilled by jumbos, and apply a restraining stress to the rock as the bolt nut is tightened against a washer and the face of the rock. Two types of rock bolts are available. A split rod type with a steel wedge acts to expand and press the bolt against the sides of the hole as it is inserted; a second type has a shell at the end of the bolt that expands and grips the inside of the hole when the bolt is turned. Rock bolts are spaced every few feet and often support a wire mesh pressed up against the surface to screen loose rocks [22].

Slipforming in the placement of concrete liner is done with a portable formwork operating on a shutter principle [49]. Multiple collapsible forms on the slipforming machine alternately open to create a space against the tunnel wall into which concrete is poured and then close to permit the machine to travel forward.

Steel liners are built by welding steel plates about 1-in. (25.4-mm) thick together. However, the liners often have oxidation problems and require the costly services of skilled welders [45].

Precast concrete segments have been successfully used as a tunnel lining [50]. Cast in several different shapes, the segments are held together with wooden dowels to form a ring. Thousands of these rings may support the tunnel.

Shotcrete, or sprayed concrete, has been used extensively in underground construction. It eliminates the need for formwork, binds to any surface, sets quickly, and can be used in a variety of structures [70]. The mortar is easily piped to the point of application with light, convenient equipment. Its drawbacks are that it has a higher unit-for-unit cost than normal concrete, requires skilled personnel, and leaves an uneven finish. There are two ways to apply shotcrete. With a dry mix, a dry mortar is fed to a nozzle where water is added; the mixture is then sprayed on the tunnel surface. In the wet mix method, a ready-mixed shotcrete is forced through a hose with compressed air to the nozzle where air jets from a separate hose dispense the shotcrete as a spray. The wet mix is a more recent innovation, offering a more controlled water/cement ratio and less of a dust problem than dry mix. A tunneling construction technique, commonly referred to as the New Austrian Method, sprays about 4 in. (101.6 mm) of shotcrete to rock-bolted tunnel walls. The shotcrete fills surface irregularities and hardens to become an integrated part of the rock.

Deep caverns are built using methods of deep shaft construction and tunneling, often in conjunction with controlled blasting and drilling. Deep rock caverns will not require excessive reinforced concrete structural strength to resist the large hydrostatic pressures associated with buried structures cut and covered in deep excavated pits; however, it is costly to generate access to them [15].

State-of-the-Art Reviews

Two recent state-of-the-art papers on tunneling give a more detailed picture of construction techniques. Reference 22 describes, in detail, the production and support techniques currently used, ground control methods, and safety and cost considerations. The paper draws largely from inspections of recent tunneling projects and interviews with experts in the field.

Reference 10 examines soft-ground tunneling. There is some discussion of ground stabilization techniques and equipment, but the emphasis of the paper is on the design of flexible and rigid tunnel linings. The report states that the greatest difficulties in soft-ground tunneling arise from the presence of ground water in pervious zones or an overabundance of large boulders. Cost overruns which result because the severity of these conditions is underestimated may be reduced by thoroughly assessing subsurface conditions before bidding.

Other papers on tunneled structures include applications to deeply based missile systems [36,37] and subways in urban areas [38].

Ground Water Control

Various methods are available to control ground water during construction of underground facilities and to control its seepage into the completed structure.

Ground Water Control During Construction. Underground construction below or near the water level is possible when ground water near the site is altered. This can be done by wellpoints, deep wells, chemical stabilizers, ground freezing, pile or sheet driving, and other methods.

Wellpoints. An effective way to avoid ground water problems during construction is to lower the water table to a depth at which it does not interfere with work. Wellpointing is common and can effectively lower the water table up to about 18 ft (5.4 m) below ground level. It works best in sandy soil, but is least effective in fine-grained soils of low permeability [22]. Wellpoints are usually jetted into position by a high-capacity pump; predrilling is sometimes needed when rock or gravel makes jetting unsuccessful [71]. Water is removed from an individual wellpoint by a vacuum-centrifugal pump through a vertical riser. The water table is drawn down locally as an inverted cone around each wellpoint. An array of wellpoints is located around the construction site. This allows the water table to be lowered over a large area.

Use of wellpoints with a vaccum-centrifugal pump will not substantially lower the water table; it is thus acceptable only for shallow excavations. Dewatering to deeper levels can be done by an ejector-pump or by eductor wellpoint systems based on venturi-type flow. This type of system can remove water to depths of 100 ft (30 m), but equipment and power costs are high [22]. Also, wellpoints may remove fine particles from the soil, causing settlement problems.

Deep Wells. Deep wells are deeper and larger than individual wellpoints. Surface vertical turbine pumps or submersible pumps are used to draw down water over a large area. The same inverted cone shape as that of a wellpoint is established, but is much larger. Because of cost, the number of deep wells is usually minimized, since an individual deep well is much more expensive than a wellpoint [22]. Deep wells are not effective in stratified or impermeable soils. As with wellpoints, deep wells can cause ground settlement problems due to the removal of fines in the soil.

Chemical Stabilizers. Use of chemical stabilizers or grouting is common for stabilizing the soil mass, preventing water inflow, and providing increased soil compressive strength. With chemical stabilization, the grouting fluid is pressure-injected into the soil where it sets or gels to seal voids and reduce permeability. Chemical stabilization of soil was used as early as the 1920s in the Joosten Process for water control.

Two types of grouts are available: suspension grouts and solution grouts (also called chemical grouts). Suspension grouts, which provide for suspension of materials in water, normally contain Portland cement as the setting agent and bentonite to provide stability during injections. They are effective only for filling voids in soil that are about twice the suspended particle size and thus are effective only down to the coarse sand range of soils [71,22]. For additional saturation of the soil, a second stage of injection with a solution or chemical grout is commonly used. Solution grouts are also used alone, but are more expensive than suspension grouts [71].

Solution grouts are often called chemical grouts because of the chemical reaction which occurs between two or more constituents to form a gel. The fluid viscosity of the chemical grout determines how well it will penetrate into the soil. The Joosten Process is a form of chemical grouting and involves a "two-shot" process. A two-shot process injects a primary ingredient into the soil, followed by a second injection of a gelling ingredient. This process is still in use today. Recent developments include single-shot chemical stabilizers which gel over time.

Stabilizing grouts are injected either through driven lances or by drilled holes. Driven lances are inexpensive, but are limited in depth (about 40 ft [12 m]) and cannot be used around obstructions [71]. Frequently used in drilled holes is a special sleeved and perforated grout tube which allows placement of grout at specific depths without loss of material back into the tube (called the tube-a-manchette method [136]). Different grouts can be used in the same system. Major pores are closed by first injecting lower-cost suspension grouts followed by solution grouts. It is not uncommon for soil volumes as large as 2 million cu ft (56 000 m^3) to be treated for construction [103]. Grouting tubes are typically spaced about 3 ft (0.9 m) apart, but this varies based on soil conditions.

Grout placement in rock is described in Reference 103 for tunneling projects in Scandinavia.

Ground Freezing. Control of ground water by means of ground freezing has proved to be an effective and successful method for many construction projects. Ground freezing is expensive, but recent improvements in equipment and techniques have made it competitive with other methods, particularly for short-term projects where the ground freezing time is minimized [103,137]. Ground freezing has applications in all forms of underground excavations, including open-cut excavations and tunneling.

The ground freezing method uses refrigeration to freeze ground water in the area of excavation so that work can proceed in a water-tight barrier. Evaluating use of ground freezing depends on many factors, including site conditions, soil characteristics, ground water content and flow, the contractor's experience with the method, and, most importantly, cost tradeoffs with other methods. Two methods are used for ground freezing. The most common is the use of a brine (salt solution) refrigerant system. The other method, which has had increasing application, is the use of liquid nitrogen (LN_2).

References 138 and 139 describe a typical brine refrigerant system, which includes a refrigeration plant, surface piping, refrigerator piping in the ground, and temperature-monitoring instrumentation. The refrigeration plant cools and delivers the cold brine to the piping network. Modern refrigeration plants are built as trailers and are mobile for transport to the job site. This limits the size or capacity of the units to about 500 tons (453.5 tonnes) of refrigeration (TR); thus, multiple, smaller units are typically used [139]. The cooled brine is distributed to the refrigeration pipes by an insulated surface piping system. The refrigeration pipes are placed after drilling in the desired loations. These pipes are closed-ended and allow for circulation of the brine solution. Placement of the refrigeration pipes requires accurate drilling. Reference 139 notes that the required accurate drilling and placement of pipes usually represents the largest cost for ground freezing systems.

Placement of LN_2 for ground freezing has several operational advantages over brine systems [141]. However, cost is often the deciding selection factor. The liquid nitrogen is purchased from suppliers and can be stored in on-site tanks or delivered to the job site by tank truck for smaller jobs. The refrigerant is supplied to freeze pipes by surface-insulated pipes. Freeze pipe systems, which are described in Reference 140, typically include concentric pipes with down pipe and riser systems for return flow, although some concepts allow for the LN_2 to be released directly to the soil. References 140 and 141 compare the advantages and disadvantages of the LN_2 system to those of the brine system.

Pile and Sheet Driving. Water may also be restricted from the construction site by installing an impermeable underground wall around the excavation. The barrier dams off circulation of underground water and permits construction below the water table.

Temporary steel-sheet piles which have been used for this purpose are being replaced by concrete diaphragm walls that are frequently made a part of the permanent structure. Three types of concrete walls are used: cast-in-place, prefabricated, and secant pile walls [103].

Cast-in-place or cast-in-situ walls are built by digging a bentonite, slurry-stabilized trench. A cage of steel rebar is lowered into the trench. The slurry is then displaced as concrete is tremied into the bottom of the trench. The trench is completely filled with concrete and allowed to cure. The resulting wall then restricts water flow and thus controls ground water during construction.

Prefabricated, reinforced, concrete panels are cast before being placed in a slurry-stabilized trench to create a wall. A bentonite-cement mixture is added to the slurry to act as a grout, which hardens to seal the separations between the prefabricated panels. Prefabricated walls have better finished surfaces, higher quality control, and can take on a greater variety of shapes than the cast-in-place walls. However, they are about 20 to 30 percent more expensive.

A secant pile wall is a line of bored, cast-in-place concrete piles, intersecting each other to form a continuous wall. A Benoto rig is a piling rig often used to construct the piles by driving a special casing into the ground while removing soil inside the casing with a mechanical grab. The mechanical grab is a mechanical clamp bucket similar to the dragline which goes down into the casing and lifts out the soil. The piling rigs can bore through obstructions and secure the piles into bedrock. Secant pile walls cost about as much as cast-in-place walls.

Other Ground Water Control Methods. Alternative methods of ground water control during construction include compressed air, caissons, and electro-osmosis.

Compressed air is used in underground construction to center the hydrostatic pressure in the soil and so retard the influx of ground water. Clay is an ideal soil for compressed-air tunneling, since it tends to dry out and strengthen [98].

Due to the relatively high cost of the equipment involved (compressors, air locks, etc.) and the hazards to workers, compressed-air methods are now used less frequently. If the compressed air creates a direct channel through the soil to the surface in a subaqueous tunnel (a "blow"), the tunnel may flood. Crews working under high-pressure conditions must work shorter shifts for higher wages due to the dangerous work environment. Reference 22 provides details on the operation of a compressed-air tunnel and its limitations.

Caissons are traditionally used to construct piers and other underwater structures. Their use has expanded recently to include underground construction in water-laden soils. Large pipes and tunnels have been constructed with caissons [13]. The caisson is a waterproofed shelter that is lowered down around the excavation site as the hole deepens. Compressed air in the caisson prevents water from flowing up through the floor where earth is removed.

Electro-osmosis increases water flow to wellpoints [22]. Cathodes are installed in the wellpoints in a sandwick. A sandwick is when a hole is drilled and filled with sand. This sand column allows water to percolate into and up the sand without pressure building up. Steel pipes, acting as anodes, are driven into the ground on 10- to 20-ft (3- to 6-m) centers. When the electrodes are charged with a current of 10 to 30 A at 100 V, water will flow from the anodes to the cathodes. Although this method provides effective stabilization of fine-grained soils (silt or clay), it is not widely used.

Choice of System. The choice of a system for ground water control during construction depends on the type of construction, water levels, soil type, and special requirements. The type of construction (shallow excavation, deep excavation, deep shaft, or tunneling) is important, but beyond this, the depth of the excavation and the area of coverage are key considerations. The entire area of the structure, plus additional area for operations and side wall stability, will typically be exposed during excavation for construction. Thus, this entire area will require ground water control at one time. On the other hand, tunneling can use segmented construction with sequential water control as the work progresses. Reference 102 describes how the sinking of deep shafts (800 m) under unfavorable water conditions in clay soil and flowing soil (quicksand) is done by ground freezing.

Selecting the appropriate means of water control requires a detailed knowledge of the site's geology. This includes information on soil type, how it varies with depth, level of the ground water, whether the soil is stratified, soil permeability, and range of particle sizes. A detailed study of the site by borehole samples is required to depths below that of the excavation. Adequate numbers of samples should be collected to describe the site geology in detail.

Special requirements may govern the choice of ground water control during construction. The use of wellpoints or deep wells can cause settlement in the area if fines are removed or if the soil is a type that shrinks when dewatered. In some built-up areas, dewatering is prohibited in order to avoid settlement of ground water [22], and other options must be used. Long tunnels which cross ground water flows can act as a dam, raising the water level on the upstream side and lowering it on the downstream side. This can cause problems such as basement flooding or reduction of well levels. Such a problem was encountered during construction of the Konig-Heinrich-Platz metro station at Duisberg, West Germany. The solution, described in Reference 105, was a diaphragm wall with gaps which was sealed by freezing during construction. After construction, the ground water was able to flow again through the gaps. The gap freezing was combined with sequenced construction to allow ground water flow during construction.

Often, one method of ground water control is not sufficient. Combinations of several methods are often used in a single project because of varying soil properties and depth of excavation around the construction area. Reference 138 describes such a situation, where cast-in-place concrete diaphragm walls were used in vertical shafts, along with chemical grouting followed by the use of ground freezing during tunneling between the vertical shafts.

Reference 22 compares methods for stabilizing and dewatering various types of soils (see Figure 2).

Pertinent References. Numerous references were collected which address the control of ground water during construction. References 22, 103, 71, and 136 provide details on methods and applications of wellpoints, deep wells, and chemical stabilizers. The topic of ground freezing is extensively covered in Reference 99. References 103 and 69 provide information on pile and sheet driving. These references provide more detailed information on ground water control during construction.

Waterproofing of Structures. Reference 74 contains a complete and organized discussion of waterproofing underground concrete structures.

The surfaces of underground structures are often exposed to ground water at high hydrostatic pressure. "Waterproofing" is any method of making concrete in underground walls less permeable to the influx of ground water.

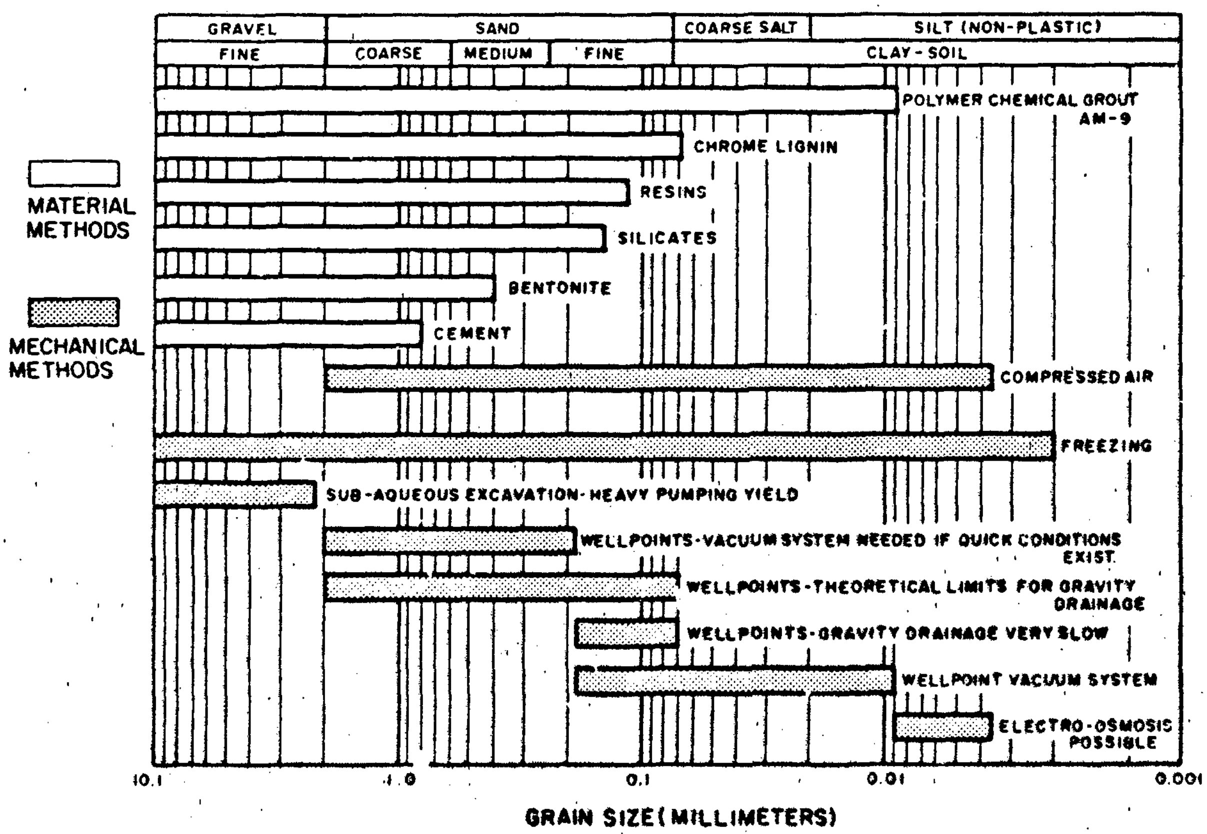


Figure 2. Comparison of methods for stabilizing and dewatering soil. (From Reference 22.)

The permeability of concrete is an experimentally obtained measure of how freely water can flow through the concrete for a given water pressure applied over a unit surface area. Three principal factors influence a concrete wall's permeability: (1) concrete constituent properties, (2) methods of concrete preparation and application, and (3) subsequent treatments or coatings.

The proportion of cement, aggregate, water, and admixtures in concrete is shown to affect permeability [74]. Increasing the maximum aggregate size or the water/cement ratio will increase both the coefficient of permeability and leakage rate through the concrete. Admixtures have been developed that create water-repellent linings in the pores of the concrete and decrease permeability. Polymer-impregnated concretes are used in underground structures for their impermeability and resistance to freezing. Fiber-reinforced concretes are also used for their increased strength.

Improperly installed concrete is more apt to crack and leak. Voids from honeycombing or segregation of the constituent materials may also increase leaking. Vibrating the concrete during placement can greatly increase the waterproofing level of an underground structure.

Asphalt and other sealants have been applied to the surfaces of underground concrete walls [75]. The coatings may be applied by heating the asphalt or coal-tar pitch to 350°F (192.5°C) and mopping it on the concrete surfaces. Several coats are added. An alternative method under study is a cold-applied sealant that is sprayed on and is much easier to apply.

Concrete in clay soils may seal naturally when clay particles present in infiltrating ground water plug concrete pores [72].

Cost Considerations

Recent publications have discussed construction factors affecting costs, compared costs between construction factors and methods, and offered detailed cost breakdowns and estimating procedures.

Cost Factors

Many factors influence a project's final cost. Reference 29 points out that geotechnical conditions, the tunnel's size and depth, the location of required power sources, and the availability of labor and materials are all important cost factors in tunnel boring. Labor costs will tend to be the greatest expense, followed by material costs and equipment depreciation.

An evaluation of a nuclear power plant concept [79] revealed that locating the facility underground with a cut and cover technique would be 11 percent more expensive than an aboveground plan. The increased cost was SOI attributed to direct construction costs being 70 percent higher, the need for special equipment for ventilation and other functions, and the additional time required to build the underground structure. More costs are incurred from hardening underground tunnels to resist blasts or seismic loads. A design cost study [85] estimates that hardening a tunnel to resist a seismic load of 0.5 g would increase construction costs by 35 percent.

Several suggestions have been proposed to decrease expenses. The use of instrumented field test section in tunnel support has shown significant construction savings in numerous tunneling projects [54]. A clearer understanding of the ground conditions provided by the test sections helps reduce unexpected problems. Reference 91 compares two documented case histories to show that sponsors of underground construction projects may reduce final costs and legal expenses by sharing the inevitable risks of tunnel construction with the contractors. Better contracting saves time, trouble, and money.

Cost Comparisons

Several studies have compared costs among various construction methods and underground designs. Underground or earth-sheltered buildings show more economic promise when considered over the entire life of the structure. According to Reference 90:

> Earth sheltered design, like any other approach, is cost effective only for appropriate conditions of site, climate, building use, program, and economics. Given the right conditions, however, an earth-sheltered design will substantially reduce operating, maintenance, and repair and replacement costs during the life cycle of a building when compared with conventional design, while increasing initial construction costs very little, if at all.

New construction techniques for rigid, impermeable walls have been compared in a study of subway construction costs [88]. Given favorable site conditions, a tremie concrete slurry wall or a precast concrete panel slurry wall would cost only about 90 percent as much as a conventional cast-in-place concrete wall. Underground subway station construction costs were also compared to show that an underground station using a tunneled earth excavation technique with an 85-ft (25.5-m) overburden would cost about 25 percent more than one constructed by cut and cover methods with a 20-ft (6-m) earth cover, and 47 percent more than a cut and cover station with a 6-ft (1.8-m) cover.

Similar comparisons are available in the literature for three areas of application: subways, power plants, and homes or large buildings. One study [89], which focuses on the expenditures in West Germany for subways over the past few years, states that there is little current cost difference between open cut, shield method, and the New Austrian Method (also known as Shotcrete Method). However, in soft, water-bearing ground, compressed-air, shield-driven tunneling may cost two or three times as much as the cut and cover method.

Reference 77 compares the costs of siting a nuclear power plant underground. The investigation found that a cut and cover buried facility would cost 14 to 25 percent more and a mined rock plant 10 to 18 percent more than a surface power plant. A second report [86] states that costs for siting a nuclear power plant underground in rock are about 25 percent more.

Reference 80 examines the costs of underground homes and large public buildings. Based on life-cycle cost figures of five case studies: "It does appear clear, however, that the use of earth-sheltering does not increase construction costs in any notable way, and may in fact represent a decrease in some cases" [80]. An example earth-sheltered house is cited as costing 28 percent more to construct, but 12 to 20 percent less to own and operate over the 30-year life of the home.

Detailed Cost Estimates

Several reports give detailed construction cost breakdowns and estimating procedures. Reference 22 explains tunneling costs, including manpower and equipment allocations. Detailed cut and cover excavation costs for different depths and soil conditions are presented in a report on underground naval facilities [78]. Reference 9 gives an in-depth review of tunnel and shafting costs, cost-estimating procedures, and data for use in underground emplacement of nuclear explosives. References 22 and 78 provide factors that must be considered in cost estimation. Physical factors to be considered in cost estimating of underground construction projects are: (1) location and accessibility, (2) geology and hydrology, (3) general environment (climate, altitude), and (4) operational requirements including intended use, operational life, general configuration (number of tunnels, shafts, etc.), depth alignment and grade requirements, and environmental control requirements (ground water, air quality, etc.).

Security and Survivability

One benefit of locating a structure underground is the increased protection provided from threats of force as compared with an aboveground siting. This has been the driving consideration behind the use of underground construction for many military facilities. Threats of force can come in many forms, including, but not limited to, the following:

- Terrorists or subversives
- Chemical-biological weapons
- Air-delivered munitions
- Artillery fire
- Fuel-air explosions
- Well-armed military troops.

Military installations are not the only facilities that have used underground construction techniques as protection from these threats. Another example is civil defense shelters to protect the civilian population from nuclear and conventional weapons effects. Nuclear power plants have also recently been considered for underground siting. Belowground siting provides nuclear power plants with more protection from terrorists and aircraft impact than an aboveground facility unless the latter is substantially hardened. Reference 77 considered in detail the security (anti-terrorist) advantages offered by belowground siting of nuclear power plants.

The various threats of force can be classified into two groups: threats to security and threats to survivability. "Security" is defined here as protective measures taken to minimize loss or damage of material, information, and personnel located within a facility due to terrorist or subversive activity. "Survivability" is defined as protection provided against acts of war, including attacks with nuclear, chemical, biological, high-explosive or fuel-air explosive weapons. Aircraft impact could fall under either heading, but will be considered here under survivability (this could include a military aircraft attack, a terrorist hijacking, or a commercial airliner accident). The following discussion of each threat is limited to a comparison of the protection provided by underground versus surface construction practices.

Security

Protection of a facility from terrorist or subversive groups has been a subject of increasing concern. Several studies have been performed to develop means of providing increased security [142,143,144]. Belowground siting is often considered for this purpose. The primary consideration in selecting security measures, including choice of siting, is the magnitude of the threat. Security threats can be divided into three levels based on the tools or equipment available to the attacker. The lowest threat level would be a saboteur/pilferer equipped with hand tools, such as a sledgehammer, bolt cutters, or hand drill, or small electric- or gasoline-powered tools such as saws or drills. Included in this threat would also be equipment such as that used by rescue squads to aid trapped accident victims. The second level of threat sophistication would include use of items such as burning bars, cutting torches, and bulk explosives (dynamite, plastic explosives, and small, linear-shaped charges). While the first threat level would include single-shot rifles and pistols, the second level may have automatic weapons capable of firing sustained bursts at the target. A third level of attack could include tools/weapons such as heavy linear- or point-shaped charges and shoulder-fired weapons such as the bazooka and recoilless rifle. However, this third threat level stops short of the amounts of equipment that could be used in an infantry assault.

The first level of threat is much less substantial than the latter two. Protection can be provided in the aboveground facility with minimal cost impact. The increased costs associated with belowground construction are not warranted. The remaining two threat levels are much more substantial, with the third level being the most severe. In such cases, belowground siting can provide benefits over an aboveground structure even if the aboveground facility is substantially "hardened" to provide the required security level. It should be noted that, given enough time, a well-planned and well-equipped terrorist force can eventually penetrate any structure. Consequently, security requirements are usually stated in terms of minimum intrusion denial time requirements for a given level of terrorist sophistication.

Compared to an aboveground structure, one advantage of an underground facility is the concealment inherent in its location. Reference 77 describes how this factor works as a deterrent by making it more difficult to plan an attack. A terrorist group must be sophisticated enough to have access to facility design documents in order to have sufficient knowledge of the physical makeup of an underground structure.

A second advantage of an underground facility is that it minimizes attack points. Unless the structure has a very shallow burial, the viable attack points are limited to entryways and structure penetration points (for ducts, pipes, wiring, etc.). The more deeply a structure is buried, the more this is true. A typical aboveground structure offers access through roof slabs and wall slabs as well as entryways and structure penetrations. With suitable cost increases, it is possible to harden an aboveground facility to reduce the possibility of forced entry through roof and wall slabs. Reference 142 includes an in-depth study of six concepts for structures to meet very stringent security requirements. Both aboveground and belowground concepts were included. The study showed that substantial hardening of the aboveground exterior wall and roof slabs was required to provide protection equivalent to the buried concepts. It was considered unrealistic to try to achieve these extreme roof- and wall-hardening levels. Doing so would produce a massive aboveground structure which would be substantially mounded with earth and, for all intents and purposes, buried. Use of very thick reinforced SOI concrete slabs aboveground does not provide a security level equivalent to a deeply buried structure [142].

Comparing the vulnerability of entry systems to terrorist attacks also favors underground construction. Unless specially constructed entry corridors are provided, breaching of an aboveground building entry system constitutes entry into the facility. On the other hand, the nature of underground structures requires entry systems which run from the surface down to the facility. If the surface entryway is breached, then the terrorist must still proceed underground to the facility and breach a second entry before the security of the building is compromised. Reference 66 describes the security provided by such long entry systems to underground facilities. Multiple barriers can be placed along this path to provide increased intrusion prevention. An aboveground structure can have an entry corridor for the same purpose. However, such a corridor would be vulnerable to attack through its walls or roof, and hence would have to be substantially hardened to be an effective deterrent.

Another advantage of an underground facility is that the security force needed to guard the facility is reduced. Depending on the type of facility, such as a weapons storage facility, the cost of security personnel required could be quite high. Thus, the overall cost of constructing and maintaining an underground facility could be lower than that of an aboveground facility.

final advantage of underground siting for security purposes is capture of intruders. Because the likely mode of entry by intruders is through entryways, the threat becomes localized and easily identifiable. Providing sufficient physical intrusion protection in entryways to give security forces time to react properly will yield a natural place of entrapment. The limited entry points of underground siting are a disadvantage; although it is difficult for a terrorist group to enter a buried facility, it does become possible for them to render a facility inoperable. The use of sufficient high explosives at entryways could close down the structure, trapping personnel and contents. Earth-moving equipment would be needed to clear the obstruction, and rapid deployment or operations by the facility would not be possible.

Survivability

Traditional aboveground construction does not protect from substantial threats of force such as nuclear blast, air-delivered munitions, artillery fire, or fuel-air explosions. Even survival from low overpressures ($\leq$ 50 psi [35 150 kg/m^2] side-on, long duration) requires very substantial hardening of aboveground facilities, as does survival of direct impact by artillery, aircraft, or air-delivered munitions. Much higher loads (> 50 psi [35 150 kg/m^2], long duration) are easily achieved in fuel-air explosions and, to a greater degree, in nuclear detonations when the facility is close to ground zero. Pressures on the order of 300 psi (210 900 kg/m^2) side-on inside the cloud are not unusual. The cost-effectiveness of underground construction compared to aboveground construction becomes more attractive as the level of threat increases.

A cost comparison analysis was made using a variation of the example structure shown in Figure 3. This structure is 170 ft (51 m) long by 36 ft (10.8 m) wide, and 10 bays long by two bays wide. The structure is one level, with a floor-to-roof height of 15 ft (4.5 m). A uniform static live load of 250 psi (175 750 kg/m^2) was applied to the roof. Two computer programs were used: one to design an aboveground structure and the other for a belowground structure [148]. The belowground structure used was a cut and cover surface flush structure. Input for these programs included the material properties, design specifications, yield size of the bomb, and the overpressure produced at the

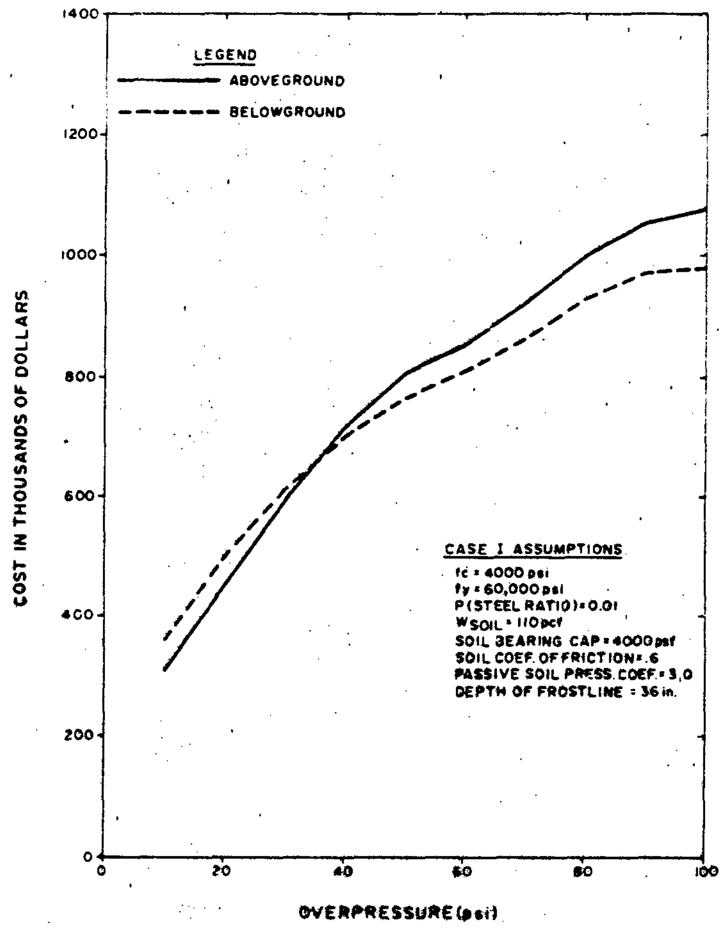


Figure 3. Cost vs. overpressure for example structures.

building location as a result of the bomb. Cost rates for material, equipment, and labor were obtained from the *1984 Means Construction Cost Data*. The concrete strength of 4000 psi (2.812 million kg/m^2) and the steel strength of 60,000 psi were used for the analysis.

The output included detailed specifications of the size of the structural members (i.e., walls, columns, roof, foundation, etc.). A value for the total cost was determined from each run of the programs. These values for the aboveground and belowground structure are plotted against overpressure in Figure 3. The cost for the aboveground and belowground structure is found to be equivalent at an overpressure of approximately 35 psi (24 605 kg/m^2). The aboveground structure is more economical for overpressure below 35 psi (24 605 kg/m^2), while the belowground is more economical for greater overpressure.

Soil overburden mitigates the loads delivered to a structure for explosions in air. Nuclear detonations, fuel-air explosions, and artillery fire are typically air bursts which generate severe shocks to the atmosphere. These blast waves reflect off the ground surface and drive a shock wave into the soil. Shocks attenuate much more quickly in soil than in air. Thus, a buried structure will realize a lower shock strength than a surface structure the same distance away from the point of an air burst. Similarly, for aircraft impact, the ground attenuates the forcing function associated with the crash. Thus, in these cases, underground construction provides increased protection with increased depth of burial. Of course, higher costs are associated with increased burial depth.

Air-delivered weapons that can penetrate the soil are another threat category, along with any weapon capable of burial before detonation. Underground explosions near a buried structure can produce effects as severe as, or much more severe (for very close or in contact) that an air blast on aboveground structures. The structure cannot be protected from buried explosions until it is located deeper than the weapon's capability to penetrate soil, which increases construction cost. For air-delivered bombs, penetration depths of 50 ft (15 m) are not unusual. Use of a burster slab at the ground surface above the buried structure is one option. The slab causes the weapon to operate prematurely before deep burial is achieved. However, such a slab must cover the entire facility, including overlap, to account for the bomb's trajectory angle. Use of a burster slab also increases construction costs.

The decision of whether to use aboveground hardened construction or underground construction (which also may require hardening beyond that required by soil overburden alone) is based on construction cost plus other considerations such as effects on operations, life-cycle costs, and security requirements. Reference 142 studied this problem extensively, comparing the construction costs and life-cycle costs of aboveground and belowground structures. The structures were subject to the same survivability requirements--i.e., that the structures should withstand direct impact by a 500-lb (200-kg) air-delivered bomb, aircraft impact (B747), and about a 50-psi (35 150-kg/m^2) long duration, side-on overpressure. The aboveground concepts required a much more substantial and costly structure, but the buried concepts had greater excavation costs. The siting was for level terrain with a high water table and very deep (beyond construction depths) bedrock similar to coastal areas around Houston, TX. The costs were very competitive for the two forms of construction [142]. For lesser threats, it is expected that aboveground construction would result in lower costs to provide the same level of survivability. For greater threats (e.g., close to a nuclear weapon ground zero), it is totally infeasible to consider aboveground construction. Reference 147 describes model tests on buried cylindrical structures representing the response expected when located near ground zero of a nuclear explosion.

Chemical-biological weapons survivability is becoming an important issue on many new military construction projects. Reference 142 provides a detailed description of the protective measures to be taken in facilities designed to protect against chemical-biological attack. There is no advantage of belowground construction for this threat. The explosive loads associated with a chemical-biological weapon [145] are minor compared to those of previously mentioned weapons. Chemical-biological weapons will generally be used with other explosive weapons. The facility design challenge then is one of withstanding the blast loads of other weapons without allowing chemical-biological agents to enter the structure. There is no real advantage or disadvantage to underground construction for a chemical-biological threat. The requirements of a chemical-biological filtration system are the same for above- and belowground facilities.

Energy Savings

Recent publications pertaining to energy considerations for earth-sheltered structures have (1) discussed factors influencing energy consumption, (2) given temperature data and calculation methods, and (3) compared energy expenditures for above- and belowground buildings.

Energy Factors

The earth surrounding an underground structure has a thermal inertia that insulates the building and dampens thermal loads from daily and seasonal variations in air temperature. The ground has a relatively stable temperature near the comfort range of the building. Thus, there would be lower required heating and cooling loads than with a comparable aboveground structure.

While less or smaller mechanical equipment is needed to meet the energy demands of an underground building (heaters, air conditioners, etc.), there is often additional expense for ventilation ductwork [109,107]. Overall, the operating costs are lower and, when life-cycle costs are considered, this may prove a strong incentive for choosing an underground design.

Energy Details

Reference 108 contains data on monthly weather conditions for 29 locations throughout the United States. It examines the climate in various parts of the country and assesses the energy effectiveness of earth-tempering. Estimates of earth temperatures as a function of depth, season, mean annual temperature, etc., can be found using an equation given in Reference 84.

Energy Comparisons

The cooling costs are 20 percent less for the Central Library in Fort Worth, TX [106], because it is located underground. In a study of underground homes [80], savings in space heating paid for additional construction expenses within 20 years. The underground houses then proved more economical than conventional homes over a 30-year life cycle. Reference 80 also cites energy savings from two additional underground buildings: a college library in Minnesota costs 28 to 44 percent less to heat, and an elementary school in Virginia saves 49 percent on heating and cooling costs.

Energy Comparisons of Construction Methods

An investigation of alternative methods of earthbreaking [35] compares the energy required to remove 1 cu in. (163.8 mm^3) of rock:

Earthbreaking Method (Cutter)	Btus Applied/ cu in of Rock Removed
Mechanical Clipper	0.6 - 2.0
Ultrasonics	0.055
Flame Jet	0.01
Rock Melting	0.004

A description of earthbreaking methods is as follows:

Mechnical clipper--uses drilling and shearing techniques.

Ultrasonic cutting--uses high frequency vibrations to dislodge rock.

Flame jetting--a fuel-air mixture is combusted through a nozzle at a sonic or supersonic velocity. Impingement of the jet on a rock surface causes erosion and spalling with thermally induced expansions.

Rock melting--a laboratory technique used to weaken or melt rocks with laser heating.

3 EXAMPLE ANALYSIS

This chapter describes an example facility considered for underground siting and examines its possible construction with the various methods described in the literature. The methods of ground water control that can be implemented are considered, as well as the security and survivability aspects of locating the facility underground.

Example Selection

Figure 4 illustrates the chosen facility, which is to be a semi-hardened communication center. The structure is 170 ft by 35 ft by 15 ft (51 m by 10.8 m by 4.5 m) high. Access by truck to a load area inside the facility entrance is required. Personnel access is also provided. The structure is box shaped and contains 25 office stations and a mechanical support room. An alternate emergency exit, sized for personnel only, is required, and is to be located away from the primary personnel and vehicle entryways.

Construction Methods

The example structure is examined for several different construction techniques, including aboveground construction, shallow excavation, deep excavation, deep shaft, and tunneling.

Aboveground

Siting the structure aboveground will require a hardened structural design of thick, reinforced concrete walls and roof slabs if the facility is to withstand any substantial security or survivability threat. If a nuclear exterior threat is included, overburden will be required as protection from radioactive fallout. Figure 5 illustrates an aboveground facility concept with earth surrounding.

The facility is likely to be massive due to the weight of the structure plus the overburden, so the substructure must be able to transfer the building loads to the ground without excessive settlements or subgrade failure. Settlement is a major concern in areas of high water table and generally poor soil conditions of low compressive strength. The soil's bearing capacity must be able to withstand the expected building loads to prevent shearing failure.

Bearing capacity can be increased by several approaches, including the use of driven friction piles, bell piers, extended mat foundation, and the use of stabilizers. These can be used individually or combined, depending on the structure's needs and the soil properties. Figure 6a illustrates a structure built over soil which has been chemically treated by grout material. Figure 6b shows an extended mat foundation or skirt which spreads the structure weight over a larger area. Figure 6c illustrates the use of friction piles to prevent settlement, and Figure 6d shows the use of bell piers.

Security and survivability of the aboveground structure are limited. The facility can be entered by force at any point around the structure if the intruders are well equipped; there is no single weak point. This type of aboveground structure could withstand low overpressure threats such as a distant nuclear explosion or air-delivered bombs or artillery which does not maintain a direct or nearby hit. However, protection

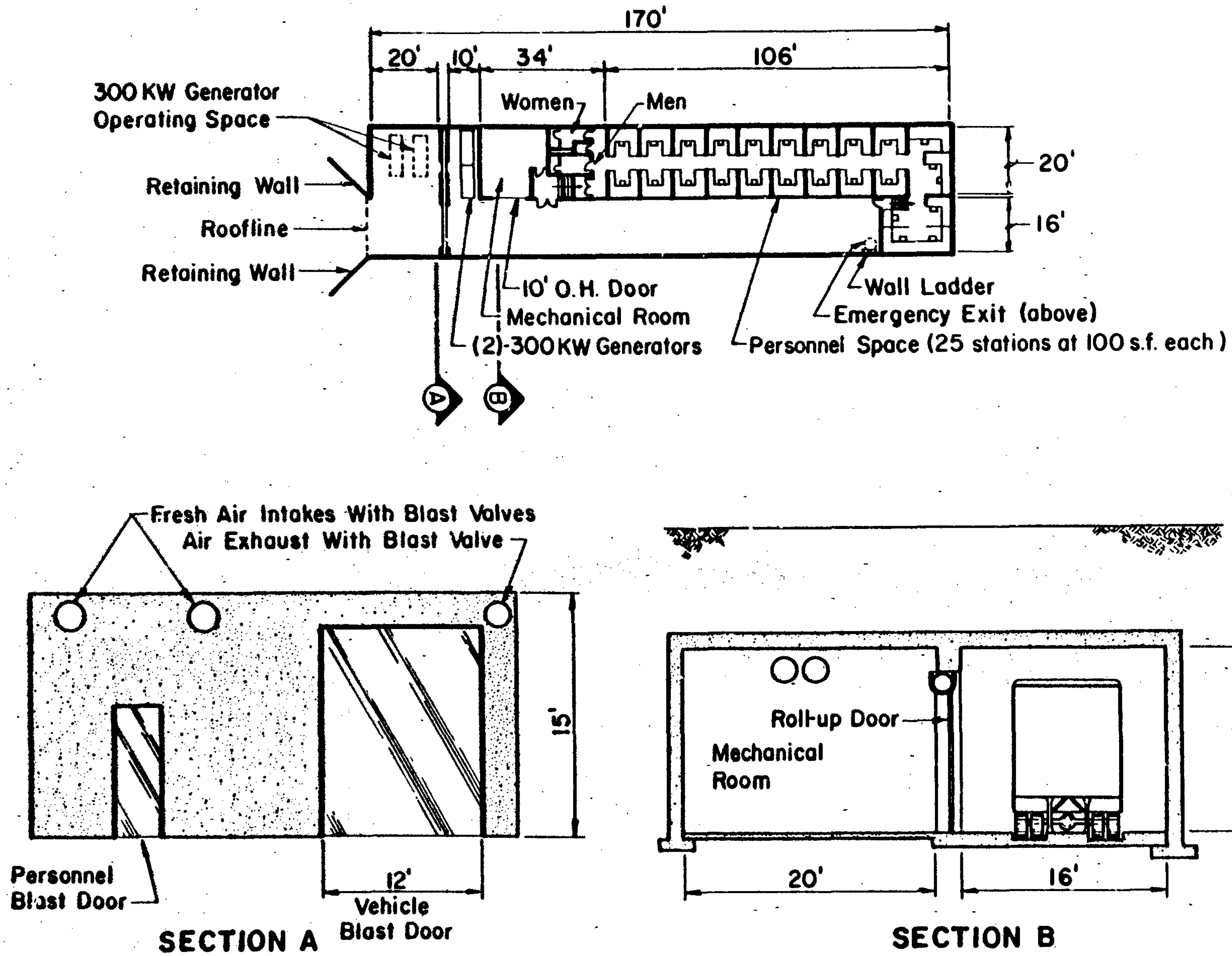
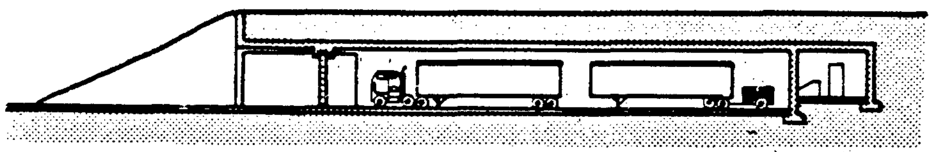


Figure 4. Example structure.



LONGITUDINAL SECTION ALTERNATIVES A & B

Figure 5. Aboveground facility with earth surrounding.

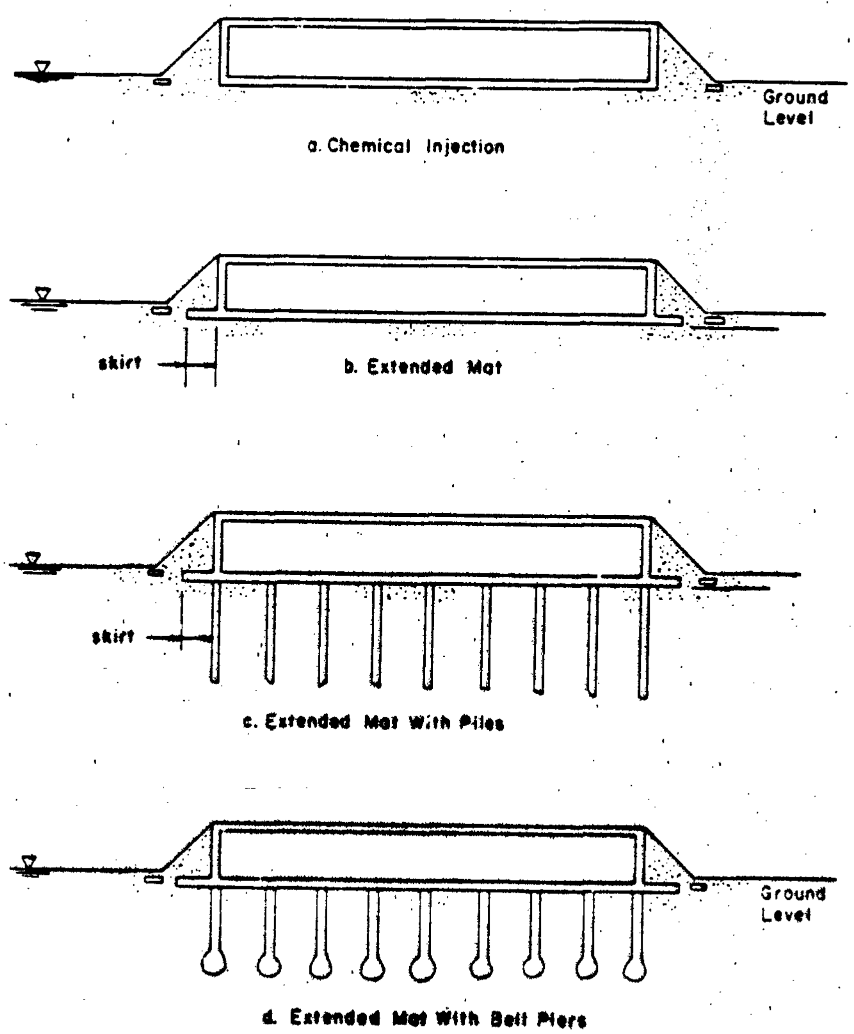


Figure 6. Aboveground configurations.

from close-in blast effects or direct impact by weapons or aircraft is very hard to provide.

Operational considerations favor an aboveground facility. This siting easily provides the requirement for vehicle access. Personnel entrances are convenient, and emergency exits are easily satisfied. Supply and return air is accessible for the facility, including changing air that contains vehicle exhaust.

Shallow Excavation

A shallow excavation for a facility of this size would be a cut and cover operation. Figure 7 shows a shallow buried concept for the example facility. In stable soils with a low water table, excavation is easy because ground water control is not a factor and sidewalls maintain stability without collapse. However, in areas with unstable soils and a high water table, methods such as use of chemical stabilizers, wellpoints, deep wells, or ground freezing must be used.

Settlement is a concern in areas with soils of low bearing capacity. If the soil's ultimate bearing capacity is not much greater than the expected pressure, the applied loads must be reduced either by the foundation redesign alternatives described in Figure 6 or by modifying the soil by injecting soil stabilizers. For a high water table, injection of soil stabilizers serves a dual purpose: controlling ground water and increasing soil bearing capacity. In a high water table condition, a shallow buried concept has an advantage over an aboveground concept. The structure can "float" by means of weight compensation, in which the weight of the excavated soil equals the weight of the structure and overburden. When this condition is met, the soil load does not increase, settlement is minimized, and the foundation and structure are considered to be floating. In practice, an exact balance is not likely to be achieved; thus, the use of friction piles along with a floating structure is common.

Security for a shallow buried concept has been improved only slightly over that of an aboveground siting. The side and near walls are protected, but the roof slab and entryways are weak points. Survivability has also not been increased significantly. Unless very substantial hardening is provided, the structure is still very vulnerable to high nuclear overpressures, direct hits by munitions, and close-in detonations of munitions.

Compared with an aboveground structure, operational considerations are very similar for a shallow buried concept. Vehicle access is easily provided, along with personnel access and emergency exits. Supply and return air is also easily accessible.

Deep Excavation and Deep Shaft

Deep burial will greatly increase the structure's survivability. Depths to the roof slab of 40 ft (12 m) or more provide significant hardening against the posed threats. This type of burial can be achieved by a very deep cut and cover operation. A structure at this depth in unstable soils may require a deep shaft construction operation with excavation at the shaft bottom. Figure 8 illustrates a deep burial concept.

Ground water control is an important consideration in deep burial. Wellpoints are ineffective because of the depth of construction, and even deep wells may be impractical or expensive due to the need for close spacing. Chemical grouting and ground freezing methods can be used. For shaft construction, ground freezing can be used at a saturated layer until the shaft construction and lining have progressed to the dry ground below.

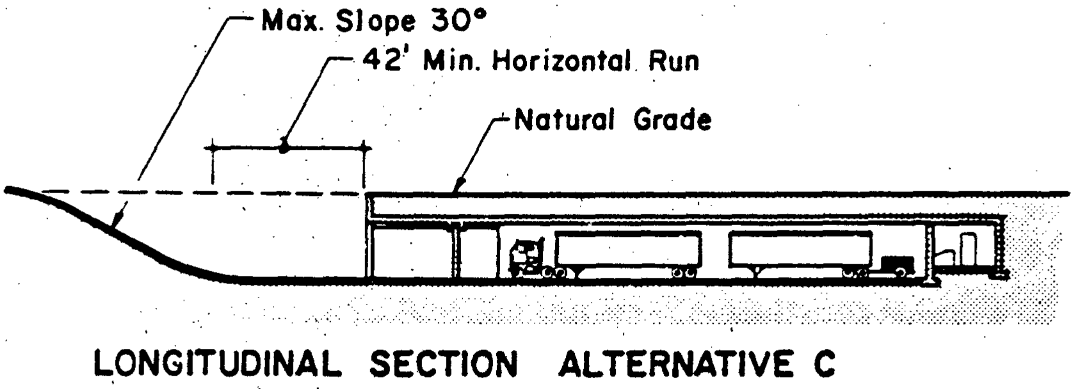


Figure 7. Shallow excavation for example facility.

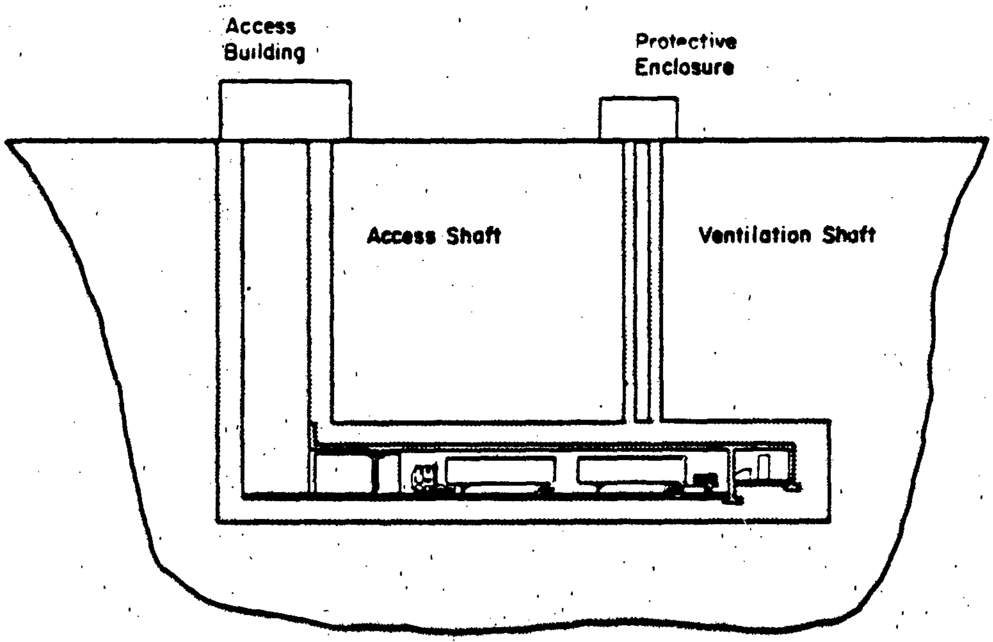


Figure 8. Deep shaft structures.

Thus, ground freezing does not have to be in place during the entire construction. A combination of ground water control methods can be used during construction.

Hydrostatic pressures can be critical in designing structures buried at depth much below the ground water table. Overall hydrostatic uplift can result if the resultant buoyancy force is greater than the weight of the structure. For massive concrete structures, this is generally not a problem. One advantage of deep burial is lighter construction because of a reduced threat of force. For very deep structures or when the surface attack threat is considered to be minimal (such as a low surface overpressure), the structural design may be driven by the siting and not the exterior threat. Both a lighter resulting structure and hydrostatic uplift may be realized. Use of an extended mat and friction piles may be necessary to distribute the structure weight. Another concern is the slabs' ability to resist the bending stresses associated with hydrostatic uplift pressure. The example structure does not have long, unsupported spans, so this is not a substantial problem; however, other concepts may encounter this difficulty. A thick slab with double reinforcements is a common solution.

Operational considerations do not favor a deeply buried facility, since access is difficult for both vehicles and personnel, and a lift system to the surface is required. An aboveground structure is provided for this purpose which serves as a loading dock for vehicles and for personnel entry. If vehicles must be stored in the structure, the lift must be sized to accommodate their size and weight. However, this may be prohibitively expensive, and a separate tunnel system may have to be provided from the surface to allow a long ramp for vehicular traffic. Emergency exits are not easily provided. One concept would provide for truck access by ramp tunnel and personnel emergency exit by shaft. Mechanical ventilation and ventilation of vehicle exhaust present operational problems as does cooling of emergency power systems located in the buried structure.

Security from terrorist attack is excellent for such a structure. The only vulnerable areas are the entryway and mechanical penetration of the structure; however, the threat is localized and easily identifiable. One security drawback is that the structure can be closed down easily. Although it may be difficult for intruders to enter the actual facility, it could be rendered inoperable by closing the entryways. Bulk explosives can be placed to collapse entryways, but will require the use of heavy construction equipment to reopen the facility.

Tunneling

Tunneling in mountainsides to provide facility protection (see Figure 9) is commonly used, particularly in Europe and the Scandinavian countries. The choice of a site for tunneling is important, because poor geology and flood-prone rock will escalate construction costs. The length of the tunnel relates directly to construction cost and techniques. Short tunnels through rock will typically proceed by blasting and excavation. Very long tunnels and tunnels through soft rock or soil will use special machinery which is not cost-effective for short tunnel lengths. The example facility is not large, and its size alone constitutes a small tunnel length. However, deeper burial into the mountainside provides greater survivability.

Tunnel size is fixed by vehicle access requirements. A single facility entrance is common for hardened facilities located in mountainsides. Emergency exits can be provided by constructing a shaft to the mountain surface or a second tunnel access.

Choosing an Underground Construction Method

The various underground construction methods discussed as options for the example facility must be evaluated on a site-specific basis, since factors such as site geology will vary significantly in different locales. The advantages and disadvantages of each option must be weighed, and each alternative's costs and energy use must be evaluated. The most effective options can then be considered in terms of the various constraints posed by the individual site.

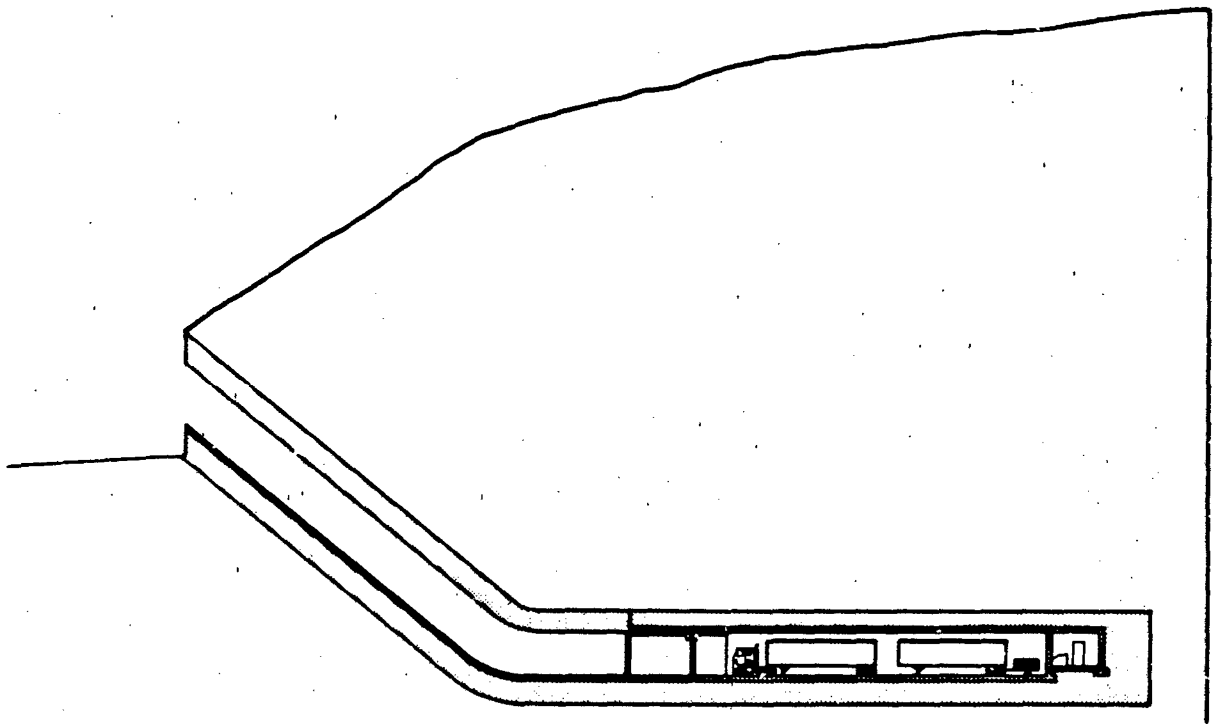


Figure 9. Tunneled structure.

4 CONCLUSIONS AND RECOMMENDATIONS

This report has described a survey of literature covering various methods used in underground construction. The Army will use this information to identify and compare methods for building hardened facilities that can resist threat forces and are safe, cost-effective, and energy-efficient.

In general, the literature revealed that construction costs are greater for underground structures; however, aboveground structures do not provide security or survivability against external attack unless they are substantially hardened. In providing this level of protection, the construction costs for shallow underground structures are competitive with those of hardened aboveground facilities. The belowground structure becomes more economical at relatively low overpressures of 35 psi (24 605 kg/m^2) or greater. Deeply buried structures or structures tunneled into mountainsides represent the most expensive options, but provide the greatest level of survivability. Such facilities provide survivability even for very substantial exterior threats.

Operating costs of underground buildings are normally lower than those of aboveground buildings. Depending on the geographical locations of the building and the costs of energy, the savings in cooling and heating costs could vary from 20 to 49 percent for the underground buildings as compared to the aboveground conventional buildings. Therefore, the life-cycle costs of underground buildings could be lower than those of aboveground buildings over a 20- to 30-year life cycle.

The construction of large, underground, hardened facilities is technically feasible. Therefore, it is recommended that underground structural systems be evaluated to determine their vulnerable components for various external threats. Cost-effective improvements can then be identified to enhance the systems' security and survivability.

APPENDIX A:

REFERENCES SURVEYED

Reference List

Following is the complete list of references compiled for the literature survey conducted for this study on underground construction methods. The computer literature abstracts search was conducted by the National Technical Information Service, Compendex, and the Defense Technical Information Center to identify journal articles and reports relevant to the study.

1. Brekke, Tor L., Thomas L. Lang, and Francis S. Kendorski, "Some Design and Construction Considerations for Large Permanent Underground Openings at Shallow Depths," *Proceedings, International Society for Rock Mech.*, 3rd Congress, Vol 1, Part B (1974), pp 1507-1513.

2. Iffland, Jerome S. B., "Practical Design of Concrete Diaphragm Walls," *Transp. Res. Board. Transp. Res. Rec.*, No. 684 (1978), pp 37-43.

3. Provost, A. G., and G. G. Griswold, "Excavation and Support of the Norad Expansion Project," *Trans. Inst. Min. Metall.*, Sect. A, Vol 88 (Oct. 1979), pp A171-A182.

4. Green, Bruce H., and David A. Summers, "UMR Minerals Building: An Innovative Approach to the Construction of Underground Buildings," *Annu. UMR DNR Conf. Energy Proc. 7th, Energy Future: Prophets, Profits & Policies*, Rolla, MO, USA, Oct 14-16 1980 (Univ. of MO, Rolla, USA, 1980), pp 198-205.

5. Wickham, George E., and Henry R. Tiedemann, *Research in Ground Support and Its Evaluation for Coordination with System Analysis in Rapid Excavation* (Apr. 72) 178 pp, NTIS: AD-743 100.

6. Soland, Duane, E., Harold M. Mooney, Duane Tack, and Richard Bell, *Excavation Seismology* (Mar. 1972), 228 pp, NTIS: AD-742 146.

7. Haller, H. F., H. C. Pattison, and B. Shimizu, *Interrelationship of In-Situ Rock Properties, Excavation Method, and Muck Characteristics* (11 Jan. 1972), 151 pp, NTIS: AD-740 781.

8. *Federal Excavation Technology Program - 1972-1973 Report* (Interagency Committee on Excavation Technology, Washington, DC., Jan. 1975) 40 pp, NTIS: PB-252 601/0.

9. Hair, J. L., *Construction Techniques and Costs for Underground Emplacement of Nuclear Explosives* (Apr. 1969), 290 pp, NTIS: AD-689 443.

10. Nair, M. G., B. K. Palit, and R. N. Verma, "Soil Structure Interaction in Deep Open Cuts," *Int. Symp. on Soil Struct. Interaction*, Univ. of Roorkee, India, Jan. 3-7 1977 (Abhay Rastogi for Sarita Prakashan, Meerut, India, 1977), pp 79-83.

11. Isaac, I. D., and C. Bubb, "Engineering Aspects of Underground Cavern Excavation at Dinorwic. Geology at Dinorwic," *Tunnels Tunnelling*, Vol 13, No. 3 (Apr. 1981), pp 20-25.

12. Watson, John D., *Full-Scale Field Test Results of the REAM Concept for Hard Rock Excavation* (Jan. 1973), 78 pp, NTIS: AD-757 116.

13. "Caisson-crade System Supports Sewer Pipe," *Construction Materials and Equipment* (Jan. 1977), pp 45-46.

14. Hunt, Martin, "Herne City Railway. Contract 5," *Tunnels Tunnelling*, Vol 10, No. 10 (Dec. 1978), pp 42-43.

15. Oberth, R. C., and C. F. Lee, "Underground Siting of Candu Power Stations," *Underground Space*, Vol 4, No. 1 (Jul.-Aug. 1979), pp 17-27.

16. Hamel, Laurent, and David Nixon, "Field Control Replaces Design Conservatism at World's Largest Underground Powerhouse," *Civ Eng* (New York) Vol 48, No. 2 (Feb. 1978), pp 42-44.

17. Peck, Ralph B., "Technology of Underground Construction Present and Future," *Rapid Excavation and Tunneling Conf. Proc*, San Francisco, Calif., June 24-27, 1974, Vol 1 (Soc. of Min. Eng. of AIME, New York, NY, 1974), pp 5-14.

18. Kroeger, W., J. Altes, and K. H. Escherich, "Cut-and-Cover Design of a Commercial Nuclear Power Plant," *Trans. of the Int. Conf. on Struct. Mech. in React. Technol., 4th, Vol J(a): Loading Cond. and Struct. Anal. of React. Containment*, San Francisco, CA, Aug. 15-19, 1977 (Comm. of Eur. Communities, Luxemb, 1977), Pap. J 2/3, 8 pp.

19. Rajagopalan, K., "Theory and Design of Cut and Cover Method," *Indian Concr. J.*, Vol 55, No. 12 (Dec. 1981), pp 353-360.

20. Peck, R. B., A. J. Hendron, Jr., and B. Mohraz, *State-of-the-Art of Soft Ground Tunneling*, North American Rapid Excavation and Tunneling Conference, Chicago, IL (June 5-7, 1972), pp 259-286.

21. *Deep Tunnels in Hard Rock. A Solution to Combined Sewer Overflow and Flooding Problems* (Wisconsin Univ., Milwaukee, Coll. of Applied Science and Engineering, Nov. 1970), 211 pp, NTIS: PB-210 854.

22. Mayo, Robert S., Thomas Adair, and Robert J. Jerry, *Tunneling, the State of the Art* (Jan. 1968), 27 pp, NTIS: PB-178 036.

23. Steiner, Walter, and Herbert H. Einstein, *Improved Design of Tunnel Supports, Volume 5: Empirical Methods of Rock Tunneling - Review and Recommendations* (June 1980), 557 pp, NTIS: PB80-225196.

24. Farr, G., C. R. Nelson, and F. Moavenzadeh, *Experimental Observations of Rock Failure Due to Laser Radiation* (Apr. 1969), 13 pp, NTIS: PB-187 274.

25. Freeman, S. Thomas, Richard Hamburger, Dennis J. Lachel, Robert S. Mayo, and Joshua L. Merritt, "Tunneling in the People's Republic of China," *Underground Space*, Vol 7, No. 1 (Jul.-Aug. 1982), pp 24-30.

26. Hibben, Stuart G., *Soviet Tunneling Rockets* (May 1973), 11 pp, NTIS: AD-760 781.

27. Steiner, Waltr , Herbert H. Einstein, and Amr S. Azzouz, *Improved Design of Tunnel Supports, Volume 4: Tunneling Practices in Austria and Germany* (June 1980), 469 pp, NTIS: PB80-225188.

28. Gruner, Horst, "Blade Shield Tunnelling in Essen.," *Tunnels Tunnelling*, Vol 10, No. 5 (June 1978), pp 24-28.

29. Clark, George B., Levent Ozdemir, and Fun-Den Wang, *Tunnel Boring Machine Technology for a Deeply Based Missile System*, Volume II, State-of-the-Art Review (Aug. 1980), 119 pp, NTIS: AD-A092 013/2.

30. "Misshapen Mole Face Cracks Record Hard Rock," Anon, *Construction Materials and Equipment* (Aug. 1977), pp 42-45.

31. "Tunnelers Outmaneuver and Subdue Treacherous Rock," Anon, *Construction Materials and Equipment* (June 1977), pp 40-42.

32. Wheby, Frank T., and Edward M. Cikanek, *A Computer Program for Estimating Costs of Hard Rock Tunnelling (COHART)* (May 1970), p 242, NTIS: PB-193-272.

33. Wang, Zhen Xin, "Shanghai Tunnel Projects Spur Construction Innovations," *Civ. Eng.* (New York), Vol 52, No. 12 (Dec. 1982), pp 36-38.

34. Nazir, C. P., "Rapid Underground Tunnelling Technique," *J. Inst Eng* (India), Civ Eng Div, Vol 60, Pt. CI (4 Jan. 1980), pp 202-204.

35. *Feasibility of Flame-Jet Tunneling. Volume I, Summary Report* (United Aircraft Corp., East Hartford, CT, Research Labs., May 1968), 52 pp, NTIS: PE-178 198.

36. Clark, George B., Levent Ozdemir, and Fun-Den Wang, *Tunnel Boring Machine Technology for a Deeply Based Missile System. Volume I, Application Feasibility. Part 2* (Aug. 1980), 90 pp, NTIS: AD-A092 012/4.

37. Clark, George B., Levent Ozdemir, and Fun-Den Wang, *Tunnel Boring Machine Technology for a Deeply Based Missile System. Volume I, Application Feasibility. Part 1* (Aug. 1980), 116 pp, NTIS: AD-A091 976/1.

38. *Difficult Ground Tunnelling Techniques* (Parsons, Brinckerhoff, Quade and Douglas, New York, Dec. 1962), 71 pp, NTIS: PB-168 295.

39. Einstein, H. H., C. W. Schwartz, W. Steiner, M. M. Baligh, and R. E. Levitt, *Improved Design for Tunnel Supports: Analysis Method and Ground Structure Behavior, A Review* (May 1980), 503 pp, NTIS: PB80-225329.

40. *1-GWh Diurnal Load-Leveling Superconducting Magnetic Energy Storage System Reference Design, Appendix D: Superconductive Magnetic Energy Storage Cavern Construction Methods and Costs* (Fenix and Scisson, Inc., Tulsa, OK, Sep. 1979), 16 pp, NTIS: LA-7885-MS(V.5).

41. DiLouie, Richard H., Jr., "Practical Considerations in Tieback Construction," *ASCE J. Constr. Div.*, Vol 107, No. 2 (June 1981), pp 181-191.

42. Musso, G., "Jacked Pipe Provides Roof for Underground Construction in Busy Urban Area," *Civ. Eng.* (New York), Vol 49, No. 11 (Nov. 1979), pp 79-82.

43. Gaylord, E. H., S. L. Paul, and G. K. Sinnamon, *Investigation of Steel Tunnel Supports* (Aug. 1975), 170 pp, NTIS: PB-253 005/3.

44. Girnau, Guenter, "Lining and Waterproofing Techniques in Germany," *Tunnels Tunnelling*, Vol 10, No. 3 (Apr. 1978), pp 36-45.

45. "Concrete Wins Decision over Steel," Anon, *Construction Materials and Equipment* (Dec. 1977), pp 54-55.

46. Deere, D. U., R. B. Peck, J. E. Monsees, and B. Schmidt, *Design of Tunnel Liners and Support Systems* (Feb. 1969), 419 pp, NTIS: PB-183 799.

47. Young, G. A., and R. E. Sennett, *Development of Improved Design Procedures for Underground Structural Support Systems in Rock* (4 Apr. 1978), 79 pp, NTIS: PB-300 393/6.

48. Wickman, George E., and Henry R. Tiedmann, *Research in Ground Support and Its Evaluation for Coordination with System Analysis in Rapid Excavation* (Apr. 1972), pp 178, NTIS: AD-743 100.

49. "Concrete in Shafts and Tunnels," Parts 1 & 2, Anon, *Concrete* (June 1983), pp 57-58 and (July 1983), pp 35-36.

50. "Sprayed Fibrous Concrete Tunnel Support," Anon, *Concrete* (Nov. 1983), pp 9, 11.

51. Peck, R. B., D. U. Deere, J. E. Monsees, H. W. Parker, and B. Schmidt, *Some Design Considerations in the Selection of Underground Support Systems* (Nov. 1969), 179 pp, NTIS: PB-190 443.

52. Mahar, J. W., H. W. Parker, and W. W. Wuellner, *Shotcrete Practice in Underground Construction* (Aug. 1975), 501 pp, NTIS: PB-248 65/0.

53. Ward, W. H., and D. L. Hills, *Sprayed Concrete: Tunnel Support Requirements and the Dry Mix Process* (c1977), 29 pp, NTIS: PB80-227432.

54. Lane, K. S., *Field Test Sections Save Cost in Tunnel Support* (Apr. 1975), 67 pp, NTIS: PB-246 982/3.

55. Parker, Harvey W., Gabriel Fernandez-Delgado, and Loren J. Lorig, *Field-Oriented Investigation of Conventional and Experimental Shotcrete for Tunnels* (Aug. 1975), 660 pp, NTIS: PB-252 672/1.

56. Paul, S. L., G. K. Sinnamon, and R. Ferrera-Boza, *Structural Tests of Cast-in-Place Tunnel Liners* (Aug. 1976), 115 pp, NTIS: PB-267 302/8.

57. Einstein, Herbert H., Amr S. Azzouz, Charles W. Schwartz, and Walter Steiner, *Improved Design of Tunnel Supports: Executive Summary* (Dec. 1979), 55 pp, NTIS: PB80-134547.

58. Selmer-Olsen, Rolf, "Examples of the Behavior of Shotcrete Linings Underground," *Shotcrete for Ground Support, Proc. of the Eng. Found. Conf.*, Easton, MD, Oct 4-8, 1976 (ASCE, New York, NY; Am. Concr. Inst. [ACI Publ n. SP-54], Detroit, MI, 1977), pp 722-733.

59. Kotulla, B., and V. Hansson, "Analysis of the Impact of an Aircraft Crash on Underground Concrete Ducts with Protective Slab at Reactor Buildings," *Trans. of the Int. Conf. on Struct. Mech. in React. Technol., 4th, v K(a): Seism. Response Anal. of Nucl. Power Plant Syst.*, San Francisco, CA, Aug 15-19, 1977 (Comm. of the Eur. Communities, Luxemb., 1977), Pap. J 8/8, 12 pp.

60. Albritton, Gayle E., and Jimmy P. Balsara, *Response of Buried Vertically Oriented Cylinders to Dynamic Loading* (June 1980), 13 pp, NTIS: AD-A090 354/2.

61. Sisson, George N., "Underground for Nuclear Protection," *Underground Space*, Vol 4, No. 6 (May-June 1980), pp 341-348.

62. Kar, Anil K., "Projectile Penetration into Buried Structures," *ASCE* J. Struct. Div., Vol 104, No. 1 (Jan. 1978), pp 125-139.

63. Lang, Curtis, *Vulnerability Characteristics of Emergency Operating Centers (EOC's) in Blast-Risk Areas* (Jan. 1977), 131 pp, NTIS: AD-A035 868.

64. Cost, Van T., and Gayle E. Albritton, *Response of MX Horizontal Shelter Models to Static and Dynamic Loading* (18 June 1982), 15 pp, NTIS: AD-A117 098/4.

65. Cristy, G. A., and C. H. Kearny, *Expedient Shelter Handbook* (Aug. 1974), 318 pp, NTIS: AD-787 483.

66. *Advanced Structural Concepts for Weapons Storage - Flat and Mountainous Terrains* (U.S. Construction Engineering Research Lab., Champaign, IL, June 1983), 466 pp, NTIS: AD-A133 540.

67. *Alternative Constructional Measures to Tighten Up on Security in Surface Nuclear Plants as Compared with Underground Nuclear Power Plants for Extreme Loads*, Final Report (Zerna - Schnellenback, Ingenieursozietaet Ever Konstruktiven Ingenieurbau, Bochum [Germany, F.P.], Dec. 1981), 287 pp, NTIS: DE83780208.

68. Keenan, W. A., and L. C. Nichols, *Design Criteria for Soil Cover Over Box-Shaped Ammunition Magazines* (May 1980), 100 pp, NTIS: AD-A089 300/8.

69. Hagerman, T. H., "Groundwater Problems in Underground Construction," *Large Permanent Underground Openings, Proc Int Symp.*, Sep. 23-25, 1969, Oslo, Norway (Int. Soc. Rock. Mech., 1970), pp 319-21.

70. Chokshi, C. K., "Shotcrete and Its Uses in Underground Construction," *Indian Concr. J.*, Vol 53, No. 8 (Aug. 1979), pp 207-209, 219.

71. Moller, K., "Groundwater Control for Underground Construction," *Ground Eng.*, Vol 9, No. 3 (Apr. 1976), pp 43-46.

72. Opershtein V. L., "Waterproofing of Walls of Open Caissons," *Soil Mechanics & Foundation Eng* (English Translation of Osnovaniya, Fundamenty I Mekhanika Gruntov), No. 2 (Mar.-Apr. 1969), pp 115-18.

73. Craig, R. N., and A. M. Muir Wood, *A Review of Tunnel Lining Practice in the United Kingdom*, (C1978), 381 pp, NTIS: PB-301 078/2.

74. McDonald, James E., and Tony C. Liu, *Concrete For Earth-Covered Structures* (Sep. 1978), 81 pp, NTIS: AD-A061 469/3.

75. Pepper, Leonard, *Evaluation of Asphaltic Waterproofing Systems for Concrete Structures* (Jan. 1964), 60 pp, NTIS: AD-752 110.

76. Akridge, J. M., and C. C. Benton, *Passive Cooling for Hot Humid Climates* (1981), 5 pp, NTIS: DE82016231.

77. Allensworth, J. A., J. T. Finger, J. A. Milloy, W. B. Murfin, and R. Rodeman, *Underground Siting of Nuclear Power Plants: Potential Benefits and Penalties* (Aug. 1977), 261 pp, NTIS: SAND-76-0412.

78. Hibbard, R., L. Pietrzak, and S. Rubens, *Subsurface Deployment of Naval Facilities* (Dec. 1972), 111 pp, NTIS: AD-762 838.

79. Pinto, S., P. Gibbs, P. Telleschi, *Layout and Containment Concept for an Underground Nuclear Power Plant* (Sep. 1978), 34 pp, NTIS: DE82700603.

80. "Cost and Code Study of Underground Building: A Report to the Minnesota Energy Agency," Anon, *Underground Space*, Vol 4, No. 3 (Nov.-Dec. 1979), pp 119-136.

81. *Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formations, Volume 18. Facility Construction Feasibility and Costs by Rock Type* (Parsons, Brinckerhoff, Quade and Douglas, Inc., New York, Apr. 1978), 100 pp, NTIS: Y/OWI/TM -36/18.

82. "Atlanta's New Airport Terminal One Year Early, Within Budget," Anon, *Civ. Eng.* (New York), Vol 50, No. 11 (Nov. 1980), pp 54-58.

83. Huck, P. J., M. N. Iyengar, K. S. Makeig, and J. Chipps, *Combined Utility/Transportation Tunnel Systems - Economic, Technical and Institutional Feasibility* (July 1976), 242 pp, NTIS: PB-262 067/2.

84. Odello, Robert J., *Low-Energy Structures Concepts* (Dec. 1980), 30 pp, NTIS: AD-A103 107.

85. Yanev, P. I., and G. N. Owen, *Design Cost Scoping Studies, Nevada Test Site Terminal Waste Storage Program, Subtask 1.3: Facility Hardening Studies* (Apr. 1978), 128 pp, NTIS: JAB-99-123.

86. *Nuclear Power in Rock, Principal Report* (Statens Vattenfallsverk, Stockholm [Sweden], June 1977), 71 pp, NTIS: INIS-mf-4763.

87. Terasawa, K., R. O'Toole, and M. Goldsmith, *Probablistic Analysis of the Cost for Surface-Sited and Underground Nuclear Power Plants* (Mar. 1978), 77 pp, NTIS: NP-23802.

88. O'Neil, Robert S., "Subway Construction Costs: The Role of the Engineer," *ASCE J. Constr. Div.*, Vol 106, No. 4 (Dec. 1980), pp 447-454.

89. Girnau, Guenter, "Costs and Benefits of Underground Railway Construction," *Underground Space*, Vol 6, No. 6 (May-June 1982), pp 323-330.

90. Swenson, Mark G., "Economic Test for Earth-Sheltered Design," *Underground Space*, Vol 7, No. 2 (Sep.-Oct. 1982), pp 105-109.

91. Sperry, Joe, "Evaluation of Savings for Underground Construction," *Underground Space*, Vol 6, No. 1 (Jul.-Aug. 1981), pp 29-42.

92. Dobina, A. S., and N. A. Evstropos, *Formation of Underground Cavities by the Use of Explosives* (Feb. 1969), 16 pp, NTIS: PB-183 293T.

93. Peterson, Carl R., *Study of a Continuous Drill and Blast Tunneling Concept* (May 1973), 59 pp, NTIS: AD-757 114.

94. Watson, Richard, and J. Edmund Hay, *Continuous Explosive Fragmentation Techniques* (1 May 1972), 16 pp, NTIS: AD-751 022.

95. Isaac, I. D., and C. Bubb, "Engineering Aspects of Underground Cavern Excavation at Dinorwic - 2. Drilling and Blasting," *Tunnels Tunnelling*, Vol 13, No. 5 (June 1981), pp 15-21.

96. Cobbs, James H., "Blind Boring for Shafts," *Underground Space*, Vol 3, No. 4 (Jan.-Feb. 1979), pp 195-200.

97. Rutherford, Howard E., "Raise Boring 20-Ft Diameter Shafts," *Min. Congr. J.*, Vol 65, No. 8 (Aug. 1979), pp 21-23, 69.

98. "Compressed Air Use in Soft Ground Tunneling," *ASCE Journal of Construction Engineering and Management*, Vol 109, No. 2 (June 1983), pp 206-213.

99. Jessberger, Hans L. (ed.), "International Symposium on Ground Freezing, 1st, 1978," *Eng. Geol.*, Vol 13, No. 1-4 (Apr. 1979), Int Symp on Ground Freezing, 1st, Bochum, Ger. (Mar. 8-10, 1978), 550 pp.

100. Konz, Peider, Lothar Garbe, and Kurt Aenri, "Railway Tunnel, Born.," *Consult. Eng.* (London), Vol 42, No. 9 (Sep. 1978), pp 42-43.

101. Chelnokov, S. S., *Present Methods of Preparing Frozen Ground for Excavation* (May 1960), 9 pp, NTIS: AD-701 176.

102. Vyalov, S. S., Yu Zaretsky, B. B. Berger, I. F. Los, V. L. Lukin, and I. N. Florin, *Sinking Deep Mine Shafts by the Freezing Method*, Prepr - Ground Freezing, Int. Symp, 2nd, ISGF '80, June 24-26, 1980 (Norw. Inst. of Technol., Trondeim, 1980), pp 980-988.

103. O'Rourke, T. D, "Systems and Practices for Rapid Transit Tunneling," *Underground Space*, Vol 4, No. 1 (Jul.-Aug. 1979), pp 33-44.

104. Martin, David, "Rockbursts Imperil Construction of Norway's Largest Underground Power Station," *Tunnels Tunnelling*, Vol 14, No. 10 (Nov. 1982), pp 23-25.

105. Weiler, Albert, and Jochen Vagt, "Gap Freezing Solves Groundwater Problem for Duisburg Metro," *Tunnels Tunnelling*, Vol 13, No. 11 (Dec. 1981), pp 31-34.

106. "Below Ground Plan Lowers Library Cost," Anon, *Building Design and Construction* (June 1979), pp 64-65.

107. "Science Building Goes Underground for Energy Efficiency," Anon, *Building Design and Construction* (Apr. 1979), p 20.

108. Labs, Kenneth, "Regional Analysis of Ground and Aboveground Climate," *Underground Space*, Vol 6, No. 6 (May-June 1982), pp 397-422.

109. Bartos, Michael, J., Jr., "Underground Buildings: Energy Savers?" *Civ. Eng.* (New York), Vol 49, No. 5 (May 1979), pp 80-85.

110. Young, H. W., R. R. Wright, R. W. Swenson, A. W. Stone, and I. Hoch, *Legal, Economic, and Energy Considerations in the Use of Underground Space* (Sep. 1974), 129 pp, NTIS: PB-236 755/5.

111. Dayman, Bain, Jr., Ronald C. Heft, Donald W. Kurtz, Tad W. Macie, and John A. Stallkamp, *Alternative Concepts for Underground Rapid Transit Systems*, U.S. Dep. Transp. (Rep) DOT/TST, n 77-31 (Mar. 1977), 35 pp.

112. Turton, R. R., "Geotechnical Aspects of Disposal and Containment of Low-Level Radioactive Wastes," *Proc. Ont. Ind. Waste Conf. 24th*, Toronto, Ont., May 30-June 1, 1977, Sponsored by Ont. Minist. of the Environ., Toronto (1977), pp 257-290.

113. "Earthmoving Key to Rapid Construction of U.S. Store and Underground Car Park," Anon, *Int Constr*, Vol 14, No. 1 (Jan. 1975), pp 25-27.

114. "Japan Creating an Underground World," Anon, *Construction Materials and Equipment* (Nov. 1977), pp 37-46.

115. Leistner, H. G., R. E. Jones, and W. J. Walker, *Structure-Medium Interaction and Design Procedures Study. Volume 1 Analysis Method, Theory, Verification and Applicability* (Oct. 1969), 245 pp, NTIS: AD-863 248/1.

116. Komendant, August E., "Earth-Covered Structures," *Underground Space*, Vol 3, No. 6 (May-June 1979), pp 279-284.

117. Dodds, Donald J., *Review and Critical Analysis of the State-of-the-Art in Underground Works Construction* (Feb. 1972), 223 pp, NTIS: AD-894 105/6.

118. Kao, A., R. Blackmon, and E. McDowell, *Facility Simulation Model for Advanced BMD Systems. Volume IIIB, Structural Module: Program Reference Manual* (USA-CERL, Apr. 1975), 113 pp, NTIS: AD-A011 226.

119. *Recommendations for Better Management of Major Underground Construction Projects. Executive Presentation*, National Committee on Tunneling Technology, Washington D.C., Subcommittee on Management of Major Underground Construction Projects (1978), 31 pp, NTIS: PB-293 543/5.

120. Stubstad, John M., William F. Quinn, Marcus Greenberg, Walter C. Best, and Mounir M. Botros, *Design Procedures for Underground Heat Sink Systems* (Apr. 1979), 188 pp, NTIS: AD-A068 926/5.

121. Kao, A., R. Blackmon, and E. McDowell, *Facility Simulation Model for Advanced BMD Systems. Volume IIIC, Structural Module: Program Listing* (USA-CERL, Apr. 1975), 158 pp, NTIS: AD-A010 713/6.

122. Kao, A., R. Blackmon, and E. McDowell, *Facility Simulation Model for Advanced BMD Systems. Volume IIB, Executive Control Module: Program Reference Manual* (USA-CERL, Apr. 1975), 22 pp, NTIS: AD-A009 745.

123. *Draft Environmental Impact Statement for the MX: Buried Trench Construction and Test Project* (Department of the Air Force, Washington, DC, 1977), 138 pp NTIS: AD-A126 407/6.

124. Mahrenholtz, O., D. V. Reddy, and W. Bobby, "Limit Analysis of Internally Pressurized Cut-And-Cover Type Underground Reactor Containments," *J. Am. Concr. Inst.*, Vol 79, No. 3 (May-June 1982), pp 220-225.

125. Paulson, Boyd C., Jr., "Underground Transit Station Construction in Japan," *ASCE J. Constr. Div.*, Vol 108, No. C01 (Mar. 1982), pp 23-37.

126. Carmody, John, and Douglas Derr, "Use of Underground Space in the People's Republic of China," *Underground Space*, Vol 7, No. 1 (Jul.-Aug. 1982), pp 7-11, 14-15.

127. Yanagida, Shinji, "Construction Plan of Ueno Underground Station for Tohoku Shinkansen," *Civ. Eng. Jpn.*, Vol 19 (1980), pp 76-90.

128. Banjamin, A. Lloyd, John Endicott, and R. J. Blake, "Design and Construction of Some Underground Stations for the Hong Kong Mass Transit Railway System," *Struct. Eng.*, Vol 56A, No. 1 (Jan. 1978), pp 11-20.

129. "Garage and Tower are Built in Tandem," Anon, *Eng. News. Rec.*, Vol 206, No. 6 (Feb. 5, 1981), p 36.

130. Krupka, Robert A., *An Evaluation of the Shelter Potential in Mines, Caves and Tunnels* (11 June 1965), 2 pp, NTIS: AD-617 111.

131. Hoff, George C., William F. McCleese, and James M. Holzer, *Shock-Absorbing Materials, Report 4, Aging of Backpacking Materials* (Nov. 1968), p 249, NTIS: AD-681 910.

132. Kroeger, W., J. Altes, R. Rongartz, P. H. David, and K. H. Escherich, *Assessment of Erecting Nuclear Power Plants Below Ground in an Open Building Pit, Final Report of a Study for the Minister of the Interior BMI - No. SR 44* (Jan. 1978), 1 p, NTIS: Juel-1478.

133. Senseny, P. E., and H. E. Lindberg, *Theoretical and Laboratory Study of Deep-Based Structures, Volume II, Model Tests and Analyses of Mighty Epic Structures* (15 Jan. 1979), 153 pp, NTIS: AD-A090 218/9.

134. Patterson, J. T., "Hazardous Atmospheres in Underground Construction," *Prof. Saf.*, Vol 24, No. 9 (Sep. 1979), pp 25-33.

135. "Large Wheel Loaders," Anon, *Min. Mag.*, Vol 142, No. 4 (Apr. 1980), 12 pp, between pp 328 and 349.

136. Ischy, E. and R. Glossop, "An Introduction to Alluvial Grouting," *Proceedings of the Institution of Civil Engineers* (Mar. 21, 1962), pp 449-474.

137. Jumikis, A. R,. "Cryogenic Texture and Strength Aspects of Artificially Frozen Soils," *Engineering Geology*, 13 (1979), pp 125-135.

138. Miyoshi, M., T. Tsukamoto, and S. Kiriyama, "Large Scale Freezing Work for Subway Construction in Japan," *Engineering Geology*, 13 (1979), p 397-415.

139. Braun, B., J. Shuster, and E. Burnham, "Ground Freezing for Support of Open Excavations," *Engineering Geology*, 13 (1979), pp 429-453.

140. Veranneman, G., and D. Rebhan, "Ground Consolidation with Liquid Nigrogen (LN_2)," *Engineering Geology*, 13 (1979), pp 473-484.

141. Stoss, K., and J. Valk, "Uses and Limitations of Ground Freezing With Liquid Nitrogen," *Engineering Geology*, 13 (1979), pp 485-494.

142. Whitney, Mark G., et. al., *Munition Storage Concepts for Use in Flat Terrain*, Volumes I and II, Southwest Research Institute, prepared for Construction Engineering Research Laboratory, Technical Report M-338 (Dec. 1983), AD-A139 169/4.

143. *Barrier Technology Handbook*, SAND 77-0777 (Sandia National Laboratories, 1981).

144. Garza, Luis R., *Testing Services for Construction Materials Building System Components and Barriers Used in Physical Security*, Volumes 1-4, prepared for the Department of the Navy Civil Engineering Laboratory by Southwest Research Institute (July 1982).

145. Whitney, Mark G., G. J. Friesenhahn, W. E. Baker, and L. M. Vargas, *A Manual to Predict Blast and Fragment Loadings from Accidental Explosions of Chemical Munitions Inside an Explosion Containment Structure, Volumes I and II*, prepared for the U.S. Army Corps of Engineers, Huntsville Division under contract DACA87-81-C-0099 by Southwest Research Institute (Apr. 1983).

146. Hemphill, Gary, *Blasting Operations* (McGraw-Hill, 1981).

147. Chocran, Thomas B., William M. Arkin, and Milton M. Hoenig, *Nuclear Weapons Databook, Volume I, U.S. Nuclear Forces and Capabilities*.

148. Kao, A. M. et al., *Facility Simulation Model for Advanced BMD Systems*, Technical Report C-28 (USA-CERL, Apr. 1975), AD-A009 743.

Search Keywords

The following keywords were used to search the literature databases.

Buildings

Silos

Silo

Power Plant

Tunnel

Storage

Warehouse

Underground

Construction

Cost

Waterproofing

Security

Survivability

Vulnerability

Referenced Journals

The following is a complete list of journals from which relevant information was gathered for this study.

American Society of Civil Engineers Journal of Construction Division

American Society of Civil Engineers Journal of Structural Division

American Society of Civil Engineers Journal of Construction Engineering and Management

Building Design and Construction

Civil Engineering

Civil Engineering in Japan

Concrete

Construction Methods and Equipment

Consulting Engineer

Engineering Geology

Engineering News Record

Ground Engineering

Indian Concrete Journal

International Construction

Journal of the American Concrete Institute

Journal of the Institution of Engineers (India)

Mining Congress Journal

Mining Magazine

Professional Safety

The Structural Engineer

Tunnels and Tunnelling

Underground Space

USA-CERL DISTRIBUTION

Chief of Engineers
ATTN: Tech Monitor
ATTN: DAEN-ASI-L (2)
ATTN: DAEN-CCP
ATTN: DAEN-CW
ATTN: DAEN-CWE
ATTN: DAEN-CWM-R
ATTN: DAEN-CWO
ATTN: DAEN-CWP
ATTN: DAEN-EC
ATTN: DAEN-ECC
ATTN: DAEN-ECE
ATTN: DAEN-ECR
ATTN: DAEN-RD
ATTN: DAEN-RDC
ATTN: DAEN-RDM
ATTN: DAEN-RM
ATTN: DAEN-ZCE
ATTN: DAEN-ZCF
ATTN: DAEN-ZCI
ATTN: DAEN-ZCM
ATTN: DAEN-ZCZ

FESA, ATTN: Library 22060
ATTN: DET III 79906

US Army Engineer Districts
ATTN: Library (41)

US Army Engineer Divisions
ATTN: Library (14)

US Army Europe
AEAEN-ODCS/Engr 09403
ISAE 09081
V Corps
ATTN: DEH (11)
VII Corps
ATTN: DEH (15)
21st Support Command
ATTN: DEH (12)
USA Berlin
ATTN: DEH (11)
USASETAF
ATTN: DEH (10)
Allied Command Europe (ACE)
ATTN: DEH (3)

8th USA, Korea (19)

ROK/US Combined Forces Command 96301
ATTN: EUSA-HHC-CFC/Engr

USA Japan (USARJ)
ATTN: AJEN-DEH 96343
ATTN: DEH-Honshu 96343
ATTN: DEH-Okinawa 96331

416th Engineer Command 60623
ATTN: Facilities Engineer

US Military Academy 10966
ATTN: Facilities Engineer
ATTN: Dept of Geography & Computer Science
ATTN: DSCPER/MAEN-A

AMMRC, ATTN DRXMR-WE 02172

USA ARRCOM 61299
ATTN: DRCIS-RI-I
ATTN: DRSAR-IS

AMC - Dir., Inst., & Servc
ATTN: DEH (23)

DLA ATTN: DLA-WI 22314

DNA ATTN: NADS 20305

FORSCOM
FORSCOM Engr, ATTN: AFEN-DEH
ATTN: DEH (23)

HSC
ATTN: HSLO-F 78234
ATTN: Facilities Engineer
Fitzsimons AMC 80240
Walter Reed AMC 20012

INSCOM - Ch, Instl. Div
ATTN: Facilities Engineer (3)

MDW, ATTN: DEH (3)

MTMC
ATTN: MTMC-SA 20315
ATTN: Facilities Engineer (3)

NARADCOM, ATTN: DRDNA-F 01760

TARCOM, Fac. Div. 48090

TRADOC
HQ, TRADOC, ATTN: ATEN-DEH
ATTN: DEH (19)

TSARCOM, ATTN: STSAS-F 63120

USACC, ATTN: Facilities Engr (2)

WESTCOM
ATTN: DEH, Ft. Shafter 96858
ATTN: APEN-IM

SHAPE 09055
ATTN: Surv. Section, CCB-OPS
Infrastructure Branch, LANDA

HQ USEUCOM 09128
ATTN: ECJ 4/7-LOE

Fort Belvoir, VA 22070 (7)
ATTN: Canadian Liaison Office
ATTN: Water Resources Support Ctr
ATTN: Engr Studies Center
ATTN: Engr Topographic Lab.
ATTN: ATZA-DTE-SU
ATTN: ATZA-DTE-EM
ATTN: R&D Command

CRREL, ATTN: Library 03755

WES, ATTN: Library 39180

HQ, XVIII Airborn Corps
and Fort Bragg
ATTN: AFZA-FE-EE 28307

Area Engineer, AEDC-Area Office
Arnold Air Force Station, TN 37389

Chanute AFB, IL 61868
3345 CES/DE, Stop 27

Norton AFB, CA 92409
ATTN: AFRCE-MX/DEE

NAVFAC
ATTN: Engineering Command (7)
ATTN: Division Offices (6)
ATTN: Naval Public Works Center (9)
ATTN: Naval School, Morell Library
ATTN: Naval Civil Engr Lab. (3)

NCEL ATTN: Library, Code L08A 93041

Defense Technical Info. Center 22314
ATTN: DDA (12)

Engr Societies Library, NY 10017

Natl Guard Bureau Instl. Div 20310

US Govt Printing Office 22304
Receiving Sect/Depository Copies (2)

US Army Env. Hygiene Agency
ATTN: HSHB-E 21010

National Bureau of Standards 20760

331
03/22/85

END

FILMED

7-85

DTIC