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DEEP OCEAN CABLE BURIAL CONCEPT DEVELOPMENT

By

P. K. Rockwell

August 1976

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Seafloor cable systems are failing in increasing numbers due to fishing-trawler-induced damage. It has been demonstrated that the burial of seafloor cables markedly reduces the incidence of damage. The objective of this work was to identify viable cable burial system concepts and to perform the research and analysis necessary to select the most promising approach to burying cables 3 feet deep in the seafloor to depths of 6,000 feet. The three major problem areas considered were the propulsion, excavation, and running gear

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subsystems. Propulsion systems investigated included towing, thrusters, tracks or wheels, and cable traction. Excavating means included fluidizing, plowing, water jetting, trenching, and direct insertion of the cable. The running gear systems investigated were skids, rolling elements, and a water cushion. Subsystem candidates were combined into system concepts, and the concepts were rated according to their power and force requirements, probability of cable damage, capability of handling different soils and terrains, controllability, weight, size, and complexity. It was concluded that the system with the best chance of successfully burying cables in the deep ocean while meeting the operational requirements and design requirements would be self-powered with thrusters, supported on skids, and utilize vibratory plowing and/or water jetting for the burial means.

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INTRODUCTION

Seafloor cabling systems are being employed by the Navy in increasing numbers. Their applications include power and communication transmission to and from remote locations, acoustic research and development ranges, and surveillance system trunk lines. The cable systems are quite vulnerable to damage from commercial fishing activities, ships' anchors and other natural and man-made hazards. Recent increases in bottom fishing activities have produced a marked escalation of bottom-laid cable failures [1], resulting in unreliable cable systems and a staggering increase in expenditures for cable repair operations. In August 1974, the Civil Engineering Laboratory (CEL), realizing that the problem was worsening and severely hampering Naval operations, proposed a program to provide a system which would efficiently and effectively bury cables in the seafloor, eliminating all but major natural hazards and intentional acts.

The first phase of the deep ocean cable burial program was to identify the techniques and equipment that are currently available to bury cables and pipelines, both on land and underwater, and to define the operational requirements that a deep ocean cable burial system must satisfy. With this background information, viable hardware concepts were identified and compared, and the most promising approach was selected. This work, sponsored by the Naval Facilities Engineering Command, is summarized in this report. In addition, recommendations are made which identify the research and development required to produce a military cable burial system capable of burying cables in seafloor sediments to a water depth of 6,000 feet.

BACKGROUND

Failures of bottom-laid cable systems, both military and commerical, are attributed to both natural and man-induced phenomena. Natural failures typically occur in shallow (0 to 20 fathoms) water near the shore end of the cable and are caused by wave-, current-, and surge-induced motion, resulting in abrasion and corrosion degradation of the cable protection systems. Ship anchor drag also causes cable failures in shallow water. Deep-water (greater than 20 fathoms) failures are caused almost exclusively by scallopers and trawlers, with isolated failures attributed to turbidity currents and ice scour.

The specific threat to cable integrity to which this program is addressed is that due to fishing operations. Fishing trawls drag massive ''otter boards'' or ''doors'' along the seafloor, one at each end of the net opening, to keep the trawl nets open (Figure 1). These steel-edged doors may weigh as much as four tons and penetrate a foot or two into the

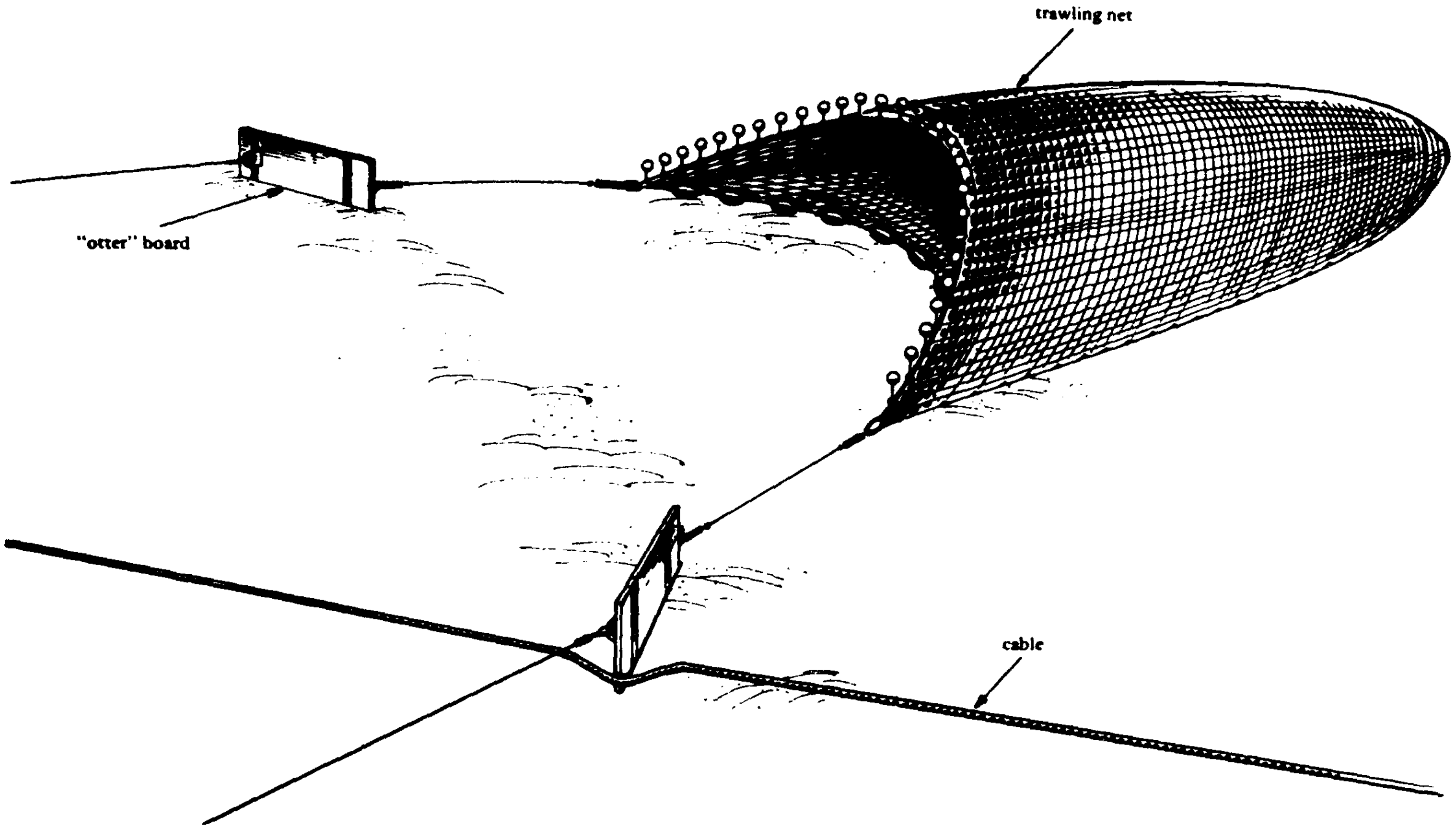

Figure 1. The bottom trawl.

seafloor. When the doors encounter a cable, the cable is often snagged and broken. No reasonable amount of armoring or mechanical protection can protect the cable. Since cable repairs cost in the vicinity of $300K per repair and because the number of cable failures is increasing at a rapid rate, the economic justification for reducing cable vulnerability is clear. In addition, the strategic and operational value of military cable systems provides further incentive to solve this severe problem.

For the last 25 years, telephone and electric utility companies have been burying their service lines on land to protect them from the elements and provide more reliable service to their customers. As the number of transoceanic cables increased and the incidence of damage to the cables became unacceptable, the Bell Telephone System decided that burial of cables in the seafloor might protect these cables from damage as it did on land. In 1966, the first Sea Plow was developed. It was found that damage to cables buried by this and later Sea Plows was all but eliminated. Burying cables in the seafloor effectively removes them from the primary hazard, bottom fishing, as well as current-induced motions and anchor drag for all but deeply penetrating anchors.

The Sea Plow is a large platform, mounted on skids, with a plowshare and cable guide mechanism penetrating into the seafloor. The plow, which is towed from the surface, is an uncomplicated piece of machinery, but it suffers from a number of deficiencies that makes it unacceptable for military cable installations.

Depth: The existing plow is limited to 500 fathoms. This depth was adequate to protect cables against traditional food fishing, but overfishing and new markets, such as fish meal, fertilizer, and high protein animal meal, are driving trawlers to 1,000 fathoms.

Surface Support: Only two vessels are capable of providing the support services required by the plow (a Canadian and a French ice breaker/cable layer) for the following reasons:

a. The tow force required is as high as 100,000 pounds. This force, coupled with the slow burial speed (1 knot), requires large amounts of power, bow and stern thrusters for ship control, and a sophisticated navigation system.

b. The newest plow (Sea Plow IV) weighs 23 tons; thus, the ship must have a large-capacity over-the-side handling system.

c. The plow can bury cables only while they are being laid, thus, the ship must be a cable layer, carrying large amounts of cable.

Repeater Burying: Sea Plow IV plows a 16-inch-wide ditch at all times so that repeaters may be buried. Since the cable requires only a 4-inch-wide trench, and repeaters occur only once every 20 miles, a significant waste of energy is associated with this operation.

Trafficability: Since the plow is mounted on skids, obstacles, such as rocks, often cause the device to stall, and it must be recovered and the operation restarted. Some cable, then, is left unburied.

Plow Insertion: Difficulties in inserting the plow in the seafloor require about 1 nautical mile (nm) before the plow is fully engaged. The cable is left partially buried in the interim.

Availability: Because the plow relies on one or two ships for operation (the French ship may not be capable of supporting Sea Plow IV), and because the plow is owned by private industry, the cable plowing system is not readily available to the military.

The only other method that has been used to bury cables in the deep ocean is water jetting. Repeaters that had not been buried by the Sea Plow were jetted into the sediment. In one case a jet pump was held by a submersible manipulator [2], and in the other case a specially designed jet fixture was mounted on the end of a drill string [3]. Both attempts were successful, but this type of operation is very slow (and, therefore, not suitable for burying hundreds of miles of cable), expensive, and has been accomplished only in sandy bottoms. In addition, submersible operations of this type are quite dangerous. The drill string mounted jetting device is limited to about 600 feet because the string excursion becomes too great to control.

It is clear, then, that the Navy requires an improved means of burying deep-ocean cable installations in the seafloor. The approach taken to complete the first phase of this program, and reported here, is the following.

1. Establish the operational requirements that the improved cable burial system must meet, such as burial depth, water depth, soil type, available surface support, and characteristics of present and future cable installations which must be protected.

2. Analyze existing techniques for burying cables (and pipelines) underwater and on land, identifying methods that are applicable to the deep-ocean cable burial problem at hand.

3. Define deep-ocean burial system concepts that utilize feasible burying means previously identified. Consider various methods of self-propulsion, and compare these with a passive (towed) system.

4. Specify, quantify where possible, and analyze the system concepts, taking into account their capabilities vis a vis established operational requirements, physical embodiment, power requirements and efficiency, problem areas requiring preliminary research or development, engineering and technical difficulties, shipboard requirements, and probability of success.

5. Select the most promising concept or concepts, and establish development plans necessary to bring the conceptual system to the experimental hardware stage.

While it has been demonstrated that burying a cable provides an excellent measure of protection against fishing activities, it is clear that not all cable failures can be avoided. Failure of a buried cable presents several problems unique to buried cables; that is, how is the cable found, and how is access gained to the cable to effect a repair. Also, once the cable is repaired, how is it buried again. The first two items, location and repair, are not intrinsically part of a cable burial system, and would unnecessarily complicate the hardware and threaten the success of the development program. Therefore, location and repair of a buried cable are not imposed as requirements of the cable burial system. Also, the telecommunication industry is currently developing a system to locate and repair buried cables. Since failure of buried cables will be an unlikely event, the repair system will be rarely used, and, therefore, should be available to the Navy on a contractual basis as needed. Burying the cable after a repair is made will be within the capabilities of the cable burial system, as it is foreseen that cables which must be buried may already have been repaired one or more times. Burial of a repair section is also within the capabilities of the cable repair system being developed.

CABLE BURIAL SYSTEM REQUIREMENTS

To develop a cable burial system that will provide adequate protection to Naval cable installations, a set of operational requirements must be identified and ranked in their order of importance. The requirements identified below are divided into general operational requirements and specific requirements. The general requirements are the more important ones, and impact heavily on the selection of a good concept. Specific requirements affect subsystem capabilities which must be part of any of the concepts.

General Operational Requirements

a. Bury cable no less than 3 feet in the seafloor without damaging the cable.

This requirement, the most important, is the basic objective of the entire program. A cable burial mission analysis [1] determined that damage due to fishing activities will be eliminated if the cable is buried 3 feet deep in water depths greater than 20 fathoms. Obviously this must be accomplished without damaging the cable. The mission analysis also determined that a 6-foot burial depth is required in water depths from 5 to 20 fathoms, principally due to the anchor drag threat. Although it is important to meet this shallow-water requirement, it is felt that the increased burial depth has little impact on concept selection. Also, it may be more effective to use nearshore cable burial techniques that are being developed separately to depths of 20 fathoms.

b. The cable burial operation must be supported from a ship of opportunity.

The Bell Sea Plow buries cable during a cable-laying operation, weighs 23 tons, and requires a nominal tow force of 50,000 pounds at a speed of 1 knot. Use of a ship of opportunity, although ranked second in importance, has the furthest reaching effect on the burial system concepts. Because available ships have limited weight-handling and thrust capabilities, a smaller, lighter-weight system is required. Force reduction techniques and/or elimination of towing for propulsion will be necessary. The burial system must be capable of burying previously laid cables since the support ship will not necessarily be a cable layer. Surface support systems must be modularized and self-contained such that they can be readily installed on a variety of ships. A deck-handling system and portable power generation system must be supplied. The importance of not damaging the buried cable increases, as the support ship may not have a cable repair capability. Many specific requirements, discussed later, result from this general operating requirement.

c. The system must bury cable in all seafloor soils except rock and coral.

Most deep-ocean cable routes occur on sand, silt, or clay bottoms. Because of the areal variability of soil type and the difficulty of changing to different burial systems in mid-operation, the selected burial system must be capable of operating in all seafloor soils. Bottom-trawling techniques cannot be used in rocky areas; therefore, cable burial in rock is not required. Nearshore rock and coral cable route installations are being developed separately.

d. The burial machine power requirement must not exceed 500 hp.

Although this value is somewhat arbitrary, this power level is within current capabilities of power generation, distribution, and cable and connector technology. If the power load is much higher than 500 hp, a higher frequency distribution system would be desirable to save transformer weight [4]. This would require non-standard components which would adversely affect the simplicity and reliability of the system. Higher voltage levels could be used to reduce the conductor size, but cable and connector insulation would present problems. Also, a higher power level would require a larger power generation system which impacts on the ship support requirement discussed earlier.

e. The cable burier must be capable of avoiding minor obstacles.

This requirement is essential to the integrity of the burying machine and of the cable. Minor obstacles include glacial erratics (boulders deposited by melting glaciers), debris, small rocky areas, reefs, or depressions. An obstacle detection system will be required, that can feed information to the burier control system. Large obstacles, such as extensive rocky areas, ridges or valleys, will have to be avoided by employing carefully selected and investigated cable routes.

f. Repeaters must be buried.

Repeaters occur only occasionally, and, if they were left unburied, a large measure of protection would still be afforded to the cable system.

However, the importance of the cable system, the expense of repairs, and the increase in fishing operations all dictate that as much of the cable be buried as possible, including repeaters.

g. The system must be simple and reliable.

This requirement is at odds with most of the others, which imply a high degree of sophistication and complexity. In essence, this requirement constrains the selection of exotic techniques which oversolve the problem at the expense of a complex system prone to nuisance breakdowns. Certainly, the cable burial system will have to be sufficiently sophisticated to perform well in a rather trying environment.

An implication of this requirement is that the effort should lean toward engineering development to extend and improve existing technology, rather than to perform basic research to validate ''blue sky'' ideas.

Specific Operational Requirements

a. The system must bury previously laid cable.

This requirement results from operating with ships of opportunity but is also important for other reasons. A cable-laying ship operates at speeds to 8 knots, while a cable-burying operation proceeds at about 1 knot. If the burier can bury cables only while they are being laid, the cable-laying operation is inefficient, and the probability of the laying operation being interrupted by adverse weather increases. Obstacles, breakdowns, and deteriorating weather can be handled more easily if the two operations are not being carried out at the same time. Burying previously laid cables will allow unburied cable systems which are in current use to be protected by the burial system.

Certain operational advantages result from a two-step operation as well. For the installation of a high priority cable system, the cable laying could proceed at 8 knots, and the system be made operational. The cable could then be buried at a later date without having delayed the cable system's use.

Finally, the burial system's capability to pick up and drop a cable, implied by this requirement, allows rapid abandonment of the burial operation if the weather worsens, eliminates the necessity of deploying and retrieving the burial system with the cable threaded through the machine, and allows burial of repair sections.

b. The burier must be able to track the cable.

Previously laid cables are not necessarily straight, so the burying machine must sense changes in cable direction. The sensor must provide information to the machine's control system and/or the support ship to avoid damaging the cable or overturning the machine.

c. The system must be able to bury spliced repair sections of cable.

Even if a cable has not been in place for a long time, it may have been damaged and repaired prior to burial. Older cables almost certainly will have been repaired. A means of burying these slack sections of cable, whether it be the primary burial means or a subsystem, must be provided.

d. Additional specific requirements as developed in Reference 1 are shown in Table 1.

STATE-OF-THE-ART

Cables and pipelines have been buried on land and under waterways for many years and lately in ocean bottoms. This section discusses the variety of techniques used to accomplish burial tasks, examines their advantages and disadvantages, and, where applicable, references burial systems using these techniques underwater.

Trenching/Excavating

Trenching and excavating are the most common methods used for installing buried cables and pipelines. Typical equipment used includes backhoes, chain/bucket trenchers, and excavating wheels. In the mid-1960s, a Belgian firm modified an excavating wheel trencher to bury 600 feet of power cable at depths to 40 feet in the river Scheldt [5]. The trencher was capable of excavating a 5-foot-deep, 20-inch-wide trench at a rate of 150 ft/hr. About the same time, a conventional backhoe was modified for underwater use that could excavate 200 feet of 4-foot-deep trench, 18 inches wide, in a day. Recently, a commercial cutter wheel trencher was modified and used in 120 feet of water to trench cable in sandstone. CEL recently used a similar trencher in coral (Figure 2).

Trenchers such as these are attractive in that they can be used in material as hard as granite. Wheel and chain/bucket trenchers can be equipped with cable feed mechanisms that allow placing the cable while the trench is being excavated. Backhoes require a three-step operation - trenching, placing the cable, and backfilling. In soft or sandy materials, a means to keep the trench from slumping in must be provided until the cable is installed. The major drawback for the trenching/excavating technique is that it is an inherently slow process. Supply power, usually in the 50-to-150-hp range, is well within the range considered feasible for deep-ocean cable burial.

Plowing

Plowing in cables and small-diameter pipelines was developed principally to increase the efficiency of installation. The cable can be installed through a feedshoe that immediately follows the plowshare. Little or no surface restoration is required since very little earth is forced out of the slot. Plowing cables has been proven feasible for deep-ocean cable burial by the Sea Plow (discussed in the Introduction) and by two Japanese firms that have developed plows. Repeater handling has been accommodated by lowering auxiliary plowshares to widen the ditch, or by plowing a repeater-sized ditch over the entire cable route. The hardware required for plowing cables is relatively simple, a particularly attractive feature for deep-ocean application.

Table 1. Specific Operational Requirements of Cable Burial System

Threat		
Depth of operation, D (fm)	5 through 1,000	
Depth of burial (ft)	6 if D <20 fm 3 if D >20 fm	
Environment		
Sea conditions	NORMAL	SEVERE
Wind speeds (kt)	11 to 16	40
Significant wave height (ft)	6 to 7.5	12
Periods (sec)		
Average	4.8 to 5.4	6.8
Swell	6.8 to 7.6	9.6
Average wave lengths (ft)	79 to 99	158
Currents (kt)	0.2 to 2	5
Soil Conditions		
Shear strength (psi)	0.18 to 2.2	4 to 7
Bulk unit weight (pcf)	78 to 116	
Angle of internal friction (deg)	30 to 42	–
Slopes (deg)	5 to 10	20
Operations		
Speed of advance (kt)	>0.5 if D <20 fm >1 if D >20 fm	
Cables to be buried:		
Type	Caged armor coaxial, 21 Quad, SF, SD	
Minimum bend radius (ft)	10 (21 Quad)	
Range of sizes – OD (in.)	0.66 to 4.41	
Length of cable run (nm)	up to 1,000	
Repeaters to be buried	SB repeater	SD repeater
Weight		
in air (lb)	–	636
in water (lb)	–	353
Length (in.)	288	41.5
Diameter (in.)	6	13

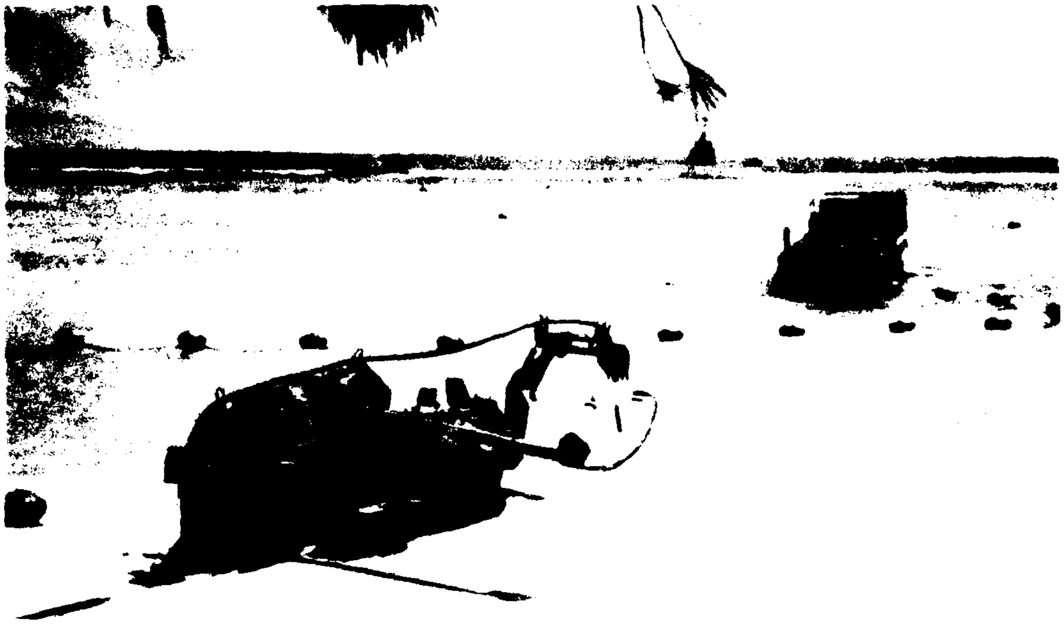

Figure 2. Trencher modified for shallow-water coral trenching.

The disadvantages associated with plowing center on the high force required to penetrate the soil, both vertically and horizontally. In order to effect initial plow penetration, and to keep the plow in the soil, ocean plow machinery has been very heavy (19 to 23 tons). To support the plow on the seafloor, large skids are used. The skid drag coupled with the force required to plow can be as high as 100,000 pounds. Since deep-ocean plowing systems are towed from the surface, the high towing force, high weight, and slow speed of operation impose requirements on the surface support ship that are not easily met. The high drawbar pull requirement was recognized as a problem for land cable plows when the undergrounding of services for older residential communities was increasing. Tractors, required because of their high drawbar pull capability, caused surface damage which had to be repaired. Analytical and experimental investigation of vibrating the plowshare showed that up to a 99% reduction in drawbar pull could be achieved [6-14], allowing the use of smaller, rubber-tired machines. Roughly half of the total power requirement is supplied to vibrate the plow, and the other half for running the machine. This approach worked well on experimental plows, and now most major equipment manufacturers supply vibratory plow equipment. To date, vibration has not been employed for deep-ocean plows.

Water Jetting

Water jetting is used mainly for burying offshore oil pipelines. The jetting machine straddles the pipeline and extends into the seafloor to the desired depth of burial. Water or an air-water mixture is supplied to the machine from the surface. These systems are generally high-flow, medium-pressure systems (20,000 to 30,000 gpm at 1,000 to 2,500 psi) that are towed along the pipeline [15]. The jets break up the soil, and then air or water eductors lift the soil/water mixture out of the trench. The pipeline settles into the trench after the machine passes, and natural action eventually backfills the trench. The main disadvantage to jetting a trench for the cable to settle in is the large amounts of power required. Comparing four operational pipeline jetting systems working at capacity, the average power supplied per unit excavation rate is [17,18,19,16]:

$$P_{D_{avg}} = \frac{11.6\ \text{hp}^*}{\text{ft}^3/\text{min}}$$

Using this power-excavation rate density figure for a deep-ocean cable burial system would require over 1,000 hp. These systems normally operate at 5 to 30 ft/min (1 kt = 101 ft/min) and work best when guided by a stiff pipeline. They also are constrained to work in a relatively firm soil so that the excavation will not fill in before the pipeline settles into place.

Analytical studies for pure jetting (i.e., where no equipment penetrates the seafloor) have shown that the power-excavation rate density can be as low as 0.4 hp/ft^3/min [20]. Using this figure, 40 hydraulic horsepower would have to be supplied to jet a 3-foot-deep, 4-inch-wide trench at a speed of 1 knot. No information was encountered which discussed the effect of depth of cut and speed of advance on power requirements. Pure jetting is a simple technique that has been used with some success by the Pisces Submersible and the Alcoa Seaprobe. Disadvantages of pure jetting are that (1) the amount of material which must be excavated depends on the angle of repose of the soil, (2) there is no positive means of ensuring the desired burial depth, and (3) backfill depends on resedimentation of the excavated soil.

Jet Plowing

As the name implies, jet plowing combines the features of both waterjetting and conventional plowing. This technique has been used quite successfully by the Harmstorf Hydro jet and Aquatech cable plow for shallow water and river crossing [17-25]. In essence, the water jets loosen the soil in front of the plowshare, reducing the frontal resistance on the plowshare. The soil is kept in suspension until the plowshare and cable guide pass, whereupon it settles. Very little soil is actually removed from the ditch, and no backfill is required. The Harmstorf unit is equipped with a vibration means to help break up competent soil. Jet plows are usually pulled with winches from a barge or from shore. Total power required ranges up to 1,500 hp. These systems historically have required supervision and inspection by divers, which is not to say they cannot be redesigned to operate without first-hand supervision.

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* In Reference 26, this function is referred to as Nominal Overall Specific Energy $\left(\frac{\text{in/lb}}{\text{in.}^3}\right)$.

Dredging

Dredging, which combines a rotating cutting head and suction pump for spoil removal, is a very effective means of removing soil. Two similar devices, the Mole [27] and the Gopher [28], are pipeline machines that straddle the pipe and have mechanical cutters on each side of the pipe angled towards each other. The cutters dislodge the soil which is then removed by a suction dredge pump. The Gopher also has water jets and air-lift pipes to help remove the spoil. The most technically advanced dredging system for burying pipelines is currently under development by Tecnomare (Italy) [29]. It is a tracked crawler machine with two dredge cutters mounted on articulated arms. The system may be programmed to dredge a prearranged path, or it may be manually controlled from the surface. Dredge spoil is pumped to the rear of the machine to bury the pipeline after it has settled in the trench. The system can be made neutrally buoyant and is supplied from the surface with 1,300 hp. Dredging is a proven underwater excavation technique, but generally requires large amounts of power, excavates more soil than necessary for burying a cable, is slow, and does not lend itself well to backfilling.

Fluidizing

Fluidizing is a technique where water is pumped into the soil at such a rate that as it flows out of the soil, the individual soil particles are buoyed up by the water. The soil/water mixture achieves a fluid or ''quick'' condition which will not support applied shear forces.

Shell Laboratories (The Netherlands) has developed a fluidizing system for burying pipelines [30]. The soil is fluidized under a predetermined sag length, and the weight of the pipe and fluidizing device causes the pipeline to ''sink'' into the fluidized soil. This technique works in sandy (noncohesive) soil, but to date it has been stymied by cohesive (clay) soils as the intergranular forces cannot be overcome and the soil will not fluidize.

Related Techniques

Other techniques which have been used or proposed for burying cables and pipelines include cavitation cutting, high-pressure water jetting, directional drilling, and piercing tools.

Cavitation cutting is basically a forced erosion process that depends on the formation and violent collapse of bubbles in a fluid. The cavitation erosion is caused by the shock wave produced when the bubble collapses, and the energy density is sufficient to erode materials such as rock and metal. The intensity of the cavitation, and, therefore, the penetration rate, increases with hydrostatic pressures [31]. Cavitation cutting development is still in its infancy, and acoustic transducers powerful enough to produce the necessary threshold energy levels for high ambient pressures have not been developed. This technique produces localized energy densities effective for drilling through rock.

High-pressure water jetting, or ''water cannon,'' is a technique that has particular application for fracturing rock. To generate high pressures, a rapidly moving piston impacts on a slug of water and extrudes it through a nozzle, producing a very high velocity water impulse. The water impulse jet of a prototype underwater unit used for cleaning scale from steel is about 1/2 cm in diameter, and the device requires 250 hp [32]. The application of high-pressure water jetting or cavitation cutting for high-volume excavation in soft materials has not been reported.

Directional drilling is a technique reported on by Valent [33] for installing the nearshore end of a cable system. Its attractive feature is that a shore-based drilling rig can drill under the surfzone and rocky areas to a distance offshore where nearshore effects have dissipated. Piercing tools, such as the Pneuma Gopher, have been developed to dig their way from one point to another when trenching is undesirable, such as under a busy highway. Both of these techniques are suitable for producing a relatively short path through which cabling can be led after the hole is made.

CONCEPT DEVELOPMENT

The major problem areas associated with existing ocean cable burial systems are the machine/soil interface, and the machine/surface support control and propulsion interface. These problem areas are quite closely related; for example, the large forces experienced in the machine/soil interface cause problems in propulsion and control for the support ship. To approach a solution to these general problem areas, three major categories were analyzed, and the resulting information combined in various ways to formulate concepts. These categories are:

1. Excavation Subsystem
2. Propulsion Subsystem
3. Running Gear Subsystem

To provide a common basis for comparision of the various techniques of burying cables, a set of parameters was selected from the specific operational requirements which represent maximum normal operating conditions. Each concept was analyzed to determine the power required and the resistance force produced by operating under these conditions. Maximum allowable target values for size, weight, and force required were also assigned as they must be used for some of the power and force calculations. The values are shown in Table 2, and power conversion efficencies are shown in Table 3.

The burial machine weight and size were selected as desirable maximum values to allow convenient handling from ships of opportunity. The size affects water drag on the system and bottom stability. Machine weight impacts on the running gear/soil interface forces and allowable ground pressure. The machine speed and current profile create a drag force on the umbilical cable, which is at maximum when the current profile adds to the system speed at maximum operating depth. The trench dimension is typical for most of the burying operations. The system must slow down or consume more power for repeater burial or deeper burial. Finally, the soil characteristics have a large impact on power and force. For tougher materials, the system must slow down or consume more power, and for weaker soils the speed can be increased or the power reduced.

Several excavation techniques that have been used or suggested for burial of objects in the seafloor are inappropriate for deep-ocean cable burial because of their inability to meet some of the basic operating requirements. Therefore, they could be eliminated without performing a detailed power analysis.

Fluidization. The fluidization process is not applicable since it is intended for cohesionless materials (i.e., sands) and depends on the absence of intergranular attractive forces for successful operation. Recent tests with Shell's fluidizer showed that the system stalls when clay is encountered [34]. Many of the seafloor soils which will be encountered are cohesive, and switching burial equipment in mid-operation is not an acceptable solution to the deep-ocean cable burial problem.

Blasting. Blasting is not an appropriate method of burying long cable runs in sand and clay since it is best used for fracturable materials such as rock and coral, is a batch (rather than continous) process, and to date, requires divers to prepare blast holes and set the charges.

Table 2. Design Parameters

Burial machine weight	10 tn (max)
Burial machine size envelope	12 ft wide x 25 ft long x 10 ft tall (max)
Motion resistance force	5 tn (max)
Power	500 hp (max)
Speed	1 kt (101 ft/min)
Current	2 kt at surface 0 at 300 ft
Trench dimensions	36 in. deep x 4 in. wide
Umbilical cable	3-in. diameter 6,500 ft long
Soil characteristics	Clay Undrained shear strength, $S_u = 4$ psi Bulk density, $\rho = 100$ lb/ft^3

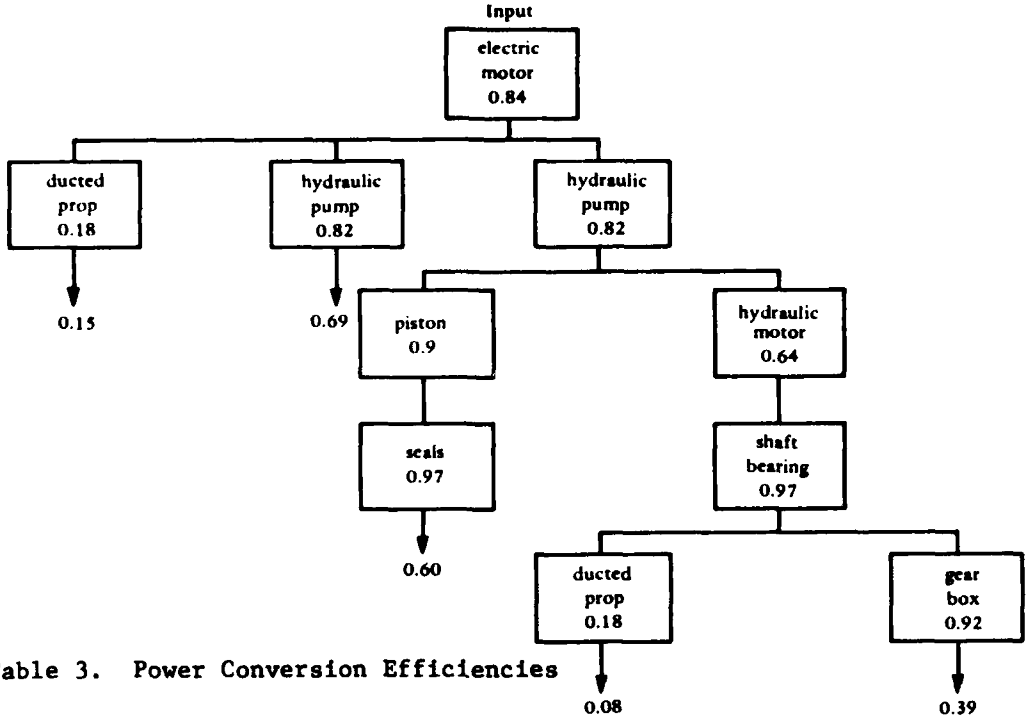


Table 3. Power Conversion Efficiencies

Cavitation Cutting and High-Pressure Jetting. Both of these techniques use the principle of focusing moderate amounts of energy to achieve ultra-high energy densities to cut, fracture, or erode materials such as rock and metal. As such, they are not suitable means of excavating a trench in soft materials. High-energy density water jets achieve 100,000 to 5,000,000 psi in a jet 1/16 inch in diameter. The optimal cutting range is 20 nozzle diameters, and the jet pressure should be at least 10 times the material strength [35]. Extrapolating this information to digging a 3-foot-deep trench in a typical (4-psi) seafloor soil suggests a nozzle size of 1-1/2 inch and jet pressure of 40 psi (minimum). Thus, it can be seen that the high-pressure water jetting technique provides nominally 2,500 times the pressure required to cut seafloor soil, and the jets are so small that only a localized area of soil would be excavated. Extrapolation of high-pressure water jet theory to soil excavation leads to standard (low-pressure) jetting techniques. Cavitation cutting results in pressures and cutting volumes similar to high-pressure water jetting.

Direct Insertion. Using this method, the cable is simply forced into the soil with, for example, a heavy wheel. The wheel must be forced through the soil while penetrating 3 feet into the bottom. Preliminary analysis showed that, even if the wheel were water lubricated such that an 80% reduction in frictional resistance could be attained, the forward force required to push the wheel through the soil ranges from 4,400 pounds for a 4-inch-thick wheel to 7,900 pounds for a 16-inch-thick wheel. In addition, the force on the wheel required to achieve 3 feet of penetration ranges from 7,000 pounds to 28,000 pounds. This approach was eliminated because full penetration is not assured, tracking the cable is a difficult process, and the probability of damaging the cable is very high since the cable could be forced into a rock or other hard surface.

SUBSYSTEM ANALYSIS

The following sections present force and power analyses and discuss the subsystem candidates which appear to be most appropriate for a deep-ocean cable burial system.

Excavation Subsystems

Plowing. Plowing cables into the soil is a relatively simple and quite effective means of burying cables. Plowing has been used extensively and very successfully on land and has had some success underwater. The basic problems with cable plowing are the high force required to move the plow through the soils (drawbar force) and the force required to achieve and maintain plow penetration. Appendix A and Reference 36 discuss drawbar force predictions for a plowshare.

Appendix A shows that the total drawbar force required to move a plowshare through the soil is larger for clay than for sand, and is velocity dependent.

$$F_{TOT} = C_v F_s + F_I$$

where F_{TOT} = total resistance

C_v = a velocity coefficient determined from Figure A-1

F_s = force due to static soil resistance

= $S_u A_s + S_u N_c A_f$

F_I = an inertial term

= $(1/2)\rho_s A_f C_D v^2$

S_u = undrained shear strength

A_s = side area of plow

A_f = frontal area of plow

N_c = dimensionless coefficient $\simeq$ 10

ρ_s = soil mass density

C_D = drag coefficient $\simeq$ 1.5

v = velocity

To guide the cable to the bottom of the 3-foot ditch without exceeding a minimum bend radius of 5 feet, the feedshoe/plow length must be 10 feet (Figure A-2). Using the design parameters discussed previously, the total force required to pull the plowshare at a speed of 1 knot is $F_{TOT} = 44,000$ pound. This formulation for predicting drawbar pull compares favorably with results published for Sea Plow III [37].

References 8 through 14 present analytical and experimental results of using plowshare vibration to reduce the drawbar force required to move the plowshare through the soil. In particular [13], it has been shown that for vibratory plowing, the use of a raked, wedge-shaped blade with machined grooves (Figure 3) reduced the average horizontal plowing force in a silty sand by 98 to 99% when the plowshare was vibrated at a frequency of 20 to 40 Hertz at an amplitude of 3/8 inch. In addition, vibrating the plowshare aids in achieving and maintaining depth of penetration. In the case above, a 95% reduction in drawbar force gives

$$F_{TOT_{\text{reduced}}} = 2,200 \text{ lb}$$

which is well within the target requirement of 10,000 pounds. (Note: Other contributions to drawbar force will be discussed later.) This reduction in drawbar force will impact significantly on the support ship power requirements for towing, and ease control problems.

The power required to vibrate the plowshare is also an important consideration. Appendix A shows that the power required to produce vibrations is 14 hp. Water drag and added mass effects on the power required for vibration are negligible. To move the vibrating plowshare at 1 knot:

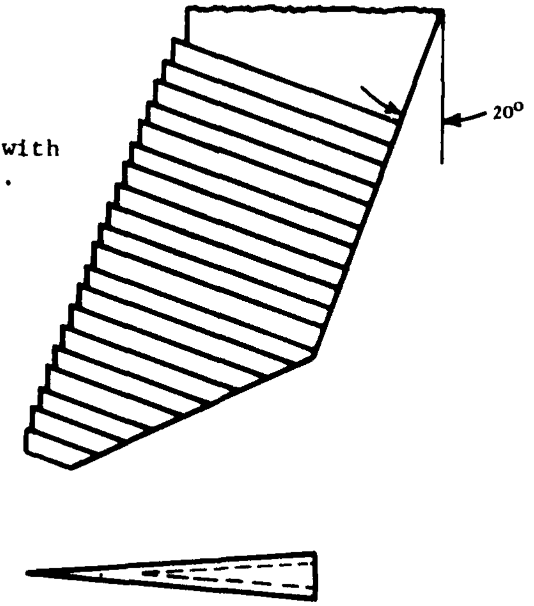


Figure 3. Raked plowshare with machined grooves.

$$P = F v = (2{,}200 \text{ lb}) (1.69 \text{ ft/sec}) = 7 \text{ hp}$$

$$P_{Total} = 21 \text{ hp}$$

Without vibration,

$$P_{total} = F v = (44{,}000 \text{ lb}) (1.69 \text{ ft/sec}) = 135 \text{ hp}$$

So in addition to a significant decrease in drawbar force, vibrating the plowshare also results in a reduction in net power requirements.

Trenching. Two types of trenchers are considered, the endless chain-bucket trencher and the cutter wheel trencher. Both types of trenchers normally rotate such that the cutting action is in the direction of machine travel (upmilling) (Figure 4). The machine, then, must supply sufficient drawbar force to overcome the cutting resistance. If, however, the trenching means rotates in the opposite direction (climbmilling), cutting resistance acts to push the machine forward, and to lift the device out of the trench. Appendix B presents a force and power analysis of both chain and wheel trenchers.

For a wheel trencher or chain trencher, the bucket comes in contact with the soil and, when forced through the soil, fails it in a manner similar to the plowshare discussed previously. The total force required to cut the soil is

$$F_{TOT} = S_u A_f N_c + \frac{S_u A_s}{2}$$

where the first term represents the soil bearing resistance force, and the second a shearing resistance force [38]. N_c in this case is a dimensionless factor $\simeq$ 3 because of free surface effects.

For a chain-bucket-type trencher with the boom angled 60 degrees below horizontal the analysis in Appendix B shows that the maximum power required to excavate a 4-inch-wide, 36-inch-deep trench at 1 knot is

$$P_{max} = 108 \text{ hp}$$

For upmilling the forces on the unit are

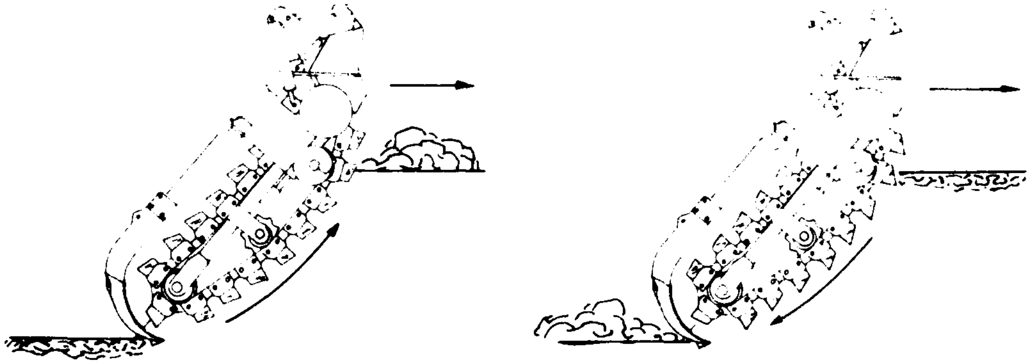
$$F_{UP} = -2{,}675 \text{ lb}$$

$$F_{FWD} = -2{,}620 \text{ lb}$$

With the system operating in the opposite direction (climbmilling), the forces are

$$F_{UP} = 2{,}560 \text{ lb}$$

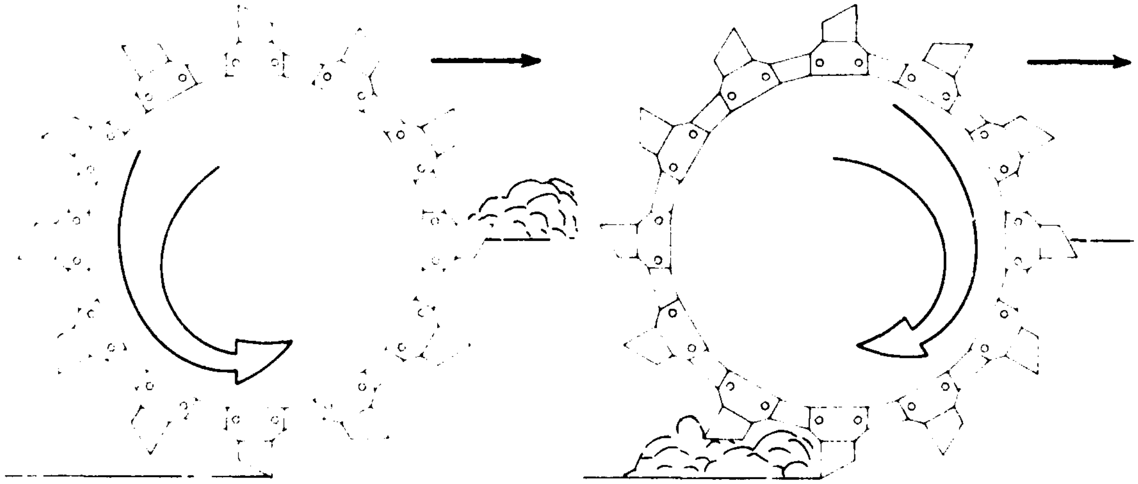
$$F_{FWD} = 2{,}620 \text{ lb}$$



(a) Upmilling.

(b) Climbmilling.

A. Chain Bucket Trencher.



(a) Upmilling.

(b) Climbmilling.

B. Wheel Trencher.

Figure 4. Trenching modes.

and the power requirement is the same. For the cutting wheel trencher, a parallel analysis results in

$$P_{max} = 94 \text{ hp}$$

For upmilling

$$F_{UP} = -3{,}515 \text{ lb}$$

$$F_{FWD} = -4{,}430 \text{ lb}$$

and for climbmilling

$$P_{max} = 94 \text{ hp}$$

$$F_{UP} = 3{,}350 \text{ lb}$$

$$F_{FWD} = 4{,}430 \text{ lb}$$

Climbmilling appears attractive in that, for the same power as upmilling, a drawbar assist of 2,600 to 4,400 pounds is available to overcome the running gear/soil interaction forces, cable drag, and water drag on the machine. The machine must weigh greater than the upward force to keep the trencher from digging itself out of the trench. However, the incidence of stiff clays or rocks may cause the cutting wheel or trencher to climb out of the trench, resulting in instability of the machine and possible damage to the machine and the cable. Shock absorbing, braking, and possibly other control systems must be incorporated into the trencher. It may also be necessary to direct a water stream on the buckets to loosen and remove trenched soil.

For upmilling, the system can be very light (neutral if desired) since the cutting force provides a significant downward force, but the machine must provide 2,600 to 4,400 pounds of drawbar force in addition to the other forces acting against the system's forward progress. Power requirements in both cases are high due to the high digging rate required for a 1-knot speed of advance.

Water Jetting. Although water jet excavation is the most common means employed for pipeline burial, very little analytical or experimental information was encountered in the literature. References 39 and 40 discuss research performed on jetting in sand. The trench depth is related to the jet flow parameters by

$$d^3 = C_1 Q(p + C_2)^{1/2}$$

where d = trench depth

Q = flow rate

p = jet water pressure

C_1 = constant determined by grain size

C_2 = constant determined by distance from jet to seabed surface

It can be seen that the excavation depth increases more rapidly with increasing flow rate than with increasing pressures. If the hydraulic power, $P = Q\,p$, is kept constant, increasing the flow rate will produce a deeper trench than increasing the pressure. Also, the trench depth decreases as the speed of the jet across the seafloor increases. To estimate the power required to jet a ditch into the seafloor, the power and performance of two pipeline jetting devices and a planned cable jetting device were used to calculate a power density function, defined as

$$P_D = \frac{\text{Delivered Power (hp)}}{\text{Soil Excavation Rate (ft}^3\text{/min)}}$$

Table 4 is a summary of the jetting systems' characteristics and resultant power densities. The variation in power densities for the three systems is not readily explained, but may be the result of several factors:

System 3 is still on the drawing board and may be underpowered.

Systems 1 and 2 may be excavating more soil than the nominal trench dimensions.

Systems 1 and 2 may be supplying more power than is required to do the job.

Table 4. Characteristics of Three Jetting Systems

Characteristic	System 1 [41]	System 2 [16,42]	System 3 [20]
Trench depth (ft)	12	7	1.2
Trench width (ft)	9	9	2
Trench shape	rectangular	rectangular	triangular
Speed (ft/min)	3.3	47	50
Flow (gpm)	36,000	16,000	300
Pressure (psi)	28	1,750	125
P_D (hp/ft^3/min)	1.7	5.5	0.4

The average value of these three systems is taken as an estimate for the power density function for burying cables. To jet a 4-inch-wide, 36-inch-deep trench at a speed of 1 knot, the soil excavation rate is 101 ft^3/min. Using $P_{D_{avg}} = 2.5\ hp/ft^3/min$, the total power required is 256 hp.

Auger Trenching. Auger trenching and cutter head dredging are basically very similar mechanisms in that a rotating surface fails the soil. The basic difference is that augers physically remove the spoil where dredges crumb the soil and a dredge pump removes the spoil. A dredge cutter head is basically spherical which requires that the trench depth equal the trench width on a single pass. Thus, to attain a 3-foot-deep trench, the trench must be 3 feet wide. Since the trench need only be 4 inches wide, more work than necessary is being done, which leads to higher power requirements.

Double vertical counter-rotating augers have been used with some success for burying pipelines. Very little information was available in the literature, so a power analysis parallel to that for trenching was performed (Appendix C). The power level for one 4-inch-diameter auger was 75 hp, somewhat higher than for vibratory plowing and about the same as for trenching. The soil removal rate, however, requires an auger speed of 5,000 rpm. This high rotary speed required by the soil removal rate associated with a 1-knot speed of advance appears unrealistic for soil cutting. Encountering a rock or other unyielding surface at that speed would most likely damage the auger considerably. The force necessary to move counter-rotating augers through the soil is expected to be near that for vibratory upward soil cutting (2,200 pounds) in that the soil is being lifted and failed at a rapid rate.

Propulsion Subsystems

Towing. Virtually all of the cable and pipeline burial systems rely on towing as their primary means of propulsion. Most use the kedging anchor technique with power winches on the support barge. Since this process is slow and may necessitate stopping while anchors are reset, it is not suitable for deep-ocean cable burial. The Bell and Japanese cable plows are towed from a ship, which lays cable simultaneously. For the Bell system, 2,000 shp is required to tow with an average tension of 33,000 pounds at an average speed of 1 km/hr [37]. Taking the ratio of the delivered power to the supplied power results in the overall efficiency (exclusive of the prime mover)

$$\eta = \frac{P_{del}}{P_{sup}} = \frac{(33,000\ lb)\ (0.911\ ft/sec)}{2,000\ hp} \left(\frac{hp}{550\ ft\text{-}lb/sec}\right)$$

$$\eta_{overall} = 0.06$$

Of the total tension supplied, 2/3 goes into plowing and 1/3 is used to overcome other drag forces. The supplied power for plowing, on the average, is 36 hp. While towing is highly inefficient from a power standpoint, it is not meaningful to compare other propulsion system efficiencies with that for towing, because the power is presumably already available on the support ship.

Towing is the simplest propulsion system resulting in the least complicated machine control system and requiring no electrical power transmission. Towing has a number of drawbacks, however.

1. Ship of opportunity navigation systems are not sufficiently accurate to allow burying previously laid cables without picking up the cable and leading it back to the machine. Burying cables while laying requires the use of a cable-laying ship.

2. Cable-laying ships generally operate at 5 to 8 knots, and plowing-while-laying averages about 1/2 knot due to ship thrust limitations. This mismatch makes the laying operation inefficient, and makes the laying/burying operation more vulnerable to adverse weather conditions.

3. Supplying propulsion from a surface ship forces the burying machine to move at ship speed, regardless of bottom conditions. Thus, quick response ship control is required to avoid breaking the tow cable or damaging the burying machine.

4. Handling three cables from the support ship - umbilical, tow cable, communication (buried) cable - presents a substantial entanglement problem.

5. A ship of opportunity has no fine control over the path of the machine - the machine must simply follow the ship.

6. Supplying large towing forces at slow speeds makes ship control difficult. Sideways thrust control is essential. Utilizing force reduction techniques will reduce the severity of some of these problems, but the ship/machine control problem will remain.

Track/Wheel Propulsion. Tracked and wheeled vehicle mobility has been developed extensively for all types of terrain except ocean bottoms. The only vehicle of consequence to traffic the seafloor is the RUM vehicle, a converted land-based tracked vehicle. At that, RUM was not called upon to provide large drawbar forces, and its weight on the seafloor is often controlled from the surface. Underwater bulldozers developed in Japan have been reported in trade journals recently, but no performance information has been available.

The basic mechanism for determining the drawbar force, or tractive effort, developed by a tracked or wheeled vehicle is based upon Coulomb's theory:

$$F_T = W \tan \phi + A c$$

Where F_T = tractive effort (lb)

W = vehicle weight (lb)

ϕ = friction angle

A = contact area (in.^{2})

c = cohesive index, S_u (lb/in.^{2})

For the target weight of 20,000 pounds dry (17,300 pounds wet), and an allowable ground bearing pressure of 2 psi, the contact area can be found as:

$$A = \frac{W}{2 \text{ psi}} = 8{,}650 \text{ in.}^2$$

Therefore, the tractive force is:

Sand: $\phi = 30^\circ$, $c = 0$

$F_T = 17{,}300 \tan 30^\circ = 10{,}000$ lb

Clay: $\phi = 0$, $c_{surface} \simeq 1$ psi

$F_T = 8{,}650$ lb

These are theoretical and, probably, optimistic values. Also, typical seafloor soils are not uniformly clay or sand, and the effect of water, ground bearing pressure, sinkage, and slippage has not been established for seafloor application. Nevertheless, these values are in the range that an improved cable burial system will be operating. In Reference 43, two vehicle types (6 x 6 wheeled, and two-tracked conventional) were shown to be possible configurations for a seafloor-crawling work vehicle.

Another configuration for a mobile vehicle, a screw-wheel concept, was studied in detail in Reference 44. A screw-wheel configuration is basically an Archimedes screw with the blades arranged in a helix around a cylinder. This device has been shown quite effective in ''screwing'' its way through water and marshy soils, but suffers from extreme friction losses in sand. For the configuration discussed in Reference 44, four screw-wheels are installed such that they can orient to operate in the screw modes (for clays), or turn 90 degrees to operate in a wheel mode (for sands). Intermediate materials may require intermediate (hence, screw-wheel) settings.

Propelling a cable burier with tracks, wheels, or screw-wheels is particularly attractive in that the machine may be accurately controlled, either remotely or automatically, to follow the cable and avoid obstacles, or even in a search mode to find the cable which is to be buried. These vehicles also can climb slopes, climb obstacles, and control their speed to match the soil and terrain conditions. The most obvious disadvantage is that this type of propulsion system depends on the soil characteristics for mobility and drawbar effectiveness. Since seafloor soils are generally weak, variable, and often times their characteristics unknown, vehicle performance cannot be predicted with any confidence. This, coupled with general lack of experience in seafloor trafficability, makes it impossible to judge whether a burial system propelled with tracks, wheels, or screw-wheels will be successful. Finally, these types of running gear are relatively complicated mechanisms that may impact on the reliability of the burial system.

Thrusters. One of the most common means of propelling underwater craft, thrusters, includes open and shrouded propellers and jet pumps. Propeller theory is well known, although propeller design is iterative in nature. Since a prop uses the water medium to develop thrust (as opposed to soil for traction), it is relatively straightforward to predict the performance of a propeller driven machine. Propeller efficiency is defined as:

$$e_p = \frac{ehp}{shp}$$

where e_p = propeller efficiency

ehp = effective horsepower = thrust x velocity

shp = shaft horsepower

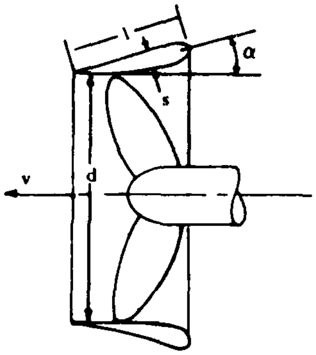
It can be seen that if the vehicle is stationary, the propeller may be generating large amounts of thrust, but the ''efficiency'' will be zero. Thus, several propeller configurations are considered from the standpoint of thrust and power rather than efficiency. A preliminary analysis on ducted and non-ducted propellers is summarized in Tables 5 and 6. In one case, two 5-1/2-foot-diameter non-ducted propellers will provide 8,000 pounds of thrust at a burial speed of 2.48 ft/sec (1.5 knots), requiring 160 shp. In the case where the machine is stalled, two-ducted propellers, 4 feet in diameter, can supply 9,400 pounds of thrust at 160 shp. In general, ducted propellers are more ''efficient'' (i.e., require less shp for the same output conditions) by 10 to 30% than non-ducted propellers. One major advantage of thruster propulsion is that, by operating at a constant thrust level, the machine speed will vary as a function of the soil resistance. Thus, in tough materials, the machine will proceed more slowly than in soft materials, and overstressing of the excavating means will be eliminated. Also, props may be directly driven from submersible electric motors, or by hydraulics, and may be articulated to provide continuous steering control.

Cable Traction Propulsion. Pipeline burial systems generally straddle the pipeline, depending on the pipe for guidance, and some use traction drives to pull themselves along the pipeline. The most distinct advantage of a cable burial machine which pulls itself along the cable is that it clearly will follow the cable. The breaking strength of 18,000 pounds for unarmored SD cable is adequate for a system that meets the target force requirement of less than 10,000 pounds. There are two major problems identified for this type of propulsion system. While the traction unit is pulling itself along the cable, it is also ''pushing'' it astern. Any slack in the cable will be taken up by the traction unit and will result in buckled cable astern, which will tend not to stay in the trench and may damage the cable. The other problem is one of size. In order to avoid overstressing the cable locally, the traction unit must be approximately 35 feet long for SD cable. This requirement will result in a large, unwieldy burial machine. Finally, the traction unit is a relatively complex piece of equipment which may prove unreliable on the ocean bottom where the sediment content of the water may be very high due to the machine's presence.

Table 5. Thrust for Ducted Propellers at Zero Advance Speed*

Assumptions

Torque Q = 2,000 ft-lb = constant
shp ≤ 100 hp
$v = 0$
$d = 4$ ft
Blade thickness fraction = 0.045
Mean width ratio = 0.189
Rake angle = 15°
Number of blades = 4
$\frac{\text{Total blade area}}{\pi D^2/4} = 0.55$



	Nozzle A		Nozzle B	
	$\ell/d = 0.50$ $s/\ell = 0.15$ $\alpha = 12.7°$		$\ell/d = 0.83$ $s/\ell = 0.15$ $\alpha = 12.7°$	
	Case 1	Case 2	Case 1	Case 2
n (rps)	4	3.5	4	3.5
shp (hp)	91.3	79.9	91.3	79.9
p/d	1.21	1.38	1.21	1.38
T (lb)	4,915	4,453	5,325	4,704

* See Table 6 for definition of terms.

Table 6. Thrust Delivered by One 4-Blade Propeller Attached to Stern of Water-Submerged Vehicle

Assumptions:

Blade form: elliptical
Blade section: ogival
Mean width ratio: 0.2 (mean blade width/propeller diam)
Blade thickness fraction: 0.05 (blade thickness at shaft/propeller diam)
Wake fraction: 0 (wake velocity/vehicle velocity)
Thrust deduction coefficient: 0 (const x wake fraction)

Definitions:

T = propeller thrust (lb)
Q = propeller torque (ft-lb)
v = vehicle velocity (ft/sec)
d = propeller diam (ft)
n = propeller rotational speed (rev/sec)
p = propeller pitch (ft) (axial advance per revolution; thus, if the medium is unyielding, v = pn)
shp = shaft horsepower (hp) ($2\pi Qn/550$)
epp = effective horsepower (hp) (tv/550)
e_p = propeller efficiency (ehp/shp)

d (ft)	p/d	n (rev/sec)	ehp (hp)	shp (hp)	e_p	T (lb)	Q (ft-lb)	v (ft/sec)
3.0	0.62	4.63	3.18	10.95	0.29	700	700	2.50
5.0	0.74	1.56	3.18	7.48	0.43	700	420	2.50
3.0	0.58	5.55	5.00	20.80	0.24	1,100	328	2.50
5.0	0.68	1.92	5.00	13.50	0.37	1,100	615	2.50
3.0	0.54	6.41	6.82	32.50	0.21	1,500	444	2.50
5.0	0.65	2.27	6.82	21.30	0.32	1,500	821	2.50
3.0	0.50	7.08	5.00	33.50	0.15	1,623	415	1.69
5.5	0.60	3.00	6.00	72.50	0.08	4,000	2,120	0.83
5.5	0.65	3.00	18.06	80.20	0.23	4,000	2,340	2.48
6.0	0.73	3.00	11.50	158.00	0.07	7,000	4,620	0.90
6.0	0.75	3.00	22.90	160.40	0.14	7,000	4,680	1.80
6.2	0.90	3.00	3.28	247.00	0.01	10,000	7,210	0.19
6.2	0.90	3.00	9.80	247.00	0.04	10,000	7,210	0.56
6.3	0.90	3.00	37.70	272.00	0.14	10,000	7,950	2.08

Oscillating Valved Disk Propulsion. The last propulsion means that was investigated for deep-ocean cable burial is an application of an innovative idea called the Alveolator concept [42]. In essence, when a body (such as a disk) is accelerated through a fluid, there is a mass of the fluid which must also be accelerated. This is an ''added'' or virtual mass. In the case of a disk accelerated through water, the added mass term is given by

$$M_a = K_d \rho_w \frac{8}{3} r^3$$

where M_a = added mass

K_d = added mass coefficient (1.2)

ρ_w = mass density of water

r = disk radius

The acceleration of this significant mass produces a force that may be used to drive a second body to which the disk is attached. If the disk is valved such that the valves are closed when the acceleration is in a direction to provide the desired force (Figure 5), and the valves are open when the disk is accelerated in the opposite direction, a net driving force is produced. A mathematical model was developed for a cable-burying machine (plow) propelled by an Alveolator disk. Representative values were selected for machine weight, soil shearing and viscous forces, and drag forces. A digital analysis performed on the computer showed that the system moved along the seafloor with a net velocity of 0.25 ft/sec, but that the motion was oscillatory with an amplitude of nearly 4 feet. Optimization of the system parameters and the driving function may reduce or eliminate the machine oscillation and increase the speed. The major drawbacks of this system are the engineering difficulties involved in implementing the valved disk means and that the concept is unproven except by mathematical simulation. Note that if the machine is fitted with a plow, the plow vibrates due to the vibration of the machine, and the force required for plowing may reduce considerably due to plow vibration. The computer results showed that the average power required for propulsion and excavation is 172 hp. Since the driving function for the disk has a large amplitude (5 feet) and low frequency (1 Hertz), a double-acting hydraulic ram can be used as the prime mover.

Running Gear Subsystems

A major component of the resistance to forward motion for a cable burial machine is the interaction between the machine's running gear and the soil.

Skids. The mechanism for predicting the resistance between a skid and the seafloor is not well established, but is generally considered to be dominated by friction in sandy soils and be shearing resistance in clay soils; that is,

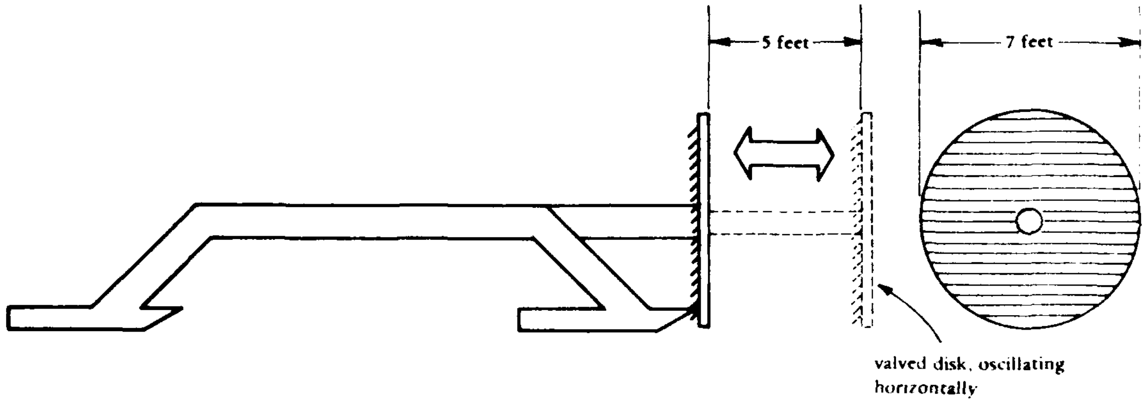


Figure 5. Alveolator concept.

$$F_f = \frac{1}{2} A_s S_u \qquad \text{for clay} \qquad (1)$$

$$F_f = \mu N \qquad \text{for sand} \qquad (2)$$

where F_f = ''friction'' force (lb)

A_s = skid area (in.^{2})

S_u = surface shear strength (0.5 to 1.0 psi)

N = weight of machine (lb)

μ = coefficient of friction ($\sim$0.5)

The problem with using these formulas directly is that the effect of water and bearing load on the coefficient of friction and on the shear strength is not known. To get an estimate of these effects, data from towing Sea Plow III with the plowshare disengaged show the following:

$$N = 28{,}600 \text{ lb}$$

$$A_s = 12{,}500 \text{ in.}^2$$

$F_{f_{avg}}$ = 5,000 lb (no plowing, water drag, or cable drag forces included)

This force may be used to obtain effective friction and shear strength values from Equations 1 and 2.

$$S_{u_{eff}} = \frac{2 F_f}{A_s} = 0.8 \text{ psi}$$

$$\mu_{eff} = \frac{F_f}{N} = 0.2$$

The target cable burial system weighs 17,300 pounds wet; therefore,

$$N = 17{,}300 \text{ lb}$$

Selecting an allowable ground bearing pressure of 2 psi, the skid area required is

$$A_s = \frac{17{,}300 \text{ lb}}{2 \text{ lb/in.}^2} = 8{,}700 \text{ in.}^2$$

Therefore,

$$F_{f_{clay}} = \frac{1}{2} A_s S_{u_{eff}} = 3{,}500 \text{ lb}$$

$$F_{f_{sand}} = \mu_{eff} N = 3{,}500 \text{ lb}$$

Although these resistance values, coupled with those of several of the excavation candidates, result in total drawbar force within the target limitation of 10,000 pounds, it would be desirable to reduce the skid resistance to a minimum. It is reasonable to expect that a 50% reduction in motion resistance might be attained by forcing water between the skids and the soil to lubricate the interface. With a nominal skid area of 60 ft^2, each of two skids can be 4 x 8 feet long. The following assumptions are made

(a) Water flow from back of skids = machine speed

(b) Water flow from sides of skids = 50% machine speed

(c) Water layer = 1 in. thick

(d) Supply pressure = 10 psi

$$P = Q\,p = \left\{(0.083\ \text{ft})[8\ \text{ft} + (32\ \text{ft})(0.5)](1.69\ \text{ft/sec})\right\}$$
$$(10\ \text{lb/in.}^2)(144\ \text{in.}^2/\text{ft}^2)[\text{hp}/(550\ \text{ft-lb/sec})]$$

$$P = 9\ \text{hp}$$

Thus, an additional 9 hp may reduce the drawbar force required by 1,750 pounds for sand and for clay.

The major advantage of using skids to support the burial machine is their simplicity and reliability. However, their ability to negotiate obstacles is limited, the resistance prediction outlined above will be affected greatly by how much soil is pushed ahead of the skids, and the water lubrication technique is not proven technology and must be tested.

Rolling Elements. One means of reducing motion resistance due to the running gear/soil interface is to provide passive rolling elements such as tracks or wheels. Rolling elements have the capability to negotiate some obstacles, as discussed in the propulsion section. Liquid-filled tires can be designed to vary the nominal unit ground pressure, which could prove beneficial when different soil conditions are encountered. Bekkar [43] predicts that the motion resistance for wheels or tracks is 1,000 to 1,500 pounds, significantly less than that for unlubricated skids. Also, differential braking or articulation of the rolling elements can be an aid in machine steering. The drawbacks of rolling elements include their complexity (relative to skids) and the uncertainty in motion resistance and trafficability predictions.

Water Cushion Vehicle (WCV). A WCV is similar in concept to an air cushion vehicle, except that water flow and pressure is used to support the platform at the water/soil interface vice air at the air/water interface. A distinct advantage of the WCV concept is that the machine frame/soil interface is separated by a layer of low-pressure water. Thus, the motion resistance is reduced to that force necessary to shear the water layer, or essentially zero. Reference 45 describes a WCV concept which, assuming roughly half of the power supplied is used for thrust, requires approximately 750 hp for the cushion flow. Since the target cable burial system is half the size of the concept described in Reference 26, a WCV cable burier would require on the order of 375 hp for cushioning. Because the pressure is very low, the flow must be large, and there may be a significant problem with scouring under the vehicle. Although a WCV may provide a means of eliminating vehicle frame/soil resistance, it is an unproven concept, requires large amounts of power, may have stability problems, and its low (6-inch) ground clearance will cause problems in negotiating obstacles.

CONCEPT SELECTION

To make the concept selection from the various combinations of excavation, propulsion, and running gear subsystems, parameters were identified for comparing the combinations. Each parameter was also assigned a criticality or importance factor. Each system or subsystem was judged on its capability to meet the design parameters, and this capability was then weighted by the importance factor. In general, the higher the score, the better the system.

The importance factors were given the following values:

4: Essential for the system to meet its mission requirements.

3: Important from the standpoints of feasibility and meeting target design parameters.

2: Desirable, to increase reliability, probability of success, and to keep development time and costs within reason.

1: Little impact on the probability of success, but still important to system reliability, efficient performance, and ease of operation.

The performance and design parameters are discussed below in their order of importance. Score ranges are shown for each parameter in Tables 7 through 11.

Cable Damage Probability - (Weighting Factor: 4). An essential feature of a cable burial system is that it bury the cable without damaging it. Scores are biased to reflect that even a moderate chance of damaging the cable is unacceptable.

Total Power -(Weighting Factor: 3). The power to be supplied through an umbilical was calculated, and each concept rated according to its power level.

Force Requirements - (Weighting Factor: 3). The total motion resistance, including cable drag, soil resistance, and other drag forces, was calculated, and each concept rated according to its force level.

Soil Capability - (Weighting Factor: 3). The burial system must perform in sand and clay, and it would be ideal if it could cut rock as well. Concepts were downgraded significantly if they were limited to either sand or clay.

Steering/Control - (Weighting Factor: 3). Since the burial system must be capable of burying previously laid cables, a good capability for steering the machine to follow the cable is important. This factor also impacts on cable damage probability.

Target Weight/Size - (Weighting Factor: 2). Meeting the weight and size target values is desirable from the standpoint of ship handling, transportation, and ease of operation.

Ship Support Impact - (Weighting Factor: 2). The requirement that the system be operable from ships of opportunity was judged, taking into account ship power, control, handling, and predicted deck space requirements.

State-of-the-Art - (Weighting Factor: 2). Since a cable burial system is needed soon, concepts were downgraded if they required extensive research and development to prove their validity, or if the probability of success was judged to be poor.

Obstacle Effects - (Weighting Factor: 2). The obstacles considered in this category included buried or partially buried items such as rocks, cables, or debris. Concepts were downgraded if encountering such an obstacle would severely damage the machine or cable, or preclude continued operation.

Complexity - (Weighting Factor: 1). The complexity of the system impacts mainly on reliability and maintainability of the system. A complex system will require more comprehensive design and testing efforts, but will have minor impact on the eventual success of the system.

The selection process was done in two stages. The major subsystem candidates (excavation, propulsion and running gear/subsystems) were rated and selected, then the survivors were combined into the various overall system candidates, and these candidates were rated.

Excavation Subsystem (Table 7)

The candidates under consideration include vibratory plowing, water jetting, auger trenching, and trenching. For a climbmilling trencher, a score of 6 is possible as a bonus for aiding in propulsion. Vibratory plowing and water jetting scored the highest, specifically because of their low probability of damaging the cable, high probability of success, and minimal effect of buried obstacles. Climbmilling bucket trenching also scored well enough to be retained. Although the excavation method is relatively complicated, the force assistance is a considerable benefit. The other candidates were downgraded mainly in the complexity and effect of buried obstacles categories. Vibratory plowing, water jetting, and climbmilling bucket trenching are retained as candidate excavation subsystems.

Table 7 Excavation Subsystem

Subsystem	Power Input (hp) 0-50 5 50-150 4 150-300 3 300-500 2 >500 1	Force (kips) <0 6 0-1 5 1-2.5 4 2.5-5 3 5-10 2 >10 1	Soil* SCR 5 SC 4 S 1 C 1	Cable Damage Probability Very Low 5 Low 4 Med 1 High 0	Complexity Simple 5 Med 3 Very 1	Target Weight & Size Good 5 Prob 4 Chance 3 Not both 2 Neither 1	SOTA Yes 5 Not u/w 4 No, close 3 Quest 2 No 1	Buried Obstacle Effect Little 5 Some 4 Damage 2 Can't Handle 1	Total Score	Percentage
Weighting	3	3	3	4	1	3	2	2		
Possible	15	18	15	20	5	15	10	10	108	100
Vibratory plow (14 @ 0.39 = 36 hp)	5/15	4/12	4/12	5/20	3/3	3/9	4/8	4/8	87	81
Water jetting (Avg 256 hp)	3/9	5/15	4/12	5/20	5/5	3/9	5/10	5/10	90	83
Auger trenching (75 @ 0.39 = 192 hp)	3/9	4/12	4/12	4/16	1/1	3/9	2/4	2/4	67	62
Bucket trencher (climbmilling) (108 @ 0.39 = 277 hp)	3/9	6/18	4/12	5/20	1/1	3/9	2/4	2/4	77	71
Bucket trencher (upmilling) (108 @ 0.39 = 277 hp)	3/9	3/9	4/12	5/20	1/1	3/9	4/8	2/4	72	67
Wheel trencher (climbmilling) **(94 @ 0.39 = 241 hp)**	3/9	6/18	4/12	5/20	1/1	2/6	2/4	2/4	74	69
Wheel trencher (upmilling) (94 @ 0.39 = 241 hp)	3/9	3/9	4/12	5/20	1/1	2/6	4/8	2/4	69	64

* SCR – sand, clay, rock　S – sand
SC – sand, clay　C – clay

Table 8. Propulsion Subsystem

Subsystem	Power Input (hp)* 0-50 5 50-150 4 150-300 3 300-500 2 >500 1	Steering/Control Good 5 Med 3 Poor 1	Target Weight & Size Good 5 Prob 4 Chance 3 Not both 2 Neither 1	SOTA Yes 5 Not u/w 4 No, close 3 Quest 2 No 1	Complexity Simple 5 Med 3 Very 1	Support Ship Impact None 5 Little 4 Med 3 Great 1	Total Score	Percentage
Weighting	3	3	3	2	1	3		
Possible Score	15	15	15	10	5	15	75	100
Towing (0 power transmitted)	$\frac{5}{15}$	$\frac{1}{3}$	$\frac{5}{15}$	$\frac{5}{10}$	$\frac{5}{5}$	$\frac{1}{3}$	51	68
Track/wheel (31 @ 0.31 = 99 hp)	$\frac{4}{12}$	$\frac{5}{15}$	$\frac{3}{9}$	$\frac{2}{4}$	$\frac{1}{1}$	$\frac{4}{12}$	53	71
Thrusters (~31 @ 0.15 = 207 hp)	$\frac{3}{9}$	$\frac{5}{15}$	$\frac{4}{12}$	$\frac{5}{10}$	$\frac{3}{3}$	$\frac{4}{12}$	61	81
Alveolator (~175 hp)	$\frac{3}{9}$	$\frac{1}{3}$	$\frac{2}{6}$	$\frac{1}{2}$	$\frac{1}{1}$	$\frac{3}{9}$	30	40

* Required for 10,000-lb thrust @ 1 kt.

Table 9. Running Gear Subsystem

Subsystem	Power Input (hp) 0-50 5 50-150 4 150-300 3 300-500 2 >500 1	Resistance (kips) 0-1 5 1-2.5 4 2.5-5 3 5-10 2 >10 1	Complexity Simple 5 Some 4 Med 3 Very 1	SOTA Yes 5 Not u/w 4 No, close 3 Quest 2 No 1	Total Score	Percentage
Weighting	3	3	1	2		
Possible score	15	15	5	10	45	100
Skids (lubricated)	$\frac{5}{15}$	$\frac{4}{12}$	$\frac{4}{4}$	$\frac{2}{4}$	35	78
Skids (unlubricated)	$\frac{5}{15}$	$\frac{3}{9}$	$\frac{5}{5}$	$\frac{5}{10}$	39	87
Rolling elements	$\frac{5}{15}$	$\frac{4}{12}$	$\frac{3}{3}$	$\frac{4}{8}$	38	84
Water cushion vehicle	$\frac{2}{6}$	$\frac{5}{15}$	$\frac{1}{1}$	$\frac{1}{2}$	24	53

Table 10. Power and Force Summary

Concept No.	Subsystem	Force Required (lb)	Subsystem Power Out (hp)	Efficiency	Input Power	Total Transmitted Power	Percent-age**
1	**Skids (lub)** **Vib plow** **Towing**	1,750 2,200 7,850*	10 14 24	0.69 0.39 –	14 36 –	50	67
2	**Skids (unlub)** **Vib plow** **Towing**	3,500 2,200 9,600*	0 0 29	– – –	– – –	36	67 67
3	**Rolling elements** **Vib plow** **Towing**	1,500 2,200 7,600*	0 14 23	– 0.39 –	– 36 –	36	62
4	**Skids (lub)** **Water jet** **Towing**	1,750 0 5,650*	10 – 17	0.69 – –	14 256 –	270	66
5	**Skids (unlub)** **Water jet** **Towing**	3,500 0 7,400*	0 – 23	– – –	– 256 –	256	66
6	**Rolling elements** **Water jet** **Towing**	1,500 0 5,400*	0 – 17	– – –	– 256 –	256	59
7	**Skids (lub)** **Trenching** **Towing**	1,750 -2,620 3,030*	10 108 9	0.69 0.39 –	14 277 –	291	57

(continued)

Table 10. Continued

Concept No.	Subsystem	Force Required (lb)	Subsystem Power Out (hp)	Efficiency	Input Power	Total Transmitted Power	Percent-age**
8	Skids (unlub)	3,500	0	–	–	277	57
	Trenching	-2,620	108	0.39	277		
	Towing	4,780*	15	–	–		
9	Rolling elements	1,500	0	–	–	277	54
	Trenching	-2,620	108	0.39	277		
	Towing	2,780*	9	–	–		
10	Rolling elements	1,500	0	–	–	110	74
	Vib plow	2,200	14	0.39	36		
	Track	7,600*	23	0.31	74		
11	Rolling elements	1,500	0	–	–	311	70
	Water jet	0	–	–	256		
	Track	5,400*	17	0.31	55		
12	Rolling elements	1,500	0	–	–	306	67
	Trenching	-2,650	108	0.39	277		
	Track	2,780*	9	0.31	29		
13	Skids (lub)	1,750	10	0.69	14	211	75
	Vib plow	2,200	14	0.39	36		
	Thruster	7,850*	24	0.15	161		

(continued)

Table 10. Continued

Concept No.	Subsystem	Force Required (lb)	Subsystem Power Out (hp)	Efficiency	Input Power	Total Transmitted Power	Percentage**
14	Skids (unlub) Vib plow Thruster	3,500 2,200 9,600*	0 14 29	– 0.39 0.15	– 36 197	233	75
15	Rolling elements Vib plow Thruster	1,500 2,200 7,600*	0 14 23	– 0.39 0.15	– 36 153	189	72
16	Skids (lub) Water jet Thruster	1,750 0 5,650*	10 – 17	0.69 – 0.15	14 256 116	386	77
17	Skids (unlub) Water jet Thruster	3,500 0 7,400*	0 – 23	– – 0.15	– 256 152	408	75
18	Rolling elements Water jet Thruster	1,500 0 5,400*	0 – 17	– – 0.15	– 256 113	369	72
19	Skids (lub) Trenching Thruster	1,750 -2,620 3,030*	10 108 9	0.69 0.39 0.15	14 277 62	353	66
20	Skids (unlub) Trenching Thruster	3,500 -2,620 4,780*	0 108 15	– 0.39 0.15	– 277 98	375	66

(continued)

Table 10. Continued

Concept No.	Subsystem	Force Required (lb)	Subsystem Power Out (hp)	Efficiency	Input Power	Total Transmitted Power	Percent-age**
21	Rolling elements	1,500	0	–	–	337	66
	Trenching	-2,620	108	0.39	277		
	Thruster	2,780*	9	0.15	60		

* Includes:
Cable drag = 3,400
Machine drag = 500
See Appendix D.

** See Table 11.

Table 11. Overall Rating

Concept	Total Power (hp) 0-50 5 50-150 4 150-300 3 300-500 2 >500 1	Total Force (kips) 0-1 5 1-2.5 4 2.5-5 3 5-10 2 >10 1	Soil SCR 5 SC 4 C 1 S 1	Cable Damage Probability Very low 5 Low 4 Med 1 High 0	Steering/ Control Very good 5 Good 4 Med 3 Fair 2 Poor 1	Target wt/ Size Prob Good 5 Prob 4 Chance 3 Not both 2 Neither 1	Ship Support Impact None 5 Little 4 Some 3 Moderate 2 Great 1	No. of Complex System 0 5 1 4 2 3 3 2	SOTA Yes 5 Not u/w 4 No, close 3 Quest. 2 No 1	Obstacle Effects Little 5 Some 4 Damage 2 Can't Handle 1	Total Score	Percent-age
Weight	3	3	3	4	3	2	2	1	2	2		
Possible	15	15	15	20	15	10	10	5	10	10	125	100
1	5/15	2/6	4/12	4/16	1/3	5/10	1/2	4/4	4/8	4/8	84	67
2	5/15	2/6	4/12	4/16	1/3	5/10	1/2	4/4	4/8	4/8	84	67
3	5/15	2/6	4/12	4/16	1/3	4/8	1/2	3/3	2/4	4/8	77	62
4	3/9	2/6	4/12	4/16	1/3	5/10	1/2	5/5	5/10	5/10	83	66
5	3/9	2/6	4/12	4/16	1/3	5/10	1/2	5/5	5/10	5/10	83	66
6	3/9	2/6	4/12	4/16	1/3	4/8	1/2	4/4	2/4	5/10	74	59
7	3/9	3/9	4/12	4/16	1/3	4/8	1/2	4/4	2/4	2/4	71	57
8	3/9	3/9	4/12	4/16	1/3	4/8	1/2	4/4	2/4	2/4	71	57
9	3/9	3/9	4/12	4/16	1/3	3/6	1/2	3/3	2/4	2/4	68	54
10	4/12	2/6	4/12	5/20	5/15	3/6	4/8	2/2	2/4	4/8	93	74
11	2/6	2/6	4/12	5/20	5/15	3/6	4/8	3/3	2/4	4/8	88	70

(continued)

Table 11 Continued

Concept	Total Power (hp) 0-50 5 50-150 4 150-300 3 300-500 2 >500 1	Total Force (kips) 0-1 5 1-2.5 4 2.5-5 3 5-10 2 >10 1	Soil SCR 5 SC 4 C 1 S 1	Cable Damage Probability Very low 5 Low 4 Med 1 High 0	Steering/ Control Very good 5 Good 4 Med 3 Fair 2 Poor 1	Target wt/ Size Prob Good 5 Prob 4 Chance 3 Not both 2 Neither 1	Ship Support Impact None 5 Little 4 Some 3 Moderate 2 Great 1	No. of Complex System 0 5 1 4 2 3 3 2	SOTA Yes 5 Not u.w. 4 No. close 3 Quest 2 No 1	Obstacle Effects Little 5 Some 4 Damage 2 Can't Handle 1	Total Score	Percentage
Weight	3	3	3	4	3	2	2	1	2	2		
Possible	15	15	15	20	15	10	10	5	10	10	125	100
12	$\frac{3}{9}$	$\frac{3}{9}$	$\frac{4}{12}$	$\frac{5}{20}$	$\frac{4}{12}$	$\frac{2}{4}$	$\frac{4}{8}$	$\frac{2}{2}$	$\frac{2}{4}$	$\frac{2}{4}$	84	67
13	$\frac{3}{9}$	$\frac{2}{6}$	$\frac{4}{12}$	$\frac{5}{20}$	$\frac{4}{12}$	$\frac{4}{8}$	$\frac{4}{8}$	$\frac{3}{3}$	$\frac{4}{8}$	$\frac{4}{8}$	94	75
14	$\frac{3}{9}$	$\frac{2}{6}$	$\frac{4}{12}$	$\frac{5}{20}$	$\frac{4}{12}$	$\frac{4}{8}$	$\frac{4}{8}$	$\frac{3}{3}$	$\frac{4}{8}$	$\frac{4}{8}$	94	75
15	$\frac{3}{9}$	$\frac{2}{6}$	$\frac{4}{12}$	$\frac{5}{20}$	$\frac{5}{15}$	$\frac{3}{6}$	$\frac{4}{8}$	$\frac{2}{2}$	$\frac{2}{4}$	$\frac{4}{8}$	90	72
16	$\frac{2}{6}$	$\frac{2}{6}$	$\frac{4}{12}$	$\frac{5}{20}$	$\frac{4}{12}$	$\frac{4}{8}$	$\frac{4}{8}$	$\frac{4}{4}$	$\frac{5}{10}$	$\frac{5}{10}$	96	77
17	$\frac{2}{6}$	$\frac{2}{6}$	$\frac{4}{12}$	$\frac{5}{20}$	$\frac{4}{12}$	$\frac{4}{8}$	$\frac{3}{6}$	$\frac{4}{4}$	$\frac{5}{10}$	$\frac{5}{10}$	94	75
18	$\frac{2}{6}$	$\frac{2}{6}$	$\frac{4}{12}$	$\frac{5}{20}$	$\frac{5}{15}$	$\frac{3}{6}$	$\frac{4}{8}$	$\frac{3}{3}$	$\frac{2}{4}$	$\frac{5}{10}$	90	72
19	$\frac{2}{6}$	$\frac{3}{9}$	$\frac{4}{12}$	$\frac{5}{20}$	$\frac{3}{9}$	$\frac{4}{8}$	$\frac{4}{8}$	$\frac{3}{3}$	$\frac{2}{4}$	$\frac{2}{4}$	83	66
20	$\frac{2}{6}$	$\frac{3}{9}$	$\frac{4}{12}$	$\frac{5}{20}$	$\frac{3}{9}$	$\frac{4}{8}$	$\frac{4}{8}$	$\frac{3}{3}$	$\frac{2}{4}$	$\frac{2}{4}$	83	66
21	$\frac{2}{6}$	$\frac{3}{9}$	$\frac{4}{12}$	$\frac{5}{20}$	$\frac{4}{12}$	$\frac{3}{6}$	$\frac{4}{8}$	$\frac{2}{2}$	$\frac{2}{4}$	$\frac{2}{4}$	83	66

Propulsion Subsystem (Table 8)

Propulsion system candidates include towing, tracks/wheels, thrusters, and the alveolator concept. Note that the power input for towing is zero since it is assumed that the support ship already has the shaft horsepower for towing. Towing was downgraded mainly in the limitations it places on the support ship and in steering/control, which impacts on its ability to bury previously laid cables. Nevertheless, towing scored high in other areas and is retained as a propulsion candidate. Tracks/wheels scored low in the state-of-the-art and complexity areas, but scored well enough in control and ship support requirements to be retained. Thrustors scored the highest in spite of the high power requirement. The alveolator concept was discarded due to its complexity, the fact that it is unproven, and the predicted difficulty in controlling its direction. Thus, the remaining propulsion concepts are towing, track/wheel, and thrusters.

Running Gear Subsystem (Table 9)

The potential candidates include lubricated and unlubricated skids, rolling elements (wheels or tracks), and a water cushion vehicle (WCV). The WCV scored very low in power, complexity, and state-of-the-art areas, and, therefore, was eliminated. Of the remaining concepts, it remains questionable whether or not lubrication will effect the predicted force reduction; therefore, lubricated skids were rated questionable in the state-of-the-art parameter. Nevertheless, the score was high enough to retain lubricated skids along with unlubricated skids and rolling elements.

Overall System Evaluation (Tables 10 and 11)

The excavation, propulsion, and running gear subsystems that were retained were combined in all possible ways to select the best overall concepts. Table 10 presents a force and power summary of the twenty-one combinations. Note that the ship power required for towing is not included in the power estimate. Also, the concepts with track/wheel propulsion have rolling elements for the running gear subsystem because of the propulsion subsystem.

Each concept is rated in Table 11. The results show that all the concepts that included trenching as the excavation means scored low no matter what the other subsystems were. These low scores are due mainly to complexity, obstacle effects, chance of success, and, to some extent, power. Towing also scored low in all combinations because of the lack of steering control, and the impact on ship support requirements. The four best scoring combinations are:

Concept	Excavation Subsystem	Propulsion Subsystem	Running Gear Subsystem
16 and 17	Water Jet	Thruster	Skids (lubricated or unlubricated)
13 and 14	Vibratory Plow	Thruster	Skids (lubricated or unlubricated

SUMMARY

1. Water jet trenching is basically simple and proven technology, but it requires more power than other trenching systems to excavate at a speed of 1 knot. Water jet trenching is particularly suited to burying repeaters and cable anomalies.

2. Trenching augers must rotate at approximately 5,000 rpm to trench at 1 knot and are susceptible to damage from rocks buried in the soil.

3. Conventional (upmilling) trenching has a high resistance force, is susceptible to damage when encountering buried obstacles, and the 1-knot speed requirement is in excess of normal maximum trenching speeds.

4. Climbmilling trenching provides a very desirable propulsion assistance force, but is susceptible to damage from buried obstacles, requires too much power, and may be unsuitable for the high excavation rate resulting from 1-knot forward speed requirement.

5. Vibratory plowing has been shown to reduce normal plowing resistance forces by 90-99% on land, is relatively insensitive to damage from buried obstacles, and has achieved speeds in excess of 1 knot in some land soils. In addition, the vibration allows the plow to achieve and maintain maximum penetration; thus, the burial machine can be made lighter. Vibration also aids in dislodging subsoil rocks. The power requirement is in the middle of the acceptable range, and the system is basically uncomplicated. Auxiliary devices must be employed to bury repeaters and cable anomalies.

6. Towing for primary propulsion imposes unacceptable constraints on the support ship. The ship must have adequate power to tow the system and must maintain a precise heading and course while traveling at 1 knot. This quality of control requires bow thrusters and, ideally, stern thrusters as well as excellent navigation feedback between the ship and the burying machine. Also, towing allows only gross course changes of the burying machine. Towing via the umbilical cable may be employed as an auxiliary propulsion means for a self-propelled burial system.

7. The oscillating disk propulsion means is unproven technology, may result in a cumbersome and complex system, and may lead to steering and control difficulties.

8. Track/wheel propulsion has excellent steering and control features, may prove to have good slope-climbing and obstacle-climbing ability, and requires nominal power. However, tracking depends on the seafloor soil properties and may not allow selecting one configuration which will perform in all soils. Generating thrust with tracks or wheels has not been proven for seafloor operation.

9. Thrusters (shrouded props) are proven in deep ocean use, and their performance can be predicted since they depend on a known media (water) for thrust. They can be controlled easily in both magnitude and direction of thrust to provide excellent steering and control capabilities. Thrusters lend themselves to direct drive with electric motors that reduces power conversion losses, compensating for the inefficiency of the thrusters themselves.

10. Skids are the least complicated running gear for a bottom-traversing machine and have been used successfully in the past. The force required to move unlubricated skids is near 4,000 pounds, but it is expected that this force can be reduced by water lubricating the contact surface.

11. Rolling elements, such as tracks or wheels, reduce resistance to motion and can provide some steering control by differential braking. They must be large to reduce the nominal unit ground pressure. Since they are rotating, they are somewhat complicated and are susceptible to jamming from sediment.

12. The water cushion vehicle is an unproven concept, requires large amounts of power, and the skirt flow may wash away the soil and cause the system to jet itself into the seafloor. Vertical stability may cause burial depth variations, and the small skirt clearance makes it difficult to operate in non-level terrain.

CONCLUSIONS

1. It is concluded that the deep-ocean burial system concept with the best chance of success, which will provide positive burial depth and which meets power, weight, size, ship support, and speed requirements, is comprised of the following major subsystems.

Excavation subsystem - vibratory plowshare or water jet

Propulsion subsystem - self propelled by thrusters

Running gear subsystem - lubricated skids

2. The primary operating mode should be the burial of previously laid cables so that (1) the support ship need not be a cable layer, (2) problems with the cable-burying operation will not threaten the cable-laying operation, and (3) repair sections or existing cables can be buried. Towing may be used as an alternate propulsion means.

3. The auxiliary systems required include:

(a) Cable guide mechanism, hydraulically controlled to attach to and lift cable into feed shoe.

(b) Cable following sensors which feed data to machine control system to steer the burying machine along the cable route.

(c) If vibratory plowing is the final excavation subsystem, a jet pump system capable of burying repeaters, hockles, kinks or cable anomalies which cannot be fed through the feed shoe.

(d) Fail-safe means to allow disengaging the cable should the burial machine fail.

(e) Magnetometer or other device for locating previously laid cable.

(f) Obstacle avoidance sonar system.

(g) Television and hydrophones.

RECOMMENDATIONS

It is recommended that preliminary investigation, including model studies, in the following areas be initiated in order to validate the conclusions drawn in this report.

1. Determine the drawbar force reduction resulting from an upward cutting vibratory plow in typical seafloor soils. Determine the optimum frequency and amplitude as a function of soil type and speed of advance.

2. Investigate the effect of water lubricating skids and feed shoes as a function of water pressure, nominal unit ground pressure, and flow rate.

3. Validate the pressure and flow required for jetting a 36-inch-deep trench in seafloor soils.

Track/wheel propulsion scored highly in most categories, and might be expected to result in a more efficient, more easily controlled, and more versatile cable burial system than the propulsion subsystem selected. However, supportive information, tests, or experience with tracked systems are not available, and, as such, these candidates were downgraded principally because their probability of success is questionable. It is recommended that research, development, and testing be performed to determine whether track/wheel vehicles are capable of meeting the needs of a cable burial system. Specifically, the drawbar force that such a system can generate, its slope-climbing ability, and its obstacle-handling capabilities in typical seafloor soils should be determined.

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Appendix A

PLOW RESISTANCE FORCE AND POWER ANALYSIS

From Reference 36, the static soil resistance for a plowshare moving through a cohesive soil (clay) is given by

$$F_s = S_u A_s + S_u N_c A_f$$

where F_s = Static soil resistance (lb)

S_u = Undrained shear strength (4 lb/in.^{2})

A_s = Side area of plow (in.^{2})

N_c = Dimensionless coefficient ($\simeq$ 10)

A_f = Plow frontal area (in.^{2})

As the velocity of the plow increases, the static soil resistance must be modified by a velocity coefficient, C_v (Figure A-1), and an inertial term, F_I, must be added:

$$F_I = \frac{1}{2} \rho A_f C_D v^2$$

where ρ = soil mass density ($\simeq$ 3 lb-sec^2/ft^4)

C_D = drag coefficient (0.7 to 1.5)

v = velocity (ft/sec)

The total force, then, is

$$F_{TOT} = C_v F_s + F_I$$

For the problem at hand, we have plow and feed shoe dimensions (Figure A-2).

$$w = 4 \text{ in.}$$

$$h = 36 \text{ in.}$$

$$\ell = 120 \text{ in.}$$

$$C_v = 1.09$$

Thus,

$$A_s = 2 h\ell = (2)(36 \text{ in.})(120 \text{ in.}) = 8{,}640 \text{ in.}^2$$

$$A_f = w\ h = (4 \text{ in.})(36 \text{ in.}) = 144 \text{ in.}^2$$

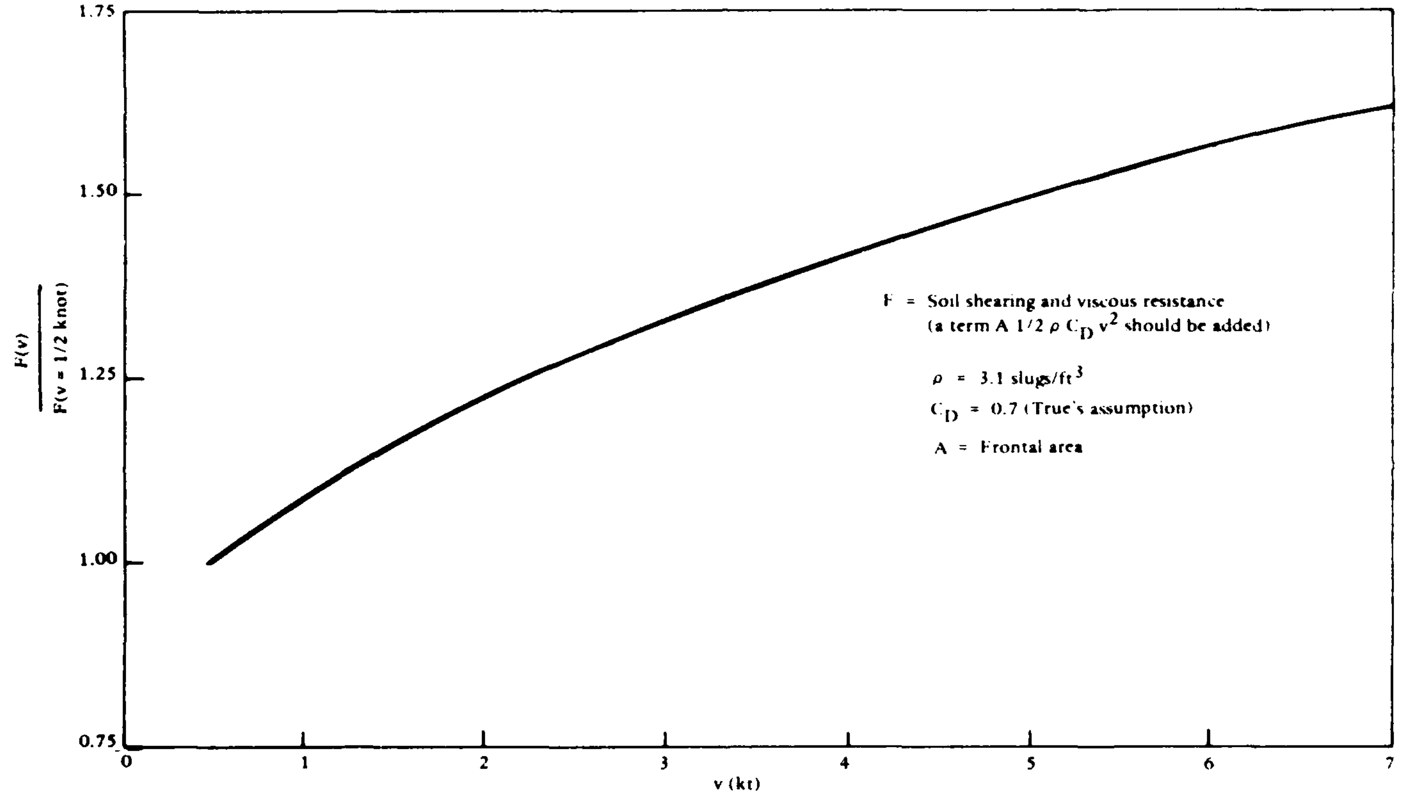
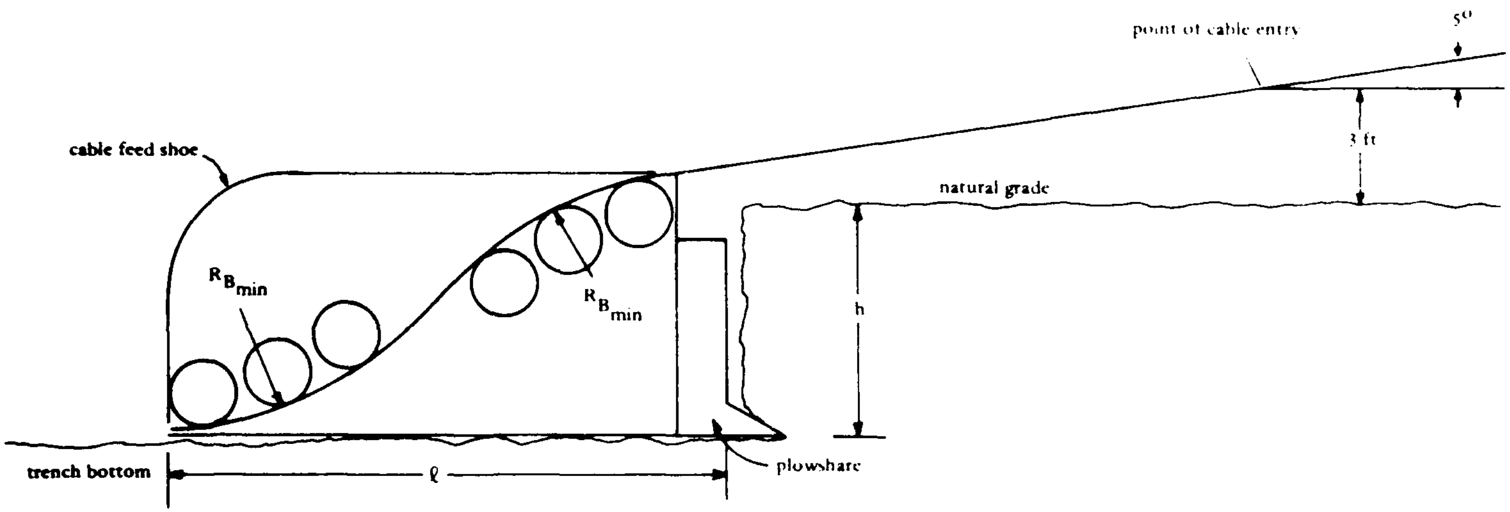


Figure A-1. Velocity dependency of soil shearing and viscous resistance.

Minimum bending radius, R_B = 3.5 ft ~ 5 ft
Burial depth, D = 3 ft
Plow width, ω = 4 in.



feed shoe	ℓ	h	ω
cable	9 ft	3 ft	4 in.
plow	1 ft	3 ft	4 in.

Figure A-2. Cable plow/feed shoe size estimates.

For clay, then

$$F_{TOT} = (1.09)\left[(4\ \text{lb/in.}^2)(8{,}640\ \text{in.}^2) + (4\ \text{lb/in.}^2)(10)(144\ \text{in.}^2)\right]$$

$$+ \frac{1}{2}\ (3\ \text{lb-sec}^2/\text{ft}^4)(1\ \text{ft}^2)(1.5)(1.69\ \text{ft/sec})^2$$

$$= (1.09)(34{,}560 + 5{,}760) + 6$$

$$\boxed{F_{TOT} = 44{,}000\ \text{lb}}$$

Achieving a 95% reduction in force due to upward soil cutting vibration gives

$$\boxed{F_{TOT_{\text{reduced}}} = 2{,}200\ \text{lb}}$$

In cohesionless soils, (sand) the situation is much the same, but F_s is given by

$$F_s = \frac{\gamma_b\ N_q\ A_f\ D}{2} + \frac{\gamma_b\ A_s\ \mu\ D}{2}$$

where γ_b = Soil buoyant unit weight ($\simeq$ 40 lb/ft^3)

N_q = Dimensionless parameter ($\simeq$ 90 for friction angle $\phi = 40^\circ$)

D = Depth of embedment (ft)

μ = Friction coefficient ($\simeq$ 0.5)

Therefore, we have

$$F_{TOT} = C_v\ F_s + F_I$$

$$= (1.09)\left[\frac{(40\ \text{lb/ft}^3)(90)(1\ \text{ft}^2)(3\ \text{ft})}{2} + \frac{(40\ \text{lb/ft}^3)(60\ \text{ft}^2)(0.5)(3\ \text{ft})}{2}\right]$$

$$+ 6$$

$$= 1.09(5{,}400 + 1{,}800) + 6$$

$$F_{TOT} = 7{,}900\ \text{lb}$$

A 95% force reduction due to vibration gives

$$\boxed{F_{TOT_{\text{reduced}}} = 400\ \text{lb}}$$

Thus, it can be seen that clay soils exhibit the worst case for drawbar pull requirements.

In order to determine the power required to vibrate the plow (the feed shoe is isolated from the plowshare to prevent cable damage and reduce power requirements for vibration), consider a vibrating mass

$$x = A \sin \omega t$$

where A = the amplitude

ω = the frequency

Then

$$\dot{x} = A \omega \cos \omega t$$

$$\ddot{x} = -A \omega^2 \sin \omega t$$

Instantaneous power is given by

$$P = F v = m \ddot{x} \dot{x}$$

$$= - m A^2 \omega^3 \sin \omega t \cos \omega t$$

$$P = - m \frac{A^2 \omega^3}{2} \sin 2 \omega t$$

The power which must be supplied is the root mean squared power, or

$$P_{rms} = \left(\frac{1}{T} \int_0^T P^2 \, dt \right)^{1/2}$$

where the period $T = 1/f = 2 \pi/\omega$

$$P_{rms} = \left[\frac{\omega}{2\pi} \int_0^{2\pi/\omega} \left(- \frac{m A^2 \omega^3}{2} \right)^2 \sin^2 2 \omega t \, dt \right]^{1/2}$$

$$= \left(\frac{m A^2 \omega^3}{2} \right) \left(\frac{\omega}{2\pi} \right)^{1/2} \left(\int_0^{2\pi/\omega} \sin^2 2 \omega t \, dt \right)^{1/2}$$

$$= \left(\frac{m\ A^2\ \omega^3}{2}\right)\left(\frac{\omega}{2\pi}\right)^{1/2} \left(\frac{t}{2} - \frac{\sin\ 4\ \omega\ t}{8\omega}\Bigg|_0^{2\pi/\omega}\right)^{1/2}$$

$$P_{rms} = \frac{m\ A^2\ \omega^3}{2\ \sqrt{2}}$$

For the steel plowshare, triangular in cross section with ω = 4 inches and ℓ = 12 inches, one has

$$m = \frac{\rho V}{g} = \frac{\rho\left(\frac{1}{2}\ \ell\ \omega\ h\right)}{g}$$

$$= \frac{(0.28\ \text{lb/in.}^3)(0.5)(4\ \text{in.})(12\ \text{in.})(36\ \text{in.})}{384\ \text{in./sec}^2}$$

$$= 0.63\ \text{lb-sec}^2/\text{in.}$$

From References 13 and 14 one selects

$$A = 0.25\ \text{in.}$$

$$f = 1{,}800\ \text{rpm or}\ \omega = 188.5\ \text{rad/sec}$$

Therefore,

$$P_{rms} = \frac{(0.63\ \text{lb-sec}^2/\text{in.})(0.25\ \text{in.})^2(188.5\ \text{rad/sec})^3(\text{ft}/12\ \text{in.})}{2\sqrt{2}} \left(\frac{\text{hp}}{500\ \text{ft-lb/sec}}\right)$$

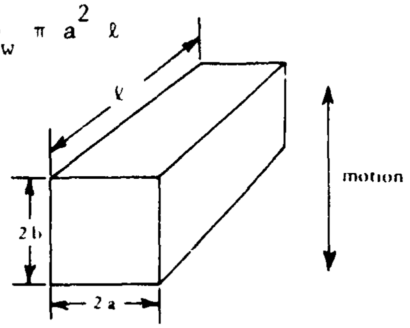
$$\boxed{P_{rms} = 14\ \text{hp}}$$

For A = 0.375

$$P_{rms} = 32\ \text{hp}$$

In addition to the mass of the plow, a mass of water, the added mass, will also be accelerated and will add to the power requirement. Approximating the triangular plowshare cross section with a rectangular cross section, the added mass is given by (Reference 46):

$$m_a = K_1 \rho_w \pi a^2 \ell$$



$$P = m_a \ddot{x} \dot{x}$$

$$= - K_1 \rho_w \pi a^2 \ell A^2 \omega^3 \sin \omega t \cos \omega t$$

$$= \frac{- K_1 \rho_w \pi a^2 \ell A^2 \omega^3 \sin 2 \omega t}{2}$$

where $x = A \sin \omega t$

$\dot{x} = A \omega \cos \omega t$

$\ddot{x} = - A \omega^2 \sin \omega t$

The power which must be supplied is the rms power

$$P_{rms} \triangleq \left(\frac{1}{T} \int_0^T P^2 \, dt \right)^{1/2}$$

where the period $T = 1/f = 2 \pi/\omega$

$$P_{rms} = \left[\frac{\omega}{2\pi} \int_0^{2\pi/\omega} \left(\frac{K_1 \rho_w \pi a^2 \ell A^2 \omega^3}{2} \right)^2 \sin^2 2 \omega t \, dt \right]^{1/2}$$

$$= \left(\frac{K_1 \rho_w \pi a^2 \ell A^2 \omega^3}{2} \right) \left(\frac{\omega}{2\pi} \right)^{1/2} \left(\frac{t}{2} - \frac{\sin 4 \omega t}{8 \omega} \Bigg|_0^{2\pi/\omega} \right)^{1/2}$$

$$= \frac{K_1 \rho_w \pi a^2 \ell A^2 \omega^3}{2 \sqrt{2}}$$

The approximated triangular plowshare is a 2 x 12-inch rectangular rod, 36 inches deep.

$$a = 1 \text{ in.} \approx 0.083 \text{ ft}$$

$$\ell = 1 \text{ ft}$$

$$A = 0.021 \text{ ft}$$

$$\omega = 189 \text{ rad/sec}$$

$$a/b = 1/18 = 0.056, \qquad K = 2.23 \text{ (Reference 46)}$$

$$P_{rms} = \frac{(2.23)(2 \text{ lb-sec}^2/\text{ft}^4)(\ )(0.083 \text{ ft})^2(1 \text{ ft})(0.021 \text{ ft})^2(189 \text{ rad/sec})^3}{2\sqrt{2}} \left(\frac{\text{hp}}{550 \text{ ft-lb/sec}}\right)$$

$$P_{rms} = 0.2 \text{ hp}$$

which is negligible.

Appendix B

EXCAVATION ANALYSIS FOR TRENCHING

CHAIN-DRIVEN BUCKET TRENCHER

In order to calculate the forces required to excavate a trench, some trencher configuration must be selected. From Reference 47 one selects

chain speed = 9.2 ft/sec

bucket distribution = 1 bucket/ft

The other parameters required are as follows (Figure B-1):

Depth of cut, $D = 3$ ft

Width of cut, $w = 4$ in.

Speed of advance, $v = 1.69$ ft/sec

Soil shear strength, $S_u = 4\ \text{lb/in.}^2$

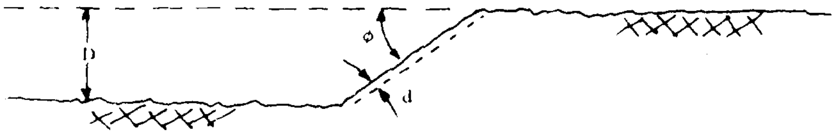


Figure B-1. Trench configuration.

The total force required to cut the soil is the sum of the soil bearing resistance and the soil shearing resistance (friction) [38] or

$$F_{TOT} = F_b + F_f = A_f N_c S_u + \frac{A_s S_u}{2}$$

where F_{TOT} = total cutting force required

F_b = soil bearing resistance

F_f = soil shearing resistance (friction)

A_f = frontal area

N_c = factor $\simeq 3$

A_s = shear area

Select ϕ = 60 degrees and the bucket length ℓ_b = 8 inches. The bucket rate is

$$\dot{B} = \frac{\text{chain speed}}{\text{bucket distribution}} = \frac{9.2\ \text{ft/sec}}{1\ \text{bucket/ft}} = 9.2\ \text{buckets/sec}$$

Soil removal volume rate required is

$$\dot{V} = w\ D\ v = (0.33\ \text{ft})(3\ \text{ft})(1.69\ \text{ft/sec}) = 1.69\ \text{ft}^3/\text{sec}$$

Then the bucket volume must be

$$V_b = \frac{\dot{V}}{\dot{B}} = \frac{1.69\ \text{ft}^3/\text{sec}}{9.2\ \text{bucket/sec}} = 0.18\ \text{ft}^3/\text{bucket}$$

The depth of cut for each bucket is found by

$$V_b = w\ d\ \ell_b$$

or

$$d = \frac{V_b}{w\ \ell_b} = \frac{0.18\ \text{ft}^3}{(0.33\ \text{ft})(0.67\ \text{ft})} = 0.83\ \text{ft} = 10\ \text{in.}$$

Thus, for each bucket,

$$A_f = w\ d = (4\ \text{in.})(10\ \text{in.}) = 40.0\ \text{in.}^2$$

and

$$A_s = (w + 2\ d)\ell_b = [4\ \text{in.} + 2(10.0\ \text{in.})](8\ \text{in.}) = 192\ \text{in.}^2$$

Using these values in Equation B-1, one has

$$F_{\text{TOT per bucket}} = S_u \left(A_f\ N_c + \frac{A_s}{2}\right)$$

$$= (4\ \text{lb/in.}^2) \left[(40.0\ \text{in.}^2)(3) + \frac{192\ \text{in.}^2}{2}\right]$$

$$\boxed{F_{\text{TOT}} = 864\ \text{lb/bucket}}$$

An additional force is that required to lift the soil from the trench

$$F_{lift/bucket} = V_b \rho_s \sin \theta$$

where ρ_s = soil density = 100 lb/ft^3

$$F_{lift} = (0.18 \text{ ft}^3/\text{bucket})(100 \text{ lb/ft}^3) \sin 60^\circ = 16 \text{ lb/bucket}$$

The maximum force which will be applied is the sum of the lift force and total force times the number of buckets in contact with the soil.

$$N_b = \frac{D}{\sin \theta} \text{ (bucket distribution)} = \frac{3 \text{ ft}}{\sin 60^\circ} \text{ (1 bucket/ft)}$$

$$= 3.5 \text{ buckets}$$

$$F_{max} = (F_{TOT} + F_{lift})\, N_b$$

$$= (864 \text{ lb/bucket} + 16 \text{ lb/bucket})(3.5 \text{ buckets}) = 3{,}080 \text{ lb}$$

The torque required

$$\tau_{max} = F_{max}(\text{moment arm}) = F_{max}(r + d)$$

where r is the chain drive radius = 0.75 ft (Reference 47)

$$\tau_{max} = (3{,}080 \text{ lb})(0.75 \text{ ft} + 0.82 \text{ ft}) = 4{,}840 \text{ ft-lb}$$

The angular velocity is

$$\omega = \frac{\text{chain speed}}{2\pi r}\left(\frac{2\pi \text{ rad}}{\text{rev}}\right) = \left(\frac{9.2 \text{ ft/sec}}{\pi(1.5 \text{ ft})}\right) 2\pi = 12.3 \text{ rad/sec}$$

Then,

$$P_{max} = \tau_{max}\,\omega$$

$$= (4{,}840 \text{ ft-lb})(12.3 \text{ rad/sec})\left(\frac{\text{hp}}{550 \text{ ft-lb/sec}}\right)$$

$$\boxed{P_{max} = 108 \text{ hp}}$$

The forces acting on the trencher are as follows:

Case 1: Trencher rotating in conventional (upmilling) direction

$$F_{UP} = -F_{TOT}\ N_b \sin\phi - F_{lift}\ N_b$$

$$= (-864\ \text{lb})(3.5) \sin 60^\circ - (16\ \text{lb})(3.5)$$

$$\boxed{F_{UP} = -2{,}675\ \text{lb}}$$

$$F_{FWD} = -F_{TOT}\ N_b \cos\phi$$

$$= -(864\ \text{lb})(3.5)(\cos 60^\circ)$$

$$\boxed{F_{FWD} = -2{,}620\ \text{lb}}$$

Case 2: Trencher rotating in forward direction (climbmilling)

$$F_{UP} = F_{TOT}\ N_b \sin\phi - F_{lift}\ N_b$$

$$= (864\ \text{lb})(3.5) \sin 60^\circ - (16\ \text{lb})(3.5)$$

$$\boxed{F_{UP} = 2{,}560\ \text{lb}}$$

$$F_{FWD} = F_{TOT}\ N_b \cos\phi$$

$$\boxed{F_{FWD} = 2{,}620\ \text{lb}}$$

EXCAVATING WHEEL

The same parameters and assumptions apply as in the chain-driven bucket trencher, and the development is basically the same.

Tip speed = 9.2 ft/sec
Bucket distribution = 1 bucket/ft
Bucket length, ℓ_b = 8 in.
Wheel diameter = 8 ft

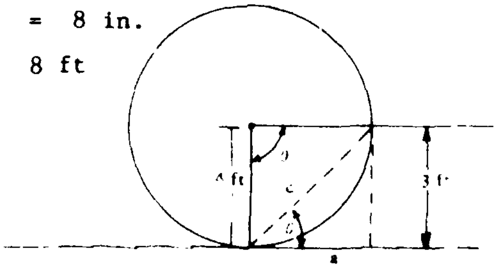


Figure B-2. Excavating wheel configuration.

From Figure B-2

$$a = 4^2 - 1^2 = 3.9 \text{ ft}$$

$$b = 3.0 \text{ ft}$$

$$\tan \phi = \frac{b}{a} \therefore \phi \quad 38^{\circ} = 0.66 \text{ rad}$$

also,

$$\theta = \cos^{-1} \frac{1}{4} = 75.5^{\circ} = 1.32 \text{ rad}$$

Therefore, arc $c = \theta r = 5.3$ ft

$\dot{B}$, $\dot{V}$, V_b, d, A_f, and A_s are the same as for the chain-driven bucket trencher; therefore,

$$F_{TOT} = 864 \text{ lb/bucket}$$

and

$$F_{lift} = 16 \text{ lb/bucket}$$

The number of buckets in contact with the soil

$$N_b = (\text{arc } c)(\text{bucket distribution}) = 5.3 \text{ buckets}$$

$$F_{max} = (F_{TOT} + F_{lift})N_b = (864 \text{ lb} + 16 \text{ lb})(5.3) = 4{,}460 \text{ lb}$$

$$\tau_{max} = F_{max}(\text{moment arm}) = (4{,}660 \text{ lb})(4 \text{ ft} + 0.82 \text{ ft}) = 22{,}000 \text{ lb-ft}$$

The angular velocity is

$$\omega = \frac{\text{tip speed}}{\pi \text{ d}} \left(\frac{2 \pi \text{ rad}}{\text{rev}} \right) = \frac{9.2 \text{ ft/sec}}{(\pi)(8 \text{ ft})} (2 \pi) = 2.3 \text{ rad/sec}$$

Then

$$P_{max} = \tau_{max} \, \omega = (22{,}500 \text{ ft-lb})(2.3 \text{ rad/sec}) \left(\frac{\text{hp}}{550 \text{ ft-lb/sec}} \right)$$

$$\boxed{P_{max} = 94 \text{ hp}}$$

The forces acting on the trencher are:

Case 1. Trencher rotating in conventional (upmilling) direction:

$$F_{UP} = -\int_{0}^{\theta} F_{TOT} N_b \sin\theta \, d\theta - F_{lift} N_b$$

$$= 4{,}580 \cos\theta \Big|_{0}^{75.5^{o}} -85 = 1{,}150 - 4{,}520 - 85$$

$$\boxed{F_{UP} = -3{,}515 \text{ lb}}$$

$$F_{FWD} = -\int_{0}^{\theta} N_{TOT} N_b \cos\theta \, d\theta$$

$$= -4{,}580 \sin\theta \Big|_{0}^{75.5^{o}}$$

$$\boxed{F_{FWD} = -4{,}430 \text{ lb}}$$

Case 2. Trencher rotating in climbmilling mode

$$F_{UP} = -\int_{\theta}^{0} F_{TOT} N_b \sin\theta \, d\theta - F_{lift} N_b$$

$$= 4{,}580 \cos \int_{75.5^{o}}^{0} -85 = 4{,}580 - 1{,}150 - 85$$

$$\boxed{F_{UP} = 3{,}350 \text{ lb}}$$

$$F_{FWD} = -\int_{\theta}^{0} N_{TOT} N_b \cos\theta \, d\theta$$

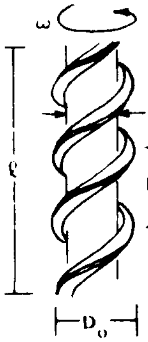
$$= -4{,}580 \sin\theta \int_{75.5^{o}}^{0}$$

$$\boxed{F_{FWD} = 4{,}430 \text{ lb}}$$

Appendix C

POWER ANALYSIS OF AUGER TRENCHING

To estimate the power required to auger a trench in the seafloor consider a single vertical auger with the following characteristics



Outside diameter, $D_o = 4$ in.
Inside diameter, $D_i = 2$ in.
Length, $\ell = 36$ in.
Pitch, $p = 3.6$ in.

Figure C-1. Auger configuration.

With a 3.6-inch pitch, 10 revolutions of the auger are required for a ''slug'' of soil cut from the bottom of the trench to reach the top.

Assumptions:

Half of the auger cuts new material

The same forces apply as for trenching (bearing resistance and friction)

$$F_{TOT} = S_u \left(A_f N_c + \frac{A_s}{2} \right)$$

where S_u = undrained shear strength = 4 lb/in.^{2}
A_f = frontal area of the auger blade
N_c = dimensionless constant ($\simeq 3$)
A_s = side area of the auger

$$A_f = \frac{1}{2}\left[\frac{\pi\left(D_o^{\ 2} - D_i^{\ 2}\right)}{4}\right] = 4.7 \text{ in.}^2$$

$$A_s = \frac{1}{2} \pi D_o \ell = 226 \text{ in.}^2$$

Then

$$F_{TOT} = 4\ \frac{\text{lb}}{\text{in.}^2}\left[(4.7\ \text{in.}^2)(3) + \frac{226\ \text{in.}^2}{2}\right]$$

$$= \underset{\text{bearing resistance component}}{56\ \text{lb}} + \underset{\text{frictional component}}{452\ \text{lb}} = 508\ \text{lb}$$

The frictional component of the total force has a moment arm of $D_O/2 = 2$ inches, and the bearing resistance moment arm is from the center of the auger blade face, or 1.5 inches. Assuming that the normal force from the bearing resistance component is modulated by a coefficient of friction of 0.5, the required torque is

$$\tau = \mu F_f r_f + F_s r_s$$

$$= [(0.5)(56\ \text{lb})(1.5\ \text{in.}) + (452\ \text{lb})(2\ \text{in.})]\ \frac{\text{ft}}{12\ \text{in.}} = 78\ \text{ft-lb}$$

The required removal rate is

$$\dot{V} = (4\ \text{in.})(36\ \text{in.})(1.69\ \text{ft/sec})\left(\frac{\text{ft}^2}{144\ \text{in.}^2}\right) = 1.69\ \text{ft}^3/\text{sec}$$

The volume of soil trapped by one pitch length of the auger is

$$V = 2\ A_f\ p = (2)(4.7\ \text{in.}^2)(3.6\ \text{in./rev}) = 0.02\ \text{ft}^3/\text{rev}$$

Therefore, the required angular velocity is

$$\omega = \frac{\dot{V}}{V}\left(\frac{2\ \pi\ \text{rad}}{\text{rev}}\right) = 0.02\ \text{ft}^3/\text{rev}\ \ 2\ \pi = 530\ \text{rad/sec} = 5{,}000\ \text{rpm}$$

Therefore, the power required is

$$P = \tau\ \omega = (78\ \text{ft-lb})(530\ \text{rad/sec})\left(\frac{\text{hp}}{550\ \text{ft-lb/sec}}\right)$$

$$\boxed{P = 75\ \text{hp}}$$

Appendix D

CABLE AND MACHINE DRAG

CABLE DRAG

The drag on the umbilical cable was determined using the following assumptions.

Cable diameter = 3 in.

Cable weight = 0.64 lb/ft

Water depth = 6,000 ft

System velocity = 1.69 ft/sec

Current velocity = 3.38 ft/sec at surface
= 0 at 300 ft

Vehicle weight = 20,000 lb

It was also assumed that the support ship is located directly above the cable burial machine. The configuration and current profile are shown in Figure D-1.

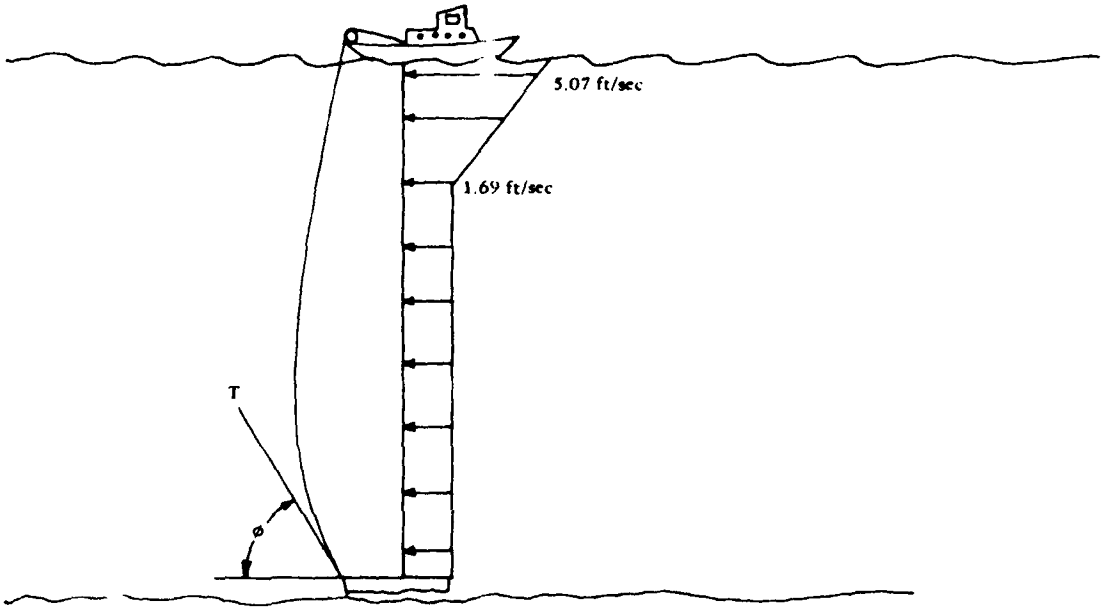
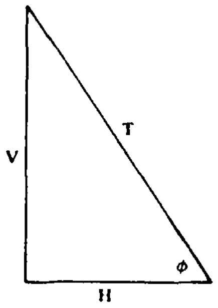


Figure D-1. Current profile.

A computer analysis* was performed to determine tension T and angle ϕ as a function of cable length. The results, which are accurate to ±20% due to problem simplifications made to accommodate the computer, are plotted in Figures D-2 and D-3. Of particular interest is the horizontal component of tension T, since the burier propulsion system must provide this force in addition to the other forces acting on the burier. Table D-1 shows the vertical and horizontal components of T as a function of cable length. A cable length of 6,500 feet and a horizontal component of 3,400 pounds were selected as representative values for concept evaluation.

Table D-1. Vertical and Horizontal Components of T as a Function of Cable Length

Cable Length (ft)	ϕ (deg)	T (lb)	V (lb)	H (lb)
6,100	75	11,400	11,000	3,000
6,200	63.5	8,500	7,600	3,800
6,300	57.4	7,100	6,000	3,800
6,400	54.2	6,200	5,000	3,600
6,500	52	5,500	4,300	3,400
6,600	50.2	5,100	3,900	3,300
6,700	48.8	4,800	3,600	3,200
6,800	47.7	4,600	3,400	3,100
6,900	46.8	4,400	3,200	3,000
7,000	46	4,300	3,100	3,000



$V = T \sin\phi$

$H = T \cos\phi$

BURIAL MACHINE DRAG

Assume that the machine frontal dimensions are width = 12 feet and height = 10 feet. Then,

$$w/h = 1.2$$

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* ''DESADE'' by R. A. Skop, Naval Research Laboratory.

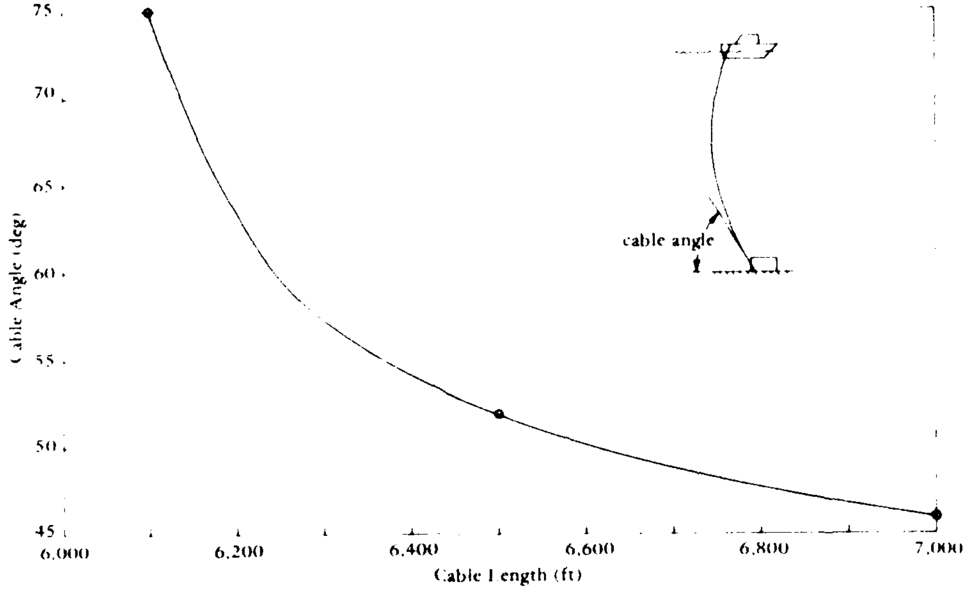

Figure D-2. Umbilical length versus angle.

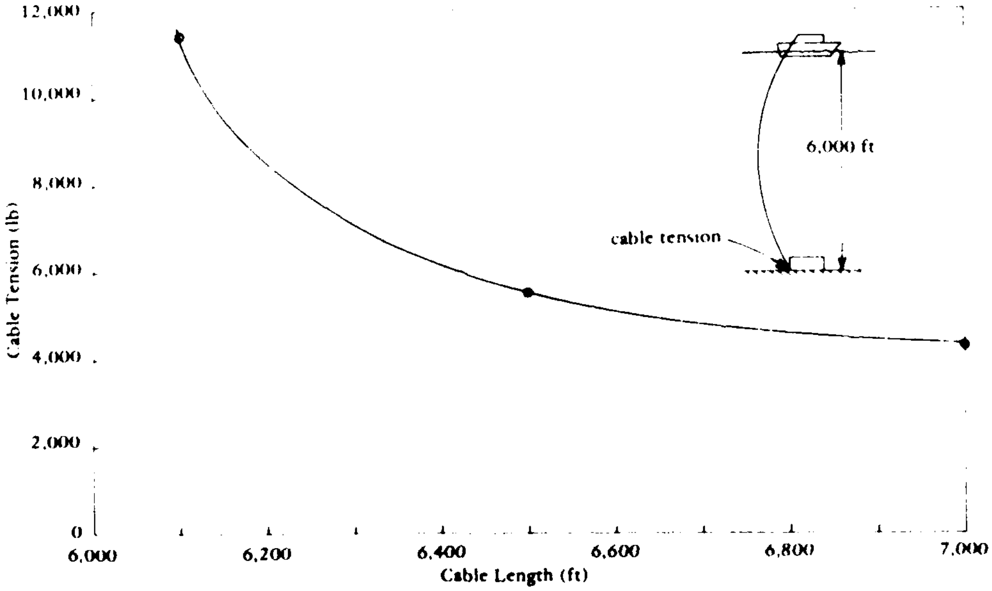

Figure D-3. Umbilical length versus tension.

From Reference 46, $C_d \simeq 1.2$

$$F_D = C_D \frac{\rho_w}{2} A v^2$$

where C_D = drag coefficient

ρ_w = mass density of seawater

A = frontal area = 120 ft^2

v = velocity = 1.69 ft/sec

Then,

$$F_D = (1.2)(1/2)(2\ lb\text{-}sec^2/ft^4)(120\ ft^2)(1.69\ ft/sec)^2$$

$$\boxed{F_D = 411\ lb}$$

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