ORNL-HUD-19
UC-41 — Health and Safety

U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

SYSTEM REQUIREMENTS FOR UNDERGROUND UTILITY INSTALLATION

W. J. Boegly, Jr.
W. L. Griffith
W. C. Ulrich

CIVIL DEFENSE RESEARCH PROJECT

OAK RIDGE NATIONAL LABORATORY · OPERATED BY UNION CARBIDE CORPORATION FOR THE U.S. ATOMIC ENERGY COMMISSION

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce, Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.65

ORNL-HUD-19
UC-41--Health and Safety

Contract No. W-7405-eng-26

DIRECTOR'S DIVISION

Civil Defense Research Project

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Work supported by the Department of Housing and Urban Development and the U. S. Atomic Energy Commission under Interagency Agreement No. IAA-H-2-69 AEC 40-155A-68.

FEBRUARY 1971

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Oak Ridge, Tennessee
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ABSTRACT

As a part of an effort to assess the state of the art of new tunneling technology and to determine the applicability of tunneling methods to utility installation, system requirements for the installation of underground utilities have been developed. The characteristics of typical utility systems are described and analyzed to determine areas where certain methods of installation may provide advantages over other alternatives. Both trenching and tunneling techniques as means of providing the installation space are assessed.

Installation of utilities by tunneling methods is generally more expensive at present than by trenching except when the utility is installed at great depths. However, if primary distribution lines are installed at great depths, there may be problems in making service connections. The use of "utility tunnels" offers an attractive solution to utility problems in dense urban areas, but they require a high initial investment whether constructed by tunneling or trenching techniques.

If several utilities are to be directly buried in the same right-of-way, the joint or common use of the same trench appears to offer advantages. Conduit systems capable of containing both cables and pipes also offer a potential for minimizing the excavation necessary for installation and maintenance.

1. INTRODUCTION

The U. S. Department of Housing and Urban Development (HUD) is responsible for the application of new technology to the solution of urban problems. One example of the direction taken in fulfilling this responsibility is that of investigating the possibility of installing underground utilities using tunneling instead of trenching. A principal advantage of tunneling is the potential for reducing surface excavation and the attendant traffic interference and noise associated with trenching. The Oak Ridge National Laboratory was requested by HUD to assess the state of the art of tunneling technology and to determine the applicability of tunneling methods to utility installation. The purpose of this report is to describe the system requirements for the installation of underground utility distribution networks in existing urban areas. The described system is to be capable of carrying out all of the functions necessary for the installation and operation of a utility. Both trenching and tunneling techniques as a means for providing installation space are assessed. The current status of tunneling technology is reviewed in two companion reports.[1,2]

In this analysis, it has been assumed that wholesale rebuilding and replacement of existing utilities in dense urban areas will not occur. In special instances such as urban renewal and freeway construction when major utility relocations are required, incorporation of new concepts such as utility tunnels may be practical. However, in any new utility installation (even those involving a very few utilities), the concepts outlined in this report can be applied.

The upgrading and extension of utility systems is a constant and necessary process. In most urban areas the space beneath the street is congested with buried utilities, and repairs or extensions of these utilities are complex and expensive. Furthermore, new utility installations or extensions may well have to be located below an interlocking array of existing utilities indicating that tunneling methods may be a solution for future utility installations. Also, the advent of new underground utility systems, such as pneumatic mail transport, central heating and cooling, community antenna television circuits (CATV), and pneumatic solid waste transport pipelines will create an additional demand for underground space. How these new utilities could be located within the existing networks of buried pipes and cables presents a significant problem. Fig. 1.1 illustrates the tangle of pipes and cable ducts under a typical street in New York City in 1916; one can only wonder what this intersection would look like today if it were dug up.

Fig. 1.1 Corner of Wall and William Streets, New York City in 1916 Showing Complexity of Underground Utility Systems. (Photo Courtesy of Consolidated Edison Company of New York)

Because of the overlapping that exists in many cities, the cost of change is high. Recently, for example, in a 1600 ft. extension of the 6th Avenue subway line in New York, only the utilities that would interfere with the subway were relocated; however, the cost of this relocation and the need to maintain continuity of utility service was about $2,000,000 out of the total contract price of $7,500,000.[3]

Not only are utility extensions in urban areas costly, there are the attendant problems of noise, dirt, and interference and delays in pedestrian and vehicular traffic. Other intangible cost items such as wear and tear on pavement resulting in the need for more frequent repaving, increased wear on vehicles and increased fuel consumption due to detours, and the cost of traffic accidents caused by roadway interference are also present, but are much more difficult to assess. Another factor which must be kept in mind when discussing utility installations is that much of the damage caused to existing utilities is a direct result of the installation of new utilities or the repair of existing components.[4] For example, the electric company, while excavating for a new duct, may accidentally cut into a telephone cable. By tunneling, it might be possible to eliminate many of these problems.

If tunneling methods were used for utility installation, the size of the opening could range from "tunnels" just large enough to hold individual pipes, conduits, or cables to tunnels large enough for people to work in them (utility tunnels). Previous studies have been made to assess the feasibility of the use of utility tunnels in urban areas, and the major conclusions are that the tunnels are more expensive on a first-cost basis than the installation of individual buried utilities.[5,6] This is caused in part by the cost of providing expansion space in the tunnels so that future extensions will not require additional excavation. Attempts have been made to assess the cost benefits of the utility tunnel concept, but the results have not been conclusive.[5] The American Public Works Association is currently examining the feasibility of combining utility tunnels with transportation systems, and is also investigating the cost benefit relationship between buried utilities and utility tunnels.[7]

2. CURRENT UTILITY INSTALLATION PRACTICES

At the present time the common underground utilities are gas, water, and sewers. Only in downtown areas and selected subdivisions are electric and telephone wires located underground, although there is a trend toward placing these utilities underground in new construction. Some large cities also have steam or hot water distribution systems for heating large buildings. In many new urban renewal projects and large project developments (for example, Allegheny Center in Pittsburgh, Pennsylvania[8]), central heating and cooling systems are being installed. However, in the near future, the major underground utility demand appears to be for water, sewer, gas, electric, and telephone services.

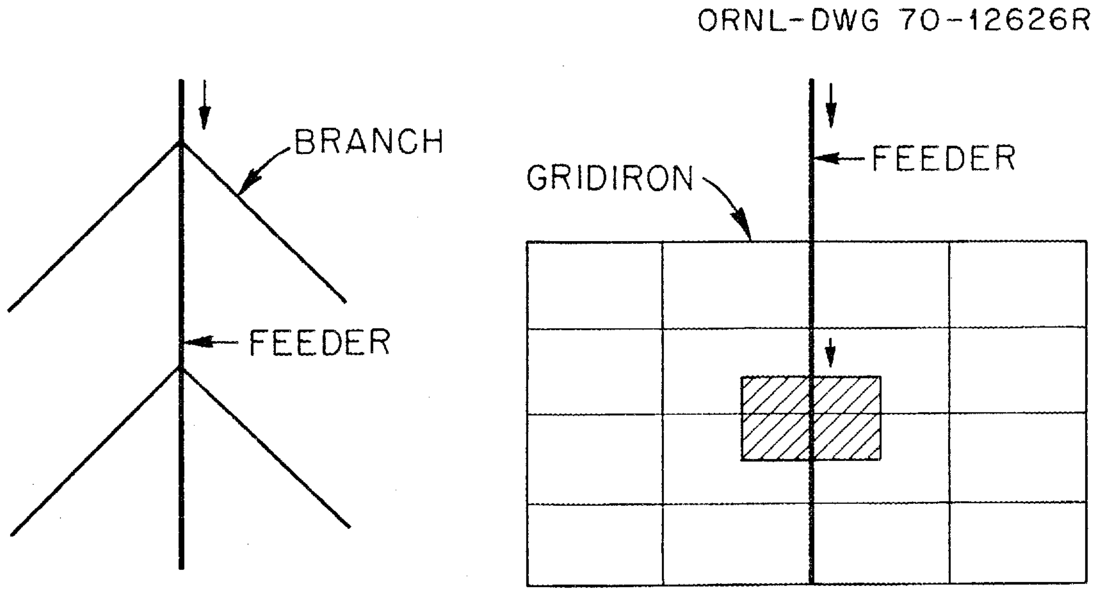
A brief description of the structure of the individual utility systems follows. It must be noted that these descriptions are simplified, and that variations from the described practices are quite common.

2.1 Description of Utility Systems

2.1.1 <u>Water</u>

The water distribution system is that part of the total water system which transmits the water from distribution reservoirs to the consumer. The layout of the distribution system depends on the street plan, topography, and the location of the supply and storage facilities. There are two basic types of distribution systems: a branching pattern, and a gridiron or network pattern.[9] These types are illustrated in Fig. 2.1. The branching pattern is mainly used in suburban areas. One obvious drawback of this type of pattern is the dead ends where the possibility of stagnant water conditions exist. The gridiron or network pattern is more common in built-up areas where a more reliable supply for fire fighting capability is needed; however, it is often required in subdivisions by zoning regulations. The network pattern allows water to be supplied to a given point from two directions and avoids dead ends.

In general, with the network system each street will contain at least one water main with the mains interconnected at each street intersection. Valves are installed at pipe junctions to provide the ability to shut off a leaking or broken line until repairs can be made. Depending on the design of the system, as many as three valves are generally installed at each intersection. Other valves in a water distribution system are located on each service connection and at each fire hydrant.



(*a*) BRANCHING PATTERN WITH DEAD ENDS

(*b*) GRIDIRON PATTERN WITH CENTRAL FEEDER

Fig. 2.1 Typical Water Distribution System Patterns[9]

Valves are normally installed with a valve box attached to the top to allow the valve to be operated from the surface. Larger valves may be installed in pits or manholes for access. Repairs to valves directly buried in the ground, of course, require excavation for access to the valve itself. The valves for small service connections* are almost always directly buried and access to these valves requires excavation. A typical service connection is shown in Fig. 2.2.

Since a major function of a city water system is to provide fire protection, hydrants are located at predetermined points. Fire protection requirements also determine the pipe diameter and water flow rate to be

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*In water systems, these small valves are commonly called corporation cocks.

provided. The National Board of Fire Underwriters requires 8-inch pipe as the minimum diameter, but will permit 6-inch pipes in gridiron systems if the length of pipe between interconnections is less than 600 feet. If fire protection is not required, 4-inch or less pipe sizes can be installed. This practice is normally followed only in low-density suburban areas. In areas where fire-protection capability is required, the National Board of Fire Underwriters standard is for hydrants to be spaced to serve areas within a radius of 200 feet. These hydrants are normally installed at street intersections, although in large city blocks they may be required at other locations.

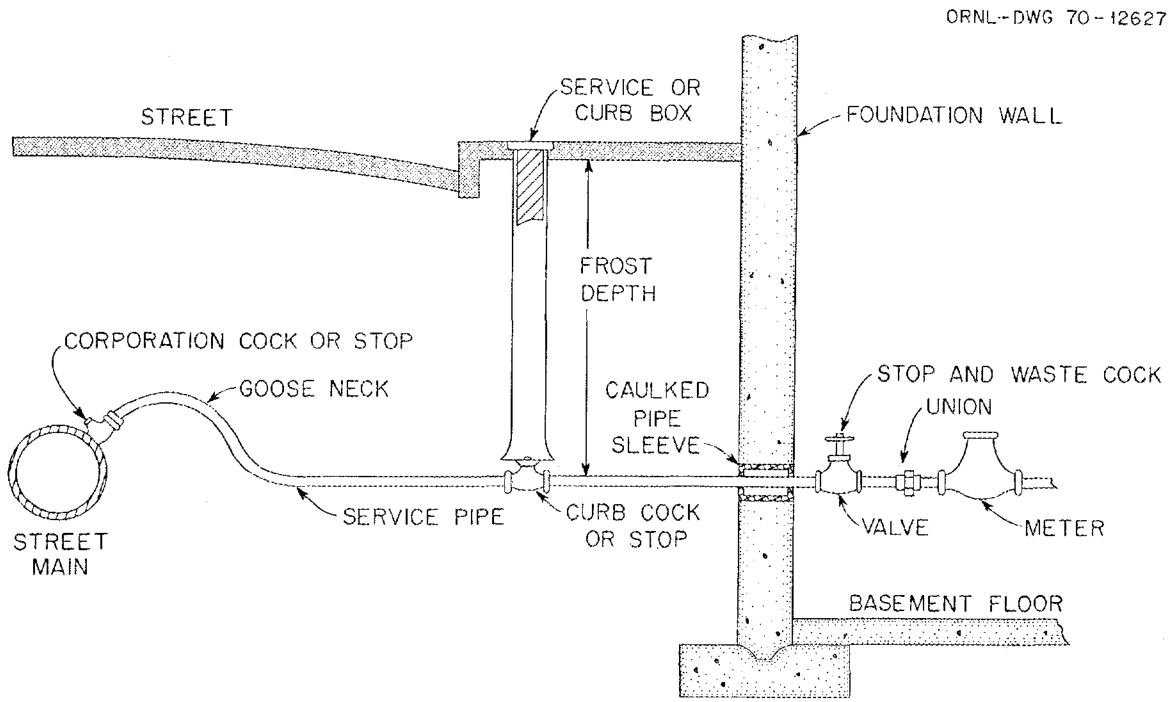

Fig. 2.2 Typical Water Service Connection[9]

As previously described, a water distribution system is composed of a large number of valves, hydrants, and interconnections. Table 2.1 presents data from a number of cities listing the miles of pipe in the system and the number of valves, hydrants, and service connections per mile. The number of small valves (corporation cocks) used on service connections is not included in this table, but is at least equal to the number of service connections per mile. Each of the valves, hydrants, and service connections represents a point at which access from the surface, either through manholes, valve boxes, or by excavation, will be required for operation and maintenance of the water system.

Table 2.1 Physical Characteristics of Typical Water Distribution Systems*

City (Date)	Miles of Mains	Hydrants per Mile	Valves per Mile	Service Connections per Mile
St. Louis, Mo. (1967)	1,364	11.3	16.0	117
Philadelphia, Pa. (1967)	3,202	7.9	23.0	165
Salt Lake City, Utah (1969)	859	7.0	12.2	77
New Orleans, La. (1966)	1,324	9.9	8.8	102
Seattle, Wash. (1969)	1,649	9.7	8.4	-
Chicago, Ill. (1966)	4,093	11.1	10.4	125
San Jose Water Works (1967)	1,584	5.1	-	88
Los Angeles, Calif. (1967)	6,586	6.7	14.0	92
Akron, Ohio (1970)	1,019	-	11.9	85
Providence, R. I. (1969)	809	6.1	13.7	80

*Data from annual reports prepared by municipal water departments or private water companies.

2.1.2 Sewers

There are two basic types of sewer systems used in the United States. The first of these is the combined sewer system in which waste waters from domestic and industrial sources are collected along with storm water runoff in a single collection system. The second type consists of a collection system for domestic and industrial wastes, and a separate system of storm sewers. Construction economy favors the installation of combined sewers; however, emphasis is currently being directed to the use of separate sewers to avoid hydraulic overloading of sewage treatment facilities caused by the peak flows from storms. In the past this problem was overcome by by-passing the waste which could not be handled in the treatment facility directly to the outfall. Recently, it has been found that the pollutants present in storm water runoff are significant and that treatment of this waste is often necessary.[10] Installation of separate sewers allows sanitary sewage and storm water to be collected separately and treated before release.

In the design of sewer systems every effort is normally directed toward a system which will allow gravity flow. Because of the gravity flow requirements, sewers must be installed with definite grades which, because of topographical features, results in their being at various depths. Pumping systems or force mains may be installed where topographic features require deep excavation. Many of the construction problems encountered in the installation of sewers for sanitary waste could be eliminated by the use of pumped or pressurized systems which would eliminate grade considerations and the need for deep excavation in some areas. However, the energy costs for pumping and the possibility of power and pump failures tend to reduce the advantages of the pumped sewer concept. The application of pumped sewers for storm sewers or combined sewers is difficult because of the extreme variability of waste flows in these systems.

In the case of combined sewers, each sewer must be connected to the waste producer as well as to each catch basin located in the street for collecting storm water. Manholes must be installed at frequent intervals to allow the sewers to be cleaned and to make connections between other sewers. Current design practice calls for manholes at each sewer junction, at each change in grade or change in pipe size, or at intervals of about 300 feet.[11] Valves and other special fittings are not normally found in sewer systems.

In most new installations, branch fittings for service connections are installed as the sewer is constructed, and the user later connects to these fittings. If a minimum number of street cuts is desired, lines may be installed from the main sewer to the property line at the time the sewer is built.

2.1.3 Natural Gas

Natural gas systems can have both transmission and distribution functions. However, consumers do not normally receive gas directly from transmission systems. Upon entering the distribution system from the transmission system, the gas is reduced in pressure. Both low pressure (about 0.5 psi) and intermediate pressure distribution systems (up to 50 psi) are employed. Where intermediate pressure systems are used, additional pressure reduction is generally provided for each customer at the meter. An odorizing agent is commonly added to assist in detecting leaks in the distribution system and on the customer's premises. Valving is provided to localize service outages and to stop the flow of gas in the event of a break or leak. Since corrosion of metal gas mains is a major concern, distribution mains constructed of steel pipe generally require protective coatings and/or cathodic protection. The feasibility of plastic pipe for gas distribution systems has been demonstrated and its use is undergoing rapid growth. In the next year or two, it is expected that the use of plastic pipe will increase to about 25 percent of the total annual installation milage.

Valves used in distribution mains are generally located in vaults or valve boxes to provide protection and permit proper maintenance and operation. In low pressure service and on smaller lines (i.e., 2-inches and under), plug-type valves are most commonly used. As shown in Fig. 2.3, there are generally two valves on a gas service line, one at the connection to the main and the other at the customer's meter.[12] Where taps are made on the mains for service connections, full opening plug or gate valves are preferred.

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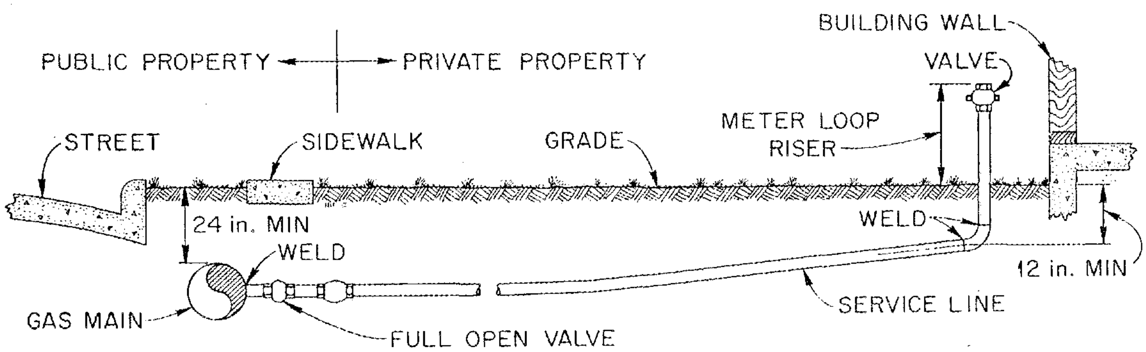

Fig. 2.3 Typical Gas Service Connection[12]

2.1.4 Electric Power

Underground electric power systems are different from aerial systems in that the conductors are larger and they are located closer together. Because of the close proximity of the conductors, and because heat transfer from the cable is restricted, thermal considerations become the main design problem. These factors thus limit the number of power cables that can be incorporated in a single installation without excessive reduction of the current-carrying capacity of the cables.

As in the case of water systems, a number of wiring patterns (e.g., radial, loop, and network) are used to distribute electricity to the consumer.[13] The choice of wiring pattern used depends on the degree of reliability required.

The lowest voltages in the distribution system generally occur at the consumer's utilization level. Typically, this is 120/240 V, single phase, three wire for residential and small consumers, and 120/208 V or 265/460 V, three phase, four wire for commercial areas and industrial users. Higher voltages exist in the distribution system depending on the size of the individual loads, the total load, the load density, size of the area, and the distribution pattern used. The trend in distribution voltages in high density urban areas currently is toward the use of high voltages similar to those used in aerial transmission for long distances. This has been brought about by the development of improved high voltage underground cables.

Underground cables can be buried directly in the soil or placed in underground conduits or ducts which are installed separately. The use of a duct system allows the cable to be installed at a later date when needed, or allows existing cables to be removed and replaced without excavation. When conduit banks are installed, extra ducts are normally included to provide space for future expansion. The conduit system, with its inherent flexibility for cable installation and replacement without excavation is commonly used in dense urban areas. Ducts are generally constructed of vitrified clay tile, or fiber, cement-asbestos, concrete, or plastic pipe.

Installation of cables in ducts is performed by pulling the cable between manholes which are usually located at each street intersection. Not only are the manholes utilized for installing and removing cables, they also are the major points in the distribution system where the cables can be spliced together to form the network used. Because the manholes are the only points at which the cable can be serviced without removal, they must be located at each point where two cables are connected together. Much smaller openings (hand holes) are normally installed at points where connections are made between the main system and the wires to the consumer. In addition, it is necessary to have space and access available for transformers and switching devices. In urban areas these units are normally installed in underground vaults adjacent to the building served or in the building basement.

In less-dense areas, underground cable is installed by burying it directly in the ground. Manholes are not normally used in this kind of installation.

2.1.5 Telephone

The basic components of a telephone system are: telephones, teletypes, and other customer communications equipment; wire system connections to central offices; switching equipment in the central office; and trunk-line systems between central offices. Only the connecting line systems from the individual user equipment to the exchanges and the trunk-lines between exchanges are of concern in this report. Both systems generally consist of cables containing as many as 2700 pairs of conductors in lead or plastic sheathing. The cables are buried directly in the earth or installed in a duct system similar to that described for electric power. The principal differences between telephone and power duct systems are: (1) thermal effects are not a problem in the low voltage telephone system, so more ducts may be grouped together into one large duct bank, and (2) the cables must be protected from moisture to a greater degree than power cables. This is done by passing dry air through the cable sheath. In order to supply sufficient air at large distances from the central stations, pipelines are run with the cables, or portable supplies (bottled compressed air) are used. Cable connections are made in manholes or in specially designed connection cabinets located above ground.

In order to improve the transmission efficiency of telephone cables, the inductance of the telephone line is generally increased by placing low-resistance coils with magnetic alloy cores (called "loading coils") in each phone line every 2000 to 6000 feet depending on the line application. The large number of loading coils required for each cable is installed by sealing banks of these coils in containers to handle small systems, or placing large banks of coils in cabinets for large applications. Working space must be provided for access to cabinets when they are used.

Since buried telephone cables are permanently installed and are not amenable to rapid large-scale changes, system reliability can be achieved by providing extra conductors, by using multiple cables, and by providing multiple cable routes. When this added reliability is provided (as "cable and sheath insurance") at the consumer's level for critical applications, there are attendant extra charges.

2.1.6 Community Antenna Television (CATV)

Community antenna television (CATV) systems are increasing in popularity in areas where standard television broadcast reception is poor; they are also capable of augmenting the amount of programming available to subscribers by originating programs for distribution on available channels (as many as 80) for transmission and reception.

Basically, these systems consist of a central receiving antenna and facilities for amplifying and transmitting the signals over a distribution network. This network generally consists of coaxial cables, with amplifiers located at regular intervals. Amplifier spacing is determined by attenuation and aging characteristics of the cable but is normally 1500 to 2000 feet.

Coaxial cables can be installed overhead on existing power or telephone poles, placed in underground conduit, or buried directly in the ground.

2.1.7 Central Heating

In some dense urban areas, buildings are heated by steam or hot water transmitted from a central heating plant.[14] The basic differences between steam and hot water distribution systems are: (1) steam systems must be equipped with traps to drain liquid (condensate) from the steam lines, (2) steam lines are larger in diameter than hot water lines of the same energy-carrying capacity and operating temperature, (3) steam systems are frequently equipped with pressure reducing stations, and (4) steam systems normally employ only one pipe. Condensate is normally discharged to sewers, but it can be returned to the central plant, depending on the economics of the operation and the likelihood of contamination of the condensate. Hot water systems almost always return the water after removal of the useful heat.

Heat exchangers are sometimes used by each customer to prevent contamination of the main circulating water and to allow higher distribution pressures and temperatures to be used than the customer requires. The distribution system is made up of insulated pipes which may be in concrete envelopes buried directly in the ground as shown in Fig. 2.4 or installed in utility tunnels. If pipes are installed in conduit systems, they are sloped to drain so that the insulation can be kept dry. Expansion loops or joints are placed every few hundred feet and insulated pipe guides and supports are used to prevent concentrated bearing loads due to thermal expansion of the pipes. Expansion loops are preferred since they are relatively maintenance free, but bellows, slip-joint, and ball-and-socket joints are used where space is limited. Expansion joints are generally not buried directly in the ground but are located in manholes or vaults. Unless the pipes are installed in tunnels, manholes are provided at frequent intervals to permit access to traps, expansion joints, and valves for maintenance. Drainage from conduit systems or traps is removed by sump pumps or steam ejectors.

2.1.8 Central Cooling

Central cooling systems have not been installed in cities to the extent that central heating systems have been; however, they are becoming more common in urban renewal projects and other large-scale developments.[8,14,16] These systems use either water, brine, or ethylene glycol-water mixtures as the heat-transfer medium. Chilled water distribution systems are similar to hot water systems but differ in the following respects because the temperature differences between the heat-transfer medium and the environment are smaller: (1) the pipes are larger in cooling systems, (2) less insulation is required (in fact, in some designs the return lines are not insulated when they are directly buried), and (3) there is less thermal contraction which must be accomodated. Steel or nonmetallic materials such as cement-asbestos are commonly used for the piping system. The lines can be directly buried or installed in conduits.

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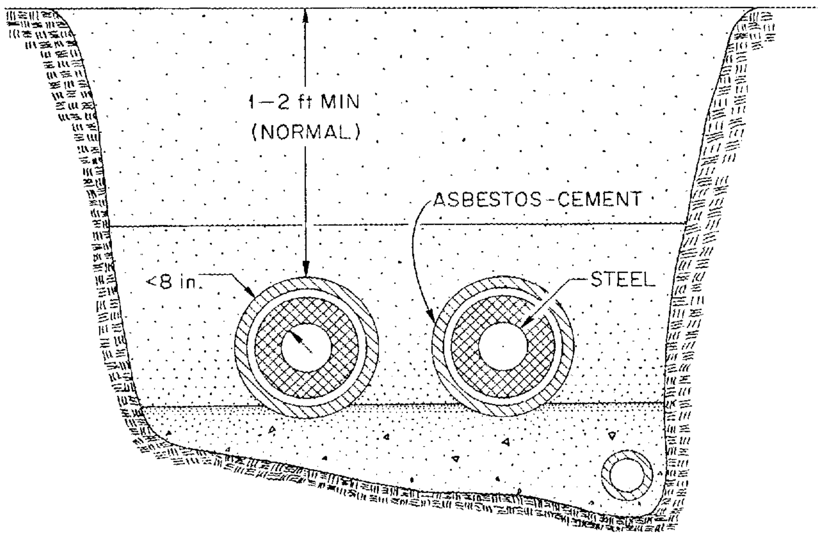

Fig. 2.4 Example of Directly-Buried District Heating Distribution Piping[15]

2.1.9 Summary

The previous sections have described current methods of utility installation. In most cases, underground utility distribution systems are made up of relatively small diameter pipes or cables which are usually placed in individually prepared installation spaces. However, in areas where large amounts of utility lines are concentrated, the utility tunnel concept may be feasible. Therefore, it appears that if new methods of installation, such as the use of tunneling, are to be considered, a tunneling machine will have to be developed which is capable of producing holes which range from a few inches to several feet in size. Appendix A describes the requirements for such a utility tunneling system.

3. CURRENT EXCAVATION PRACTICES

Since utilities are normally installed as close to the surface as possible (usually less than 10 feet deep, with the possible exception of sewers), some idea of the geologic conditions expected in this zone has been obtained by a survey of cities in the 100 largest SMSAs in the United States (for more details, see Appendix C). Basically, the survey requrested information on the average geologic conditions for depths of 0-20, 20-50, and 50-100 feet. The respondents were requested to indicate if the material generally encountered was soil (soft ground consisting of mixtures or layers of gravel, sand, silt, clay, unconsolidated rock, etc.) or rock (either hard or soft). Of the responses returned, 68 of the 72 cities indicated soil was the predominate material in the 0-20 foot zone, although some reported both soil and rock. Thus, it would appear that most of the future utility installations will probably require excavation methods or equipment capable of operating in soil. However, in local areas, there may still be a need for excavation systems which will be capable of operating in rock.

3.1 Trenching

By far the most common method of installing underground utilities is in an open trench which is excavated using conventional earthmoving equipment. In order to protect the workmen and preserve the integrity of the trench, shoring is required in deep trenches (normally over four to five feet) in soil. The major advantages of the trenching method are the ability to use specialized (though well-developed) machines for rapid excavation, and the low cost of this type of excavation. However, in congested areas where large numbers of underground utility lines may already be installed, considerable care must be exercised to insure continuity of service and prevent damage to these utilities during excavation.

For trenches in city streets, it is necessary to cut the paving material before excavation. During the period of time between excavation and backfilling of the trench, it may be necessary to either haul the earth removed to some other location or to pile it in the street. When installation is complete, it is necessary to backfill the trench and repair the pavement. Considerable care must be taken in backfilling to avoid damage to the utility and to prevent settlement of the pavement at a later date.

A modification of the trenching method is the plowing-in technique where an open trench is not excavated; instead a plow, which separates but does not turn the soil, is inserted into the earth to the desired depth and then advanced from the starting point the entire length of the run. Two methods are used to place the pipe or cable in the opening.[17] In the first method ("pulling-in"), the pipe or cable is pulled through the opening created by the plow the entire length of the opening. Because of friction, very large pulling forces are required. "Pulling-in" is normally used only with large diameter pipes or cables which cannot be fed from reels. The second method used ("feeding-in") involves feeding the cable or pipe to be buried into a "cable shoe" which lays it along the bottom of the slit as the shoe moves through the earth. More than one cable or pipe can be installed at the same time using this technique.

Plowing-in does not eliminate surface disturbance, but the total amount of earth moved is minimized. The slit is normally closed by running a heavy object over it. For obvious reasons, plowing-in cannot be used in streets unless the paving material is removed or cut beforehand.

The technique is commonly used for the installation of gas lines, and electric and telephone wires. One of its major advantages is the speed with which the operation can be performed. The Missouri Utilities Co. has reported that they have been able to install up to 10,000 ft. of plastic pipe per day in their gas system.[18] The Oklahoma Natural Gas Co. has been able to plow in 3,000 ft. of 2-in. steel pipe in 21 minutes at a cost of $400 versus an estimated cost of $2350 using conventional trenching techniques.[18]

3.2 Tunneling

The large scale use of tunneling methods for utility installation has not been common, with the possible exception of large sewers and water mains. Most utility systems do not require large tunnels, and economical methods have not been developed to produce long, small diameter tunnels. The use of tunneling is more common when the depth of the installation rules out trenching, when surface access is limited and surface disturbance is undesirable, or when it is necessary to install the utility beneath existing structures.

The act of tunneling involves the execution of three essential steps or processes. The first of these is the excavation of material from the face of the tunnel, the second is the removal of the excavated material (called spoil or muck) from the face of the tunnel and the transport of this material to the surface, and the third is the maintaining of the integrity of the opening for reasons of safety and operability. For classification purposes, the types of materials through which tunnels are excavated are rock, self-supporting soil, and soft or running ground. The three steps outlined above must be carried out regardless of the nature of the material being excavated; however, the type of material affects the manner in which a particular step is performed. The major tunneling methods currently being used are presented in Table 3.1 as a function of the material being excavated. A summary description of these alternatives is presented below.

Table 3.1 Methods Used In Tunneling Various Materials

TUNNELING PROCESSES	MATERIAL BEING TUNNELED		
	ROCK	SELF-SUPPORTING SOIL	SOFT OR RUNNING GROUND
Excavation	a. Drill and Blast b. Mechanical Excavation	a. Mechanical Excavation b. Conventional Construction Equipment c. Shield	a. Shield (under pressure)
Muck Removal	a. Trains or Trucks b. Conveyors c. Slurry Pipelines	a. Trains or Trucks b. Conveyors c. Slurry Pipelines	a. Trains or Trucks b. Conveyors c. Slurry Pipelines
Maintenance of Integrity of Opening	a. Rock Bolts b. Sprayed Concrete c. Cast-in-Place Concrete d. Steel Plate e. Cast Iron Sections	a. Pre-Cast Concrete b. Cast Iron Sections c. Steel Plate d. Sprayed Concrete e. Cast-in-Place Concrete	a. Pre-Cast Concrete b. Cast Iron Sections c. Steel Plate

3.2.1 Tunneling in Rock

The most common excavation procedure in rock tunneling is the use of a drill and blast cycle in which holes are drilled in the face of the tunnel and explosive charges are set off in these holes to extend the tunnel. The blasted material is then removed and the cycle is repeated. Depending on the condition of the rock, some form of roof support may be installed for safety considerations. Advantages of the drill and blast method are the relatively small investment in equipment required, the low cost of the energy source, and the adaptability of this method to abrupt changes in geological conditions. As disadvantages, the cyclical process is time-consuming in that one operation cannot be undertaken until the previous step is completed, there are dangers to workers from explosions and rock falls, the shock and vibration produced during the blasting operation may damage nearby structures, and often during the blasting operation more material may be excavated than necessary (also, removal of loose rock due to cracks produced by the explosions may result in the diameter of the tunnel being increased for safety purposes).

Mechanical excavators (moles) capable of producing tunnels are quite commonly used in soil and soft rock such as shale and sandstone. In the past twenty years about 100 moles have been built, and over 150 miles of tunnels have been excavated, ranging in size from 7 to 36 feet in diameter.[2] However, experience with the use of moles in hard crystalline rocks, such as granite, is not as extensive.

Construction of moles varies from manufacturer to manufacturer, but the basic design is essentially the same. Most machines consist of a rotating head unit on which are mounted cutters and rollers. Because of the nature of the cutting and crushing process, the cutting head must be directed against the working face with very large force.

Advantages cited for the use of mechanical moles are that the drilled tunnel produced has very smooth walls of the correct diameter (no overbreak), and under favorable conditions the rate of advancing the tunnel can be faster than with the drill and blast method. Disadvantages of the mechanical method are the large capital investment in the machine, the long lead time required to design and fabricate a custom machine for each job (a given machine usually is designed to cut a specific hole size in a certain rock or soil type), and the thrusts (as high as 1,500,000 lbs) required to advance the machine through the rock. Early experience with mechanical moles showed considerable "down-time" resulted due to machine failure and cutter replacement. However, recent experience has been more favorable and there is no reason to believe that these problems cannot be solved in the future.

In addition to improved mechanical mole design, interest is being directed toward new rock penetration methods such as chemical disintegration, laser beams, and thermal disintegration. One of the more promising methods is the use of high pressure water jets which have the ability to transmit large amounts of cutting energy to the rock without requiring large thrusts. The results of experiments conducted with a continuous water jet are described in a companion report.[19]

Few data are available in the literature on the economics of the drill and blast method versus the cost of machine excavation. This arises in part because moles are not in common use at the present time, and few instances occur where both methods have been used in the same rock. However, a paper study has been made for the AEC in which the estimated costs of the conventional drill and blast method have been compared with the estimated cost of using a mole to drill the same diameter tunnel.[20] Table 3.2 gives the results of this study. It can be seen that without equipment costs included, the mole produced a tunnel at a lower cost in the materials excavated, with the exception of granite. However, for a 10,000-foot tunnel, when the cost of the mole was added to the operating cost, the mole was economical only when the material being tunneled was tuff with a compressive strength of about 5,000 psi. The mole design assumed in these calculations represents no significant improvement over the current "state-of-the-art," and it was further assumed that the machine would cost the same for use in granite or in tuff, which may not be true. Another assumption which critically affects the comparison is the complete amortization of the mole during one project. Reuse is strongly indicated.

Table 3.2 Estimated Costs for 12-Foot Diameter Tunnels by Mechanical Excavation (Mole) versus Conventional Drill and Blast Methods[20]

	Drill and Blast (15 ft/shift)	Mechanical Excavation (Mole)		
		Tuff (32 ft/shift)	Dolomite (16 ft/shift)	Granite (12 ft/shift)
Elements of Boring Cost ($/ft)*				
Excavation	39	21	44	76
Haulage	19	13	19	25
Ground Support	35	12	12	14
Track, Utilities, etc.	49	44	50	59
Total Boring Cost	142	90	125	172
Equipment Cost Including Setup ($)	65, 800	476, 000	476, 000	476, 000
Estimated Total Cost for a 10, 000-foot Tunnel Including Equipment**	$1, 500, 000	$1, 400, 000	$1, 700, 000	$2, 200, 000

*All costs are direct costs to the contractor.

**Total cost of equipment is written off in the construction of the 10, 000-foot tunnel. No future use assumed for equipment.

3.2.2 Tunneling in Self-Supporting Soil

Tunneling in self-supporting soil is usually performed using a movable protective cover or shield for safety purposes until the tunnel can be lined. In shield tunneling the operating cycle consists of excavating and supporting the working face, advancing the shield, and then lining the tunnel when the shield is moved. The shield serves to protect the workers until the lining is installed. Prefabricated cast iron, steel, and concrete sections are commonly used lining materials. Excavation is normally done by hand with shovels or air-driven spades.

In some instances, moles or mechanical excavators with built-in shields have been used. In self-supporting soils the cutters or rollers that are required for rock tunneling are replaced with blades or knives that scrape the soil from the face of the tunnel. For soft materials, horsepower and thrust requirements are, of course, reduced over those needed for rock tunneling.

3.2.3 Tunneling in Soft or Running Ground

Moles or mechanical excavators are not normally used for tunneling in soft ground; the main method used is the shield system with compressed air. In 1894, this system was developed to prevent collapse of the tunnel.[21] Most of the famous subaqueous tunnels such as the New York City Hudson River tunnels were excavated using this method.

3.2.4 Muck Removal

Muck removal is a common problem in all tunneling methods. In large tunnels conventional mobile construction equipment (high-lifts, front-loaders, and trucks) can be used to remove the material from the working face and transport it out of the tunnel. Small diesel or electric trains have also been used. In smaller tunnels belt conveyors are quite often used, and some experience has been reported on the use of slurry pipeline transport systems.[22]

Muck removal appears to be the major obstacle to increasing the speed of tunneling. In the drill and blast method, it has been reported that one-third to one-half of the cycle time is devoted to muck removal operations.[23] Because of the relatively large-size pieces which are produced by the blasting operation, trucks or trains are the most common hauling method. Moles on the other hand produce smaller pieces which normally are removed from the working face by buckets on the rotating head and transported by conveyor belts to the back of the mole. This material is amenable to further transport in slurry pipelines or by conveyor belts. Muck from shield-type operations can be transported by any of the above-listed methods. When the shield is operating under pressure, the muck must be transported through air locks.

3.2.5 Maintaining the Integrity of the Ground

In all forms of tunneling, some form of ground control is required for safety purposes and for protecting the integrity of the tunnel opening. The requirements are less restrictive for hard rock tunneling than for soil; however, rock falls must be prevented. In hard rock, rock bolts are inserted and grouted into holes drilled in the upper part of the tunnel. Other methods of control involve the use of sprayed concrete or the use of precast linings of concrete, steel, or cast iron. The annular space between the lining and tunnel wall may be filled with concrete or grout for watertightness and additional support.

3.3 Horizontal Boring Techniques

A detailed study of the methods of horizontal boring has been performed by the U. S. Bureau of Mines, and it was concluded that there are a number of methods available that can provide short (up to 500 feet) holes of both large and small diameter in soil and rock.[17] The major concern, however, is the accurate location of the hole and the need for an interference warning system when drilling in areas where existing utilities and other obstructions may be present. Table 3.3 (taken from the USBM report) illustrates the cost, hole diameters, lengths, and accuracy reported for the various hole drilling methods studied.

Table 3.3 Horizontal Soil-Penetration Methods[17]

METHOD	MATERIAL BORED	MAXIMUM HOLE LENGTH (ft)	RANGE OF HOLE DIAMETER (in)	ACCURACY	PENETRATION RATES (fpm)	COST ($/ft of hole)
Spoil Augering	Soils, Soft Rock	570	2 to 84	Not Specified	0.5 to 6	For 12-in or greater diameter, $1.00 to $4.00 per inch of pipe diameter
Compacting Augering	Soils	200	1-1/4 to 4 (reamed to 8 in)	About 1° Error	2 to 8	$0.10 to $0.20 (direct drilling cost estimate)
Water Boring	Soils, Soft Rock	50*	2 to 4 (reamed to 18 in)	Not Specified	Similar to Spoil Augering	Similar to Spoil Augering
Mechanical Mole	Soils	100	3-3/4 to 5-7/8	Do	1 to 4	Not Specified
Pipe Pushing	Do	200	1 to 108	Error about .1 percent of hole length for large-diameter holes	0.1 to 0.2 and Over	For 3- to 4-in diameter, $1.90; for 12- to 30-in diameter (lined), $1.50 to $4.00 per inch of hole diameter
Overburden Drilling	Any Material Soils and/or Rock	100	4	Error about 1 percent of hole length	0.44 in Broken Rock and Gravel	Not Specified
Vibratory (sonic)	Soils	240	Up to 18	Less than 1 percent error in some cases	60	Do
Machine Tunneling	Do	Unlimited	66 to 450**	Excellent	Up to 0.25 or More	Costs Variable

*Average uninterrupted length.

**Present information shows that 50-ft-diam earth tunneling machines are in the design and construction stage.

4. REQUIREMENTS FOR A UTILITY INSTALLATION SYSTEM

The purpose of this section is to analyze the requirements of a utility installation system and to determine areas where certain methods of installation have special advantages. Also detailed are the alternate roles that surface excavation (trenching) and tunneling could play in providing the space necessary for underground utility installations.

4.1 System Requirements

A complete system for the efficient installation of underground utility distribution networks in urban areas must be capable of:

1. operating with minimum amounts of surface excavation,
2. minimizing disruption and assuring continuity and reliability of existing services,
3. providing the space necessary for the installation of the utility,
4. installing the utility in the space provided, and
5. making the connections required within the utility distribution system and with its customers.

4.2 Methods of Utility Installation

Based on current underground utility practices, the method of installation can be described as being one of three basic types. These are: (1) directly buried installations; (2) utilities that are installed in ducts or conduits previously constructed; and (3) utilities that are installed in large conduits (utility tunnels) which allow direct personnel access for installation and maintenance. Fig. 4.1 illustrates the three forms of utility installation methods.

4.2.1 Installation by Direct Burial

Directly buried systems are defined as those in which the pipe or cable is in direct contact with the ground and cannot be maintained or altered without the need for surface excavation. Direct burial is the most common method of installing underground utilities at the present time. In most cases, directly buried systems are installed by trenching, plowing-in, or jacking-in procedures although special impact tunneling devices (such as the Pneumagopher) can be used to provide installation space without producing large amounts of surface disturbance.

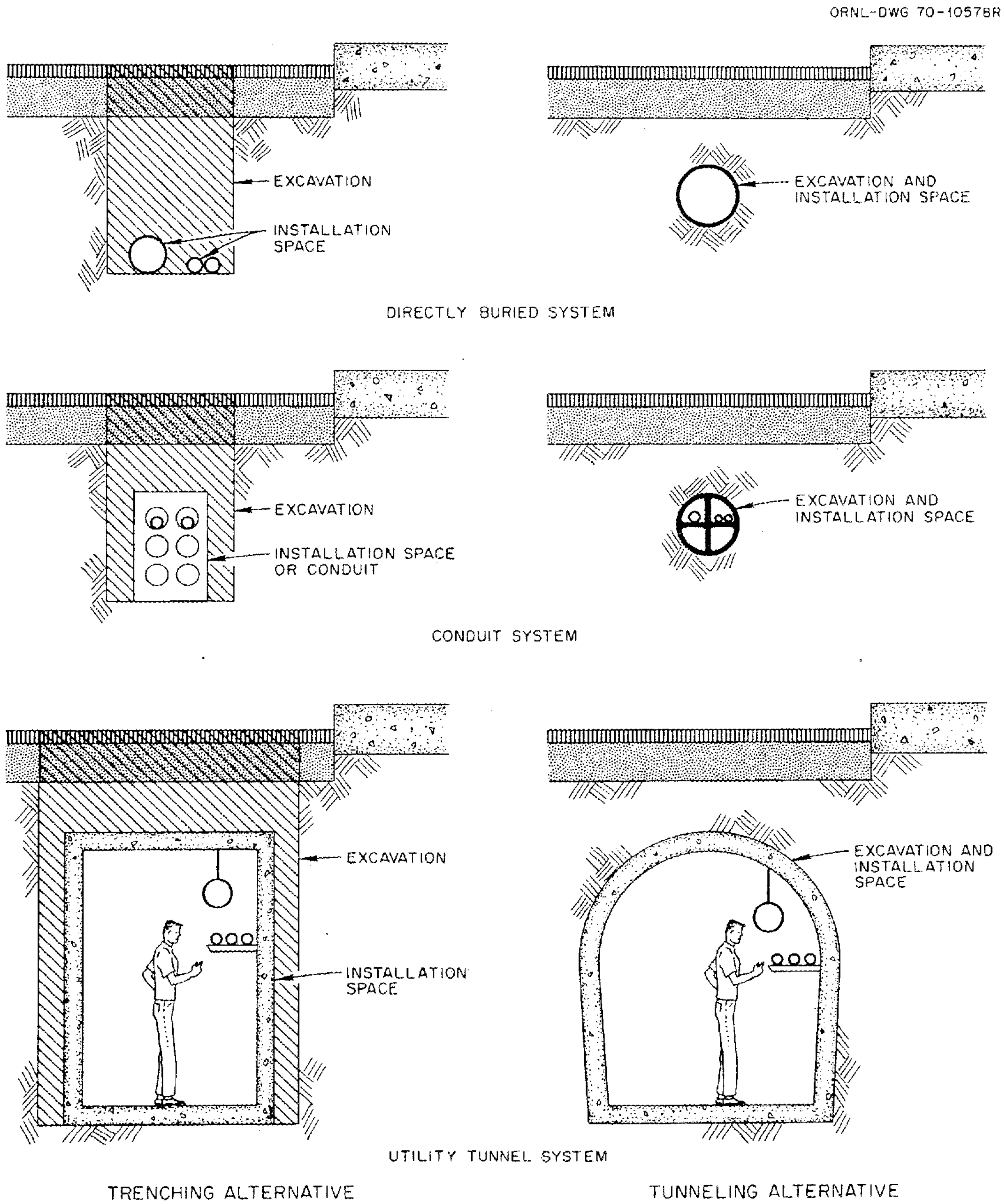

Fig. 4.1 Utility Installation Alternatives

Service connections, valves, and other auxiliaries may be located in manholes or vaults, or they may be buried directly in the earth with no access provided. Directly buried systems are not amenable to expansions to meet increased demands without further excavation. Unless manholes and access points are provided, maintenance and repairs will also require further excavation.

Recently, interest has developed in the joint use of a common trench for utility installation in suburban areas.[24,25] This method offers the advantage of excavating a single trench instead of individual trenches for each utility. Major problems in using this type of system are the concern about compatibility of multiple utilities and the need for close coordination so that all of the companies are prepared to install their pipes and cables at about the same time. Fig. 4.2 illustrates some typical installations in common trenches.[25]

4.2.2 Installation in Conduits or Ducts

Here the initial portion installed is the conduit, into which the utility is installed at a later date when needed. Utility conduits can be installed by trenching or tunneling. They are commonly used for electric power and telephone installations in large cities. Although mainly for cables, there is no reason why conduits could not contain pipes. Connections are normally made in manholes or in other underground space provided for this purpose.

The main advantages of the conduit system are the flexibility of being able to install and replace cables without excavation, and the ability to provide expansion space for future installations. However, this flexibility requires a number of access points or manholes. Thus, although future excavation can be eliminated, the need for access to the manholes may not eliminate interference with normal use of the surface. The conduit system also provides more protection to the utilities than that provided by direct burial when damage to the installation by outside sources is considered.

4.2.3 Installation in Utility Tunnels

A utility tunnel system is basically a large version of the conduit system and normally contains more than one utility. The critical

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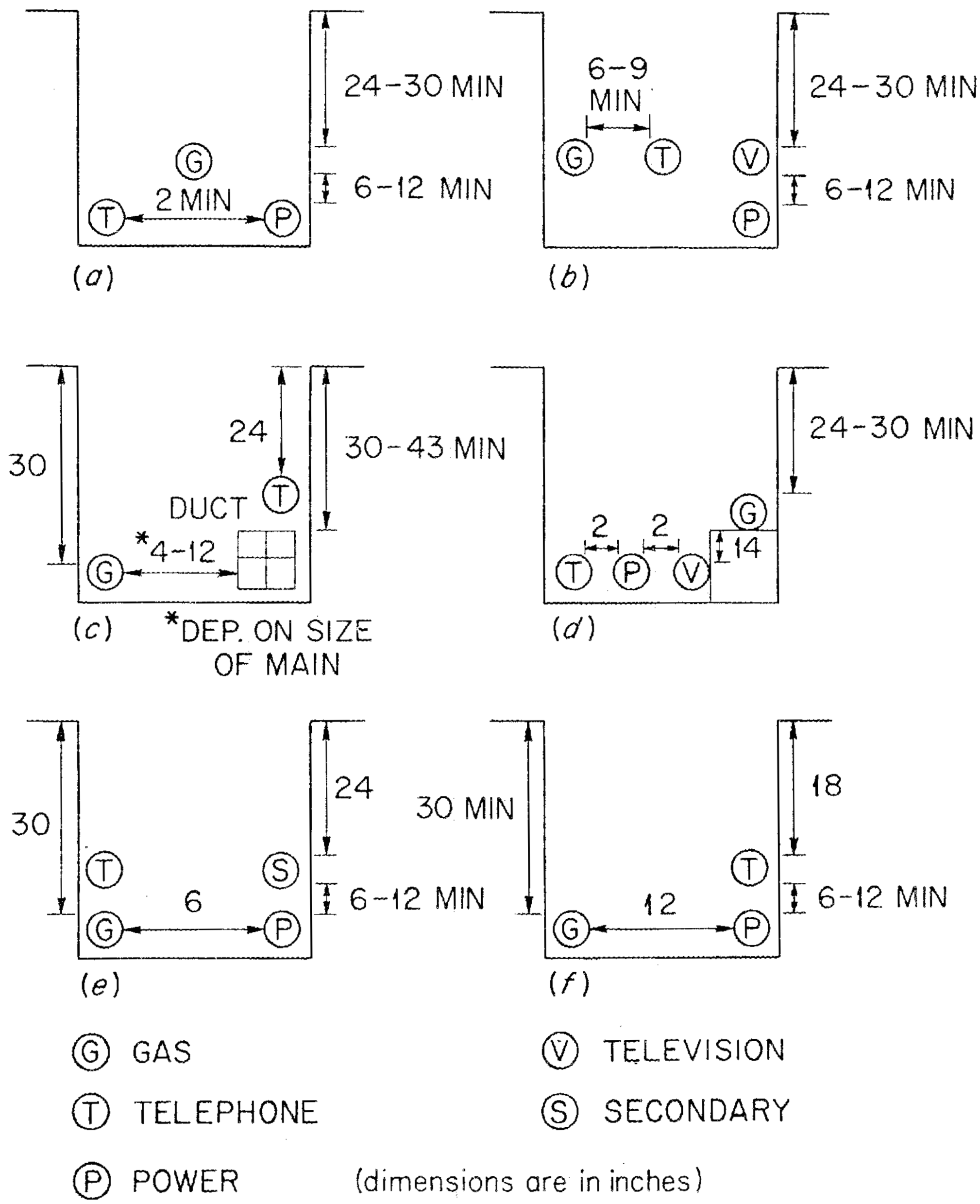

Fig. 4.2 Typical Examples of Installations in Common Trenches[25]

difference is sufficient size for direct personnel access. The tunnel is constructed initially and the utilities are installed as needed. Construction is in trenches or tunnels. Connections, where possible, are made in the tunnel to minimize surface excavation. As in the case of the conduit system, adequate expansion space must be provided for future needs.

In the United States, utility tunnels are commonly used by universities and government installations, but only rarely by cities. A survey of 19 cities and 27 universities showed that only Fairbanks, Alaska, has a city-owned utility tunnel system.[6] However, 21 universities used utility tunnels. Among utilities in university tunnels were water, gas, electric, telephone, heating and cooling, sewers, closed-circuit TV, and class bell circuits. The only complaint reported about tunnel use was the lack of expansion space which required direct burial of newer utilities outside the tunnels.

Advantages of well-planned tunnels are the ability to provide expansion with no excavation, the protected environment provided by the tunnel which reduces maintenance, and the ability to inspect and repair the utilities without excavation. As mentioned above, expansion space must be designed into the tunnel. The need to provide this expansion space along with the necessary access space produces the main disadvantage of the utility tunnel, that is, the high initial cost.

In a study performed at the Oak Ridge National Laboratory, a utility tunnel system and an equivalent conventionally buried system were designed for the White Plains Central Renewal Project in New York.[5] The estimated cost of the entire tunnel system, consisting of about 7000 feet of tunnel, was $8.2 million (including utilities). The conventionally buried system cost estimate was $4.7 million. A cost-benefit analysis was attempted, but the results were not conclusive because of incomplete data. However, there was an indication that the higher initial cost of the tunnel system could be offset by revenue from reasonable user charges. Costs were based on the use of conventional open trench excavation for both the tunnel and the buried system.

4.3 Functional Requirements

In order to satisfy the system requirements presented earlier, a number of functions must be accomplished, regardless of the method of excavation. However, there are a number of alternative methods by which each function can be accomplished for the two methods of excavation. The purpose of this section is to describe these alternatives.

Completion of the following functions is essential in providing a complete utility distribution system: (1) excavation and backfill, (2) ground control, (3) lining, (4) installation, (5) maintenance, (6) service connections, and (7) expansion.

4.3.1 Excavation and Backfill

Depending on requirements, installation spaces as small as a few inches in diameter up to several feet might be needed. Depth requirements are also variable, ranging from just below the surface to 20 feet or more.* Design considerations will also dictate the location, direction, and the alignment to grade for the installation space. The excavation must be performed with minimal interference with existing utilities. The excavation method selected will depend on such things as local geologic conditions, the amount of utilities already installed in the area, the depth of installation, and costs. After the installation has been completed, backfill is required in trenching, but not in tunneling.

4.3.2 Ground Control

While excavation is being performed and before the utility is installed, temporary ground control may be required to preserve the integrity of the opening. In the case of trenching, this is usually provided by using wood or steel shoring to prevent cave-in. For tunneling, the approach is different since not only the side walls are of concern but also the top of the tunnel. The amount of ground control necessary in tunneling ranges from the use of rock bolts in rock to the installation of temporary lining in soft ground. The temporary ground control may become part of the final lining.

In addition to geologic considerations, ground control is dependent on depth. Shallow trenches may not require ground control; however,

*Some utility tunnels at the University of Minnesota are more than 80 feet below the surface.[6]

regulations usually require shoring once a certain depth (typically four to five feet) is reached. For deep trenches, shoring becomes a significant problem and may affect the utility installation by reducing access and working area. In the case of small tunnels (physical access by personnel not possible) some remote method of providing the ground control, such as by pushing a pipe or casing into the hole, whether it is shallow or deep, is usually required. Since earth pressure increases with depth, ground control is increasingly important in deep tunnels. In large tunnels, there is the advantage of being able to install the necessary ground control from within the tunnel.

4.3.3 Lining

Once the integrity of the excavation has been assured, the final lining can be installed if required. Because of the definition of direct burial used in this report (see Section 4.2.1), lining is not required in this type of installation. However, because of being in direct contact with the earth, cables and pipes may be wrapped or coated for corrosion protection or to prevent the inflow of water. In our analysis, this coating is a requirement of the utility and not of the installation system.

Linings (ducts or conduits) are commonly used in electric and telephone distribution systems in downtown urban areas. Normally, utilities using pipes do not also use conduit systems, with the exception of certain steam heating utilities, or in cases where special conditions exist such as a pipe passing under a highway or railroad track. Lining in the case of utility tunnels is the tunnel itself.

In open-trench construction, the lining either can be constructed in place or put together in sections. In the case of tunnels, the same is true; however, for small-diameter tunnels, prefabricated linings are most common, and for large tunnels, cast-in-place linings.[2]

In addition to providing the final installation space, the lining also protects the utility from damage by installation or maintenance of other utilities or from other construction. The lining further protects the utility from factors such as corrosion or flooding.

4.3.4 Installation

During the installation phase the necessary valves and auxiliaries are connected and service connections are added. Normally, these service connections terminate at some distance from the distribution mains and can be connected to the consumer when required.

If trenching is used, the conductor can be lowered into the trench and the connections made, or as in plowing-in, the utility conductor can be pulled into the earth, and the connections made later. If tunneling methods are used, the utility line can be pulled or pushed into the tunnel, or the materials can be brought into larger tunnels and assembled. Thus, one potential advantage of open-trench installation is the use of field fabrication techniques to assemble the utility line before lowering it into the trench (not possible with small tunnels).

For the various installation systems (direct burial, conduit, or utility tunnel), installation procedures may be similar, but the materials of construction, methods of connecting, and the auxiliaries may be quite different. As previously mentioned, coatings and wrappings are often applied to pipes buried directly in the earth but may be unnecessary within conduit or utility tunnels. It may also be possible to use entirely different, perhaps cheaper, materials in conduits and tunnels for cables and pipes. However, a utility tunnel requires pipe hangers and supports such as cable trays for the utilities.

Access or space for connections (both linear and branching) are required in underground utility systems: (1) because of the need to provide consumer service connections; (2) because of pipe or cable length limitations caused by manufacturing techniques or transportation problems; (3) because of installation problems, such as friction in pulling operations; (4) because of the need to interconnect various parts of the system initially and to make connections to auxiliaries, such as loading coils, junction boxes, transformers, and valves; and (5) because of the need to build flexibility into the system.

Depending on the type of utility, these access points may be manholes, handholes, or valve boxes. In systems installed by trenching methods, the access points are normally put in at the time the utility is installed. If tunneling methods are used, the access points may be drilled later from the surface to intersect the tunnel.

In both directly buried systems and conduit systems, manholes or access points will be required for future utility installation and maintenance if minimum excavation is to be achieved. In the case of utility tunnels, large numbers of manholes may not be required, except to provide personnel access and to insert materials into the tunnel. It may also be possible to provide personnel access to a utility tunnel from building basements or parking garages through spur tunnels.

4.3.5 Maintenance

Underground utility systems routinely require maintenance and repair. Both preventive (such as repacking valves and cleaning steam traps) and emergency maintenance (such as replacing broken pipes or shorted cables) are performed on various components of a typical utility distribution system. Unfortunately, in most underground distribution systems there is no way to locate failures unless they can be detected in manholes or observed from the surface by a special detection device.

Maintenance normally requires the opening of one or more manholes, or excavation to the source of the trouble, both of which disrupt surface activities. Only if utilities were installed in tunnels large enough to allow access for maintenance could this problem be eliminated. In exchange, there are the problems of moving men and materials to the trouble in the tunnel, made easier by multiple access points. If these multiple access points are manholes, again one may disrupt the right-of-way above the tunnel. A design in crowded urban areas which might facilitate connections and maintenance is the connection of the main tunnel with the basements of buildings, perhaps on one side of the street only. Conduits could then be drilled from one basement over to others under the street for service connections.

Consideration must also be given to the safety and interference problems resulting from the concentration of different utilities in a utility tunnel. For example, telephone cables might pick up signals from electric power cables. And there is some question as to whether gas and electric lines will be permitted to share a public utility tunnel because of safety considerations, although some private tunnels have them together. Although the utility tunnel reduces the potential for damage to utilities from outside, there is always the potential for damage to utilities from installation or repair of other utilities within the tunnel (sparks from welding, impact from maintenance vehicles, etc.).

Specialized vehicles, equipment, and tools have been developed to maintain both directly-buried and conduit-contained utilities; however, the same equipment would probably not be adaptable for maintenance in utility tunnels. Thus, widespread use of utility tunnels will likely require the development of entirely new and different vehicles, tools, and techniques.

4.3.6 Service Connections

Service connections to consumers are normally made after the utility line is installed and operating. However, during the installation phase, provision is usually made for future customer service by connections to the main utility lines extended to some predesignated location, such as the curb or property line. These lateral connection terminations may be placed in access boxes, or buried in direct contact with the earth. Connections from the consumer to the access boxes can be provided by trenching, jacking-in, or tunneling.

No matter how much thought has gone into the original system design, there will always be unanticipated service connections. The service line will then have to be connected directly to the main pipes or cables in the distribution system by trenching or tunneling. If small diameter tunneling is used for service line installation, and the main line is directly buried or in conduit, it will still be necessary to excavate from the surface for the final connections. Space must be provided for workmen to tap the pipe or splice the cable since the equipment and techniques for accomplishing these tasks automatically or remotely from a small tunnel have not yet been developed for routine use. If the service line is placed in a trench, the splice or connection can be made in the trench using conventional techniques, which in the case of certain utilities, such as water and gas, can be performed without shutting down the utility. However, whether excavation is by tunneling or trenching, service line connections to cables in conduit systems present an additional problem in that the conduit itself must also be penetrated without damage to the utility. In the case of utility tunnels, it may be possible to drill the tunnel to the consumer, or vice versa, and make the connection in the tunnel where working space is available, thus eliminating surface excavation. This is a particularly advantageous feature of such tunnels.

4.3.7 Expansion

Most utility systems are undergoing frequent changes, often due to increased loads. Urban renewal, expressway construction, and suburban growth have also caused significant changes in urban utility distribution systems. In addition, because of changing demands and the need to upgrade the quality of service provided, utility companies are required to retire (in some cases without removal of pipes or cables) parts of their systems and replace the retired sections with larger capacity lines. In this report, expansion is considered as the addition or replacement of utilities within installation space previously provided. In cases where the expansion was not anticipated, further installation would be essentially the same as a new installation.

Direct burial does not provide for expansion unless spare cables or pipes are installed when the trench or tunnel is excavated. Conduit systems can more easily allow for expansion by provision of spare ducts, or by allowing removal of existing cables or pipes and replacing them with larger capacity pipes or cables. Utility tunnel systems can most easily allow for expansion by the provision of extra space at the time of installation of the tunnel without detailed study of the configuration various expansions would require, or by allowing the removal and replacement of the undersized utility lines within the tunnel. However, the cost of providing this extra space is one of the most important disadvantages of the utility tunnel concept.

Obviously, the ability of the installation system to handle expansion depends on the predictability of future utility demands. Certain system changes may be required that are almost impossible to predict (such as those related to urban renewal or expressway construction). However, the success of any installation system will depend in part on its flexibility without complete knowledge of the future.

4.4 Summary of Installation System Alternatives

As was pointed out before, the utility installation system can follow three types of design and the space can be provided by either trenching or tunneling methods of excavation. There are certain advantages and disadvantages which depend on the method of excavation, as summarized in Table 4.1. It can be seen that most of the advantages of trenching occur only in shallow trenches. As the depth of the trench increases, these advantages are reduced or lost. The major disadvantages of trenching are related to the excavation process itself: interference with pedestrian and vehicular movement caused by the excavation equipment, the excavated earth, and the equipment for removal of excess earth. Counterbalancing these disadvantages are advantages resulting from simplified access to the installation space.

Tunneling presents an almost opposite set of advantages and disadvantages. Use of tunneling appears much more feasible for deep utilities, while at shallow installation depths in most soils trenching is cheaper. Tunneling offers the advantage of minimum surface disturbance, but poses difficult problems of safety and restricted access for men, machines, and materials. Machine methods of tunneling appear to offer more rapid excavation and lower costs than non-machine methods, but at present, limited use has restricted machine development and standardization.

In general, the method of excavation used has little effect on utility installation design. Individual directly-buried utilities, conduit systems, or utility tunnels could be installed using either tunneling or trenching methods; selection of the method depends on depth of burial, amount of existing utilities, and economics.

When utility installation designs are compared, there are another set of advantages and disadvantages which are related to installation, maintenance, service connections, and expansion. These alternatives are summed up in Table 4.2.

At the present time, the most common method of utility installation is direct burial. However, the method is inflexible in terms of system expansions and repairs unless future excavation can be tolerated. If

Table 4.1 Comparison of Excavation Alternatives for Installation of Utilities

Trenching Alternative	Tunneling Alternative
Pro	Pro
1. Standard earth excavating equipment can be used.	1. Tunneling can provide installation space at depths necessary to avoid obstructions, and is not limited to open areas such as streets.
2. For shallow installations, trenching is less costly than tunneling.	2. Surface disturbance is minimized by tunneling.
3. Lining can be placed easier and faster because of direct access to work space.	3. Less excavation of material is required than for trenching.
4. Pipe can be fabricated in long sections before installation in trench.	4. Excavation is relatively insensitive to surface weather.
5. No life support systems required.	5. Promising new tunneling methods offer potential of more rapid excavation.
6. Trenching is more adaptable to changes in geology than tunneling.	
Con	Con
1. Shoring for ground control may restrict working space in deep trenches.	1. Tunnels at great depths will cause problems in service connections.
2. Working schedules are dependent on surface weather conditions.	2. Tunneling provides only the installation space, not the surface access required to install and maintain the utility.
3. More excavation is required in trenching than for tunneling.	3. Tunneling is expensive, difficult, and hazardous; ground control is required.
4. Trench must be backfilled after installation of utilities.	4. Tunnels require life support systems for workmen.
5. Material removed from trench must be stockpiled, either at site or elsewhere.	5. Access and materials handling become more complicated as working face is advanced.
6. Trenches in streets require removal and replacement of paving.	6. Machine tunneling requires very expensive custom-made machines which are sensitive to changes from predicted geology.
7. Trenches disturb the surface, interfere with traffic, and are unsightly.	7. Small market for machines has restricted their development and standardization.
8. Trenching is difficult in areas where large amounts of utilities exist.	

Table 4.2 Comparison of Utility Installation Design Alternatives

DIRECTLY-BURIED SYSTEM	CONDUIT SYSTEM	UTILITY TUNNEL SYSTEM
Pro	Pro	Pro
1. Directly-buried systems do not require ducts or linings.	1. Expansion space can be included in the initial duct installation which may minimize future excavation.	1. A utility tunnel provides both protection from external damage and a protected environment for utility installations.
2. Installation may be cheaper and faster because specialized methods (e.g., plowing-in) can be used.	2. The conduit provides physical protection for the utility.	2. Utilities are more accessible for surveillance, maintenance, and repair.
3. A minimum amount of excavation is required per utility because installation space is needed only for cable or pipe.	3. Cables or pipes can be installed or removed from ducts without excavation.	3. Expansion of utility systems can be accomplished without excavation.
4. Plowing-in or pulling-in techniques which require minimum excavation and produce a minimum of surface disturbance can be used.		4. Installation and maintenance are not dependent on weather conditions.
5. Maintenance can be performed in manholes if installed in the system.		5. Surface access points can be minimized or eliminated.
6. More than one utility can be located in a trench (joint or common trench).		6. The utility tunnel scheme is adaptable to new utility concepts.
		7. Future service connections can be made with minimum or no excavation.
Con	Con	Con
1. Because of direct contact with earth, protective coatings may be required.	1. Many manholes are required for flexibility of operation.	1. Because of access requirements within a utility tunnel, the space required may be large.
2. Extra-strong pipes and cables must be provided when installed by pulling-in technique.	2. Maintenance or repair of utilities requires opening one or more manholes.	2. Excavation is costly because of size and depth requirements, and the need to haul away excess earth.
3. Excavation must be performed for service connections when manholes are not provided initially.	3. Foreign material may get into conduits making the removal or addition of utilities difficult.	3. New installation and maintenance techniques may be required for utilities installed in utility tunnels.
4. Excavation is required to repair and replace directly-buried components. Points of failure cannot be observed without excavation.	4. Manholes afford crowded working conditions.	4. Utility tunnels are expensive on a first-cost basis.
5. Directly-buried systems are inflexible to growth in demand; system expansion requires excavation.	5. The conduit system is more adaptable to cables than to rigid pipes.	5. Ventilation, lighting, drainage, etc. are required.
6. Inspection of the initial installation must be completed before backfilling is done.		6. The possibility exists of damaging one utility while working on another.
7. Directly-buried systems are vulnerable to physical damage from external sources.		7. Access by unauthorized personnel must be prevented.
8. The actual physical location of a directly-buried utility is difficult to determine.		8. Compatibility between utilities must be considered.
9. Joint trenching requires close coordination before and during installation.		

the directly buried system is not installed with manholes, hand holes, and other means of convenient access, excavation will be required for all operations. However, in areas where changes are infrequent and expansion is limited, direct burial techniques will probably continue to be the simplest and most economical.

One modification of the directly buried system that minimizes the amount of initial excavation is the use of joint or common trenches for installation of multiple utilities. This method required close coordination between the utility companies involved during all phases of planning and installation,[24,25] and has not been used frequently in America. It may have the disadvantage of greater probability of damage to one utility by maintenance work on another, but this could possibly be offset by improved records of the actual installation produced by a photographic survey just before the trench is closed.

In congested areas where flexibility is needed together with minimum surface disturbance, conduit systems are commonly used. In general, these systems are used for cables or wires although there would appear to be a possibility of their use for pipes.[26] The main advantages of the conduit system are the ability to install, remove, and repair cables conveniently, and the ease with which expansion space can be provided by spare ducts. In order to utilize this flexibility, a large number of manholes or access holes must be installed initially so that connections can be made or broken as needed. Thus, although excavation is minimized, the potential for surface disturbance in the form of open manholes is still present.

As previously mentioned, utility tunnels are not common in cities but are quite common on (or, rather, under) university campuses. Their main disadvantage is the initial cost which is increased by the desire to provide expansion and working space. Installation of various utilities in tunnels requires that the utilities be compatible, and adequate means must be provided to prevent damage to one utility by a failure of another.

Tunnels require ventilation, lighting, access control, and alarm systems for safe operation. However, the utility tunnel allows expansion, maintenance, and repair activities to be performed without surface disturbance. The tunnel itself serves to protect the utilities from damage from outside sources and provides a protected environment which might allow the use of different and, perhaps, cheaper materials of construction for the utilities than those used with conduit or directly buried system.

5. FUTURE UNDERGROUND UTILITY INSTALLATION ESTIMATES

As the population increases, the demands placed on utility distribution systems also increase. In addition, population migration from central city areas to suburbs produces a need for wider utility distribution. Based on current trends it is also apparent that utility companies which have in the past located most of their distribution systems overhead will increase the fraction of distribution systems which are located underground.

Data with which to project future utility needs is sketchy; in the case of certain utilities (such as water and sewers), it is impossible even to determine the total number of miles of pipes or lines in existing systems because no central organization appears to tabulate this information for the entire United States.

A survey of the 100 largest SMSAs in the United States was made to determine if the demand for certain utilities in the next 20 years would be high, medium, or low.* The results of this survey are given in Appendix B. However, attempts to use the survey demand estimates to generate total miles of utility installations so far have not been successful, primarily because of incomplete data about the size of existing systems. The choice of the phrase "demand for utilities" was also misleading; perhaps a request for a numerical milage estimate would have been preferable.

Another way to predict future underground utility requirements is to assume that sewer, water, gas, electric, and telephone systems will grow at the same rate as municipal streets. This approach assumes that all are provided in each new growth area, but does not take into account system growth in areas where streets are already installed. In the case of sewers, and perhaps natural gas, these assumptions are probably quite inaccurate because large areas now being served by water, telephone, and electric utilities do not have sewers and gas at the present time, but will receive these services later as the population density increases.

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*The guideline used in the survey was the length of the existing water or sewer system.

5.1 Conventional Utility Systems

5.1.1 Water

Data from the annual reports of one public and five private water companies showed that the growth rate in the length of the water distribution system during the period 1965 to 1967 averaged three percent per year (see Table 5.1). Unfortunately, no information is available on the length of the water distribution systems in the United States. In 1967, there were approximately 530,000 miles of municipal streets in the country, and during the period 1965 to 1967, the growth rate of streets was about two percent per year.[27] If the number of miles of water mains are assumed to be approximately equal to the number of miles of municipal streets, there may have been about 530,000 miles of water mains in operation in 1968. Furthermore, the anticipated annual growth in the milage of municipal water distribution systems may be between two and three percent of the existing length. Thus, the future demand for water mains could range from 10,000 to 15,000 miles per year. At the unit cost for mains reported in Appendix C, Section C.1, this would indicate an investment of $200 to $300 million/year in water system extensions. The distribution of these costs to individual cities will, of course, depend on suburban growth and the age of installed systems, but these figures are probably representative of anticipated annual growth of water distribution systems in the near future.

5.1.2 Sewers

Estimates of the current and future milage of sewers in the United States are not available. However, the Federal Water Pollution Control Agency (FWPCA) has estimated that 28.4 million people presently live in unsewered urban communities.[28] They also estimate that sewers for these people will cost $3.9 billion, in addition to the $2.3 billion required for sewers to meet expected population growth during the period 1969-1973. These figures are for sanitary sewers only, and do not include the cost of separating combined sanitary and storm sewers or providing new storm sewers. Estimates of the cost of separating existing combined sewer systems range from $30.4 billion to $48.8 billion.

Based on the capital cost estimate developed in Section C.2, it appears that as much as 25,000 miles of sanitary sewers will be needed per year through 1973. However, an increase of about 10,000 miles per year, based on the projected growth rates of municipal streets and water systems, may be more realistic.

Table 5.1 Rates of Growth of Selected Water Systems*

Water System		Length Mains** (ft)	Mains Added (ft)	Mains Added (%)	Average Growth Rate (%/yr)
Indianapolis, Indiana	1965	7,784,555	198,679	2.6	
	1966	7,973,689	237,229	3.0	3.2
	1967	8,200,725	338,787	4.1	
Muncie, Indiana	1965	1,183,727	24,561	2.1	
	1966	1,201,565	18,609	1.5	1.9
	1967	1,202,321	24,648	2.0	
Gary-Hobart Water Co.	1965	2,354,704	50,861	2.2	
	1966	2,404,656	80,130	3.3	2.4
	1967	2,480,875	42,636	1.7	
Bridgeport Hydraulic	1964	4,886,266	170,601	3.5	
	1965	5,251,870	233,576	4.4	3.6
	1966	5,481,173	203,425	3.7	
	1967	5,677,686	161,865	2.9	
Connecticut Water Co.	1964	2,245,134	87,274	3.9	
	1965	2,386,481	88,851	3.7	3.6
	1966	2,454,999	90,849	3.7	
	1967	2,533,330	76,320	3.0	
Detroit, Michigan	1964	38,509,372	1,120,803	2.9	
	1965	39,438,151	1,225,445	3.1	2.9
	1966	40,376,989	1,043,635	2.6	

*Data from annual reports filed with state regulatory agencies, except for Detroit which publishes its own annual report.

**Length at start of year.

5.1.3 Natural Gas

In 1968 a survey was made to determine the amount of natural gas distribution piping installed in the 300 largest gas distribution systems.[29] Results indicate that around 650,000 miles of gas mains were installed at the end of 1968 (exclusive of the small service lines connecting the consumers to the mains amounting to another 350,000 miles), and that the rate of new installations for the previous two years was about 3 percent per year. It was further determined that new and replacement mains (both street mains and service lines) involved an investment of about $20,000/mile. Our studies of capital investment per mile of gas main confirm this estimate ($9,000 to $32,900/mile with an average of $18,000/mile). Thus, it appears that gas main installations in the next few years will average about 20,000 miles per year at an investment of about $400 million/year.

5.1.4 Electric Power

Electrical World magazine compiles yearly statistics on the amount and cost of extensions to underground and overhead transmission and distribution systems. Results of their surveys for the years 1956-1970 are shown in Table 5.2. It can be seen that the trend to underground utility distribution systems is increasing, and that the amount installed is approaching 7000 miles per year. In 1970, the power companies estimate that it will cost $380 million to install the 6,730 miles of underground distribution system required. In 1970, approximately 15 percent of all distribution lines installed will be underground.

5.1.5 Telephone

Estimates of the growth of underground distribution systems for telephone companies can be derived from the annual reports that the companies must file with the Federal Communications Commission. The companies are required to report the amount of conduit installed (on both a trench mile and a duct mile basis), the amount of underground cable installed in the conduit, and the total amount of buried cable in the system at the end of each year. Forms were obtained from the FCC for the years 1964 to 1969 for forty of the largest telephone companies filing reports. Included in the forty were all of the companies making up the Bell Telephone System.

Fig. 5.1 shows the amounts of underground facilities added during the past five years. Although there is a trend towards increasing the amount of underground plant installed, it can be seen that the amount installed each year is reasonably constant. Based on Fig. 5.1, a conservative estimate of yearly installation would be 50,000 to 60,000 miles of buried cable, and 2,000 to 3,000 trench miles of conduit systems.

Table 5.2 Growth of Underground and Overhead Electrical Distribution Systems*

Year	Underground Installed (Cable Miles) Transmission	Distribution	Overhead Installed (Pole Miles) Distribution
1956	354	2, 225	54, 267
1957	252	2, 563	53, 017
1958	234	1, 749	41, 145
1959	343	2, 085	43, 307
1960	242	2, 421	40, 553
1961	194	3, 253	39, 747
1962	151	4, 971	30, 808
1963	288	4, 380	29, 888
1964	213	3, 474	33, 574
1965	343	2, 854	38, 057
1966	239	3, 747	34, 555
1967	331	5, 584	38, 798
1968	175	6, 304	39, 173
1969	185	6, 366	35, 966
1970 (Est.)	283	6, 730	36, 486

*From "Statistical Reports, Part I", Electrical World, usually in 3rd issue each year (1963-1970).

Using the costs in Appendix C, Section C.5 and the amounts of underground plant estimated above, from \$380 to \$460 million will be invested in buried cable and from \$64 to \$96 million would be invested in conduit systems annually.

5.1.6 Community Antenna Television (CATV)

Considerable demand is foreseen for coaxial TV networks in the near future (see Appendix B). Currently, most of the systems are above-ground,

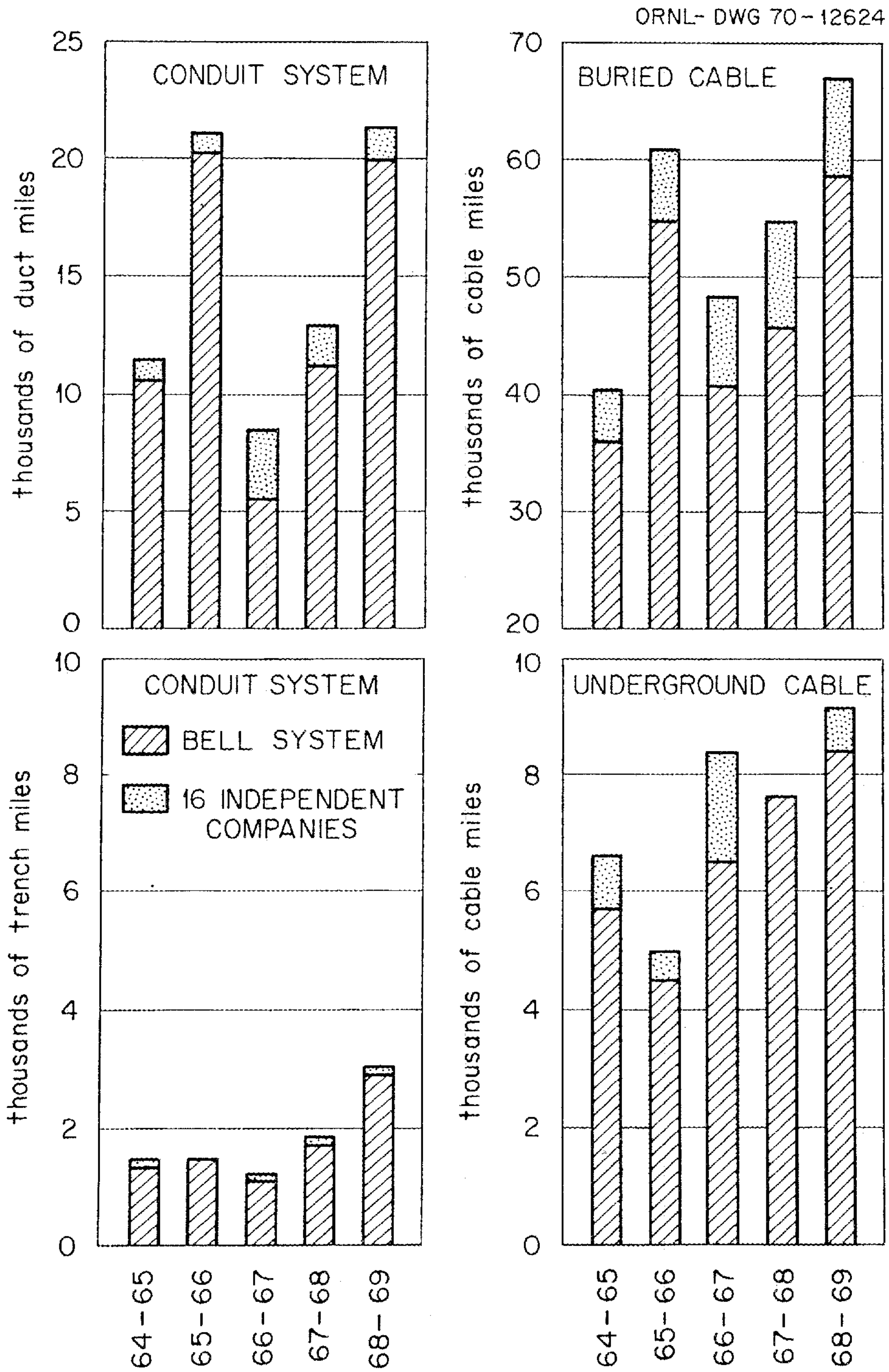

Fig. 5.1 Underground Telephone Facility Additions

but with the trend in suburban areas to providing underground services, this utility is also being installed underground. As CATV becomes more popular, the miles of underground installations may approach that for underground electric power (many thousands of miles per year).

5.1.7 Central Heating and Cooling

Because of the present rather limited use of central heating and cooling facilities, data are not available from which to make future projections. However, it would appear that such installations during the next decade would be only a small fraction of the amount of water mains and sewers, perhaps amounting to a few tens of millions of dollars per year. A deliberate government policy to reduce thermal pollution by utilizing a portion of power plant waste heat for urban heating and cooling could change this projection.[30]

5.1.8 Summary

The annual growth rate projections for the aforementioned conventional utility systems are summarized in Table 5.3.

Table 5.3 Estimated Annual Growth of Conventional Utility Systems

System	Estimated Annual Growth (miles)
Water	10,000-15,000
Sanitary Sewers	10,000-25,000
Natural Gas	20,000
Electric Power*	6,700**
Telephone*	50,000-60,000**
CATV*	5,000- 6,000
Central Heating and Cooling	-

*Underground installations.

**Cable miles.

5.2 Potential New Utility Systems

5.2.1 Pneumatic Tube Mail Delivery

Delivery of mail and telegrams by pneumatic tube transport has been carried out in Europe for many years.[31] The first tubes, installed in London in 1853, were 1-1/2 in. diameter and a few hundred yards long. At one time London had 34 miles of 2-1/4 to 3 inch tubes in its system. In Paris, about 230 miles of pneumatic tubes were installed in the sewer system beginning in 1851 to transmit mail and telegrams, and these tubes are still in use.[32,33] Pneumatic tubes were also installed in Vienna, Berlin, Milan, and Zurich. In general, tubes installed in Europe were small diameter (3 in. or less). In the United States between 1893 and 1916, pneumatic tubes up to 8 in. diameter were installed to carry mail.[34] Installations were made in New York City (28 miles), Philadelphia (10 miles), Boston (7 miles), St. Louis (2 miles), and Chicago (10 miles). The service was satisfactory and the reliability was high. Their use was discontinued because the amounts of mail to be handled exceeded the capacity of the systems. Furthermore, the systems were owned by private contractors and there was frequent criticism of the revenue received by the operators since there were no competitors.

In reviewing pneumatic tube experience in the United States and Europe, it would appear that the use of pneumatic tubes to move mail between central post offices and large office buildings should be re-examined. Currently in Germany, research is being performed on the use of large tubes (from 17.7 in. to 27.6 in.) by the German postal system.[35] The 17.7 in. tubes are pneumatically operated, but the larger tube uses a carrier which is self-propelled.

5.2.2 Advanced Solid Waste Handling

Currently, considerable interest is being directed to alternative methods of solid waste collection in urban areas.[36] Not only is solid waste collection expensive (about 85 percent of the total handling cost), it is a noisy, dirty, and dangerous occupation. Traffic congestion caused by the numerous collection vehicles has also been cited as a reason for developing alternative collection methods.

One solution to the problem would be to move the collection system underground. Pneumatic and slurry pumping systems have been proposed.[37] The Centralsug system of vacuum collection has been used in Sweden and London with great success and an installation is currently being completed in the United States.[38] In this process solid waste is collected in chutes in apartment buildings and released through valves on a preselected schedule or demand basis into the main vacuum collection system. The solid waste is transported pneumatically through the underground collection system to a main processing area where it is compacted and containerized for infrequent transport to the disposal site. No grinding or size reduction is performed before vacuum transport, since experience has shown the system will move any item small enough to be put in the chute.

In a slurry pumping system, the solid waste would be collected within the buildings, ground to reduce particle sizes, slurried with water (or sewage), and then pumped underground to a central processing area. The main difference between the two approaches described above is the need to grind the waste in the slurry pumping approach and the possible elimination of the containerized transport step.

5.2.3 Underground Material Transport

One additional method of reducing congestion in dense urban areas would be to replace freight-carrying trucks with some form of underground transportation system. This might take the form of conveyor belts or automated vehicles operating in tunnels. In London, the Postal Service has an automated railroad for moving mail and parcels between post offices.[39] Chicago also installed a tunnel system in 1908 to collect ashes and refuse in the downtown area.[40]

6. POTENTIAL BENEFITS OF AN ADVANCED UTILITY INSTALLATION SYSTEM

6.1 Direct-Cost Benefits

One desirable feature of an advanced utility installation system would be to reduce the capital costs of installation. This could be accomplished by reducing the amount of excavation required, or by reducing the cost of excavation by applying new technology. Cost reductions could benefit the consumer by rate reduction and by allowing underground utilities to be expanded into areas where they are not commonly installed at the present time.

However, in the case of most utility companies, the distribution system represents a relatively small portion of the total capital invested in the entire utility system, and only a fraction of the distribution costs are related to the installation system. As an example, Consolidated Edison in 1967 had 50 percent of its total capital invested in its distribution system. The total distribution system, however, also includes such items as transformers, station equipment, and meters, which would be needed to operate the system regardless of how the system is installed. Much the same occurs in other utility companies, with the exception of those that carry out a distribution function only and do not produce what they sell. Therefore, although hundreds of millions of dollars are spent on installations each year, and reductions in the cost of installing utilities may save large sums of money, the result, unfortunately, would probably produce only a small percentage reduction in utility rates.

6.1.1 Trenching Costs

Equipment currently available for trenching operations has evolved to the point at which significant changes in the procedures used in excavation will not produce significant cost savings per unit volume of excavated trench. Trenching machines can produce essentially any size or depth trench rapidly and economically. However, it appears that significant cost savings per mile of installed utility can be produced if more than one utility is placed in a trench, thus eliminating the need for multiple trenches.

Another method of reducing the amount of excavation and consequently, the cost, would be an increased use of plowing-in or pulling-in techniques described in Section 3.1, particularly in new subdivisions or new towns created in non-urban areas. The major deterrents to the use of plowing-in or common trenching in present urban areas are existing utilities and the need to remove paving if the installation is in an existing street.

Fig. 6.1 gives one example of the current estimated cost of trenching and utility installation as a function of the size of the installation space provided. The figures include the costs of trenching using conventional methods and present-day trench design and the additional costs for installing concrete sewer pipe.

6.1.2 Tunneling Costs

Costs of tunneling (either manual or machine) in the size ranges shown in Fig. 6.1 do not exist in sufficient number to be conclusive, but Mayo[21] suggests a cost for tunneling in crushed rock or unconsolidated sediments of about $470/ft. for 9-ft. diameter tunnels, and the reported costs for two 5.5-ft. tunnels (including a one-foot concrete lining) excavated by machine in Chicago range from $200 to $210/ft.[41]

In an analysis done by Fenix and Scisson, Inc., and Arthur D. Little, Inc. of 16 different soft ground tunneling projects involving sewer and drain, water supply, subway transit, and automobile tunnels, volume-weighted average costs of $38.41/cu. yd., $76.10/cu. yd., $130.69/cu. yd., and $183.11/cu. yd., respectively, were reported.[42] For 5.5 ft. diameter holes this gives a cost range of $34/ft. to $160/ft.

Paone,[17] et al., in their study of horizontal boring indicate that costs in the range of $1 to $4 per inch diameter per foot can be attained using procedures such as augering or pipe pushing in soil. For 5.5 ft. diameter holes, this would give costs of $66 to $264/ft. indicating that for applications where soil augering or pipe jacking can be performed, costs are in the same range as machine tunneling.

Until more rapid tunneling machines capable of producing small diameter tunnels of the size range indicated in Fig. 6.1 can be developed, or until the amount of tunneling required increases to the stage that

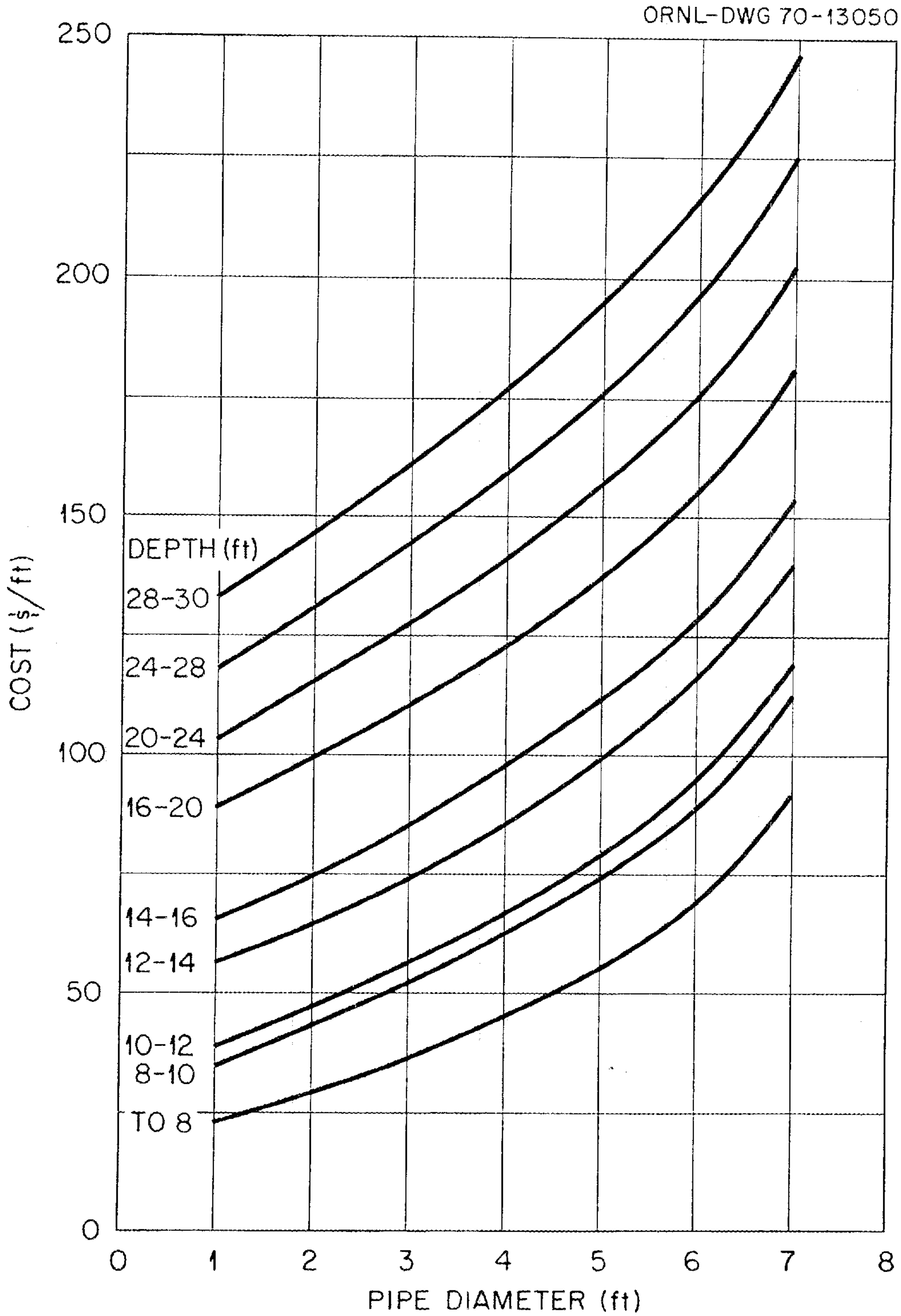

Fig. 6.1 Estimated Cost of Concrete Sewers in Trenches Requiring Shoring

machines can be amortized over many projects, tunneling for utility installation appears to be economical only in applications where utilities must be installed at great depths and open trenching is not feasible, or in areas where so many utilities are currently located that it is more economical to consider tunneling below them instead of excavating through them.

6.2 Indirect-Cost Benefits

Indirect benefits will accrue from installation systems that do not initially produce significant surface disturbances. However, these benefits are hard to quantify.[43] Such items as traffic interference, accidents caused by trenching work, interference with business operations, and damage to pavement will all occur in most street trenching operations, and to a limited extent in tunneling or boring operations. Only when excavation is performed before streets are paved, or when a trench is not located in a street can the indirect costs cited above be reduced or eliminated.

There is also some intangible value which can be assigned to an installation where little or no future excavation will be required (e.g., a utility tunnel) in providing new or expanded services. The value of this benefit will probably vary with the value of the land; that is, it would be higher in downtown areas and rather low in suburban housing areas.

Reduction in maintenance expenses to the utility companies could also be achieved by the use of utility tunnels, since maintenance activities would not require costly excavation. Although the presence of a protected environment in the tunnel should reduce the need for maintenance, discussions with utility companies indicate that they have no experience to confirm this point.

6.3 Summary

Utility systems are expanding rapidly and there are possibilities for new utilities in the future which will have to compete for underground space. The existing tangle of underground utilities in older dense urban areas may require future installations to be made below these utilities. If so, tunneling might be considered as the best, if not the only, way of providing the installation space. However, based on the figures reported in Section 6.1, which are summarized in Table 6.1, the cost of tunneling would have to be reduced by at least a factor of two to three before tunneling will achieve widespread use as a replacement for trenching.

Table 6.1 Examples of Cost of Several Different Methods of Excavation

Excavation Method	Cost of Excavation or Installation ($/ft) Pipe or Tunnel Diameter (ft) 5.5	9
Tunneling		
1. In crushed rock or unconsolidated sediments[21]	–	470
2. Two Chicago tunnels[41]	200–210	–
3. Sixteen soft ground tunneling projects*[43]	34–160	91–431
Horizontal Boring**	66–264	108–432
Trenching***	60–120	–

*Based on volume-averaged costs of $38.41/cu yd to $183.11/cu yd.

**Based on $1-4 per inch diameter/foot of length.[17]

***Based on Fig. 6.1 for 8- to 16-foot deep trenches.

Trenching, although it creates surface disturbance, is inexpensive. New installation methods such as plowing-in can produce a "trench" with minimum surface disturbance and with considerable speed. Joint utility installation in a common trench also offers the possibility of reduced cost. Because of its cost advantages, trenching for underground utility installation will continue to be the prime method in the future except in special circumstances where trenching cannot be performed.

7. CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

1. Normal growth rates of utility systems indicate that large amounts of underground installation will occur. There is also an increasing demand for placing existing aerial utilities underground.

2. Installation of utilities by tunneling methods offers a means for reducing surface disturbance.

3. If utilities are installed (by tunneling methods) at depths greater than current practice, there will be increased problems in making network and service connections.

4. Installation of utilities by tunneling methods is more expensive at the present time than by trenching except at depths that preclude trenching.

5. If several utilities are installed by trenching, the use of a common or joing trench appears to offer many advantages. However, close coordination is required in the planning and installation phases.

6. In new suburban areas, plowing-in of cables and pipes appears to be a relatively inexpensive and fast method of installing utilities.

7. The use of "utility tunnels" offers an attractive solution to utility problems in dense urban areas but they are expensive to construct.

8. Conduit systems capable of containing both cables and pipes may minimize the amounts of excavation necessary for installation and maintenance. Further studies of this concept are required.

9. If a tunneling machine is specifically developed for utility installation, it will need to operate principally in soil or soft rock, it would produce mainly small holes for individual utilities, and in most cases, it would operate relatively close to the surface.

10. If small diameter tunneling machines are to be considered for utility installation, significant developmental problems in the functional areas of muck and material transport, ground control and lining, excavation system guidance, remote operation of the system, and interference warning capability will be encountered. Integrating the mechanisms chosen to accomplish the necessary functions into one system will also require an extensive development program.

APPENDIX A

UTILITY TUNNELING SYSTEM REQUIREMENTS

Introduction

Maintaining and enhancing the quality of the total environment in the face of growing urbanization is an increasing national concern. As stated by the National Academy of Sciences,[44] underground construction offers solutions to many of the worst problems involved in the eradication of pollution and congestion now blighting urban and rural environments. In addition, underground utility construction provides enhanced protection of service in cases of severe storms and natural disasters.[45] However, current installation practices themselves produce significant disturbances of the surface environment, so improved utility installation techniques may be needed to protect and upgrade the urban environment.

Because of increasing demands on urban utility services, systems must be expanded with much of the expansion underground. Deterioration of existing underground utilities also requires replacement. Finally, advances in utility technology may bring about new and better ways of providing urban services; for example, new utilities such as solid-waste pipelines may become feasible in the future.

The expansion and improvement of existing urban utility systems goes on continually. During installation of new utility systems, it is often necessary to maintain the continuity of existing services and prevent severe disruptions of living patterns in the construction area. Current trenching methods may not meet these criteria, and alternative means of installing new and improved utility services would be desirable.

One alternative would be the development of rapid tunneling methods to provide the necessary subsurface utility installation space. Mechanical tunneling machines have been used, but operational problems caused by equipment wear and failure, and the high initial capital cost of the machines have restricted their use. In order to provide a better understanding of the problems associated with machine tunneling, an analysis was performed of system requirements to install and maintain a utility system which indicated areas where future developments will be required.

A.1 Program and System Requirements

A complete system for the efficient provision of underground utility distribution networks in urban areas will be specified. This system must operate with a minimum disruption of existing services and the surface environment.

The system must be capable of boring holes which range from a few inches to several feet in size through the earth in a safe, rapid, continuous, and economic manner. For tunnels that do not allow personnel access, the system must be remotely operated and guided, calling for a completely integrated combination of propulsion, guidance control, earth disintegration, muck or spoil removal, ground control (lining), geological prediction, and interference warning capabilities. In situations where access by men is necessary or desirable, the system must provide a safe working environment.

A.2 Functional Requirements

As described in the section "Program and System Requirements," the complete system must carry out the following functions:

1. Disintegration of _In Situ_ Matter,
2. Transport of Muck and Material,
3. Control and Lining of the Ground,
4. Propulsion of the Excavation System,
5. Guidance of the Excavation System,
6. Remote Operation of the System,
7. Geological Prediction,
8. Interference Warning, and
9. Environmental Control and Safety.

In large tunnels where men can work, the functions of guidance, remote operation, geological prediction, and interference warning are not as critical as they are for non-accessible tunnels.

A.2.1 Definition of Functional Requirements

Disintegration of In Situ Matter. - This is the most important element of the excavation system since all other activities await ground penetration.[46] Because of the wide range of hole sizes to be provided, more than one method or mechanism may be required. However, the disintegration equipment must be capable of cutting whatever material is encountered under all conditions.

Transport of Muck and Material. - This function refers to the equipment required to remove the borings (muck), bring all necessary supplies into the excavation, and provide for personnel access (if any). The nature of the transport or logistics function depends on the ground penetration method used in advancing the hole or tunnel, the size of the excavation, and the location of the staging area.

Control and Lining of the Ground. - The function of ground control is to maintain the integrity of the opening, preferably by installing the ground control structure (lining) simultaneously with the boring.

Propulsion of the Excavation System. - The purpose of this function is to provide the means for advancing the system through the ground. It must supply the thrust necessary to keep the ground disintegration component in contact with the face of the excavation.

Guidance of the Excavation System. - This function is required to provide the capability of steering the excavation system. Included in this capability are sensing and information feedback elements to assist remote operators (if any) in continuously determining system location and direction, and in making the necessary adjustments.

Remote Operation of the Excavation System. - This function is necessary to meet the required capability of the excavation system to bore holes too small to be accessible by men. It will provide the means for controlling the operation of the integrated subsystems or elements of the excavation system. In accessible tunnels, this function would not be necessary but may still be provided.

Geological Prediction.- The ability to predict the geological conditions some distance ahead of the boring machine is necessary for several reasons. First, it would give warning of impending emergency situations; and second, it would reduce excessive costs and delays resulting from unexpected changes in geologic conditions in the path of the tunnel.

Interference Warning. - The purpose of the interference warning function is two-fold: (1) to protect the excavation system from the dangers of boring into existing buried utility systems or other underground structures, and (2) to prevent damage to the subsurface structures by indicating the presence of such obstructions in the path of the machine.

Environmental Control and Safety. - For an excavation system for which manned operation is required or desired, the purpose of this function is to protect the workers from physical injury and to provide the necessary life support systems for the operators. This function is not critical when remote operation is possible.

A.2.2 Interfacing Functions

In a completely integrated system, all functions can be said to interface with each other; that is, each component or subsystem which satisfies some functional requirement must be capable of meeting the demands imposed on it by other components. However, the amount of coordination demanded by other subsystems will vary from component to component. As a result of this variation, different "degrees of interfacing" or dependency between functions may also be identified.

Table A.1 displays a classification of interfacing between the functions described above. Three classifications, based on the amount of component coordination demanded by other subsystems, are used: functions which interface (1) highly, (2) moderately, or (3) slightly.

The reasons for assigning the particular function interfacing classifications in Table A.1 are given below.

Disintegration of In Situ Matter vs. Transport of Muck and Material. - Highly interfacing. One of the requirements is that the excavation system must be capable of boring holes in a rapid manner. Limited experience with boring machines to date has shown them to be intermittently capable of outdistancing the muck removal equipment.[46] Therefore, it is essential that the muck handling system be designed to transport the *in situ* matter from the tunnel as fast as the maximum expected rate of removal from the face of the excavation.

Table A.1 Degree of Interfacing Between Functions

Function	Transport of Muck and Material	Control and Lining of the Ground	Propulsion of the Excavation System	Guidance of the Excavation System	Remote Operation of the System	Geological Prediction	Interference Warning	Environmental Control and Safety
Disintegration of <u>In Situ</u> Matter	Highly	Moderately	Highly	Slightly	Moderately	Highly	Slightly	Highly
Transport of Muck and Material	--	Highly	Moderately	Slightly	Highly	Highly	Slightly	Highly
Control and Lining of the Ground	--	--	Moderately	Slightly	Highly	Highly	Slightly	Highly
Propulsion of the Excavation System	--	--	--	Highly	Highly	Highly	Slightly	Moderately
Guidance of the Excavation System	--	--	--	--	Highly	Highly	Highly	Slightly
Remote Operation of the System	--	--	--	--	--	Highly	Highly	Slightly
Geological Prediction	--	--	--	--	--	--	Highly	Highly
Interference Warning	--	--	--	--	--	--	--	Highly

The logistics equipment must be well-matched in capacity also, to be able to keep up with the advance of the excavation. An especially complicated logistics proglem exists when the excavation opening is within the confines of a major urban area. In this case, staging considerations such as stockpiling construction materials can be as important as the underground logistics problem.

Disintegration of In Situ Matter vs. Control and Lining of the Ground. - Moderately interfacing. The rate at which primary ground support structure must be supplied and erected depends on the rate at which the excavation is advanced; the amount of lining required may depend somewhat on the method used to advance the tunnel. However, the major factor affecting the ground control system is the kind of ground through which the excavation is being made.

Disintegration of In Situ Matter vs. Propulsion of the Excavation System. - Highly interfacing. The propulsion system must supply the thrust necessary to keep the ground disintegration component in effective contact with the face of the excavation.

Disintegration of In Situ Matter vs. Guidance of the Excavation System. - Slightly interfacing. The need for guidance control does not depend on the method used for disintegrating the ground, *per se*; however, fast, precise methods are needed to guide systems that are capable of high rates of penetration.

Disintegration of In Situ Matter vs. Remote Operation of the System. - Moderately interfacing. The kind of ground disintegration component employed will have some, but not a controlling, influence on the nature of the remote operation function.

Disintegration of In Situ Matter vs. Geological Prediction. - Highly interfacing. Because the function of geological prediction involves forecasting the kind of matter expected to be encountered along the route of the excavation, it has a direct bearing on the selection of the means used to penetrate that matter.

Disintegration of In Situ Matter vs. Interference Warning. - Slightly interfacing. Although these two requirements share little functional commonality, they are related in that the operation of one must not interfere with or infringe upon the operation of the other.

Disintegration of In Situ Matter vs. Environmental Control and Safety. - Highly interfacing. The method by which *in situ* matter is disintegrated at the working face of an excavation has a direct bearing on the type and kind of environmental control and safety precautions required. For example, the drill, blast, and muck tunneling technique requires, among other things, the handling of quantities of explosives, removal of large quantities of noxious gases and dust, and the use of powerful, potentially dangerous heavy equipment for handling the muck.

Transport of Muck and Material vs. Control and Lining of the Ground. - Highly interfacing. The portion of the ground control and lining function that depends on the availability of material interfaces directly with the transport function. In addition, the ground control and muck and material handling equipment must all be compatible with each other in terms of capacity and the amount of space or excavation cross-section each occupies.

Transport of Muck and Material vs. Propulsion of the Excavation System. - Moderately interfacing. The propulsion system may provide some supporting function for the transport of muck and material, but this will be only one factor in selecting the means of propulsion for the excavating system.

Transport of Muck and Material vs. Guidance of the Excavation System. - Slightly interfacing. These two functions have little in common from the standpoint of equipment. However, because of the need for precise guidance, especially at high rates of advance, the system for transport of muck and material cannot be allowed to interfere for great lengths of time with the method used to align and guide the excavation system.

Transport of Muck and Material vs. Remote Operation of the System. - Highly interfacing. For excavations that are too small to permit access by men, the muck and material transport system must be operated from a remote location.

Transport of Muck and Material vs. Geological Prediction. - Highly interfacing. Even though these two functions do not have any equipment requirements in common, they are nevertheless closely related. Information obtained by the geological prediction function will indicate the type of muck that must be handled, and the kind of support material the system must transport to be used in maintaining the integrity of the opening.

Transport of Muck and Material vs. Interference Warning. - Slightly interfacing. These two functions have no common or conflicting requirements.

Transport of Muck and Material vs. Environmental Control and Safety. - Highly interfacing. These two functions interface directly in several ways, as in the following examples:

1. as mentioned previously, the use of powerful, potentially dangerous, heavy equipment for handling muck requires precautions to prevent accidents;
2. if internal combustion engines provide power for the muck handling equipment, control of the atmosphere must be maintained to provide safe breathing conditions for the operators; and
3. the material handling system must provide the proper kinds and amounts of ground support supplies to keep up with the advancing tunnel in order to protect workers from such dangers as rock falls and collapsing walls.

Control and Lining of the Ground vs. Propulsion of the Excavation System. - Moderately interfacing. These two functions must be compatible in that the ground control and lining equipment must be capable of installing the necessary support structure at the maximum rate at which the excavation system is capable of advancing. There are other functional requirements which affect both of these systems to a greater degree, however. These are discussed in the next several paragraphs.

Control and Lining of the Ground vs. Guidance of the Excavation System. - Slightly interfacing. These two functions have no common or conflicting requirements except perhaps that the erecting of ground support structure should not interfere excessively with operation of the guidance system.

Control and Lining of the Ground vs. Remote Operation of the System. - Highly interfacing. For excavations that are too small to permit access by men, the ground control and lining system must be operated from a remote location. No interfacing exists in accessible tunnels when remote control is not required.

<u>Control and Lining of the Ground vs. Geological Prediction</u>. - Highly interfacing. Information obtained by the geological prediction function will be used in selecting the system and materials used to satisfy the ground control and lining function.

<u>Control and Lining of the Ground vs. Interference Warning</u>. - Slightly interfacing. These two functions have no common or conflicting requirements.

<u>Control and Lining of the Ground vs. Environmental Control and Safety</u>. - Highly interfacing. The purpose of the ground control and lining function is to maintain the integrity of the opening and thus enhance the safety of the workers by protecting them from such dangers as rock falls and collapsing walls.

<u>Propulsion of the Excavation System vs. Guidance of the Excavation System</u>. - Highly interfacing. The guidance system must be able to control the propulsion system so that the excavation alignment is maintained.

<u>Propulsion of the Excavation System vs. Remote Operation of the System</u>. - Highly interfacing. For excavations that are too small to permit access by men, the propulsion system must be operated from a remote location. No interfacing exists in accessible tunnels when remote control is not required.

<u>Propulsion of the Excavation System vs. Geological Prediction</u>. - Highly interfacing. Information obtained by the geological prediction function will influence the operation of the propulsion system. Factors such as the kind of material expected to be encountered, and the presence of discontinuities in underground formations will affect the rate at which the excavation system can advance.

<u>Propulsion of the Excavation System vs. Interference Warning</u>. - Slightly interfacing. Some information feedback from the interference warning system to the propulsion system is necessary, but this link is minor compared to that required for the geological prediction function.

<u>Propulsion of the Excavation System vs. Environmental Control and Safety</u>. - Moderately interfacing. The relationship of these two functions is largely dependent on the means chosen for propelling the excavation system; the choice of an internal combustion engine would impose different

demands on the environmental control and safety function than the selection of electro-hydraulic thrusters, for example.

Guidance of the Excavation System vs. Remote Operation of the System. - Highly interfacing. For excavations that are too small to permit access by men, guidance of the excavation system must be achieved from a remote location. This is not true in accessible tunnels where remote control is not used.

Guidance of the Excavation System vs. Geological Prediction. - Highly interfacing. Information obtained by the geological prediction function is used to make any course changes needed to avoid dangerous or difficult conditions.

Guidance of the Excavation System vs. Interference Warning. - Highly interfacing. Information obtained by the interference warning function is used to make any course changes needed to avoid endangering the operators or damaging existing utilities or structures in the path of the excavation.

Guidance of the Excavation System vs. Environmental Control and Safety. - Slightly interfacing. These two functions have no common or conflicting requirements.

Remote Operation of the System vs. Geological Prediction. - Highly interfacing. The ability to operate the excavation system from a remote location requires knowledge of the geology in the path of the excavation. The remote operator requires information about such things as the kind of material the excavation machine is meeting and the presence of any discontinuities that may require changes in the mode of operation.

Remote Operation of the System vs. Interference Warning. - Highly interfacing. Information obtained by the interference warning function is used by the remote operator to make any course changes necessary to avoid endangering the operators or damaging existing utilities or structures in the path of the excavation.

Remote Operation of the System vs. Environmental Control and Safety. - Slightly interfacing. Remote operation of the excavation system implies that manned access is either not possible or not required, and environmental control and safety is not critical.

Geological Prediction vs. Interference Warning. - Highly interfacing. In addition to providing information of a similar nature, these two functions may share certain subsystems or components. For example, one element used to detect non-homogeneities in underground structure could supply information to both systems. The systems would then interpret the information according to their functional definitions.

Geological Prediction vs. Environmental Control and Safety. - Highly interfacing. Information obtained by the geological prediction function provides timely warning of dangerous or changing conditions that could affect the safety of the excavation system operators.

Interference Warning vs. Environmental Control and Safety. - Highly interfacing. The interference warning function protects the excavation system operators by indicating the presence of obstructions such as other utility systems in the path of the excavation.

A.3 Future Development Requirements

The preceeding section outlined the functions which must be accomplished by a complete utility tunneling system. In order to define the future development requirements for such a system, it is necessary to consider both the current utility installation practices described in Section 2, and the requirements for an underground utility distribution installation system given in Section 4 of this report. This consideration leads to the observation that a large number of relatively small diameter tunnels will be required if current installation practices are continued, and a lesser number of relatively large tunnels if multiple utilities are to be installed in a common space. (A large tunnel is defined as one which men can enter and perform useful work; a small tunnel is one which men cannot enter.)

Furthermore, results of the underground utility demand survey (see Appendix B), indicate that most of the tunneling for utility installation will be performed in soil (soft ground consisting of mixtures or layers of gravel, sand, silt, clay, unconsolidated rock, etc.) if installation depth does not exceed about 20 feet. Only in certain areas or at extreme depths where such rock is found would a hard rock tunneling machine be required. However, a soft ground tunneling device must be able to handle localized rock or large boulders which may be encountered.

Therefore, it appears that if tunnels are to be used for utility installation, many small tunnels for individual service lines will be needed, they will probably be relatively close to the surface, and they will be located mainly in soil or soft ground. Only where the use of "utility tunnels" is justified will there be a demand for large diameter tunnels.

Tunneling practices for large diameters are rapidly being improved and mechanized and machine tunneling methods are commonly used in soil and soft rock. In the case of small tunnels, it has been stated that horizontal boring techniques are adequate for relatively short distances (up to about 500 ft.; see Table 3.3) in soil or soft rock.[17] However, little effort has been directed toward integrating the various functions to produce a completely finished hole in one operation.

Thus small diameter tunneling will present significant developmental problems in the following functional areas: transport of muck and material, control and lining of the ground, guidance of the excavation system, remote operation of the system, and interference warning capability. In addition, integrating the mechanisms chosen to accomplish the necessary functions into one system will also require an extensive development program. High system reliability will also be required because mechanical failure may necessitate removing the machine from an inaccessible location for maintenance and repair, and the failure itself could make removal very difficult.

APPENDIX B

UNDERGROUND UTILITY DEMAND SURVEY

In order to assist in identifying requirements for underground utility installations, survey information was collected about the future needs for utilities over the next decade or two. Information was required concerning the amounts and kinds of services currently being provided, estimates of future growth projections for these services, and the identification of potential new utilities that may come into use. Because excavation (either by trenching or tunneling) must be performed in placing utilities under the ground, the range of geologic conditions that might be encountered was also sought.

Method of Acquiring Data

As a first step in acquiring the information, various publications were reviewed, including trade journals, utility company annual reports, governmental regulatory agency reports, geological surveys, and other reference material. It was soon discovered that information needed was either in a form that was not easily usable or, as in most cases, nonexistent. For example, the United States Geological Survey prepared a series of maps for the Department of Transportation concerning the Northeast Corridor High Speed Transportation Study. These maps show the locations of tunnels and quarries, and list references to borings and bedrock configurations and soil and rock properties. The map scale of 1:1,500,000 was too small to show the desired surface details and the boring references were usually too specific to give a general picture of the geology in a particular area. Study of forms required to be filed with governmental agencies such as the Federal Power Commission revealed important data about existing installations and past accomplishments, but little in the way of plans for future expansions.

Therefore, in order to obtain information about the range of geologic conditions in which a utility installation system would have to operate, to provide a basis for estimating future demands for utilities, and to identify potential new utilities, a questionnaire was prepared and sent to public works officials in all parts of the country.

To avoid the difficulty of obtaining detailed geologic descriptions, the respondents were asked to report for various depths whether material generally encountered was soil, soft rock, or hard rock. More detailed data about the geology of the cities of interest would, of course, have been desirable, but it was felt that for this analysis, a simplified style of reporting would be sufficient and more readily answered by nongeologists.

The questionnaire also asked for an evaluation of the anticipated demand in the next twenty years for utility installations, including those common today and those that may be developed in the future. The respondent was requested to indicate if he thought a demand for a particular service would develop, and, if so, to estimate the size of the demand. Guidelines were suggested for answering the demand question, and space was left for the addition of any services not listed.

The questionnaire, a copy of which is reproduced as Fig. B.1, was mailed to public works officials in 100 cities throughout the country. The 100 cities were selected from the 100 largest Standard Metropolitan Statistical Areas* (SMSAs) of the United States. The SMSAs used in the survey are those listed in the 1967 "County and City Data Book," and are based on the 1960 census figures. Some of the SMSAs contain more than one city (e.g., the Albany, New York area also includes Schenectady and Troy), and in these cases only one (not necessarily the largest) of the cities in that SMSA was sent the questionnaire. As a result, the survey does not necessarily include information on the 100 largest cities of the U. S., but it should be reasonably representative. Based on 1960 census data, the population in the 100 largest SMSAs represents about

*Standard Metropolitan Statistical Area (SMSA): To permit all federal statistical agencies to utilize the same areas for the publication of general-purpose statistics, the Bureau of the Budget has established "standard metropolitan statistical areas." Every city of 50,000 inhabitants or more according to the 1960 Census of Population or a subsequent special census prior to December 31, 1965, is included in an SMSA. As of December 31, 1965, there were 224 SMSAs in the United States.

A. Geologic Conditions

Please check the appropriate space for the type of material generally encountered in your city at the various depths indicated

	0-20 Ft.	20-50 Ft.	50-100 Ft.
1. Soil (soft ground consisting of mixtures or layers of gravel, sand, silt, clay, unconsolidated rock, etc.)	____	____	____
2. Rock			
a. Soft (shale, sandstone, etc.)	____	____	____
b. Hard (granite, etc.)	____	____	____

B. Future Services

Please check any of the following underground services for which you think a demand may develop in your city within the next twenty years, estimating the size of such demand as small, medium, or large:*

	Demand May Develop	Estimated Size of Demand*
1. Electric power distribution system	____	____
2. Telephone	____	____
3. Central heating system	____	____
4. Central air-conditioning system	____	____
5. Pressurized solid-waste disposal system	____	____
6. Coaxial (TV) cable system	____	____
7. Pneumatic tube mail system	____	____
8. Material handling conveyor system	____	____
9. Others (please list)	____	____
____________________	____	____
____________________	____	____
____________________	____	____

C. Name and Address of Person Answering This Questionnaire:

D. Please return to: W. C. Ulrich
Bldg. 4500 NM, Rm. 257J
Oak Ridge National Laboratory
Post Office Box X
Oak Ridge, Tennessee 37830

*Large Demand: On the order of the size of existing water or sewer system.
Medium Demand: 10-25% of large demand.
Small Demand: Less than 10% of large demand.

Fig. B.1 Survey to Determine Requirements for an Underground Utility Installation System

55 percent of the total U. S. population, and the cities to which questionnaires were sent include about 25 percent of the people in the U. S. Of 100 questionnaires mailed out, 80 were returned. These 80 replies came from cities which contain about 21 percent of the population in the U. S.

The geographic location of the 100 largest SMSAs is shown in Fig. B.2 and identified in Table B.1 which lists the SMSAs in order of size by population.

The questionnaire served another purpose in addition to providing information about geology and the future demand for utilities. As replies began coming in, telephone calls were made to the people who returned the forms requesting additional data about the size of present utility systems in their cities and projected or planned increases for the current year. Because most of the replies were from public works officials, and since most sewer and a high percentage of water systems are municipally owned and operated, initial emphasis was placed on these utilities.

This information was desired for two reasons. First, because the questionnaire asked for future utility demand estimations in terms of the size of existing water or sewer systems, it was necessary to know, for example, how many miles of water mains were installed in a particular city. Second, it was thought that the information would be useful in obtaining some kind of correlation between the size or extent of a utility system, population, and area served in order to assist in making growth projections.

In addition to water and sewer systems, data on municipally-owned electric and gas distribution systems were also requested. If these services were not provided by the municipality, the names and addresses of the companies supplying these utilities were obtained.

Because most of the telephone companies in the cities contacted are a part of the Bell System of the American Telephone and Telegraph Company (AT&T), a different procedure was followed in determining the extent of present underground communication facilities and planned or projected increases. The Bell System is separated into a number of administrative areas, usually consisting of a state. However, some of the larger states are divided into several areas. The collection of the desired information for individual cities would require a very extensive inventory from record maps because property accounting is done by administrative areas rather than by cities. Therefore, a summary of accomplishments toward undergrounding outside plant facilities relative to total outside plant installation for the entire Bell System was requested from the New York office of AT&T.

Summary of Replies

Response to the survey was very good; as noted previously, of 100 questionnaires mailed out, 80 were returned. The replies are summarized in Fig. B.3 where the figures indicate the total number of times each item was answered.

Although 80 questionnaires were returned, only 72 cities reported on geologic conditions. Replies showed that soil is generally encountered in 68 cities (about 95 percent) at depths of 0 to 20 feet, in 51 (over 71 percent) at depths of 20 to 50 feet, and in 29 (approximately 40 percent) at depths of 50 to 100 feet. Soft rock was indicated to exist in 15 cities (nearly 21 percent) at 0 to 20 feet, in 27 (about 36 percent) at 20 to 50 feet, and in 27 (approximately 37 percent) at 50 to 100 foot depths. Hard rock was indicated less often than either soil or soft rock, with 11 (about 15 percent) of the 72 cities listing its presence at depths of 0 to 20 feet, 18 (nearly 25 percent) at 20 to 50 foot depths, and 17 (approximately 24 percent) at depths of 50 to 100 feet. The percentages given are somewhat inconsistent because more than one material type (i.e., soil and rock) per depth range was checked on a number of questionnaires.

Of the 80 cities which returned the forms, only six did not provide any estimate of demand for future services. The summary of these 74 replies to Part B of the questionnaire shows electric power, telephone, and coaxial (TV) cable systems receiving the most "votes". Estimates of the demand for these and other services is also presented in Fig. B.3.

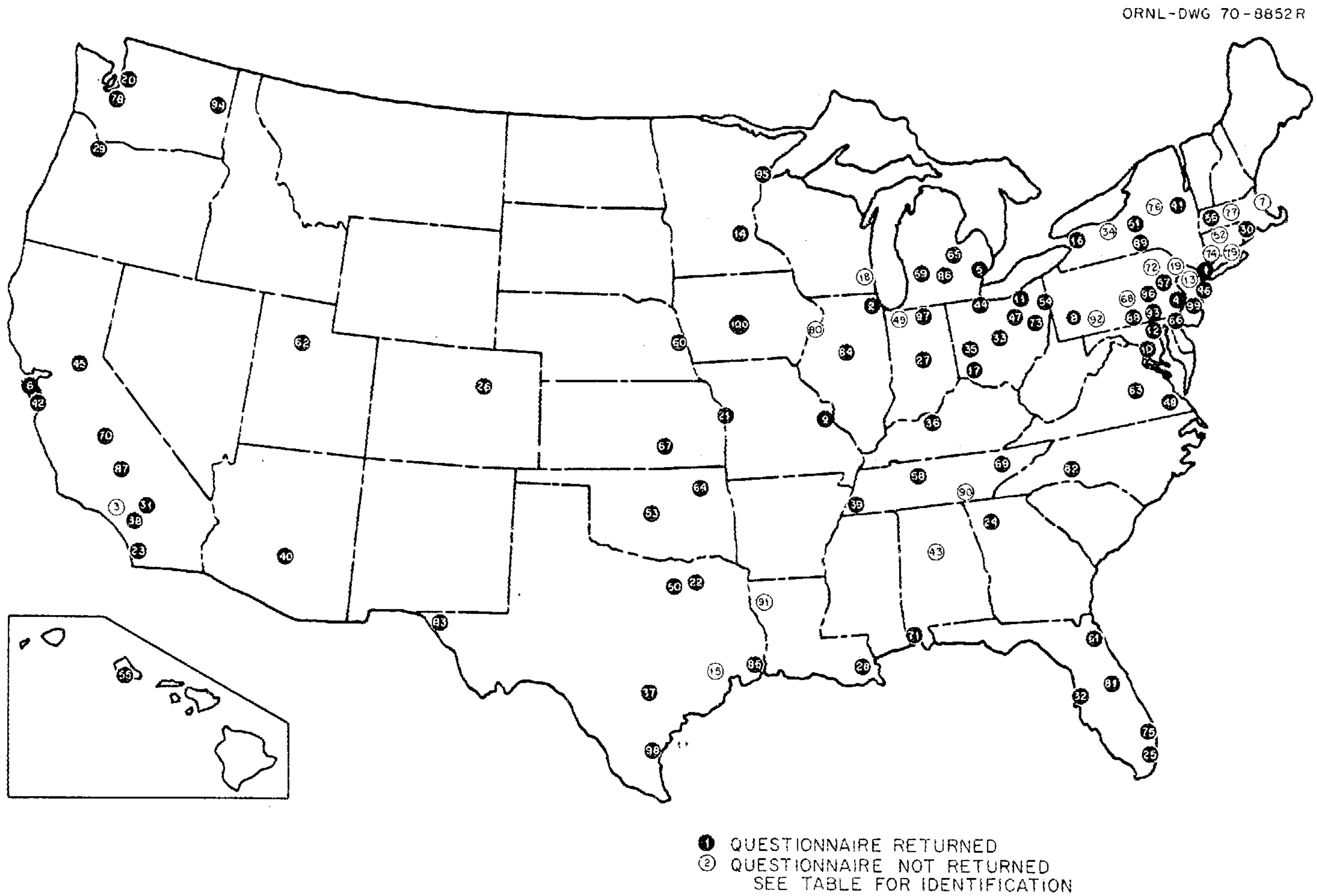

Fig. B.2 The One Hundred Most-Highly Populated Standard Metropolitan Statistical Areas of the United States, 1960 Census

- ● 1 New York, N.Y.
- ● 2 Chicago, Ill.
- ○ 3 Los Angeles - Long Beach, Cal.
- ● 4 Philadelphia, Pa. - N.J.
- ● 5 Detroit, Mich.
- ● 6 San Francisco, Cal.
- ○ 7 Boston, Mass.
- ● 8 Pittsburgh, Pa.
- ● 9 St. Louis, Mo. - Ill.
- ● 10 Washington, D.C. - Md. - Va.
- ● 11 Cleveland, Ohio
- ● 12 Baltimore, Md.
- ○ 13 Newark, N.J.
- ● 14 Minneapolis - St. Paul, Minn.
- ○ 15 Houston, Texas
- ● 16 Buffalo, N.Y.
- ● 17 Cincinnati, Ohio - Ky. - Ind.
- ○ 18 Milwaukee, Wis.
- ○ 19 Paterson - Clifton - Passaic, N.J.
- ● 20 Seattle - Everett, Wash.
- ● 21 Kansas City, Mo. - Kan.
- ● 22 Dallas, Tex.
- ● 23 San Diego, Cal.
- ● 24 Atlanta, Ga.
- ● 25 Miami, Fla.
- ● 26 Denver, Colo.
- ● 27 Indianapolis, Ind.
- ● 28 New Orleans, La.
- ● 29 Portland, Ore. - Wash.
- ● 30 Providence - Pawtucket - Warwick, R.I. - Mass.
- ● 31 San Bernadino - Riverside - Ontario, Cal.
- ● 32 Tampa - St. Petersburg, Fla.
- ● 33 Columbus, Ohio
- ○ 34 Rochester, N.Y.
- ● 35 Dayton, Ohio
- ● 36 Louisville, Ky. - Ind.
- ● 37 San Antonio, Tex.
- ● 38 Anaheim - Santa Ana - Garden Grove, Cal.
- ● 39 Memphis, Tenn. - Ark.
- ● 40 Phoenix, Ariz.
- ● 41 Albany - Schenectady - Troy, N.Y.
- ● 42 San Jose, Cal.
- ○ 43 Birmingham, Ala.
- ● 44 Toledo, Ohio - Mich.
- ● 45 Sacramento, Cal.
- ● 46 Jersey City, N.J.
- ● 47 Akron, Ohio
- ● 48 Norfolk - Portsmouth, Va.
- ○ 49 Gary - Hammond - East Chicago, Ind.
- ● 50 Ft. Worth, Tex.
- ● 51 Syracuse, N.Y.
- ○ 52 Hartford, Conn.
- ● 53 Oklahoma City, Okla.
- ● 54 Youngstown - Warren, Ohio
- ● 55 Honolulu, Hawaii
- ● 56 Springfield - Chicopee - Holyoke, Mass. - Conn.
- ● 57 Allentown - Bethlehem - Easton, Pa. - N.J.
- ● 58 Nashville, Tenn.
- ● 59 Grand Rapids, Mich.
- ● 60 Omaha, Neb. - Iowa
- ● 61 Jacksonville, Fla.
- ● 62 Salt Lake City, Utah
- ● 63 Richmond, Va.
- ● 64 Tulsa, Okla.
- ● 65 Flint, Mich.
- ● 66 Wilmington, Del. - N.J. - Md.
- ● 67 Wichita, Kan.
- ○ 68 Harrisburg, Pa.
- ● 69 Knoxville, Tenn.
- ● 70 Fresno, Cal.
- ● 71 Mobile, Ala.
- ○ 72 Wilkes-Barre - Hazleton, Pa.
- ● 73 Canton, Ohio
- ○ 74 Bridgeport, Conn.
- ● 75 Ft. Lauderdale - Hollywood, Fla.
- ○ 76 Utica - Rome, N.Y.
- ○ 77 Worcester, Mass.
- ● 78 Tacoma, Wash.
- ○ 79 New Haven, Conn.
- ○ 80 Davenport - Rock Island - Moline, Iowa - Ill.
- ● 81 Orlando, Fla.
- ● 82 Charlotte, N.C.
- ● 83 El Paso, Tex.
- ● 84 Peoria, Ill.
- ● 85 Beaumont - Port Arthur, Tex.
- ● 86 Lansing, Mich.
- ● 87 Bakersfield, Cal.
- ● 88 York, Pa.
- ● 89 Binghamton, N.Y. - Pa.
- ○ 90 Chattanooga, Tenn. - Ga.
- ○ 91 Shreveport, La.
- ○ 92 Johnstown, Pa.
- ● 93 Lancaster, Pa.
- ● 94 Spokane, Wash.
- ● 95 Duluth - Superior, Minn. - Wis.
- ● 96 Reading, Pa.
- ● 97 South Bend, Ind.
- ● 98 Corpus Christi, Tex.
- ● 99 Trenton, N.J.
- ● 100 Des Moines, Iowa

● Questionnaire returned

○ Questionnaire not returned

Underlining indicates city to which questionnaire was sent if SMSA contains more than one city.

Table B.1 The One Hundred Most-Highly Populated Standard Metropolitan Statistical Areas of the United States, 1960 Census

Total of 80 replies

A. Geologic Conditions (72 replies)

Please check the appropriate space for the type of material generally encountered in your city at the various depths indicated

	0-20 Ft.	20-50 Ft.	50-100 Ft.
1. Soil (soft ground consisting of mixtures or layers of gravel, sand, silt, clay, unconsolidated rock, etc.)	68	51	29
2. Rock			
a. Soft (shale, sandstone, etc.)	15	27	27
b. Hard (granite, etc.)	11	18	17

B. Future Services (74 replies)

Please check any of the following underground services for which you think a demand may develop in your city within the next twenty years, estimating the size of such demand as small, medium, or large:*

	Demand May Develop	Estimated Size of Demand*		
		S	M	L
1. Electric power distribution system	65	8	33	28
2. Telephone	64	6	30	33
3. Central heating system	25	20	6	0
4. Central air-conditioning system	16	12	5	2
5. Pressurized solid-waste disposal system	19	7	9	3
6. Coaxial (TV) cable system	51	16	20	16
7. Pneumatic tube mail system	9	8	1	1
8. Material handling conveyor system	6	6	0	0
9. Others	-	-	-	-
Sanitary sewer	8	1	6	3
Storm sewer (incl. deep drainage reservoir)	6	0	2	5
Water	5	1	3	2
Gas	5	1	2	3
Street Lighting	1	0	0	1
Water recycling for reuse	2	1	0	1
Traffic signal control	1	0	1	0
Drainlines	1	0	1	0
Rapid or mass transit (subway, etc.)	5	0	3	2
Truck tunnels	1	0	0	1
Pedestrian tunnels	1	0	0	1

*Large Demand: On the order of the size of existing water or sewer system.
Medium Demand: 10-25% of large demand.
Small Demand: Less than 10% of large demand.

Fig. B.3 Survey to Determine Requirements for an Underground Utility Installation System

The demand size estimates could be used in conjunction with data gathered from cities on the size or extent of present water or sewer systems to estimate the number of miles of future underground services that may be installed. For cities which did not complete or return the form, or to which no questionnaire was sent, a different procedure for determining the desired information was developed.

For example, attempts at correlating the size or extent of presently installed systems with corporate city area and population resulted in the relationships displayed in Figs. B.4 through B.7. Various correlations of variables (such as miles of lines vs. population, miles of lines vs. area, and miles of lines vs. population density) were attempted, using different coordinate systems, e.g., Cartesian, semi-log, and log-log. The best correlations obtained are those shown, i.e., miles of lines vs. corporate area times population, with log-log coordinates. Although more information of this kind is needed before a definitive correlation can be generated, some idea of the magnitude of the future demand for underground utilities can be obtained from these plots. If the anticipated future area to be served and the population is estimated, Figs. B.4 through B.7 can be used to determine the amount of a given utility required. For example, a city with a current population of 100,000 and an area of 25 square miles would have about 400 miles of water lines (see Fig. B.4). If the future anticipated growth of the city is a total population of 200,000 and an area of 50 square miles, about 700 miles of water lines will be required, or an increase of 300 miles over the present system. Thus, knowing the amount currently installed, an estimate of future needs can be obtained. These relationships may be entirely fortuitous, however, because the area of a city and its population do not generally coincide with the area and population served by a particular utility. Therefore, the area and population served must be clearly defined. Furthermore, a distinction between "number of customers" and "population served" must also be made. A water company which sells water to a utility district serving a large subdivision or a small city may list the district or city as one "customer" and not include this customer in its area served, tending to bias the correlation. Another defect is that some utility companies

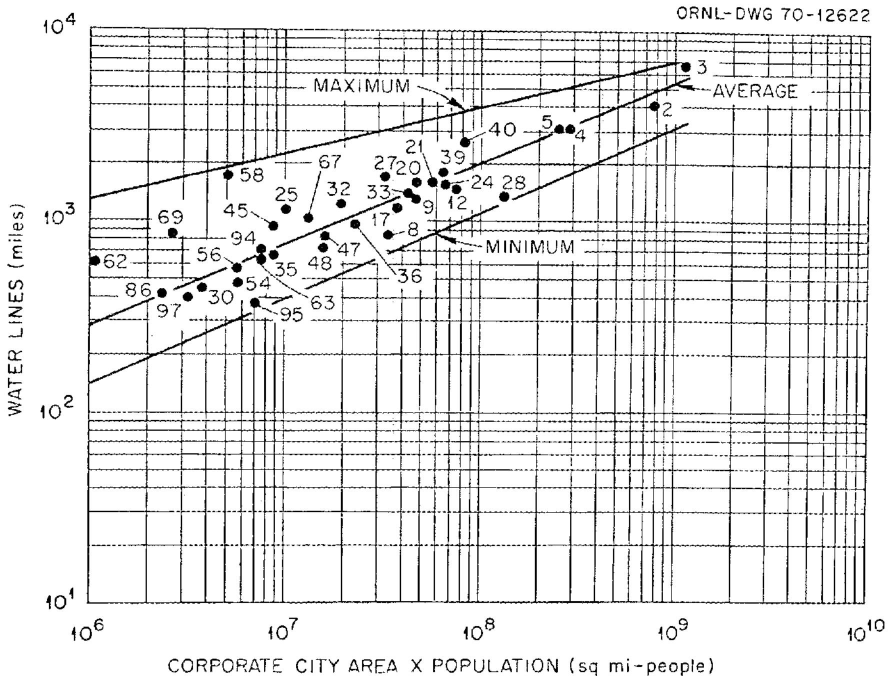

Fig. B.4 Water System Size Correlation

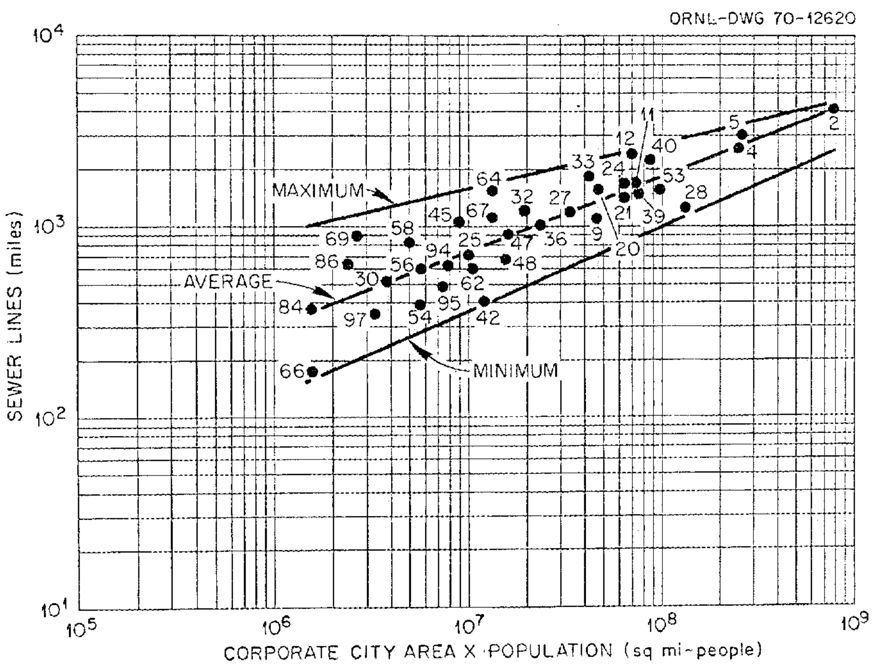

Fig. B.5 Sewer System Size Correlation

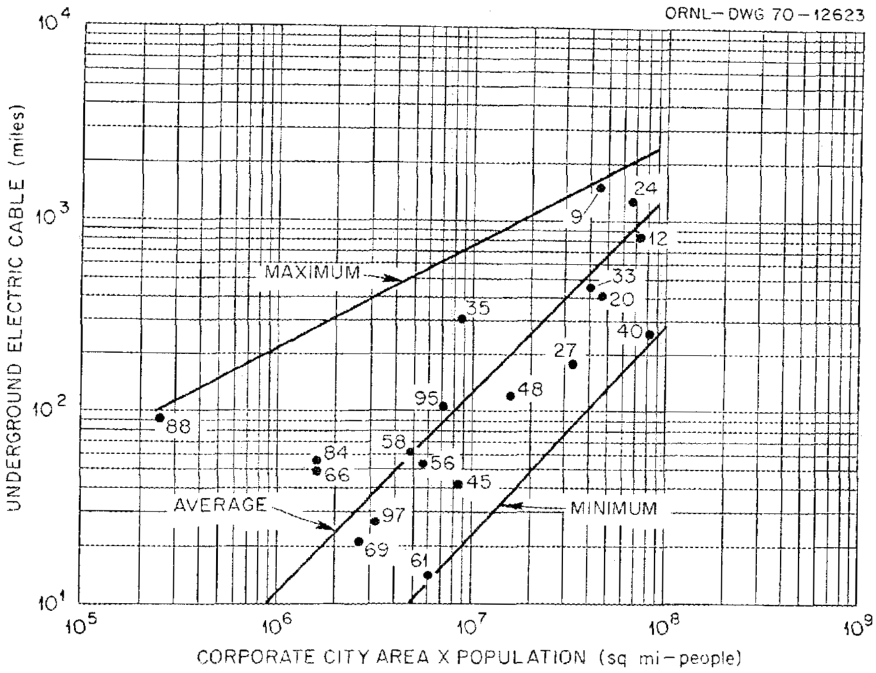

Fig. B.6 Underground Electric Power Distribution System Size Correlation

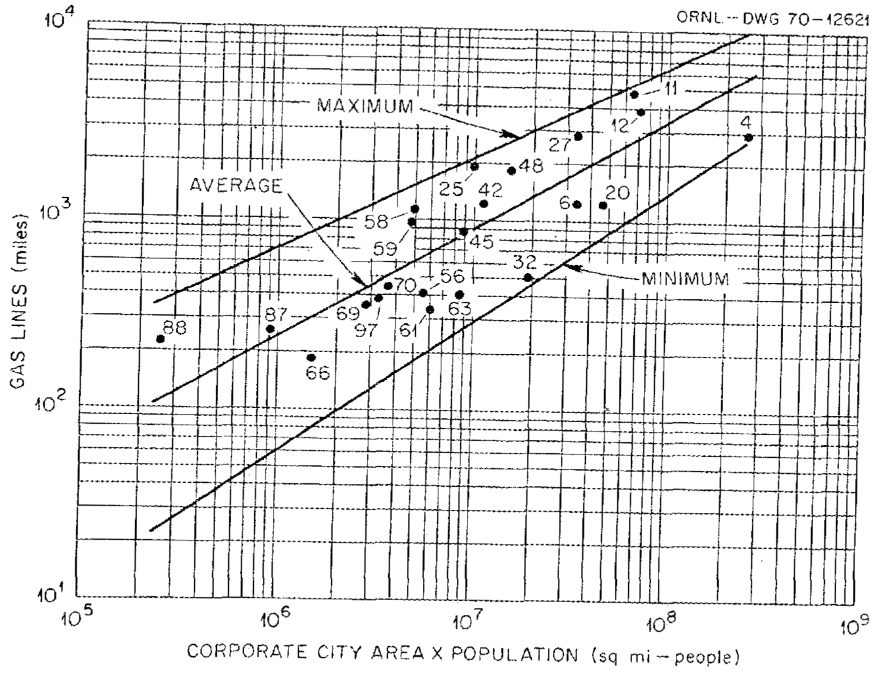

Fig. B.7 Gas Distribution System Size Correlation do not know how many miles of lines they have installed, or where they are.

Conclusions

Although the questionnaire was basically subjective in nature, the replies provide a basis for making some general conclusions about the requirements for an underground utility installation system.

Answers concerning the range of geologic conditions indicate that ground conditions will not be a major deterrent, except in certain areas or at great depths, to the use of a tunneling system. That is, tunneling machines or moles are currently available that can operate in the type of ground (soil) which was reported to exist at depths of up to 20 feet below the surface in about 95 percent of the cities which replied to the survey. Since the majority of utilities are presently installed above this level (with the possible exception of some sewers), tunnels could be placed deep enough to avoid existing utility systems and still be in ground that is relatively easy to excavate. Development of a hard-rock tunneling machine for utility installation does not appear to be justified because of the limited areas in which it could be used.

Some concept of the amounts and kinds of underground utilities expected to be provided during the next decade or two can be gained from the analysis of the replies to the portion of the questionnaire regarding future services which was presented in Fig. B.3. This figure shows the largest estimated demand for underground utilities to be those services which are now conventionally aerially provided, i.e., telephone, electric power distribution, and coaxial (TV) cable systems. It is not easy to compare these estimates with the actual effort that is being carried out in putting utilities underground, and furthermore, it is not clear whether the assumed timetable is realistic or not. For example, AT&T reported that during 1969, for the entire Bell System, 81 percent of the total new building sites were served by out-of-sight (underground) distribution facilities, and the number of sites formerly served by aerial plants which have been converted to buried facilities was equivalent to nearly 16 percent of the total new building sites. Although about 57 percent of the existing cable plant is still aerial, 64 percent of all cable plant additions were underground (see Section 5.1.5).

New utilities that may come into general use in the near future are also identified in Fig. B.3. These appear to be central heating, pressurized solid-waste disposal, central air-conditioning, pneumatic tube mail, and material handling conveyor systems. Whether these services will be installed by trenching or tunneling is impossible to predict, but presumably either method could be used.

Because transportation was outside the scope of a study of the system development requirements for underground utility installation, it was deliberately omitted from the questionnaire as a potential utility system. However, it was included on a few replies, as noted in Fig. B.3. Although the survey was not directly addressed to this point, there appears little indication of long-range plans for the coordination of the installation of utilities and underground transportation systems at this time.

APPENDIX C

CURRENT COSTS OF UTILITY INSTALLATION AND MAINTENANCE

A major problem in evaluating new or advanced utility installation systems is the lack of useful economic data regarding costs of installing and maintaining current underground distribution systems. Installation costs can be estimated by designing a series of typical installations; however, such designs are expensive if done accurately, and many problems such as the cost of excavation and variations in geological conditions tend to make these estimates of dubious value. One possible source of data which might be used to develop the necessary cost information for large systems is the annual report which utility companies (mostly private, but in some cases public) are required to file with state and federal regulatory agencies. Using the financial and statistical data in these reports, average values can be developed for entire utility distribution systems. The main disadvantages of using these sources are that maintenance costs cannot be isolated as a function of the size of the item being maintained or the type of repair performed, and the capital costs are the historical capital costs. That is, they are the book costs as of the date of installation and not the current replacement costs or amortized value. A more detailed description of the procedures used in obtaining cost data from these sources is described in a companion report.[47]

C.1 Water Systems

Annual reports were obtained for 30 private companies located in seven states. In most cases, data covering three consecutive years of operation were analyzed for each company. The average capital investment in the distribution systems was \$22,000/mile (range of \$13,700 to \$46,000/mile). The average annual cost of maintaining the distribution system was \$120/mile (range of \$30 to \$630/mile).

Municipal water departments in some cities also publish annual reports. In most cases, however, the financial data is not reported in sufficient detail to establish distribution system costs.

C.2 Sewer Systems

A number of states require that private sewer companies report annually on their operations. However, in most cases sewage collection and treatment is a municipal function and reports are not made to state agencies. Most of the private waste collection operations are small, and are not necessarily representative of the costs of large sewage collection systems. As a result, other sources would be needed to estimate these costs.

One source from which information might be obtained is the informal annual reports which some municipalities issue on their sewage collection and treatment operations. A major problem in using these sources is the variety of reporting methods used by the municipalities for capital and maintenance accounts, and the fact that some consider the customer service connection as a part of the collection system. As a result, it has not yet been possible to adequately develop capital investment or maintenance costs for sewers. However, the Federal Water Pollution Control Administration has reported that it costs about $125 per capita to provide sewers in urban areas.[28] Using this figure and estimating that housing units are about 100 feet apart and contain on the average 3.3 people, a capital cost of $50,000 per mile can be obtained.

C.3 Natural Gas Systems

Annual reports to the Federal Power Commission do not require statistical data on gas distribution systems, but rather concern themselves with transmission functions. However, certain states require the filing of annual reports with sufficient data to estimate the costs associated with installation and maintenance of mains in gas distribution systems. Eleven gas companies in the states of New York, Indiana, and Illinois were analyzed. The average value of the mains in the distribution system was $18,000/mile (range of $9,000 to $32,900/mile). Annual maintenance of mains in the distribution system averaged $340/mile (range of $70 to $1800/mile). As pointed out earlier, installation, but not necessarily maintenance, costs in the future may be reduced where plowing-in techniques can be used. In general, however, the costs reported above are for systems installed by trenching.

C.4 Electric Power Systems

Electric power utilities are required to file annual reports with the Federal Power Commission. Twenty-five different annual reports were obtained for Class A electric companies (over $2,500,000 in annual operating revenue). Statistical and cost data are required for both the miles of underground conduit and the miles of cable in the underground distribution system. However, the miles of underground cable are not separated into the fraction that is directly buried and that which is in conduit. In 1967 the average capital investment in the conduit system was $44,000/mile (range of $14,600 to $104,000/mile). The capital investment in underground cable was $12,000/mile (range of $4,400 to $22,800/mile). Annual maintenance costs are reported for the combined conduit system and the underground cable. In 1967 maintenance averaged $280/cable mile (range of $110 to $730/mile).

C.5 Telephone Systems

The Federal Communications Commission regulates the telephone industry and requires reports on an annual basis. The length and cost information required on the telephone distribution system includes: underground conduit, underground cable in the conduit, and the amount of buried cable in the system. Copies of the reports filed in 1967 for the 40 largest telephone systems (including all Bell Companies) were obtained and analyzed. In terms of capital invested, the underground conduit averages $32,000/trench mile (range of $12,700 to $50,300/mile), cables in the conduit have a value of $19,500/mile (range $14,700 to $37,000/mile), and in the case of directly buried cables, the average value is \$7,600/mile (range \$1,900 to \$34,000/mile). Annual maintenance costs for underground conduit are \$350/trench mile (range \$60/mile to \$720/mile), for the cables in the conduit \$340/mile (range \$110/mile to \$700/mile), and for directly buried cables \$110/mile (range \$20/mile to \$390/mile).

C.6 CATV Systems

Community antenna television systems are not generally licensed by the FCC nor are annual reports listing financial and statistical information required to be filed at present. Thus, although some systems have been at least partially installed underground, installation and maintenance cost data were not readily available. The only source of this information at this time appears to be the individual CATV companies.

C.7 Central Heating and Cooling Systems

No federal agency requires the filing of reports on central or district heating utilities. A number of states require reporting on an annual basis, and costs based on state reports were developed for 22 steam heating companies in Illinois, New York, Pennsylvania, and Oregon. The average value for the capital investment in all distribution systems was \$220,000/mile (range of \$17,000 to \$1,100,000/mile). The lower range represents systems that were installed many years ago when costs were lower, and these systems are not currently being expanded. The upper range represents companies operating in dense urban areas or systems which are installed in tunnels, with the cost of the tunnel being included in the value of the distribution system. Annual maintenance costs average \$4,200/mile (range of \$400 to \$19,000/mile). In this case the lowest figures are representative of companies which, because of a decrease in customers, are phasing out their steam operations. Data on companies using hot water instead of steam could not be located in sufficient number to estimate costs of these installations.

In the case of central cooling operations, data are not available since no agency regulates them.

C.8 Summary

The preceeding sections have presented estimates of the capital investment and maintenance costs for underground utility distribution systems obtained from annual reports of private utility companies. Attempts to develop similar costs from municipal utilities have not been successful. Table C.1 summarizes the available cost information. Not shown in Table C.1 are the costs of sewers, CATV, and central cooling systems, since these utilities are not normally required to file reports to regulatory agencies, or the reports issued do not contain sufficient information to enable these costs to be determined.

Table C.1 Average Capital Investment and Annual Maintenance Costs for Private Utility Distribution Systems

Utility	Average Capital Investment	Average Annual Maintenance Cost
Water ($/pipe mile)	22,000	120
Natural Gas ($/pipe mile)	18,000	340
Central Heating ($/pipe mile)	221,000	4,200
Electric Power		
Conduit ($/trench mile)	44,000	280*
Underground Cable ($/cable mile)	12,000	280*
Telephone		
Conduit ($/trench mile)	32,000	350
Cable Installed in Conduit ($/cable mile)	19,500	340
Buried Cable ($/cable mile)	7,600	110

*Maintenance costs include both the conduit system and underground cable and are reported in this table as $/cable mile.

It must be emphasized that the costs presented in Table C.1 are for systems installed at widely separated geographic locations and at different times. However, several conclusions can be drawn from this tabulation:

1. Central heating systems represent the largest capital investment and maintenance costs of the utilities for which cost data were obtained. This is undoubtedly because of the size of the pipes, the

need for insulation and removal of condensate, the provisions for accomodating thermal expansion, and the fact that these systems are mainly located in downtown areas.

2. The capital investment costs per mile for water or natural gas systems are approximately the same. However, maintenance is more costly for gas systems probably because even small leaks cannot be tolerated and must be repaired as soon as they are detected.

3. Since a conduit may contain more than one duct, the costs presented for electric power and telephone conduit systems cannot be directly compared.

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