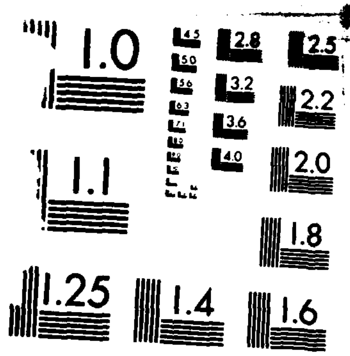
AD-A165 939 BURIAL OF UNDERSEA PIPES AND CABLES STATE-OF-THE ART ASSESSMENT(U) NAVAL FCCILITIES ENGINEERING COMMAND WASHINGTON DC CHESAPEAKE DIV M MELLOR 1976 1/1

UNCLASSIFIED CHES/NAVFAC-FPO-7619 F/G 13/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

Burial of Undersea Pipes and Cables

State-of-the-Art Assessment

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

AD-A165 939

REPORT DOCUMENT

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

3. DISTRIBUTION AVAILABILITY OF REP
Approved for public release;
distribution is unlimited

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE

4. PERFORMING ORGANIZATION REPORT NUMBER
FPO 7619

5. MONITORING ORGANIZATION REPORT #

6a. NAME OF PERFORM. ORG. 6b. OFFICE SYM
USA CRREL

7a. NAME OF MONITORING ORGANIZATION
Ocean Engineering
& Construction
Project Office
CHESNAVFACENGCOM

6c. ADDRESS (City, State, and Zip Code)

7b. ADDRESS (City, State, and Zip)
BLDG. 212, Washington Navy Yard
Washington, D.C. 20374-2121

8a. NAME OF FUNDING ORG. 8b. OFFICE SYM

9. PROCUREMENT INSTRUMENT INDENT #

8c. ADDRESS (City, State & Zip)

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT #	PROJECT #	TASK #	WORK UNIT ACCESS #

11. TITLE (Including Security Classification)
Burial of Undersea Pipes and Cables State-of the Art Assessment

12. PERSONAL AUTHOR(S)
Malcolm Mellor

13a. TYPE OF REPORT

13b. TIME COVERED FROM TO

14. DATE OF REP. (YYMMDD) 76

15. PAGES 62

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if nec.)
Pipes, Cables, Underwater construction

19. ABSTRACT (Continue on reverse if necessary & identify by block number)
This review deals with techniques for trenching, pipe burial, and cable burial. It is directed to burial of undersea pipes and cables, but there is necessarily continual reference to related work on dry land. Emphasis is given to trenching and burying in hard ground and rock.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
SAME AS RPT.

21. ABSTRACT SECURITY CLASSIFICATIO

22a. NAME OF RESPONSIBLE INDIVIDUAL
Jacqueline B. Riley

22b. TELEPHONE
202-433-3881

22c. OFFICE SYMBO

DD FORM 1473, 84MAR

SECURITY CLASSIFICATION OF THIS PAG

Burial of Undersea Pipes and Cables

State-of-the-Art Assessment

Malcolm Mellor

USA CRREL

for

Naval Facilities Engineering Command

1976

Contents

BURIAL OF UNDERSEA PIPES AND CABLES

STATE-OF-THE-ART ASSESSMENT

Malcolm Mellor

Introduction

This review deals with techniques for trenching, pipe burial, and cable burial. It is directed to burial of undersea pipes and cables, but there is necessarily continual reference to related work on dry land. Emphasis is given to trenching and burying in hard ground and rock.

It is intended as an introductory survey for the information of NAVFAC. Because of time limitations, it is by no means an exhaustive technical review. Additional information is available, and it will be drawn upon as required for design studies.

There are repeated references to frozen ground and permafrost, since CRREL has done a good deal of quantitative investigation of permafrost excavation. "Dry land" permafrost is quite similar to unjointed rock, and therefore the permafrost results are relevant to the cutting of some sedimentary rocks. However, undersea permafrost is not expected to be well bonded within a few feet of the water interface, and it is probably much weaker than dry land frozen ground.

Backhoe Trenching

Backhoe excavators provide a standard method for trenching in ordinary soils. They are also used to dig out ripped or blasted material when trenching in hard ground. They would not normally be expected to work in sound rock, although they can cope with rocks that are heavily fractured, excessively weathered, or highly porous. A powerful hydraulic backhoe fitted with a small bucket can exert tooth forces that exceed those exerted by some rock-cutting machines, but the size and shape of backhoe teeth are such that deep bites have to be taken. Consequently, stress levels are usually inadequate for true rock-cutting.

It is sometimes claimed that heavy hydraulic backhoes can excavate undisturbed frozen soils, and to some extent this is true. However, our impression is that a backhoe would only be effective in the weaker kinds of frozen soils, such as: (a) marginally frozen soils at temperatures close to 0°C, (b) frozen soils with low water content, (c) frozen soils layers that are underlain by unfrozen material.

A heavy backhoe (Koehring 505) took part in the so-called "TAPS tests" prior to construction of the Alaska Pipeline. It was fitted with back-rippers, and dug 7 ft. deep pipeline trench at 0.2 lineal feet per minute. In later tests sponsored by Koehring in July 1969, the 505 dug frozen silt at up to 126 ft^3/min, and frozen gravel at rates up to 9 ft^3/min. However, in high moisture content frozen soil colder than -10°C (uniaxial compressive strength above 1500 lbf/in^2), it is probably not a practical proposition to dig with unassisted backhoes of the typical large size. (e.g. Koehring 1066, 3 cubic yard, 142,000 lb gross weight).

A very large backhoe or hydraulic shovel can operate as a dipper dredge if mounted on a suitable barge or pontoon. It could probably dig unassisted in submarine permafrost, stiff clays, coral, and some decomposed or well fractured rocks. It would not be capable of penetrating unbroken hard rock. The other limitation would be water depth.

The largest and most powerful backhoes might be represented by the French Poclain 1000 and the U.S. Koehring 1266. The Poclain machine has an engine of 840 h.p. (SAE), and it is normally fitted with buckets from 4 to 6.5 yd^3 capacity. Gross weight of the machine is 150 tons, and it can dig to a depth of 34 ft below its track pads. The Koehring 1266 is a 130 ton, 1000 h.p. machine capable of handling a variety of large buckets. For very tough digging or special trenching it can be fitted with a small bucket only 48 inches wide. The maximum digging depth in the standard form is almost 40 ft. In the Hydro-Dredge conversion it can dig to a depth of 57 ft with a 5-1/2 yd^3 Esco rock bucket.

Either of these machines in the standard crawler form could operate without modification (other than underwater buckets) in water several feet deep. If a backhoe were to be mounted on a barge, the barge would have to be stabilized by extendable legs, spuds, or equivalent mechanisms. The operator could probably dig "blind," or he could be aided with simple control indicators. For trenches 7 ft. deep, maximum water depth for effective working might be up to about 45 ft.

In recent years there have been a number of attempts to develop and introduce underwater bulldozers, which can also be provided with a backhoe attachment. Perhaps the best known machine is that built by Komatsu.

The Komatsu underwater bulldozer was fitted with a backhoe, and trenching tests were made. The machine cut ditch 1.0 m wide and 2.5 m deep in loose saturated sand; after slumping, the open trench was 1.9 m deep and 2.3 m wide at the top. The production rate was 35 m^3/hr, or 46 yd^3/hr. (K. Fumrui, personal communication).

It is not expected that backhoe trenching will provide an acceptable solution to the current U.S. Navy cable burial problems. However, conventional backhoe trenching utilizing small machines may be a valuable supplement for work on the beach above low water mark. It may save time and money to carry out beach work by simple methods rather than by using a submarine device. The possibility of using a backhoe backripper for work in coral might also be kept in mind.

Production rates for ordinary hydraulic backhoes or hydraulic shovels can be estimated from the charts given in Table I. More specific data for backhoe dredging can be obtained.

Table I

<u>Production estimating chart for hydraulic backhoes and hydraulic shovels</u> (from "Estimating manual for hydraulic excavation," Koehring Company)

APPROXIMATE HOURLY CAPACITIES. Bank Cu. Yd. (m^3) 50-minute hour, 83% job efficiency, 15 ft. (4.5 m) depth of cut, 60° swing—material loaded into haul units on same grade as excavator

Dipper Rating, P.C.S.A. Heaped Capacity

Cu. Yd. (m^3)	3 (2.3)	4 (3.1)	5 (3.8)	6 (4.6)	7 (5.4)	8 (6.1)	9 (6.9)	10 (7.7)	11 (8.4)	12 (9.2)	13 (10.0)	14 (10.7)	15 (11.5)	16 (12.2)
Moist loam, sandy clay, broken coal	320 (245)	445 (340)	525 (402)	650 (497)	780 (597)	910 (696)	975 (746)	1085 (830)	1180 (902)	1275 (975)	1370 (1048)	1465 (1120)	1555 (1190)	1650 (1262)
Sand & gravel lignites & soft coal	300 (230)	425 (325)	500 (380)	625 (480)	750 (575)	875 (670)	935 (715)	1040 (795)	1140 (872)	1235 (945)	1330 (1017)	1425 (1090)	1515 (1158)	1605 (1227)
Common earth laterite ores	275 (210)	385 (295)	450 (345)	565 (430)	675 (515)	785 (600)	840 (640)	935 (715)	1025 (785)	1120 (856)	1215 (930)	1310 (1002)	1400 (1070)	1490 (1140)
Clay, hard, dense hard, solid coal	245 (188)	345 (265)	430 (330)	535 (410)	645 (495)	750 (575)	800 (610)	890 (680)	980 (750)	1070 (818)	1160 (887)	1245 (952)	1330 (1017)	1415 (1082)
Rock, well blasted cemented sand & gravel	235 (180)	320 (244)	410 (315)	510 (390)	610 (465)	710 (540)	760 (580)	850 (650)	940 (720)	1030 (788)	1115 (853)	1200 (918)	1285 (983)	1370 (1048)
Common excavation roots, rocks, boulders	220 (168)	295 (225)	390 (300)	485 (370)	580 (445)	675 (515)	720 (550)	810 (620)	900 (688)	990 (757)	1075 (822)	1155 (883)	1235 (944)	1315 (1006)
Clay, wet, sticky under water excavation	210 (160)	285 (217)	370 (280)	460 (350)	555 (425)	645 (490)	690 (525)	780 (597)	870 (665)	960 (734)	1045 (800)	1125 (860)	1205 (921)	1285 (983)
Rock poorly blasted ferrous ores	180 (138)	245 (187)	320 (245)	400 (305)	480 (365)	560 (425)	600 (455)	690 (528)	780 (597)	860 (658)	935 (715)	1010 (772)	1085 (830)	1155 (883)

NOTE: Duty cycle ratings should not be exceeded in dipper size planning.

I. CONVERSION FACTOR FOR JOB EFFICIENCY

Job Efficiency	Working Minutes Per Hour	Job Efficiency % of 60 Min.	Factor
Excellent	55	92	1.10
Average	50	83	1.00
Below Average	45	75	.90
Unfavorable	40	67	.807

III. CONVERSION FACTOR FOR ANGLE OF SWING

Swing In Degrees	Factor
15	1.20*
45	1.05
60	1.00
75	.93
90	.86
120	.76
180	.61

II. CONVERSION FACTOR FOR DEPTH OF CUT

Machines Less Than 100,000 Lbs.(45360 kg) Net Weight				Machines More Than 100,000 Lbs.(45360kg+) Net Weight				Depth Of Cut Conversion Factor
Maximum Depth		Average Depth		Maximum Depth		Average Depth		
Feet	metres	Feet	metres	Feet	metres	Feet	metres	
5	1.5	2.5	.75	10	3.0	5	1.5	9.7
10	3.0	5	1.5	15	4.5	7.5	2.2	1.15
15	4.5	7.5	2.2	20	6.0	10	3.0	1.00
20	6.0	10	3.0	25	7.6	12.5	3.8	.96
25	7.6	12.5	3.8	30	9.1	15	4.5	.87
30	9.1	15	4.5	35	10.6	17.5	5.3	.80
				40	12.2	20	6.0	.78

IV. LOADABILITY OF MATERIAL

Dipper Loading	Conversion Factors
Easy Digging	.90-1.00
Medium Digging	.80- .90
Medium-Hard Digging	.65- .75
Hard Digging	.40- .65

Plowing and Ripping

Plowing is an established method for cable burial on land and on the sea bottom, but in the simple form it is only applicable to unbonded soils. Even in loose soils and submarine sediments, plowing forces are high enough to create practical problems, and attempts have been made to reduce force levels by utilizing vibratory action or water jetting. Tractor rippers are essentially plows, but they are designed to work in certain types of rocks, which are known as "rippable rocks." The biggest rippers can penetrate to a depth of over 6 ft, but working to this kind of depth in a single pass would not normally be feasible in rock.

All unbonded soils can be plowed or ripped, and the main concern is the required force level, which varies with soil characteristics, plow dimensions, and plowing speed. Without going through formal calculations (using the methods of soil mechanics and agricultural engineering), some estimate can be made by rough rules of thumb. For conventional plowing near the surface of relatively dry, loose soil, we might guess the unit plowing force per unit cross-section of the disturbed swath is about 10 lbf/in^2. However, judging from the performance of Danforth anchors, a value of about 15 lbf/in^2 might be more appropriate for submarine sediments. Recognizing that there will be overbreak in the sides of the plowed furrow in most materials (especially if there is cohesion and relative incompressibility), a modest-size cable plow running 3 ft deep would have a resistance of the order of 10^4 lbf in weak material and at low speed.

For deeper plowing in stronger soils, the resistance is likely to be much higher. If geometric similarity is maintained in the true cross-section of the disturbed swath, cross-sectional area increases with the square of the plowing depth.

Over the past 10 years, Bell Laboratories have developed a series of deep-ocean cable plows for burying telephone cables. These machines are sleds that carry an adjustable plowshare and feed shoe; telephone cable is picked up ahead of the machine and laid directly into the plowed trench. The sled is towed by a surface vessel, which also lays cable immediately ahead of the plow. The plows are designated "Sea Plow;" the first, built in 1966, was Sea Plow I, the latest is Sea Plow IV. Sea Plow IV weighs close to 50,000 lbf, and its furrow is 16 in wide by 24 in deep. Towing forces are said to be of the order of 50,000 lbf, although they could on occasion approach 100,000 lbf.

P.K. Rockwell of CEL has calculated towing forces for a cable plow running 3 ft deep. For a simple plow, the forces were 44,000 lbf in clay, and about 8000 lbf in cohesionless soil.

A 10 inch gas pipeline was recently plowed in under Turnagain Arm, near Anchorage, Alaska. The contractor built a plow designed to penetrate to a depth of 5 ft (with trench about 3 ft wide). The plow was drilled to provide both 200 psi water jets and 100 psi compressed air jets. These seem to have served more for flushing than for cutting. The plow itself was mounted

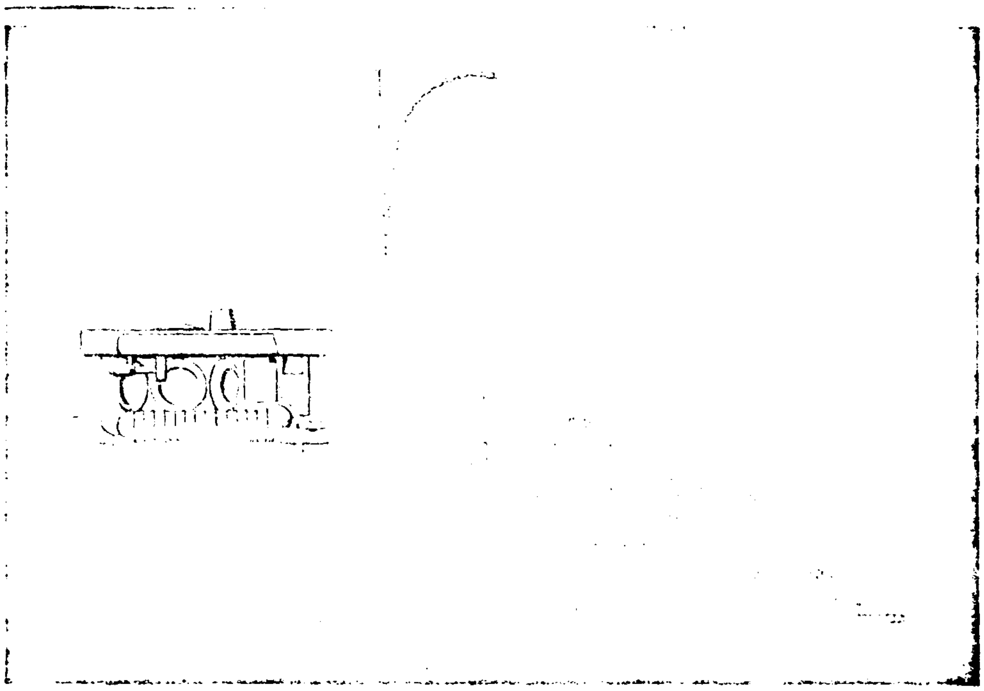


Figure 1. COMEX cable-burying underwater tractor

at the end of a 330 ft stinger, which permitted working in water depths up to 120 ft. The stinger was attached to a lay barge (about 250 ft long by 70 ft wide by 8 ft draft). The lay barge was winched forward to multiple anchors set by an attending tug. Side anchors were used to stabilize the barge in tidal currents that reached as high as 7.6 knots. In midstream, where the current scours the bottom down to gravel, the plow could only penetrate to about 2 ft.

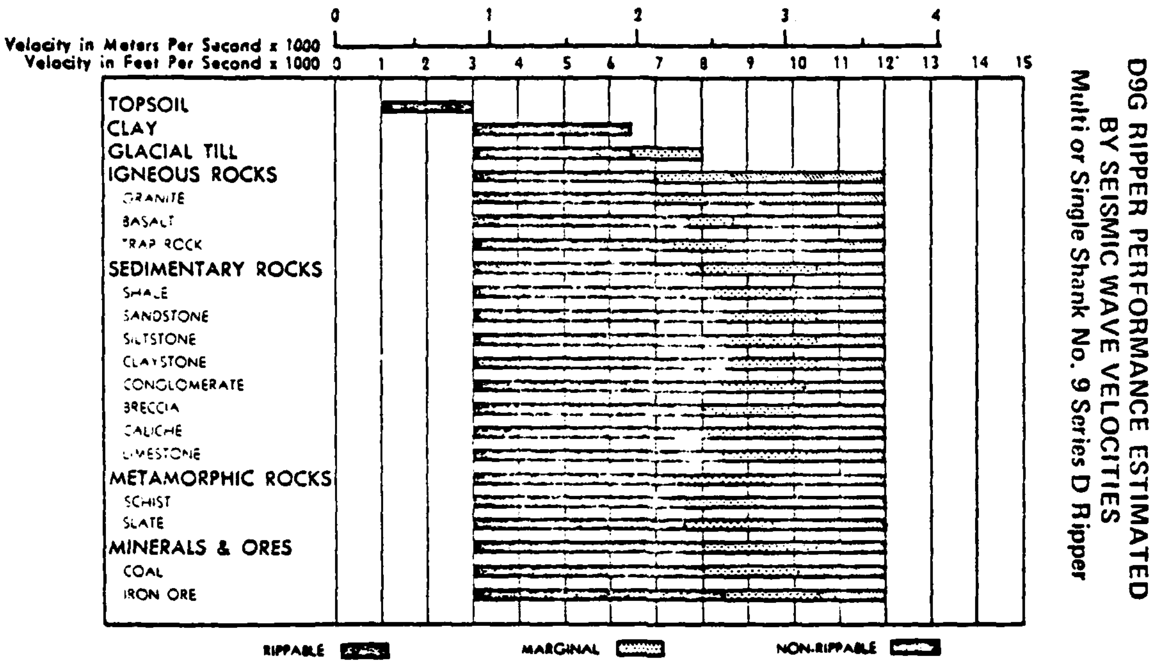
Plowing from a surface vessel with the aid of a stinger or rigid towbar is a well established technique, and it is described in at least two patents.

COMEX has built a self-propelled underwater crawler tractor that is fitted with a cable plow (Fig. 1). The tractor is electro-hydrualic, and it has no buoyancy tanks. Operators ferry to the tractor in a self-propelled lightweight 2-man submersible vehicle, the "Globule." The Globule clips on to the tractor by electro-magnetic connectors, and becomes the control cab for cable-trenching work. The plow is said to be capable of working in clay, and even in coral.

The feasibility of ripping rock, and also the estimated production rate, are judged largely on the basis of seismic wave velocity in the rock. This elastic wave velocity correlates directly with factors that control the bulk strength, such as density or porosity, elastic moduli, or size and spacing of joints, partings or laminations. Standard charts for specified types of rippers and tractors classify various rock types as "rippable," "marginal," or "non-rippable" depending on seismic velocity. Examples of such charts (see Fig. 2) can be found in the Caterpillar Performance Handbook, the Ateco Ripping Handbook, the Caterpillar Handbook of Ripping, and similar publications. With a single shank ripper on a single tractor of the heaviest category (e.g. D9), 8000 ft/sec is about the highest velocity for consistently rippable conditions, and in some types of rock the same limit would occur at less than 7000 ft/sec. At these velocities, production would probably be low.

We have not made systematic studies of tractor ripping in typical rocks, but a consideration of ripping in frozen soils provides some insight, since these materials are quite similar to unfractured sedimentary rocks.

Seismic velocities for frozen ground vary with soil type, ice content, and temperature. Velocities are quite high for ice-saturated soils below -10°C: laboratory measurements at CRREL give values of 14,500 ft/sec for sand, 12,800 ft/sec for silt, and 12,000 ft/sec for clay. Corresponding values at -2°C are 14,100 ft/sec for sand, 10,300 ft/sec for silt, and up to 8900 ft/sec for clay. In-situ values measured on frozen sands in northern Alaska are in the range 10,500 to 15,400 ft/sec, while values measured in and around the CRREL permafrost tunnel near Fairbanks are about 9000 to 11,000 ft/sec for gravel and 6200 to 9400 ft/sec for silt.



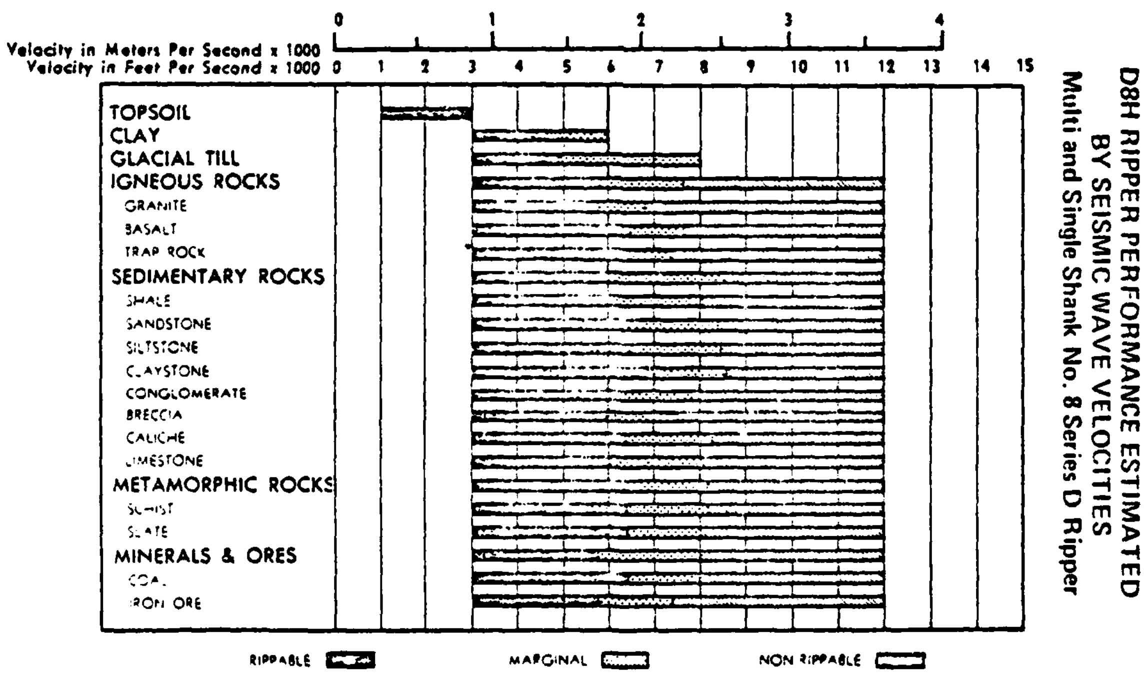


Figure 2. Examples of ripping charts.

Regarding frozen gravel as a conglomerate, the tabulated limit for "rippable" conditions would be at 8300 ft/sec for a D9G, at 6300 ft/sec for a D8H, and at 4600 ft/sec for a D7F. Corresponding values for onset of "non-rippable" conditions would be 10,200, 8000, and 5700 ft/sec respectively. Regarding frozen silt as a siltstone, the same limits would be 8500 (10,500), 6500 (8400) and 5000 (6400) ft/sec for D9, D8 and D7 respectively, where the open figures give rippable upper limit and the bracketed figures give non-rippable lower limit. Since some frozen silts and frozen gravels are known to be rippable, it appears that the standard charts are somewhat too conservative. However, there are numerous reports from Alaska of rippers being unable to penetrate frozen ground, of ripper shanks breaking because of overloading, or of ripper tips "buring-up" while trying to penetrate.

Under conditions where rippers are actually capable of working in frozen ground, they are very efficient in energetic terms. From the writer's analysis of data gathered during the 1969 TAPS tests in Alaska, specific energy consumption for a heavy ripper appears to be approximately 125 lbf/in^2 in frozen silt and 275 lbf/in^2 in frozen gravel. Data gathered in Alaska by G.R. Lange of CRREL give specific energy values in the range 110 to 510 lbf/in^2 for frozen gravel. Taking a specific energy value of 275 lbf/in^2, a ripper could break an in-place volume of 83.3 ft^3/min for every 100 h.p. applied to the work. The most powerful single-unit tractor currently available (Allis-Chalmers HD-41) is rated at 524 h.p. The Caterpillar D9G (single unit) is rated at 385 h.p., but two D9 tractors are sometimes used in tandem for ripping with a single tooth.

Present experience is that rippers can penetrate up to 5 ft in frozen ground at a single pass, with speeds of approximately 100 ft/min. Parallel passes prior to increase of penetration are beneficial. Recommended increments for increasing penetration depth are 18 to 24 in. in silt and 12 to 14 in. in gravel.

Making a check on the production rate graphs, these, like the rippability charts, turn out to be too conservative: the best predicted performance for a D9 working silt of 7000 ft/sec seismic velocity is 315 ft^3/min, but taking the measured specific energy of 125 lbf/in^2 and assuming 70% utilization of rated power, the production rate is about 500 ft^3/min.

One drawback to underwater use of rippers or plows is the high force level needed to break hard ground. The horizontal force is given by the power divided by the travel velocity; with almost perfect traction, a D9 tractor moving at low speed in first gear is theoretically capable of exerting a drawbar pull of the order of 100,000 lbf. With two D9's in tandem (a second bulldozer assisting the ripper through a push-block), the horizontal force on a single-shank ripper could conceivably reach 200,000 lbf -- if the ripper didn't break first. However, on a soft surface there are tractor limitations, and the available drawbar pull might be only about 25,000 lbf for a single D9. Rippers often "ride-up" out of strong frozen ground, lifting the tail of the tractor; this requires 20,000 to 30,000 lbf of static vertical force, and probably nearer to 50,000 to 60,000 lbf if the accelerations are taken into account.

Although underwater plowing or ripping may not appear very attractive at first sight, they are feasible for a considerable range of materials. In shallow coastal waters, conventional ripping might even be possible, using a submersible tractor such as is made by Komatsu. With such an approach there would be a loss of about 11% in deadload reaction and tractor drawbar pull, and there would, of course, be serious guidance and control problems.

To sum up, the vertical reaction needed to force a ripper into hard bed could well exceed 50,000 lbf, so that a vehicle heavier than 25 tons might be necessary. Taking into account both the ripping force and the motion resistance of the vehicle itself, the required tractive effort might be of the order of 10^5 lbf. This is too much for a self-propelled sea bed vehicle to provide, certainly if its weight is only 25 tons. In terms of direct towing by a surface vessel, we can assume that bollard pull of about 10 lbf per horsepower is attainable, leading to an estimate of 10,000 h.p. as the required tug power.

Plows and Rippers with Supplementary Aids

Plows and rippers have been modified in various ways in attempts to reduce the plowing forces. Some representative modifications are described below; all attempt to reduce force by supplying additional power.

Jet/Ripper or Jet/Plow Combinations. There are various ways of combining plows or rippers with high-pressure water jets. One method is to cut parallel slots with jets, and use rippers or plows for secondary breakage and displacement. Another method is to use jet nozzles set into the ripper tooth to increase the effective stress concentration at the tooth tip or shank edge. For plowing in soft materials, jets scour and flush so as to reduce plowing forces.

For underwater trenching to bury small pipe in Cook Inlet, Brown & Root designed a jet plow. This employed 300 lbf/in^2 nozzle pressure with a total flow rate of 3000 gal/min. There was also an air lift drawing 1500 ft^3/min. The plow was intended to have a maximum pulling force of 75,000 lbf.

The Harmstorf Company of Hamburg, Germany, has been developing and using jet plows for many years. Originally used for burying cables, some of the equipment can now handle flexible pipes up to almost 4 ft diameter. Jet pressures are believed to be in the range 100 to 180 psi, which means that the plows can only work in soft bed materials. A large crawler-mounted machine built in 1972 has a hydraulic output of 1450 h.p., which requires an input driving power of 2500 h.p. for the pump. The Chugach Electric Co. in Anchorage, Alaska, has recently acquired a Harmstorf roller-mounted plow for burying cables beneath Knik Arm. The 4 rollers are each 2 m in diameter, and over 1-1/2 m wide. Work with the machine is expected to start in the spring of 1977.

For work in hard materials, 300 lbf/in^2 is nowhere near adequate, nor is the 1000 lbf/in^2 (or even 3000 lbf/in^2) used in some of the newer pipe-burying jetting systems. To obtain useful performance in rock, we have to think in terms of nozzle pressures greater than 20,000 lbf/in^2. A longwall miner for use in coal is being developed at the University of Missouri-Rolla, and it has some features that could be applicable to a hard rock plow. However, it should be recognized that high power consumption and expense equipment is likely to be needed.

Repetitive-impulse rippers. For many years there has been interest in vibrating rippers, and several equipment manufacturers have pursued long-term development projects. One major line of rippers has heavy rubber blocks that are claimed to give a vibrating action; these actually create a complaint system that releases strain-energy after peak stress and yield has been achieved, and in our view they do not achieve the basic aim of reducing plowing force. There are on the market eccentric-mass vibrating cable plows, such as the Parsons/Koehring Saberplow DP-100, that are used by utility companies. One New England company begins spring operation in frozen ground with this device, but has to tow the plow vehicle with a surplus M-41 tank, suggesting that the vibration confers little benefit in hard ground. One way to make a repetitive-impulse ripper with limited development resources would be to embody a mid-frequency impact breaker in the tooth. A deep water undersea cable plow that utilizes vibration is at present being developed by the USN CEL.

Gas-blasting rippers. "Explosive rippers" have been considered for working "dry-land" permafrost. The idea is to place a gas-blaster discharge port at the tip of the ripper tooth to assist the fracture process. An experimental device tested in Alaska by CRREL proved disappointing. The discharge pressure of a gas-blaster is too low to induce a shock wave that can create primary fractures in rock, and there is inadequate confinement of the gas bubble at the tip of an operating ripper. However, in an underwater application the gas bubble would be confined, and it might be useful for displacing broken material.

Other groups have experimented with repetitive gas blasting in rippers. Enthusiastic reports have appeared, but we doubt that the method has much to offer in rock or very tough ground.

Conventional Channel Dredgers

A variety of floating channel dredgers are used in harbours, rivers, canals, etc., usually for clearing unconsolidated sediments.

There are three broad types: mechanical dredges that scoop up the bottom material, hydraulic dredges that suck up the bottom material, and hybrid types embodying both mechanical and hydraulic components. Brief notes on the major types of channel dredgers are given below, and selected types are discussed in more detail under separate headings.

Ladder dredge. The ladder dredge has a continuous bucket chain, or elevator. It discharges into internal hoppers, into removal barges, or into a removal pipeline. Working depth can exceed 100 ft, and in Europe there are seagoing ladder dredges capable of working in exposed locations. Ladder dredges used for mining gold and tin are discussed separately.

Dipper dredge. The old type of dipper dredge is essentially a cable-operated power face shovel mounted on a barge that can be stabilized and moved by spuds. Dipper dredges are capable of working fairly strong bed materials at depths up to about 50 ft, working limit being set by the reach of the bucket arm. Hydraulic backhoes, which are discussed separately, can also be used on dipper dredges.

Scraper dredge. This is essentially a dragline operating from a stationary barge.

Grab dredge. This is a barge carrying a clamshell or "orange-peel" drop bucket. Operating depth is almost unlimited, but control is poor. It has some capability for biting into hard materials, and can be used satisfactorily to depths of 100 ft or so in still water. In soft material and shallow water, a 1 yd^3 bucket can lift about 50 yd^3/hr.

Suction dredge. A suction dredge carries one or more centrifugal pumps and sucks up bottom material through a lift pipe. Maximum height of lift is limited, but with boosters it can exceed 100 ft. Concentration of solids in the lift pipe is up to about 20%. Average production for an older-type dredge working in soft material can be figured as about 0.4 to 0.6 ft^3/min per square inch of suction pipe cross-section for pipes from 0.5 to 1.5 ft diameter. For large modern dredges (16 to 36 in.) the production is more like 0.8 to 0.9 ft^3/min per square inch of suction pipe.

Cutterhead dredge. A cutterhead dredge carries a boom that has a shaft-driven rotary cutter and a suction pipe. The cutter breaks up the bottom material and the slurried cuttings are sucked away by the lift pipe.

Dustpan or draghead dredge. This is similar to the cutterhead dredge, but the suction pipe draws from a moving scoop or drag that is often fitted with water jets (low-pressure) or teeth that disaggregate the bed material.

Channel dredgers are highly developed vessels with solidly established operating records. While most have been used for working unconsolidated sediments, there is no obvious reason why some types could not be upgraded for work in stronger bed materials.

Floating Cutterhead Dredges

The conventional floating cutterhead dredge is a suction dredge that has an axial-rotation cutting element mounted at the intake of the suction line. The equipment is carried by a barge, which supplies power and transfers the spoil to a discharge line. The barge is usually stabilized by spuds and/or anchors.

The cutter typically consists of a set of spiral blades combined into a "basket" that is mounted on the end of a propeller shaft. The basket may be of "closed nose" or "open nose" design, and it may be fitted with replaceable blade edges or teeth. Another type is known as a "straight arm" cutter. The closed nose basket is used for digging in loose materials, while open nose baskets and straight arm cutters are used for work in hard materials (which can include coral). Cutters are up to 12 ft in diameter.

Cutter power is usually in the range 400 to 4000 h.p. On older cutterhead dredges, power is supplied by an electric motor on the barge, with direct shaft drive at 10-30 rev/min. The shaft is carried in the boom, or ladder, in special cutless bearings. On new dredges, submerged hydraulic motors (or even electric motors) may be mounted near the cutting end of the ladder.

Ladders are usually set at angles not exceeding 45°. They range in length from about 25 ft to over 150 ft.

Ladder dredges and gold dredges

Ladder dredges for harbor and channel work are used mostly in European waters. Although double-ladder machines were developed, virtually all are now of the single ladder type. Calm water is required for effective operation -- wave motion lifts the buckets out of the work.

The boom of a ladder dredge is mounted along the center line of the vessel, in such a way that it can be raised, lowered and operated at varying angles. The digging buckets are strung along a chain, with empty buckets descending the lower side of the ladder, biting into the work as they pass around the lower tumbler, and ascending to the upper tumbler for dumping.

Bucket sizes might be in the range 5 to 50 ft^3, and in typical operation the buckets would probably run about 85% full. Chain speeds vary with material type: in soft bottom the rate might be 20 to 30 buckets per minute, dropping to 9-12 buckets per minutes in stiff clays. Maximum operating depths are commonly in the range 40 to 75 ft.

We are not very familiar with channel dredgers, but chain-bucket gold dredges have been of interest because of the amount of excavation they have done in Alaska.

The gold dredges used in California, Australia, Alaska and the Yukon were very big contraptions, but stripped of all the sorting and washing plant a chain-bucket dredge could be compatible with a lay-barge. A large gold dredge is illustrated in Figure 3. Size or capacity is denoted by the bucket capacity.

The dredges in Alaska and the Yukon worked through permafrost terrain, but the gravels and overlying silts were normally thawed in advance. Nevertheless, the tailing piles that can still be seen suggest that the digging must have been fairly rugged -- there are large boulders in the gravels, and blocks have been stripped from the top of bedrock.

In Table II an attempt has been made to calculate the specific energy consumption of dredges working in the nineteen-thirties. Complete sets of operating data are hard to come by, and some interpolation has been made.

If a 6 ft^3 dredge could maintain full-bucket production it would dig 8640 ft^3/hr (144 ft^3/min), which is equivalent to 240 linear feet of 12 ft x 3 ft trench per hour (4 ft/min), assuming no overbreak. Under ideal conditions, one mile per 24-hour working day would be theoretically attainable, but the required power consumption would probably be about 300 h.p., or twice the power used on the old dredges. Dredges of 6 ft^3 capacity used to be capable of digging to about 40 ft below waterlevel; 17 ft^3 dredges could dig to 124 ft below waterlevel.

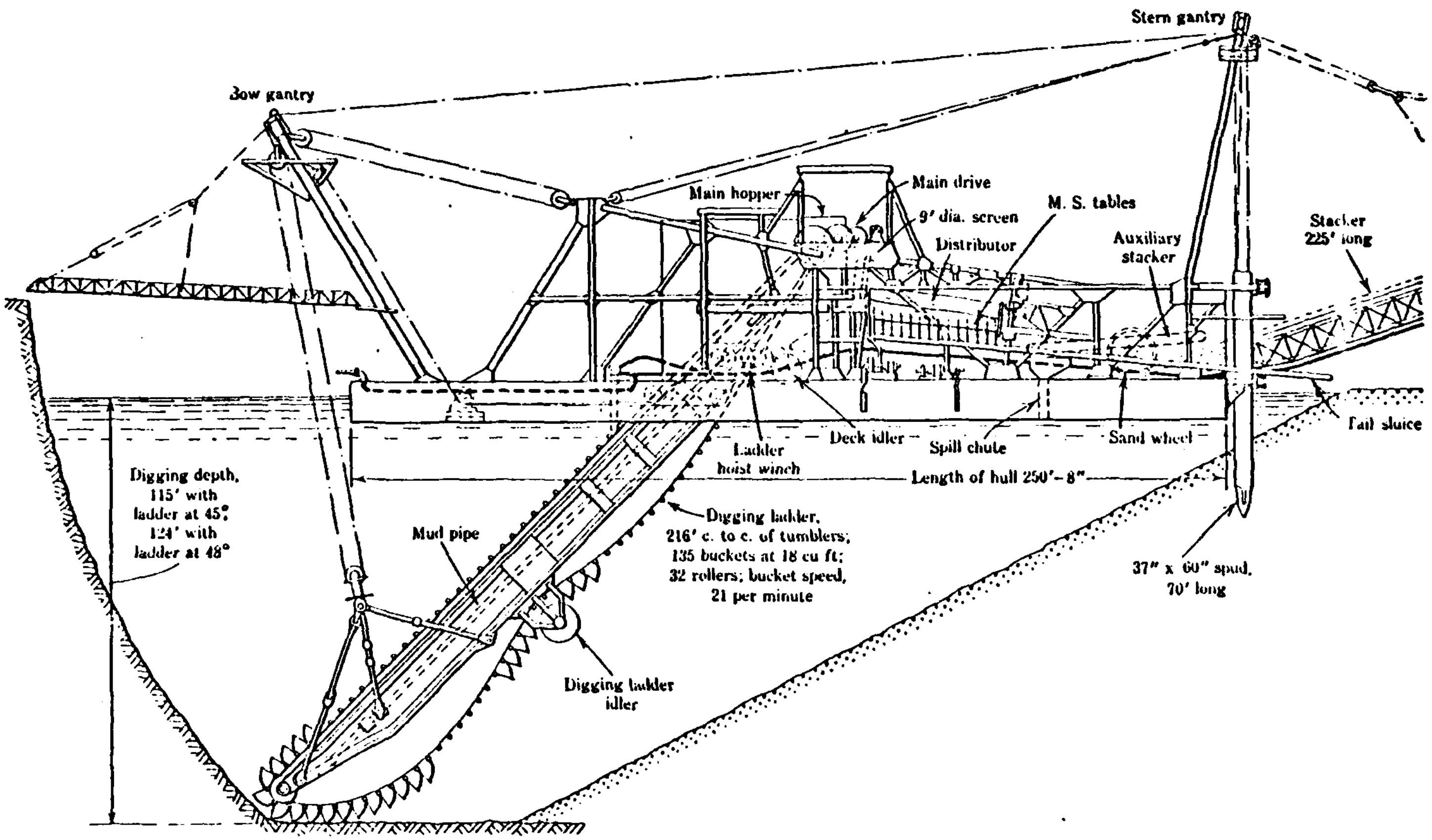


Fig. 3 18 ft^3 gold dredge with deep digging ladder.

A chain-bucket dredge designed for seabed trenching might have a significantly different configuration than a gold dredge, although the cutting sequence of a gold dredge (upcutting buckets working progressively down the advancing face) has much to commend it. The dredge barge would have to be stabilized and controlled by kedge anchors and/or spuds.

Deep Water Sand and Gravel Dredgers

In Europe, sand and gravel are "mined" by dredgers in water that is 100 ft deep or more. There are suction-dredge vessels capable of working in depths up to 230 ft. New designs have been proposed for cutterhead plant to minimize the problems arising from wave motion. These include bottom-crawling structures with towers rising above the water surface, and pivoted ladder devices that have a roller support at the bottom end.

Bottom-traveling cutterhead dredges

Bottom-traveling cutterhead dredges have been developed for burying deep sea pipe in cohesive soils. They are also under consideration for sea bed mining and sand dredging.

A very recent system is the Kvaerner-Myren trenching system developed in Norway. A sea bed unit intended for burying pipes at depths up to 500 m is operated from a 3000 ton mother ship. The 50 ton underwater unit has controlled-buoyancy spheres, and wheels for guiding it along the pipe. The cutterhead has a

Table II

Specific Energy Estimates for Gold Dredges of the Nineteen-Thirties

(Data from Mining Engineers' Handbook, 3rd Edition, 1959)

Dredge (1)	Bucket capacity	Dumping rate	Max. volumetric excavation rate	Total installed power	Digging power	Specific energy (2)
	ft^3	bucket/min	ft^3/min	h.p.	h.p.	$in\text{-}lbf/in^3 = lbf/in^2$
1	6	24	144	348		
2	3	28	84	159		
3	18	21	378	2171	600	364
4	9.5	(21)*	200	495	200	229
5	3	36	108	190	95	202
6	6	(24)*	144	298	100	159
7	9	(21)*	189	750		
8	10	(21)*	210	749	250	273
9	10	(21)*	210	749	250	273
10	6	(24)*	144	489	150	239
11	6	(24)*	144	489	150	239
12	6	(24)*	144	424	150	239

* Estimated dumping rate based on information that dumping rates were 24 to 28 buckets/min for dredges up to 7.5 ft^3, and 20 to 23 buckets/min for bigger dredges.

(1) Dredges 1 - 7 operated in northern California, dredges 8 - 12 operated near Fairbanks, Alaska.

(2) Assumes full buckets and use of full rated digging power.

diameter of 5.9 ft, and it rotates about a vertical axis at 30 to 40 rev/min. Projected trenching speeds are expected to be highest in clay (up to 500 m/hr), and less in sand. The umbilical is 750 m long. Although the developers do not mention it, a vertical axis slot miller of this kind will tend to veer off from the trenching line, as the cutter develops a force component normal to the direction of travel (this will be obvious to anyone who has used a router).

The problem of side force on a vertical-axis slot miller can be avoided by using a pair of contra-rotating cutters. An underwater pipe burying machine of this kind was the subject of a patent by C.F. Martin. This concept was developed by Oceanonics, Inc. into a working machine called the Mole, or Seamole. The original mole buried 16 in. pipe (23 in O.D. after coating) in clay (strength 200 lbf/ft^2) at a rate of 2 ft/min. The trench was 3 ft deep, 2 ft wide at the bottom, and 5 ft wide at the top. Cutter power was supplied by two 160 h.p. diesels, which suggests that the hydraulic motors were around 100 h.p. each. Maximum operating depth for the first model was 200 ft. A deep water version useable to 600 ft was later developed. This had a capability for burying 42 in. pipe. A prototype is said to have buried 12 in. pipe in Alaska, but reports are confusing and inconsistent ("North Slope," "25 ft tides"). This machine is said to have cut through frozen glacial till in the tidal flats, which seems unlikely.

A pipe-riding burial machine with twin cutterheads has also been developed by Sub Sea Oil Services (SSOS), a joint venture of Shell Italiana and Micoperi. This machine, the B70, has its cutters revolving about horizontal axes that point in the direction of travel. Driven by a 10 h.p. hydraulic motor, the cutters will handle soils, but they cannot cope with debris or hardwood.

There are several machines, or conceptual designs, that use a cutterhead on a swinging arm.

SSOS has a large swinging boom cutterhead trencher, designated the S/23. This machine is 59 ft long, with a weight of 50 tons submerged and 61 tons in air. It has variable buoyancy, and travels on the sea bed by winching two cables from anchor points. It is designed for cutting very large trenches - 9.1 to 14.75 ft wide, 0 to 8.25 ft deep per pass. The operating water depth limit is 200 ft. The operator's capsule and the machine room are maintained dry at surface atmospheric pressure. Power is electro-hydraulic. The cutterhead is supplied by a 60 h.p. electric motor which drives a hydraulic pump and hydraulic motor (useable head power is therefore probably about 40 h.p.).

A swinging boom cutterhead mounted on self-propelled crawler tracks was built under sponsorship from the Japan Society for the Promotion of the Machinery Industry. The machine weighs 66 tons in air (55 tons submerged), its overall length is 38 ft, and its total width is 16.4 ft. The cutter diameter is 2.3 ft, and it has a 30 h.p. electro-hydraulic drive. Maximum trenching width is 26 ft, and maximum trenching depth is almost 10 ft. Submerged bearing pressure of the 150 h.p. electro-hydraulic crawler tracks is 10.7 lbf/in^2. The machine, which is intended to dredge sand and clay, has sophisticated systems for control, guidance and monitoring.

Another self-propelled crawler with an articulated cutterhead dredge boom was designed in France by Groupement EPM on behalf of several companies and a government agency. A complete machine has not yet been built. This machine, known as the Tango, was intended initially for cutting trench 7.5 ft deep in water depths up to 500 ft. Maximum pipe diameter was expected to be 44 in. Overall length of the machine is 70 ft, total width is 27 ft, and the weight in air is 185 metric tons (204 short tons). There is provision for adjustable buoyancy, but planned track weight in water is 40 metric tons (44 short tons). Cutter power is 360 h.p., crawler power is 130 h.p., pump power is 360 h.p. and jet power is 180 h.p., for a total of 1030 h.p. Drives are electro-hydraulic with line supply at 5.5 kV. Design progress rates are 360 ft/hr in sand and 160 ft/hr in clay. The cutterhead is 5.9 ft in diameter and 3.9 ft long. Control by a operator inside a dry capsule is planned for the first machine.

A large twin boom cutterhead crawler has actually been built and operated by Technomare in Venice. This machine, the TM-102, is 72 ft long with its booms extended, and 46 ft long with them folded. Total width is 39 ft. Total weight in air is 190 metric tons (209 short tons), and the machine has full adjustable buoyancy. Maximum submerged weight on the crawler tracks is 30 metric tons. Maximum size of pipe that can be buried is 5.25 ft, and maximum digging depth is 13 ft. Maximum soil strength for effective operation is 700 lbf/in^2, and maximum water depth is 650 ft. Drive systems are electro-hydraulic, with 3 kV line power supplied by a 1300 h.p. diesel-electric plant on the surface vessel.

Another machine built in Italy was the Saipem "Ponga," a submersible cutterhead dredge with 4 inclined-axis milling drums. It was intended for burying pipes up to 60 in. diameter in water depths to 200 ft (with provision for extension to 500 ft). The design was considered by this writer for possible application to Arctic problems.

The machine consists of a 40 x 26 x 26 ft towed sled fitted with four cutter drums, each driven by 80 h.p. hydraulic motors (fig. 4). The sled straddles the pipe, and the drums cut the trench profile, while cuttings are flushed and fluidized by water jets. Fluidized cuttings are sucked away to the lay barge above by four 800 h.p. pumps. Power transmission is direct hydraulic.

Estimated excavation capacity is 315 to 360 ft^3/min. During tests in stiff clay (shear strength 2,500 lbf/ft^2, or 17.4 lbf/in^2) the machine cut trench at 3.5 ft/min, with a cross-section 12 ft

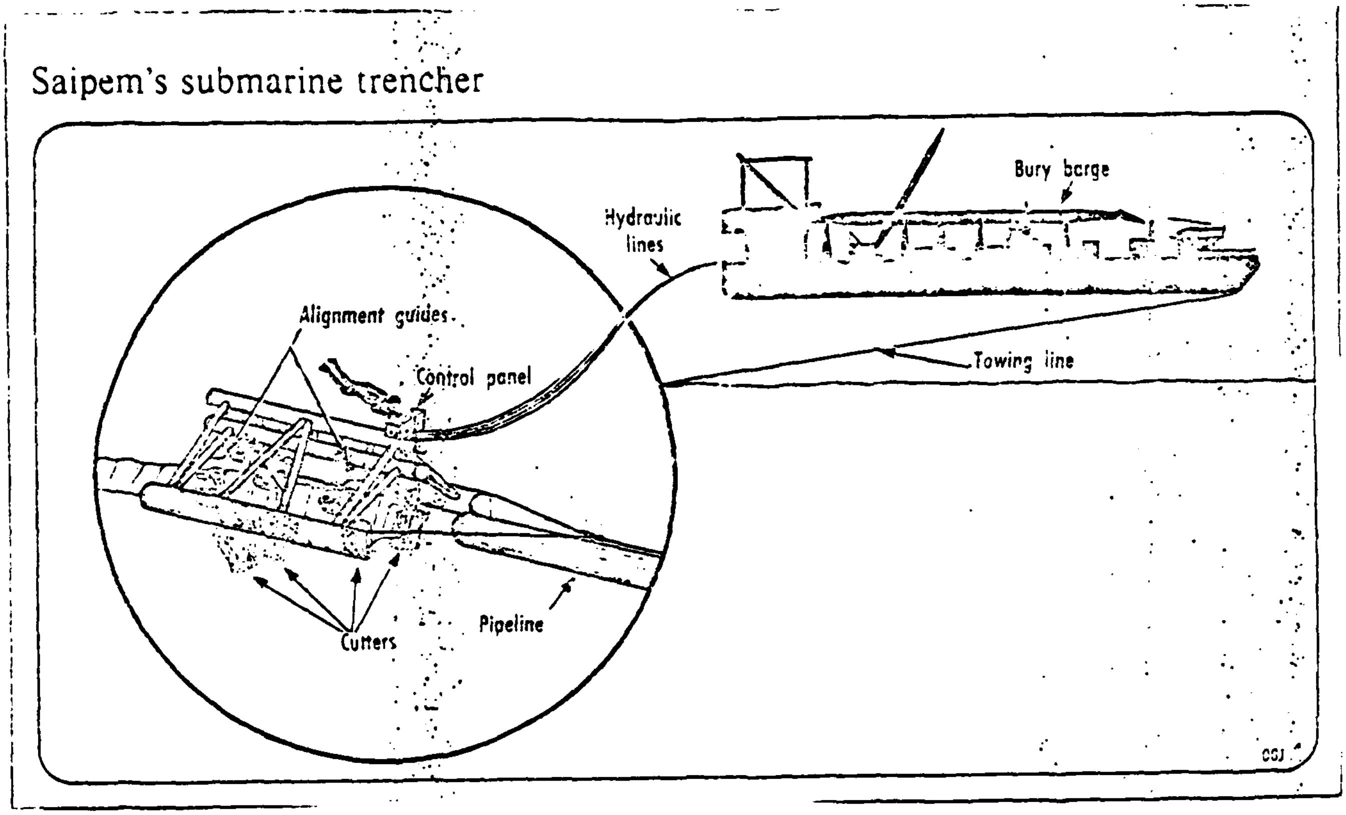


Figure 4. Submarine cutterhead dredge currently being developed for work in unfrozen clay.

wide at the top, 6 ft wide at the bottom, and a depth of 3 ft. This gives an actual excavation rate of 252 ft^3/min. If it is assumed that the hydraulic motors on the cutter drums were developing full power, the specific energy consumption for cutting (excluding fluidization and removal of cuttings) was 291 lbf/in^2. While this appears to be a favorably low value when compared with some of the values quoted for various devices working in permafrost, it should be related to the strength of the material being cut. By this token the cutting performance of the Ponga is not impressive: the dimensionless performance index, for what it is worth in this case, is 8.4, which means that the machine is about 30 times less efficient than a good modern mining or tunneling machine. However, this is probably not of much concern when the pumps of the suction dredge account for ten times as much power as the cutter motors.

In considering the Ponga in relation to Arctic conditions, it might be kept in mind that frozen gravel at -2°C could be about 25 times stronger than the clay for which the Ponga was designed, but this does not necessarily mean that such designs could not be adapted for the Arctic -- much of the submarine permafrost is probably only weakly bonded, or perhaps not bonded at all near the water interface.

The Demag Company of Duisburg produced a design for a seabed miner that was supposed to be useable for trenching. The crawler unit was intended to operate at water depths down to 16,000 ft, and most of the machinery was to be enclosed in a pressure hull. For trenching, the machine would have a cutterhead mounted on a slewing boom 33 to 50 ft long, permitting excavation across a 65 ft swath.

In 1970 the Northrop Corporation made a design study for a seabed excavator on behalf of the USN CEL. The machine was intended to excavate at rates up to 25 yd^3/min at water depths up to 6000 ft. All-aluminum construction kept weight to 30,000 lbf. The running gear consisted of 2 Sno Cat pontoons (the original open-ladder type) with a bearing pressure of 0.3 lbf/in^2. The excavating function was performed by a cutterhead dredge on an articulated boom. Drives were all electric, with 5 h.p. going to the cutterhead, 17 h.p. going to traction, and a total installed power for all functions of 54 h.p. The vehicle was 25 ft long by 20 ft wide, with an overall machine length (boom folded) of 49.5 ft. Supply line voltage was 2.4 kV. It is instructive to compare this feeble design with the brutes that have actually been put to work by ocean engineering companies.

Roadheading Machines

In the mining industry there are various boom-mounted rotary cutters, known as roadheaders, that are used for driving tunnels. One common type, known as a "PK3 type" after the Russian machine from which it derives, has a conical cutter rotating axially at the end of a slewing boom. The general form of the machine is very similar to a cutterhead dredge, and to the bottom-traveling variants of cutterhead dredges. It could obviously be adapted to a hard bottom cutterhead. Another type of roadheader has a cutter drum that rotates about an axis that is normal to the boom axis. There are also roadheaders with two or more cutting drums, or with cutting drums that traverse along a rotating beam. These machines have been modified for civil engineering use, mainly for driving tunnels through the weaker kinds of rock.

Disc Saws, Wheel Ditchers and Milling Drums

Disc saws, wheel ditchers and horizontal axis milling drums all fall into a category of machines that can be described as "transverse rotation." In principle, they can rotate either downward into the approaching work (climb milling), or upward against the approaching work (upcut milling). In the former case, the rotor tends to be self-propelling, but it also tends to climb out of the work unless an adequate reaction is provided. In the latter case, the rotor has to be thrust along in the direction of travel, and the rotor may have either positive or negative reaction in the vertical direction. In practice, upcut milling is almost always used (planing can be an exception). In upcut milling, the teeth on the rotor enter the work with almost zero chipping depth, and usually leave the work with maximum chipping depth. Cuttings are transported upward.

Large diameter disc saws have been developed for cutting concrete, asphalt, some rocks, and frozen soils. In the U.S., disc diameters range up to about 7 ft, while in the Soviet Union, where the primary interest seems to be in cutting frozen ground, diameters range up to 3 m (9.8 ft). Kerf widths are in the range 3.5 to 10 inches. Maximum cutting depth is normally less than the wheel radius.

Disc saws are effective in cutting frozen soils, concrete and some rocks, but tooth wear can be a serious problem. Traverse rates for effective operation are in the range 2 to 17 ft/min. In frozen soils, specific energy is about 4.7×10^3 lbf/in^2 for frozen gravel and about 1.8×10^3 lbf/in^2 for frozen silt. In a layered pavement consisting of asphalt (4.5 in) concrete (7.5 in), and frozen gravel (22 in), specific energy was measured around 5000 lbf/in^2 in a CRREL test. Disc saws can be used to excavate trench by a "kerf and rib" technique, cutting two parallel slots and breaking out the uncut rib between them. Taking the depth to width ratio of the uncut rib as 2, overall effective specific energy can be reduced by a factor of 5.

The problem of tooth breakage and tooth wear on disc saws can be solved, but there are some inherent disadvantages connected with the variable chipping depth.

CRREL has considerable literature and test data on large disc saws.

If underwater disc saws were seriously contemplated, it would be desirable to design them systematically rather than to make expedient adaptations from existing machines.

Bucket-wheel ditchers such as those built by Cleveland, Parsons/Koehring, Barber-Greene and Banister are standard items for trenching on land in unfrozen ground. The most sturdily-built ditchers can, with adequate power, operate in "dry-land" frozen soils and some of the softer rocks, but some people believe that they are not economical in frozen gravels because of high tooth costs ($5.11 to $12.44 per lineal foot of 5 ft x 7 ft trench in the TAPS trials).

In the 1969 TAPS trials near Fairbanks, a heavy wheel cutting 5 ft wide by 7 ft deep was able to maintain 6 ft/min, and achieve up to 8 ft/min in frozen silt. In frozen gravel, advance rates were 2.2 to 2.5 ft/min, with a few instances of 6 ft/min, presumably in weaker patches of ground. The writer has analyzed the 1969 results for the Banister H.A.K. trencher, and has calculated the following specific energy values: down to 180 lbf/in^2 in frozen silt; 660 lbf/in^2 for good production rates in frozen gravel; 240 lbf/in^2 for absolute best performance in frozen gravel.

More recent development work has been done by Banister (the Banister 710 cut 6 ft wide trench to a depth of 9.5 ft in frozen gravel), but detailed test results are not available to the writer. Both Banister and Henuset are building "super ditchers" for burying gas pipeline in Arctic Canada, and new tests are planned for early 1977. Parsons also built a very big machine, the 520 "Big Inch," which had a 20 ft diameter wheel. In the Soviet Union, there are trenchers built specifically for work in frozen ground. The ZTR-253 is said to be capable of excavating 1200 m^3/hr (706 ft^3/min). At a specific energy consumption of 180 lbf/in^2 (frozen silt), excavation at this rate would call for a wheel power of 555 h.p., which is certainly much more than the installed power of the machine. Some Russian reports on frozen ground excavation equipment seem to make claims in the same class as those made by some U.S. salesmen; the "frozen ground" they consider is probably barely-frozen silt with low water content.

On present evidence it appears that the main problem in adapting wheel trenchers for work in hard materials is to design and build more durable cutting teeth. The stressing problem does not appear to be very serious: if we assume an 18-bucket, 14 ft diameter wheel cutting to 7 ft depth, while turning at 5 rev/min and drawing 200 h.p., the maximum time-averaged tangential force of 1700 lbf per tooth. This is not a very high value for a large drag bit, but in well cemented coarse gravel there could be high-frequency force fluctuations that might give brief force pulses 7 times higher than the 1700 lbf mentioned. Nevertheless, it seems quite likely that abrasion on the relief face could present the main bit problem. Two factors seem important in designing better teeth:

(i) the teeth should be as large as is reasonably possible, ideally larger than the coarsest fraction of the gravel particles, (ii) the teeth should have properly designed hard tips that are oriented, supported, and bonded in accordance with the resultant cutting force and the tooth trajectory through the work.

Milling drums that rotate about a horizontal axis are currently being used to grade and plane asphalt and concrete pavements. A drum miller of this type was tested in frozen ground, and the specific energy consumption was estimated as 720 lbf/in^2 for frozen silt and 1310 lbf/in^2 for frozen gravel. The heavy planing bits fitted to the drum suffered considerable damage and wear in frozen gravel, but test results were sufficiently encouraging to warrant design of an experimental attachment for military construction machines. Another drum miller was tested for deep cutting of pavements. It had overall specific energy consumption of about 1700 lbf/in^2 and process specific energy of about 700 lbf/in^2.

The milling drum developed at CRREL as a permafrost excavating attachment for heavy bulldozers consisted of a powered drum, 12 ft long and 5 ft in diameter (across the cutters). Two hydraulic motors, rated at 200 h.p., were mounted inside the drum. Drum bearings and end mounts were recessed to permit cutting to more than the drum radius. The drum could be reversed end-for-end to permit either climb milling or upcut milling. Cutting teeth were heavy carbide-tipped tools designed for use on rock tunneling machines. The machine had process specific energy of about 1700 lbf/in^2 in frozen gravel and 1500 lbf/in^2 in frozen silt. The tooth pattern was not completely satisfactory, and actual power density was too low.

Underwater trench could be cut by a single horizontal axis milling drum, or by a staged sequence of milling drums. However, a drum machine would not be very suitable for trenches narrower than about 18 inches.

Ladder Trenchers and Chain Saws

Ordinary chain-type trenchers (ladder trenchers) are used mainly for digging in unfrozen soils to depths of 6-8 ft, with trench widths of 4 to 24 in. The largest soil trenchers are the chain-bucket types, that can dig to depths of 25 ft with trench widths up to 6 ft. In order for these machines to operate in harder materials, such as frozen soils, they have to be fitted with special belts, known as "frost chains." Frost chains usually carry rock-cutting drag bits with carbide tips, and they are usually quite narrow, say 8 inches or less.

On typical ladder trenchers, the cutting side of the chain is usually carried on widely spaced rollers, and the ladder frame is not a very robust structure. Thus for the cutting of hard materials, there is usually a switch to a chain saw machine, on which the chain is continuously supported by a rigid bar.

The most common type of heavy chain saw is the coal cutter. The bar of a coal cutter usually produces a kerf about 6 inches wide, and it can penetrate to 9, 11, 14 or more feet (up to 25 ft). A variety of hardened or carbide tipped bits are mounted on the chains. Coal cutters have been used for work in rock salt, potash, shale, slate, frozen soils and ice.

Some very large chain saws have been built for special jobs. During construction of the Dallas-Fort Worth Regional Airport, a contractor built a heavy shale saw that could dig to a depth of 22 ft. The saw was mounted on the boom of a hydraulic backhoe, using a wheeled carriage to provide stability and depth control. It traversed at 0.5 ft/min.

Some very big chain saws were built for burying a 10-inch gas pipeline in Alaska. The machines, the BorTunCo Roc Saws, have a very heavy chain that cuts an 18 in wide kerf to a depth of 8 ft. Details are given in an attached brochure. The machines work very well in frozen fine-grained soils and in fine gravel, but they have had difficulties in bouldery ground.

Special saws have been built for cutting harder rocks, such as limestone and marble, in quarries. These cut a narrow kerf (about 1.5 in), and have bars up to about 10 ft long. Cutting rates are rather slow - around 1 in/min.

Additional information on continuous belt machines is given in an attached report.

Repetitive Impulse Devices

For very strong rocks, it is usually impractical to consider cutting by parallel-motion tools (with the exception of diamond tools). The alternative is to use normal-indentation cutting tools. For present purposes, normal-indentation tools that require static reaction are not likely to be suitable, so that leaves inertial systems, such as percussive drills, hammers, or impact breakers.

Repetitive-impulse power tools range from "thunkers," which give a heavy blow at low frequency (e.g. piling hammers), to "buzzers," which give a small-amplitude vibration at high frequency (e.g. vibratory drivers). They can be grouped for convenience according to frequency: low frequency (of the order of 1 Hz), medium frequency (of the order of 10 Hz), and high frequency (of the order of 100 hZ or possibly higher). Because power is given by the product of frequency, force and amplitude, typical units of moderate size have an inverse relation between frequency and blow energy. Blow energy is usually of the order of 10,000 ft-lbf or more for low frequency units, of the order of 100-1000 ft-lbf for mid-frequency units, and of the order of 20 ft-lbf or less for high frequency units.

Low frequency tools are represented mainly by powered piling hammers driven by steam, compressed air, or internal combustion. Medium frequency tools are represented by impact breakers powered by hydraulics, compressed air, or direct mechanical action (with springs). High frequency tools are represented by relatively novel vibratory devices in which the primary excitation is usually by rotating eccentric mass or electromagnetic vibration, possibly coupled to the driver through a hydraulic transfer medium. All of these types have been used for breaking, drilling or pile-driving in frozen ground, but quantitative results suitable for analysis are not available.

It has been suggested that there is a minimum level of blow energy below which rock cutting becomes ineffective. Values that have been put forward as practical minima include 280, 750 and even 5000 ft-lbf per inch of cutting edge. These values are highly questionable, and indeed the whole notion seems overly simplistic. However, there may be enough validity to steer the present consideration away from very high frequency devices that develop very small blow energies. This is not to completely rule out vibratory machines. The Sonico (Bodine) BRD-100 and BRD-1000, and the Gardner-Denver "Blowtorch" have been used for drilling and driving, and there is a good deal of experience with the BRD machines in frozen ground.

Percussive rock drills develop a maximum blow energy of about 300 ft-lbf, while small hand-held pavement breakers give up to about 100 ft-lbf. Frequencies are usually less than 1000 blows/min, and a pneumatic rock drill cannot normally deliver more than about 5 h.p. at the bit. However, this represents a fairly high power density -- about 100 hp/ft^2 with a 3 in. bit.

Table III, taken from a paper by Grantmyre and Hawkes, gives blow energies for a large number of boom mounted hammer impactors. These values range from 125 to 20,000 ft-lbf (low frequency pile drivers deliver up to about 850,000 ft lbf). Corresponding frequency data are not immediately available, but machines with a blow energy of about 1000 lbf can be expected to run at 300 to 600 blows/min, while heavier machines run more slowly. For example, the Koehring RB8 runs at 225 blows/min with a 4400 ft-lbf blow.

Looking at output power and mechanical efficiency, the last named machine puts out 30 h.p. maximum, while requiring a 200 h.p. input to the compressor. A hydraulic impact breaker used by the writer (IR Hobgoblin) delivered up to 12 h.p. at the tip for a 78 h.p. diesel input. On pneumatic percussive rock drills it is quite common to require 40 h.p. input to the compressor for a 4 h.p. output at the bit. Thus the mechanical efficiency of these systems is of the order of 10% to 15%.

We can make a rough estimate of the amount of power that might be needed to cut a 12 in wide trench to a depth of 3 ft. Taking 100 $h.p./ft^2$ as the required power density, about 300 h.p.

TABLE [illegible]— Boom-Mounted Hammer-Type Impactors (published data)

Model	Blow Energy (ft-lb,)	Weight (lbs)	Blow Energy /Mass Ratio
Hydraulic Machines			
Hughes Impactor	125	285	0.44
Allied Hy-Ram 33	200	700	0.29
Krupp HM 200	400	—	—
Worthington H 400	400	650	0.62
Ingersoll-Rand G 500	500	531	0.94
Kent Hydra Ram KHR 580	500	1250	0.4
Montabert BRH 250	723	1212	0.6
Allied Hy-Ram 77	750	900	0.83
Mindev BR 40	850	450	1.89
Joy 206 HEFTI	1000	340	2.94
Mindev BR 120	1155	675	1.71
Ingersoll-Rand G 1100	1200	846	1.42
Krupp HM 600	1350	—	—
Montabert BRH 501	1447	2200	0.66
EIMCO Impactor	1500	—	—
Shand-Macol Impactor	1730	1150	1.50
CTI HD7 Nutcracker	2400	1200	2.0
Soviet Impact Ripper*	2530	1475	1.72
Gullick Dobson Impactor	3000	1650	1.82
Ingersoll-Rand G 3100	3100	—	—
Joy 514 HEFTI	20000	2400	8.33
Pneumatic Machines			
Worthington T500	500	650	0.77
Schramm B 450	550	450	1.22
Tramac 96 A	700	450	1.55
Allied Ho-Ram 6000	700	700	1.0
Guest 125	700	450	1.55
Ingersoll-Rand ABM 500	700	640	1.09
Allied Ho-Ram 7000 B	1000	1100	0.91
Kent KB 999	1000	829	1.20
Kent KB 999 HD	1000	1250	0.8
Kent KB 999 S	1000	1300	0.77
Ingersoll-Rand ABM 1000	1200	1000	1.20
Schramm B 1100	1500	770	1.95
Thiess Dynamax	1945	2336	0.83
Kent 2000	2000	1640	1.22
Allied Super Ho-Ram Model 79	3000	3050	0.98

*Ref. Mining Magazine, February, 1973, p. 139.

Table III Blow energy data for impact breakers (from "High energy impact rock breaking" by I. Grantmyre and I. Hawkes, Canadian Mining and Metallurgical Bulletin, July 1975)

TABLE [illegible] — Projectile-Type Impactors

Model	Blow Energy (ft-lb,)	Weight (lbs)	Blow Energy /Mass Ratio
Ingersoll-Rand Demon 100	3000	760	3.45
Ingersoll-Rand Demon 300	10000	2200	4.55
Arrow D 500	13500	—	—
Ingersoll-Rand Imp 1000	15000	1000	15
CMI Champion	16000	—	—
Russian Hydro-hammer	72000	11000	6.55

Table IV Blow energy data for captive projectile impact breakers (from Grantmyre and Hawkes) would have to be delivered by the cutter. This would call for an input power of 2000 h.p. or more.

Some of the design limitations of repetitive impulse devices can be overcome by projectile impact breakers. These may employ either a reuseable captive projectile, or else free projectiles. A high speed projectile impacting normally on a solid target creates a high stress level. With relatively incompressible projectile and target materials, the initial impact stress is given to a first approximation by ρcv, where ρ is material density, c is acoustic velocity for the material, and v is impact velocity.

A simple example is provided by the so-called REAM system, which was developed with funding from the Advanced Research Projects Agency (acronym translation not available, although ARPA seems to have been reamed). This system was intended to drive tunnels in hard rock by firing concrete projectiles from a 105 mm howitzer.

There have also been proposals for "missile miners" that fire continuous streams of projectiles, and CRREL studied a proposal for excavating permafrost by firing steel shot or pea gravel from an eductor-ejector.

The writer analyzed this proposed scheme, plotting input data for a wide range of projectiles, from bullets to bombs, and finding a linear correlation between crater volume and projectile energy. For impact on frozen soils at velocities up to 4000 ft/sec, specific energies were in the range 350 to 3500 lbf/in^2. In this study, specific energy did not vary systematically with impact energy, or velocity, although for rocks in general there is supposed to be a decrease (improvement) in specific energy as impact energy increases. The CRREL analysis brought out the point that energy has to be developed more by velocity than mass; otherwise, the volume of projectile material thrown against the working face becomes comparable to the volume of material broken out.

For underwater cutting, projectiles would probably have to have the water cleared from their flight path by compressed air. Alternatively, solid particles might be entrained in a high velocity water jet.

Table IV, taken from a paper by Grantmyre and Hawkes, gives blow energies for some captive-projectile impact breakers. These machines do not seem to have gained much acceptance in the commercial sphere.

In the Soviet Union, Zelenin made a major study of frozen ground excavation nearly 20 years ago, carrying out some experiments with drop-wedges. Machine designers took these tests rather literally and fitted tractors with frames that allowed a heavy wedge to be winched up and dropped onto frozen ground. It is hard to take these contraptions seriously, but if the idea were to be beefed-up we could imagine a diesel piling hammer hitting a wedge with a 30,000 ft-lbf at about 1 blow/second (55 h.p.), breaking 25 to 31 ft^3/min in frozen silt and 9.3 to 13.2 ft^3/min in frozen gravel.

One of the main attractions of repetitive-impulse devices is that they require very little bias force to be applied externally, and this could be a significant advantage in underwater work. On the other hand, if experience in surface excavation gives any indication, the general operating characteristics of impactors are not very appealing except in very hard brittle material.

Water Jets

Water jets are widely used for burying undersea pipelines and cables in cohesionless bed materials. There are various ways of using jets, such as:

1. Simple jets to dislodge and remove soil
2. Simple jets to fluidize the soil beneath lines
3. Water jets plus air jets
4. Jets plus suction dredges
5. Jets plus mechanical plows

For burying pipes, the jet nozzles can be mounted on a frame that rides along the pipe. For burying cables, jet nozzles have to be carried on some kind of vehicle, such as a sled or a submersible.

Nozzle pressures vary considerably. Some soils can be fluidized sufficiently to allow sinkage of a heavy line with a few tens of psi, starting at say 20 psi. However, to get much disruptive effect the nozzle pressure has to be an order of magnitude higher.

Pipeline bury barges using jetting equipment seem to have progressively upgraded nozzle pressures from 300 to 3000 lbf/in^2. However, even at the high end of this pressure range simple jets would not normally be used in coarse gravels and boulder clays.

P.K. Rockwell of CEL has examined the power requirements for actual jetting operations and found that for each ft^3/min of excavation rate the required power level ranges from 0.4 h.p. to 11.6 h.p. Putting these values in terms of specific energy, they translate as 92 to 2660 lbf/in^2.

Before turning to consideration of rock cutting by high pressure jets, it may be of interest to mention one other application of low pressure water jets.

During the heyday of Alaskan gold mining, sluicing or "hydraulicking" was widely used for eroding banks of frozen gravel. Low pressure water jets (hydrostatic head) directed by firehose monitors were played on the gravel, and the face was slowly cut away by a combination of melting and weak mechanical erosion. This method may still be applicable for surface excavation of frozen soils, but it is probably of little relevance in the present context.

If they can be made to cut rock effectively, high pressure water jets have certain potential advantages over rigid tools. The jet is a non-contact tool, and it suffers relatively little wear. Reaction forces on the cutting device are relatively small, so that it is not necessary to transmit high forces. However, jet cutting is very inefficient in energetic terms, so that large amounts of power are required.

The cutting of materials with high pressure water jets is a relatively new technology that has developed quite rapidly. A good introduction to the field is provided by the Proceedings of the First, Second and Third International Symposiums on Jet Cutting Technology (Coventry, England 1972; Cambridge, England, 1974; Chicago, Illinois, 1976). Two broad development approaches have been followed in jet cutting technology: (i) continuous jets, and (ii) discontinuous, or pulsed, jets. Pumps capable of providing continuous jets are currently available from commercial sources with delivery pressures up to 70,000 lbf/in^2 for small units (around 60 h.p.), and up to 20,000 lbf/in^2 for large units (600 to 1200 h.p.). CRREL worked (through a contract arrangement) with a 200 h.p. unit that had a pressure capability of 100,000 lbf/in^2, but it was incapable of continuous operation. Pulsed jets, which even after many years are still in the development stage, are generated by impact systems, and they can achieve exit pressures of the order of 10^6 lbf/in^2.

In the research area, there are two distinct schools of thought on water jet applications. One holds that intermittent ejection of slugs of water at very high velocity provides the most efficient attack, while the other maintains that continuous jets at the highest feasible pressure level are likely to be the most effective. There might also be a compromise approach involving modulation of continuous jets over a modest amplitude. There is no doubt that in some applications it may be desirable to emphasize velocity over mass in the generation of jet energy (cf. projectile impact), since there are situations where it is inconvenient to supply and remove large volumes of water, e.g. in winter excavation of "dry-land" permafrost, or in underground work. However, when spurious boundary effects are eliminated there is, as yet, little convincing evidence that specific energy consumption decreases significantly with increasing impact velocity, either for typical rocks or for frozen soils and ice. This fact, taken in conjunction with the rapid development of high pressure pump technology, suggests that continuous jets are more attractive than discontinuous jets for short-term development goals. Another factor is that continuous jets appear to be better adapted for deep penetration, which is very important in most practical applications.

In the continuous jet development field, there is a tendency to pursue ever higher discharge pressures, in the belief that efficiency improves with increasing pressure. However, there is very little evidence, either experimental or theoretical, to support this quest. On the contrary, there are some indications that, provided water volume is not a consideration, there may be an optimum pressure for a given combination of other variables and rock type. The design goal, therefore, is to estimate an optimum combination of nozzle parameters that is practically feasible.

CRREL investigations have covered the development of design schemes quite thoroughly, taking both theoretical and experimental approaches. This work has been published, and need not be described here. However, a paper that gives a large amount of experimental data for rock cutting is appended (Harris and Mellor, Cutting rock with water jets, 1974).

From previous experience and available data, we do not feel that a jet plow could be designed for work in hard rock without some development effort, and power demands might well be prohibitive. For initial design estimates, we might suppose that a jet working at some realistic pressure (say 20,000 lbf/in^2 for sea water in high power pumps) would penetrate about 15 nozzle diameters at a useful traverse speed. The problem is to assist a ripper while keeping penetration demands as low as possible. One approach would be to have jets working as "gauge cutters" for a staged series of ripper teeth. One pair of jets would point upward from the edges of the ripper tip, while another pair of jets pointed downward from the top surface of the material. Any one ripper tooth would only work a limited depth -- a following ripper would deepen the slot. However, the power demands for such a system quickly become exorbitant.

Figure 5 gives a graphical display of power and flow rate as functions of nozzle pressure and nozzle diameter. More directly, the hydraulic horsepower of a nozzle is $0.0174\ d^2 p^{3/2}$, where d is nozzle diameter in inches and p is nozzle pressure in lbf/in^2.

If we want to penetrate 6 inches in a single pass, a first guess is that the required nozzle size would be around 0.4 inches. To run a 0.4 inch nozzle at 20,000 lbf/in^2, the required hydraulic power is 7874 h.p. For a 3 ft deep trench, we might require 12 nozzles, and a total of 94,500 h.p.!

This sort of power demand could probably be reduced by clever design and development effort, but the prospects for a small system do not look good.

As far as coral is concerned, water jets might very well do a useful job, as the high porosity would help the cutting action. However, experimental data are needed.

One other type of jet that might be mentioned is the cavitating jet, which works on different principles. NAVFAC has apparently developed an interest in use of cavitating jets for underwater trenching, but we do not feel that this is feasible at the present time.

In conclusion, it might be mentioned that CRREL has been involved in jet cutting research for over 10 years. Papers have been published in journals and in the proceedings of each of the

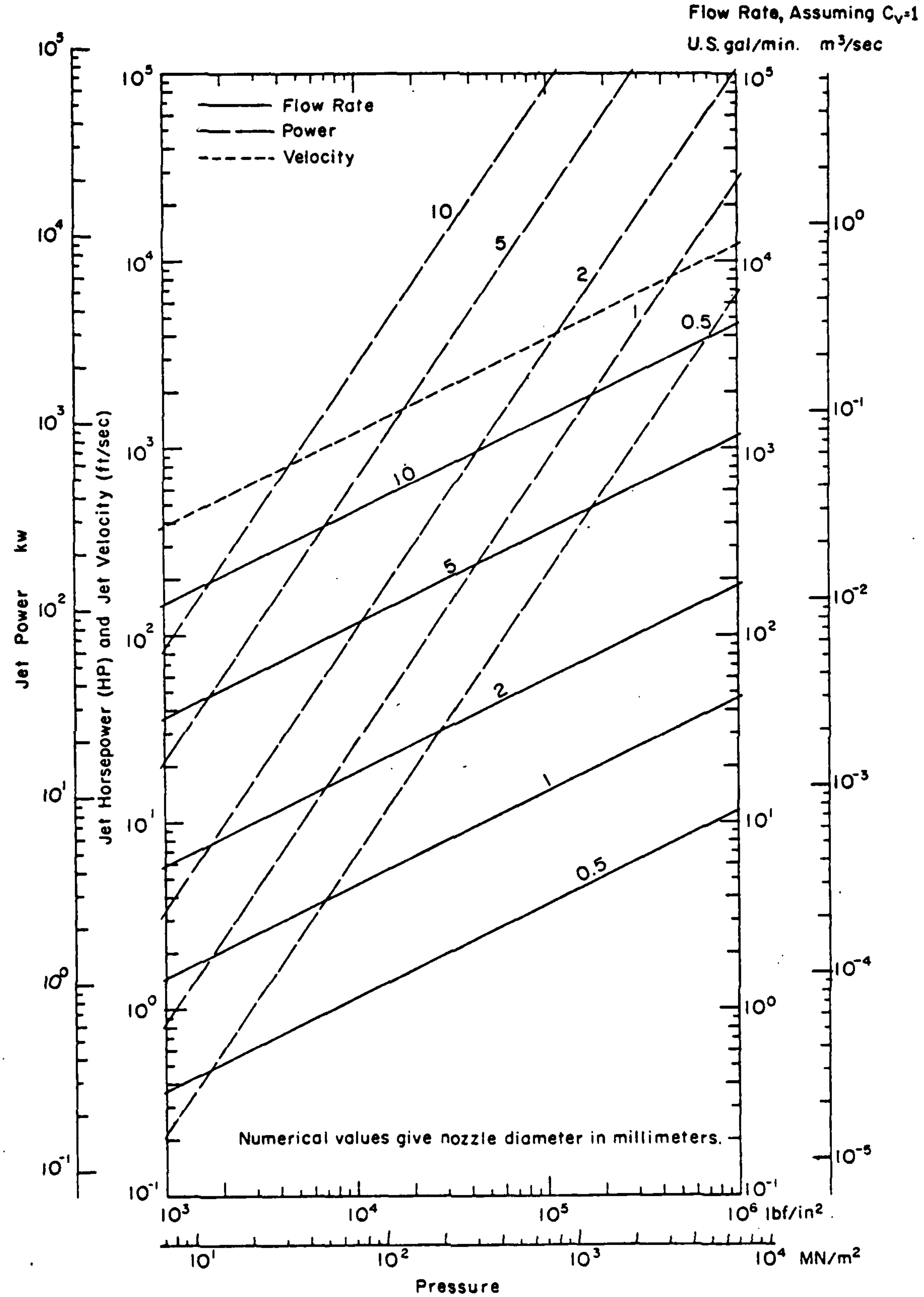


Fig 5

Jet power and flow rate as functions of nozzle pressure, with nozzle diameter as parameter (jet velocity as a function of nozzle pressure is also given).

three international symposiums on jet cutting technology. We participated in last year's NSF workshop on jet cutting, and have a 150 h.p. research pump fitted out for field work.

Flame Jets and Plasma Torches

High velocity flame jets, such as the Linde torch or the Browning burner, are used for cutting some types of rock, and periodically there are suggestions that they should be used for drilling and cutting frozen ground. CRREL has used Browning burners for drilling and slotting frozen ground, but the performance has been uninspiring.

The rocks that are cut successfully with flame torches are so-called "spallable" rocks, usually crystalline rocks with high density, high modulus, and high quartz content. The torch spalls pieces off the rock surface by inducing thermal strain discontinuities at high rates (the volume expansion coefficient for crystalline quartz is three times greater than for other common constituent minerals), and the jet velocity is sufficient to clear chips from the working surface.

Production rate data are not immediately available for flame jets in rock, but watching the progress of a flame jet channeling operation in a granite quarry is a bit like watching the grass grow. There is a possibility that rock spalling might be enhanced underwater by rapid quenching, but it is hard to imagine an effective trenching tool based on torches.

High temperature heaters have been developed for boring and tunneling in rock. Power densities of the Los Alamos "Subterrenes" were in the range 0.3 to 2.5 MW/m^2 (power densities for thermal ice drills are about the same -- up to 3.5 MW/m^2). However, the practical usefulness of these rock-boring devices still has to be demonstrated.

Ice-bonded soils do not spall; although ice has an expansion coefficient much higher than the silicate soil grains, it is impossible to heat it rapidly through the 100°C or so that would be necessary to provide the required internal strain differentials. Thus a flame torch cuts frozen soils by melting the ice cement, and then blasts the separated particles clear of the working face.

Even a very efficient melting process can be expected to be at least 30 times less efficient in energy terms than typical mechanical cutting, but rough estimates of specific energy for flame torches in frozen ground give values of the order of 10^5 lbf/in^2, i.e. about 100 times less efficient than mechanical cutting. This is not surprising, since much of the heat is dissipated by convection to the surrounding air.

Perhaps of more consequence is the inherent rate limitation of a melting process that depends on heat conduction through the solid. During drilling tests with the Browning burner, penetration rates for 6 to 9 in. diameter holes in frozen silt were from 0.4 to 1.1 ft/min, and 1 ft diameter hole was produced in frozen gravel at rates up to 3 ft/min. On the basis of these results, it is estimated that one burner of typical size might be capable of advancing the equivalent of 6 ft deep slots at rates up to 0.14 ft/min in frozen silt and up to 0.5 ft/min in frozen gravel. However, operational slotting results obtained by CRREL did not give rates as high as these.

Flame jets would operate under water of moderate depth, but they do not appear attractive, even though they constitute "zero force" devices.

Electric-arc plasma torches are being developed for metal-cutting and other purposes and it has been suggested that they might be used for excavation. In the present context they can be regarded as being in the same category as flame jets, but because they are of even higher potential they will probably be less efficient.

Explosive Techniques

Conventional explosive methods for trenching involve the basic "drill-blast-muck" cycle, whether the work is on land or under the sea. There are two general approaches. One relies on the drilling of small diameter shotholes in a pattern such as parallel lines with paired holes or with a staggered middle line ("5-spot"). The other is based on crater blasting, with a single row of charges set in shotholes of relatively large diameter.

Shotholes have to be drilled to at least the required trench depth and probably a foot or so deeper. Small diameter holes can be drilled underwater with hand-held diver tools, but for sustained production more substantial machines are needed. Conventional track-mounted pneumatic drills have been used successfully to drill small diameter holes for undersea work, although special modifications or procedures are necessary. The Navy Civil Engineering Lab has modified a conventional Worthington percussive rock drill to provide corrosion protection, sealing of bearings, hydraulics and pneumatics, and high visibiility. In the U.K., a conventional Ingersoll-Rand percussive drill has been used successfully without modification by relying on scrupulous preventive maintenance after every working shift. In shallow water, drilling is often done from the surface, using barges or platforms that have extendable legs. A surface system would probably be needed to provide large diameter holes (6 in or bigger) for crater blasting with cheap bulk explosives.*

---

*One possibility for frugal crater blasting is spring hole loading. A small diameter hole is drilled, and a camouflet chamber is blasted at its base with a small charge. The chamber is then loaded with liquid or slurry explosive to provide a cratering charge. Design data are available.

Hole stability is a problem in underwater work. In soft materials or friable rocks, holes need to be cased or to be loaded immediately to avoid loss by slumping or blockage.

Small diameter holes (2 in. or less) would usually be loaded by hand with traditional solid explosives such as dynamite. Special packaging of cartridges might be necessary, especially if delay deck charges were to be used. All-electric initiation of a multiple hole round can produce a jungle of leg wires, so that non-electric methods might well be preferable. With closely spaced holes underwater, there is a strong possibility of "flash-over." Misfires are also common, and some blasters double the charge weight to compensate for possible misfires.

Large diameter holes can be loaded with water-resistant bulk explosive using some kind of mechanical charger. However, diver control would probably still be necessary. With a row of single crater charges there will usually be a large amount of overbreak to the sides of the row, but unbroken humps may be left along the bottom between shot points.

Required charge weights for trench blasting on land can be estimated for a wide range of materials,* but comparable estimation for underwater work is still a black art. One rule of thumb used in Europe calls for the dry-land charge weight to be

*Crater blasting and bench blasting on dry land can yield 10 to 60 cubic feet of breakage per pound of explosive under optimum conditions. However, for trench blasting in rock, much heavier loads are commonly used and yield might be in the range 4 to 20 ft^3/lb. For underwater row craters, yields of 3 to 7 ft^3/lb have been obtained in hard rock.

increased by 1% for each 1 metre of water depth. However, the usual expedient is to determine loadings on site by trial and error. For blasting row craters, the simple cube root scaling that is so successful for small scale work on dry land may not work too well, as gravity body forces are highly significant underwater.

Some companies (or agencies) from time to time promote the idea of using explosives to both break the ground and expel the broken material. This procedure is usually given some jazzy name like "blow and go." It seems unlikely that such a procedure would produce consistently satisfactory results underwater, so that provision has to be made for cleaning out the blasted trench.

On land, blasted trenches are usually mucked out with a backhoe, and in shallow water a similar operation might be feasible. In deep water, mechanical removal of blasted rock could be awkward unless there is good fragmentation. With good fragmentation, a suction dredge, eductor, or air-lift might be usable.

Shallow pipeline ditches under rivers are sometimes blown in soft materials or weak rocks by charges attached to a cable and laid directly on the bed. This is referred to as string shooting. There are various rules of thumb for string shooting, some expressed in odd forms. One that has been widely used can be boiled down to an expression for charge weight per unit length as kd^2, where d is water depth. With unit charge weight in lb/ft and d in feet, k is in the range 0.043 to 0.086.

A variant of string shooting employs a continuous hose charge or a series of long sausage charges. This variant is more practical and economical now that cheap sensitized slurry explosives are readily available.

Shooting at zero depth of burial is extremely inefficient in air (an order of magnitude less efficient than optimum depth shots). Confinement by water ought to improve the situation, at least for soft materials, but the gas bubble (which represents most of the explosive energy) will still be unable to do much work on hard rock.

The other way to avoid the need for shothole drilling is to use shaped charges, either the usual radially symmetrical charges or linear shaped charges.

Shaped charges provide the standard military expedient for penetrating concrete, rock, steel and hard-ground. They have not so far found wide industrial application, except for a few special jobs such as tapping blast furnaces, piercing well casings, etc. However, shaped charges have been used to provide shotholes in underwater blasting operations where divers are used.

The standard conical shaped charge forms a jet by shock wave interaction and thus penetrates hard materials (this is known as the Monroe effect). The jet pressure far exceeds the yield stress of any material, and it carries along with it the metal of the core liner, both in the form of a spray of metal particles and in the form of a central "slug". The largest shaped charge in normal military use is the M3, which is nominally 40 lb and actually contains 30 lb of explosive. For civil use, shaped charges have been made by pouring liquid explosive (e.g. sensitized nitromethane) or sensitized slurry explosive into pressed steel cans, e.g. 15 lb of explosive in a 9 in. diameter can. For greater safety, 2-component explosives can be employed (non-explosive consituents are combined during loading).

Shaped charges have been tested systematically in frozen ground, and the results have been analyzed. For geometrically similar charges, linear dimensions of the penetration hole can be taken as proportional to either the cone diameter, or the cube root of charge weight (assuming reasonably constant explosive density). With charges of conventional proportions, penetration in frozen ground is approximately 10 times the cone diameter, or about 2.7 $W^{1/3}$ ft, where W is weight of explosive filling in lb. With a 60° cone, the average hole diameter is about 60% of the cone diameter.

For use underwater, the performance of shaped charges should not be reduced very much in shallow water, although the hole may not always scour out quite as effectively. Shaped charges alone can produce underwater trench if used in sufficient numbers, and they can also be used to punch shotholes.

Flexible linear shaped charge has been developed for cutting purposes in the past few years. This is flexible explosive strip with a V-groove moulded in its base (linear shaped charge can also be improvised by moulding plastic explosive over suitable "angle iron").

It is easy to see how linear shaped charges could be scaled up by filling casings of extruded metal or plastic with liquid or slurried explosive. A rough performance estimate can be made on the basis of data for conventional shaped charges, e.g. by assuming that penetration will be roughly 10 times the charge width. In order to punch slot to a depth of 12 ft, the required charge width would be about 14.5 in. Making a guess about the charge cross-section (similar to that for conventional 60° cone), and assuming an explosive specific gravity of 1.3, the approximate load would be 51 lb per lineal foot. The average slot width might be about 9 in. A rough check on the validity of this estimate can be made on the basis of specific energy: for the proposed linear shaped charge the specific energy is about 55,000 lbf/in^2 (assuming 1 kcal/gm heat of explosion), whereas the specific energy for a conventional shaped charge in frozen ground is about 170,000 lbf/in^2. Thus the specific energy for the proposed load is three times lower (more optimistic) than the specific energy of conventional shaped charges. Surface to volume ratio for the slot is also three times lower than for the slender hole.

Another unconventional possibility in the explosive area is gas blasting.

Gas blasting devices give an abrupt discharge of gas or vapor, usually with initial release pressures in the range 10,000 to 20,000 lbf/in^2 (explosive detonation pressures are of the order of a million psi). The small expansion between the initial discharge point and the confining medium is sufficient to drop the gas pressure below the yield stress of most materials, and there is virtually no shock wave generated by the gas release. Thus all the blasting action has to be achieved by gas expansion.

There are two well-established commercial gas blasting systems: airblast systems and compressed carbon dioxide systems. In the airblasting (Airdox) system a multi-stage compressor charges a bank of receivers, and high pressure air is discharged abruptly from a special shell when a pre-set pressure level is reached. With the CO_2 (Cardox) system, self-contained shells carry liquid carbon dioxide, which is abruptly vaporized and released through a rupturing membrane when an internal heater unit is fired electrically. There are also experimental systems that employ deflagration of gaseous fuel-oxidant mixtures. One that was developed for excavation is known as REDSOD; it fires a compressed air/propane mixture in a combustion chamber, discharging gas through a venting port.

The airblast and CO_2 systems have been tested for breaking frozen ground, with apparently conflicting results. The first series of tests, which investigated both surface excavation and tunnel excavation, gave very good results and amazingly low values of specific energy (down to 50 lbf/in^2, i.e. an order of magnitude more efficient than chemical explosives). However, these results may reflect skilfull exploitation of prevailing conditions, which perhaps included an unfrozen or permeable sublayer in the case of surface excavation. The writer's personal experience is that compressed gas shells are incapable of breaking well-cemented ice-rich frozen soils with a useful burden when they are used under realistic practical conditions.

For some special applications, e.g. for heaving surface slabs, gas blasting is very attractive, and the rapid-firing repetitive blast system (REDSOD) is particularly attractive within its range of capability. For general use, gas blasting is not likely to be a serious competitor to conventional explosives. It is incapable of primary fracturing in hard rock, the cost of explosive energy is high, and shothole requirements are at least equal to those for chemical explosives. However, it might be possible to make a useful tool for fine-grained soils (frozen or unfrozen) by coupling a repetitive gas-blast shell with a vibratory driver. Such a tool could be used to break frozen silt and frozen sand under shallow water, or to displace stiff clays.

Electrical Discharge and Electromagnetic Radiation

Electrical and electromagnetic concepts for excavation of rock or frozen ground have not yet developed into realistic practical methods, nor are they likely to do so in the near future (investigators in the USSR might disagree). Nevertheless they tend to attract attention periodically, and for the sake of completeness a few notes are included here. For more thorough coverage, a CRREL report on the subject will be available shortly.

Electrical discharge. Electrical discharge methods for breaking rock or frozen ground involve either abrupt d.c. discharge of energy stored in a bank of capacitors, or else high-loss, high-frequency a.c. discharge between implanted electrodes. The former is the basis of the electro-hydraulic technique for breaking rock and generating underwater shocks. The latter dissipates heat rapidly along preferred conduction paths, which would probably be ice-silicate interfaces in frozen soils, or wet internal surfaces in ordinary rocks. At the present time these techniques do not appear attractive even on a laboratory scale, and there are numerous objections to practical applications in the present context.

Electromagnetic Radiation. The logical way to use electromagnetic radiation for breaking rock or frozen ground is to dissipate energy inside the ground material so as to create internal fracture or to destroy ice bonds by partial or complete melting. In broad terms, attenuation of radiation in the ground can be expected to decrease as frequency decreases and wavelength increases. The goal is to find a frequency range which will provide suitable penetration while keeping dissipative power density at a useful level. Obviously, radiation at optical frequencies will not penetrate at all, while very low frequency signals will penetrate too easily. One might guess that a suitable range would be where the wavelength is about an order of magnitude greater than the maximum grain size of the soil. If a suitable frequency could be found, the radiation might be beamed into the ground at a high power level with a directional antenna. Theoretically, frozen soil should fall apart under these conditions, but the dielectric properties of frozen soils are quite complicated, and prospects for early development of such a device are not good.

The cutting of rock with lasers has evoked considerable interest in recent years, but it is not easy to see why. A beam of coherent light does not suffer geometrical attenuation; it can therefore transmit energy through the atmosphere without much loss, but this is of no great interest in excavation. A focused laser beam can create great power density at a solid surface, giving very high point temperatures. This can cause the surface of "spallable" rock to spall, provided that the beam traverses at a suitable rate. If a focused laser dwells on one point, in either spallable or non-spallable rock, the rock melts, and the molten rock provides an effective barrier to further attack if it is not swept or blown away. In short, a laser does what a flame jet or a plasma torch could do. Laser tests on frozen soils were commissioned by CRREL, but the results were not encouraging.

CRREL also commissioned laboratory tests of electron beam impingement on frozen clay and frozen sand. The resulting specific energy values were in the range 35,000 to 350,000 lbf/in^2, i.e. the process was very inefficient.

On present evidence, electrical and electromagnetic methods have not much to offer for underwater trenching.

Chemical Methods

In principle, there ought to be chemical methods for loosening rocks to permit excavation and pipe burial. One patent was found that described a chemical method for burying underwater pipelines in clay. However, during conversations with the inventor, who was contacted on another matter, it became clear that he did not regard the chemical method as having any practical value.

END
DTIC
4-86