FOUNDATION STABILITY

OF

BURIED OFFSHORE PIPELINES.

A SURVEY OF PUBLISHED LITERATURE

by

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ABSTRACT

A literature survey dealing with foundation stability of buried offshore pipelines was conducted as preliminary to a laboratory investigation of scour around pipelines by wave action.

Pipeline alignment, beach stability, soil type, wave parameters and scour are discussed as well as pipe flotation and need for soil exploration. A new idea of pipe anchoring is mentioned as well as recommendations for future research.

Abstracts of the more important papers are presented, and annotated bibliography and references are given in the Appendix.

PREFACE

The literature survey described in this report was conducted as part of the research program in the Coastal, Hydraulic and Ocean Engineering Group of Texas A&M University.

The manuscript was edited by Dr. Gisela Mahoney and typed for publication by Mrs. Joyce McCabe.

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INTRODUCTION

A pipeline buried in the seabed is protected from the forces of nature, which can become quite large and violent under storm conditions. There is a complex interaction of current- and wave-induced forces acting on a pipeline that is open to the forces of the sea. The A.S.C.E. Task Committee on Flotation Studies reports that unburied pipeline sections with specific gravities of 1.4-1.65 were moved as far as 1400 feet under the influence of Hurricane Flossy in 1956 (1). Blumberg (4) reports movements of unburied lines in the Gulf of Mexico in depths of 240 feet.

A quickly moving current on the seafloor can scour out the support of an unburied pipeline causing spanning between solid points of the bed, inducing bending stresses that the line was not designed for. As a rapidly moving current flows past the unsupported pipe, vortices are shed at a frequency that depends on the dimensions of the pipe and on the flow conditions (12). If this vortex shedding is at a frequency that approximates the natural frequency of the pipe, structural resonance can occur, and the line can begin to oscillate causing stresses that had not been accounted for.

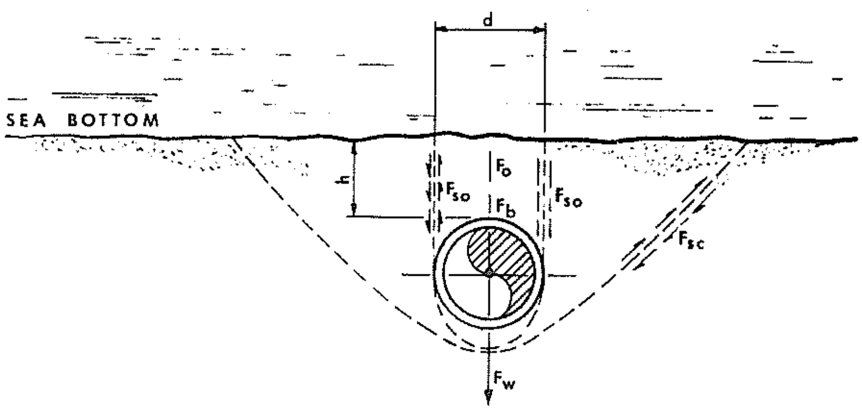
Organic damage to the coating of a pipeline can occur as barnacles and various other undersea organisms make their home in and around the shelter of a newly laid unburied pipeline.

Pipelines must be buried where crossing navigation channels. In general, the requirement for any obstruction in navigable water can be found in Paragraph 403 of the United States Code, Title 33 (28). The various Army Engineer Districts may have further restrictions with regard to pipe burial.

Beyond governmental requirements, the burial will depend on the severity of the factors outlined above as well as such non-engineering considerations as protection of oyster beds and fishing.

STABILITY OF BURIED PIPELINE

The stability of a buried pipeline is dependent on the relative magnitude of the forces that act on it. Figure 1 (7) shows the forces on a pipeline that is buried.



d = outside diameter of pipeline

h = depth of cover

F_w = weight of pipeline & contents (lbs./ft.)

F_b = buoyancy of pipeline (lbs./ft.)

F_o = weight of overburdening soil (lbs./ft.)

F_{so} = apparent shear force of overburdening soil (lbs./ft.)

F_{sc} = apparent shear force due to compression of the pipeline into the bottom soil (lbs./ft.)

Fig. 1. FORCES ON A BURIED PIPELINE

Source: Brown (7) (Fig. 7)

If the currents in the vicinity of the buried line are great enough and the bottom conditions are conducive to scour, it is possible that the overburden can scour away as shown in Fig. 2. Without cover the pipeline no longer has the anchoring effects contributed by the effective overburden pressure and the shear strength of the soil above it. It has also lost its protection as well as its anchoring so it is now exposed to hydrodynamic forces.

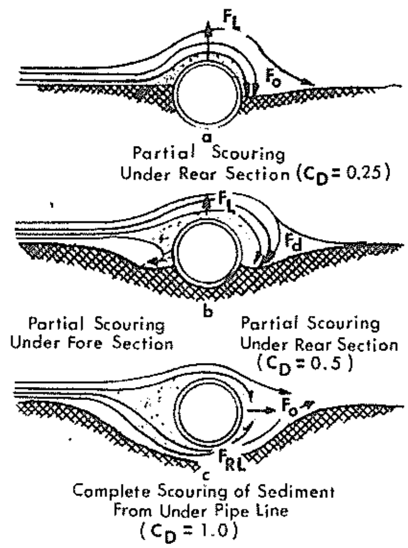


Fig. 2 TYPICAL EROSION PATTERN AT AN EXPOSED PIPELINE

Source: Blumberg (4) (Fig. 1).

If the soil overburden is composed of sediments from backfill, e.g., natural backfill, under the right conditions this sediment load can liquify and lose its shear strength. Thus, it is not able to exert a downward force on the pipeline. The pipeline, under these conditions, since its specific gravity is less than that of the surrounding medium, will now float to the soil-water interface (flotation). This exposes it to the hydrodynamic forces of the waves.

ALIGNMENT

The alignment of the pipeline is usually determined within some geographical range as most pipelines have a definite origin and destination. To optimize the route of a pipeline several factors must be considered. It must be aligned with minimal orthogonality to currents and wave direction (27). The surface of the seabed must be such that the allowable maximum radius of curvature of the line is not exceeded. Soft spots should be avoided so that flotation or spanning does not occur (17), and areas of probable scour should be avoided so as to prevent spanning and exposure of the line.

In general, the best route for an offshore pipeline is one that is orthogonal to the coastline (27, 28). This route minimizes wave forces if the line becomes exposed. Adjustment of the direction in shallow water could be done so that the line is perpendicular to wave crests as they approach the shore, if their direction of approach is other than orthogonal to the coast.

Seasonal wave heights and scour limits should be evaluated along the length of the possible alignments. The maximum wave heights give valuable parameters in determining the stability of a pipeline and the sea bottom.

Samples of bottom sediments can be obtained along possible routes by use of a piston corer shown in Figure 3, p. 36 and described by Brown (9). The engineering properties of the bottom structure can be determined from standard soil tests and become another consideration in the evaluation of the actual route of the pipeline.

The pipeline should cross the shore at an accreting or stable beach. If an eroding beach must be chosen, the line should be buried well below the expected depth of erosion.

The factors outlined above, supported by an economic analysis, can assist in determining the route of a pipeline. In some cases, it may be less expensive to leave the submerged line exposed on the ocean floor and operate an inspection and maintenance program for it, than to try to blast through a reef or excavate through clay bank. The economic analysis must include costs for possible downtime of the line and environmental damage from a break as well as the continuing cost of an inspection and maintenance crew versus the cost of burial and an inspection crew.

SCOUR

Scour is a large-scale transport of the seabed due to a momentum exchange between rapidly moving water and the individual grains that make up the bed itself. Scour of the seafloor usually occurs during large storms because they generate an excited sea state and the high-bottom velocities required to move the seabed grains. The combination of current- and wave-induced forces on the seabed will cause seabed movement. In the North Sea, Arriens (2) reports 7-feet-high wandering sand dunes. In this area it is necessary to bury lines some 10 feet to protect against spanning.

The forces that resist the movement of the seabed are different with respect to grain size and grain-size distribution of the bottom material and type of bottom material (37). Coarse sediments like sands and gravel resist movement by their weight, whereas cohesive sediments that contain clays, silts, or both resist motion by their shear strength or cohesion.

Several attempts have been made in the literature to quantify the motion of sediments. Most of this work has been concerned with basic sediment transport mechanics or the determination of "critical conditions" at the point of incipient motion (13, 21, 30, 37).

Hobbs (22) has reported laboratory tests that were undertaken to investigate the relationship between water velocity and scour. He reports that silty sands and soft clays began movement at water velocities of 1 ft/sec and significant amounts of movement occurred at 2 ft/sec. He further reported that well-consolidated clays are not affected at any velocity. Details of these experiments are not known.

Grass (21) reports that Shields described the problem of initial bed-grain instability as the functional relationship:

$$\frac{\bar{\tau}}{(\rho_s - \rho)\, gd} = \text{function of}\left(\frac{u_* d}{\nu}\right)$$

where $\bar{\tau}$ = critical average shear stress exerted by the fluid on the boundary at the flowstage when bed particles begin to move.

ρ_s = sediment density

ρ = fluid density

ν = kinematic viscosity

d = bed sediment diameter

$u_* = \sqrt{\bar{\tau}/\rho}$ = shear bed velocity

Shields' relationship was established empirically by using a number of different bed materials. He plotted the curve of his functional relationship. The work of others, although showing appreciable scatter, lends support to Shields' basic conclusion (21).

Grass (21) believes that there is no flow stage at which bottom particles are placed in motion at once. They begin to move gradually over a wide range of average bed shear stresses as the flow velocity increases. Grass conducted a statistical analysis of the incipient grain movement which resulted in a proposed extension of Shields' curve.

Eagleson and Dean (13) studied the wave-induced motion of bottom sediment particles. As a wave shoals on a beach, it becomes distorted from its deepwater shape. The trough flattens and the crest begins to steepen. The crest becomes a shorter portion of the wave length and the trough, of course, becomes longer. As a wave approaches the shore beach its oscillatory motion reaches the bed and refraction occurs. The asymmetry of a shallow water wave causes the onshore velocities to be greater but of less endurance than the offshore components of the oscillatory motion. This results in a net hydrodynamic force onshore. The beach slope and sedimentary characteristics offshore provide a resistance to this force by the downslope component of the gravity force. The relative magnitudes of these forces determine offshore, onshore or no motion of the seabed at all. As most pipelines offshore must eventually cross the surfzone and beach to a point onshore, the equilibrium characteristics of beaches are an important consideration. Eagleson, et al., (15) have discussed the equilibrium characteristics of beaches, and Eagleson and Dean (14) show a quantitative theoretical estimate of the net deposit on a length of beach in California. Silvester (40) in his discussion of coastal sediment movement also qualitatively analyzed the sand movements on and off a beach as well as in the nearshore zone in an interesting treatment.

Much valuable information can be obtained from a study of offshore surveys taken over a period of years. It can be determined if the seabed is susceptible to large-scale scour during storms if the offshore surveys are detailed and frequent enough to include seabed conditions before and after a storm. Surveys are conducted frequently in the waters off important harbors and coasts, but offshore data is generally not complete enough to serve as basis for a decision.

A general hydrographic survey should be conducted by engineers to determine not only the bathymetry of the area but also the soil, wave and current conditions on the bottom (31). The survey should be conducted throughout one year because conditions change considerably with seasons accompanying storms. Gorsline (19), and others, have presented procedures for field and laboratory investigation (in oceanographic studies). Sverdrup (39) also has outlined techniques. Miller (31) has summarized the studies needed to determine engineering parameters for the design and construction of an offshore pipeline.

In general, the scour of the seabed due to waves and currents is an extremely complex phenomenon. We can, at best, only roughly estimate the probability and extent of scour based on average or significant conditions as did Eagleson and Dean (14). It appears that soil tests, coupled with oceanographic surveys and wave hindcasting procedures, could provide an insight into the possibility of scour along the route of an offshore pipeline.

FLOTATION

Flotation occurs when a pipeline is buried in soft sediments or the trench in which it is buried is left to fill up by natural sedimentation. As this sediment settles it creates what can best be described as a very heavy liquid of little or no shear strength. Specific gravities as high as 2.0 have been reported for this mixture (8). Because pipelines are seldom if ever weighted to such high specific gravity, the lighter weight pipeline will literally float to the interface of the heavy soil-water mixture and the sea water itself. In the case where the pipeline has been backfilled by covering with soft sediments, it usually takes some degree of agitation before the sediments liquify and the pipe rises. Waves and water currents as well as seismic shock waves can provide the agitation that will liquify backfill (8).

The shear-strength characteristics of sands and inorganic silt are given by Terzaghi and Peck (41) by

$$s = (p - u_w) \tan\phi = \overline{p}\tan\phi$$

unless the soil is exceptionally loose (41).

Where: s = shear strength

p = confining pressure

u_w = pore water pressure

ϕ = angle of internal friction

$\overline{p}$ = $(p-u_w)$ or the effective pressure

Terzaghi and Peck describe a triaxial soil test on a saturated sand that is confined at a pressure P_c. Where the axial stress is allowed to alternate between $P_c + \Delta P$ and $P_c - \Delta P$, under no drainage, each alternation produces an increment Δu of pore pressure within the specimen. After a certain number of alternations the value of u_w becomes equal to the effective stress P_c and the specimen loses its strength and can no longer maintain its shape. The sudden loss of strength corresponds to liquification of the sand (41).

Blumberg (4) reports on internal waves generated in the Gulf of Mexico between seawater layers of differing density. These waves can have amplitudes of 30 or 40 feet and may generate particle velocities of 2 to

4 feet per second.

If a pipeline is buried in a soft sedimentary layer it is possible that agitation can cause the layer to liquify to some depth even below the pipeline. If the specific gravity of this liquified mixture is less than that of the pipeline, the pipeline will sink in this liquid. Brown (8) says that high longitudinal forces can be induced as the pipe deflects in the liquified mixture. He also says that these stresses are of minor importance unless they are generated near the pipe river. Krieg (28) suggests that soil-bearing properties along the route of the pipeline be investigated to prevent possible downward movements. Although these downward movements are possible, they are not probable in most areas (27). Hobbs (22) warns that sediments in which the pipe is laid can be so soft that the jetting down of a pipe in the area could cause mixing which might produce a dense fluid through which the pipe will rise immediately.

Pipes that are trenched in and then backfilled mechanically are not normally subject to a problem of flotation (22). If the backfill procedure takes a long time and considerable sedimentation is expected, however, the flotation problem is again very important (22). Under conditions of poor materials and extreme disturbance the mechanically backfilled trench could be filled with a high density liquid and the problem is the same as before.

There is a critical density of the soil and water mixtures at which the buried pipeline will begin to float through its cover. The density of a soil-water mixture can be obtained as Hobbs (22) suggests by agitating a sample and recording a series of hydrometer readings. The American Society for Testing and Materials describes the liquid limit test. Hobbs suggests an interpolation of the flow curve of the standard liquid limit test to determine the water content at the point when the soil and liquid mixture acts as a fluid with negligible shear strength. Brown (8) presents a standard type of soil test to determine specific gravities required, suggesting method of backfilling and depth of burial. The American Society of Civil Engineers Pipeline Flotation Research Council (1) has presented "state-of-the-art" tables that yield the necessary specific gravity for a pipe to (a) stay buried and (b) not sink into agitated sediments.

Bonar (5) studied pipeline flotation for the A.S.C.E. Research Council. There is a buoyancy or flotation force that acts upward on a buried pipeline in a liquified medium as well as a force that resists flotation. Bonar reports that this buoyancy force is equal to or slightly greater than the resisting force at the onset of flotation.

$$F_F = (\gamma - \gamma_{pipe}) \frac{\pi D^2}{4}$$

where: γ = unit/weight of soil (pcf)

γ_{pipe} = unit weight of the pipe (pcf)

D = pipe diameter (ft)

F_F = flotation force in pounds per linear foot of pipe

and $F_R = 7.2\, C^{\frac{1}{2}}\, D$

C = soil shear strength (psf)

D = diameter of pipe (ft)

F_R = resisting force in pounds per linear foot of pipe

Knowing that the flotation and resisting forces on the pipeline must be equal and from the required soil parameters, the unit weight of a pipe at the point of flotation can be found.

The A.S.C.E. Committee on Pipeline Installations requested comments from the pipeline industry, including consultants and contractors, on their methods of determining weighting for a submerged pipeline. It was noted that there is a large difference of opinion regarding weight required to resist buoyancy in water-covered areas. The wide variation in replies indicates that rule-of-thumb methods are involved in specifying weighting and anchoring criteria (35). Hobbs (22) shows wide variation of specific gravities of submerged pipelines. They ranged from 1.06 to 2.0 for gas lines, from 1.00 to 1.91 for empty oil lines and from 1.58 to 2.47 for filled pipelines.

SOIL EXAMINATION

Soil sampling along the route is the most important procedure in developing an idea of stability requirements. Accurate determination of the engineering properties of the seabed is needed for maintaining the stability of an offshore pipeline.

A study of the type and distribution of the bottom sediments along the route of the pipeline provides required geological information. Miller suggests the plotting of the sediment study on the base map of the route. Examination of the base map with knowledge of geologic information and the general characteristics of the sea will provide an indication of the currents at the bottom and areas of erosion and deposition.

Brown (7,8,9) suggests the use of a piston coring device which can retrieve undisturbed samples of the ocean bottom for determination of their engineering properties. The apparatus described by Brown is also shown in detail by Hvorslev (24). This coring device as shown in Figure 3 can yield 11-feet-long cores in soft clays, 6-feet-long cores in hard-packed sand, and 1-foot-long cores in stiff clays.

Brown's estimates vary, but it seems as if 50-60 cores per day can be obtained with this apparatus at depths up to 1200 feet. From these cores a determination can be made of soil shear strength, natural water content, Atterberg limits, density, and other parameters that are useful in assuring the stability of an offshore pipeline. Freeman (18) outlines the coring sequence practiced in the soil survey for the Tennessee Gas Transmission Company's line from Grand Chenier, Louisiana, to offshore platforms. Terzaghi and Peck (41) outline the use of the piston corer as well as several other coring devices and describe the application and function of each.

Miller (31) reports the use of a jet probe that enables geologists to determine the depth of bottom sediments. He reports that an experienced jet probe operator can tell if he is jetting through sand, gravel, shells or clay by the sound and feel of the pipe.

Chambers (11) described the use of a seismic exploration tool for submarine pipeline investigation. The high resolution sparker survey provides an idea of the continuity of layers on the seafloor. It is especially useful in noting changes between cores. Freeman (18) reports the use of a stratigraphic echo sounder to contour regions of Beaumont Clay in the Gulf of Mexico. He states that results were inconclusive and that there exists a real need for a more suitable instrument for pipeline surveys.

WAVE PARAMETERS

In determining wave effects on the sea bottom the first step is the selection of the design sea state (22). Wave forecasting procedures may be used to determine wave data from meteorological data (42). Application of established wave theory allows computation of the horizontal components of the orbital velocity of a wave at the required depth (22). The height of a wave is a function of the water depth, slope, and characteristics of the bottom. For a storm expected once in fifty years in the Gulf of Mexico, the maximum water velocity in 6.0 feet of water is 12 feet per second and in 17 feet of water it is 10 feet per second (18). Brown shows graphs (8) of bottom water velocity and pressure anomaly for a 50-year storm in the Gulf.

Reynolds (36) reports that first-order terms of wave theory are sufficiently accurate in determining the horizontal component of orbital velocity for pipeline design purposes. The velocity potential of a small amplitude wave is as follows (26):

$$\phi = \frac{ag}{\sigma} \frac{\cosh (h + z)}{\text{cost } kh} \cos (ks - \sigma t)$$

where: a = wave amplitude

g - gravity

σ = wave angular frequency = $\frac{2\pi}{T}$

h = distance from mean water level to bottom

z = depth from mean water level (neg. downward)

k = wave number = $\frac{2\pi}{L}$

t = time

x = distance from the origin

L = wave length

T = wave period

the horizontal component of orbital velocity may be found from the definition of the velocity potential as:

$$u = - \frac{\partial \phi}{\partial x} = \frac{agk}{\sigma} \frac{\cosh k(h+z)}{\cosh kh} \sin (kx-\sigma t)$$

When the horizontal component of orbital velocity at the bottom (z = -h) is determined, an estimate can be made from surveyed soil conditions and currents to evaluate the stability of the seabed and, consequently, that of the buried pipeline.

ANCHORING

Pipeline anchoring is a relatively new concept that has had some success (23). A pipeline anchoring system consists of long shafts on both sides of the line running through a yoke that is strapped to the line. On the bottom of the shaft is a helically shaped flange that embeds itself into the sand as a diver turns the shaft with a wrench. The shafts can be of different lengths depending on where the layer of required shear strength may be. Figure 4, (p. 37) shows a pipeline anchor used by the A.B. Chance Company to secure a 14 in. line of the Southern Union Gas Company.

Again soils surveys are essential to determine how deeply an anchor should go or if in fact an anchor can be used at all.

Bemben and Kalajian (3), Leahy and Farrin (29), and others have investigated the holding properties of anchors. The holding power of an anchor is dependent on its weight, the area of its fluke, the depth of embedment of the fluke and, of course, on the soil conditions at the site. Ship anchors and pipeline anchors differ in that a pipeline anchor must be relatively light for divers to be able to handle it. A pipeline anchor must be able to develop its full holding capacity in place whereas ship's anchors develop holding while dragging and building up a mound of bottom material. Pipeline anchors are placed carefully by hand and torqued to their maximum holding strength while ship's anchors are randomly lowered and chance plays a large part in their holding capacity. For an interesting study of anchors and the parameters that determine holding power, the reader is referred to Bemben (3), and Leahy and Farrin (29).

RECOMMENDATIONS FOR FUTURE RESEARCH

Presently, according to Reynolds (36), the horizontal component of the oscillating wave motion at the sea bottom is all that is considered in accounting for bottom movement by waves. We suggest that, although from wave theory boundary conditions the vertical component of the wave is zero at the bottom, the seepage pressures in the granular bottom as a response to wave-induced pressures be analyzed. At present, the instant of incipient motion of a granular bottom is dependent on the bottom shear stress. This is quite reasonable for a steady-flow unidirectional current over time. But the oscillatory motion of a wave and the associated pressure differentials along the seabed can induce percolation of the bedwater both upward and downward in accordance with the pressure gradient. This percolation, it is felt, can have a definite effect on the erosion characteristics of sandy or silty bottoms.

Development of a standard soils test that could be performed with cored samples from the proposed alignment to determine the erosion characteristics of the seabed should be developed. This test would have to simulate the oscillatory forces of a wave. Not only should the point of incipient motion be determined, but the probable extent in depth of scour also. The extent of the scour would be dependent on the geological conditions of the seabed around the alignment, so any soils test performed would of course have to be tempered by a knowledge of the submarine geology.

Bonar (5) relates soil characteristics and pipe properties to flotation. He used four soils of various properties but no sands. Bonar's work should be extended to a greater variety of soils. His results are presented in the form of graphs of force (flotation and resistance) versus moisture content for a particular soil and a particular pipe diameter. With data from additional tests it would be possible to plot dimensionless flotation and resistance forces as a function of an appropriate parameter.

Another problem is how to determine the level of agitation that causes liquifaction of the soil. This is especially important offshore as waves can provide the required agitation. This critical degree of agitation is dependent on the soil and wave parameters. A test must be developed to approximate the oscillatory forces of the sea for the laboratory. Terzaghi and Peck suggest a variation of the tri-axial test. A model test utilizing a laboratory wave tank with the waves running over various types of soils should be conducted to determine the effect of the oscillating pressure gradient in the pore water. The results of these tests should be compared to the results that can be obtained by Terzaghi and Peck's method which was originally for sands. It should be determined also if Terzaghi's variation on the tri-axial test is applicable to silty and clayey soils.

Given certain conditions, internal waves can occur at the interface of two liquids of different density. Consequently, they can occur at the interface between sea water and the liquified overburden. The effect of these internal waves upon the pipeline and in the soil that is not yet liquified, and ways of protecting the pipeline from the forces induced by the internal waves should be studied.

Considerable work has been done with regard to the holding power of anchors (3,29) and the parameters that determine holding power. Studies are needed to determine an optimum design for a light anchor to hold a pipeline. Accurate determination of holding power with respect to fluke area and depth of embedment and soil conditions must be made in order to determine the required spacing along a pipeline. A required spacing of anchors would be dependent on being able to determine the maximum forces on the pipeline.

A large problem arises when the submerged pipeline trench is left to fill up naturally. Natural backfilling is cheaper and considerably easier than mechanical backfilling of a pipeline trench. However, the liquid in the ditch can become very dense causing flotation. A new and inexpensive method for trench-filling should be devised as mechanically backfilled trenches rarely experience the problem of flotation.

More detailed hydrographic surveys in areas where offshore construction is important are a must. They should be taken regularly over the course of a year so as to determine seasonal differences in the seabed. If possible, surveys should also be conducted following major storms in order to determine areas susceptible to scour from storm conditions.

There is a need to put all these tests together. Each test or survey yields a certain recommendation. The synthesis of all these recommendations and findings into a rational decision-making process will yield the safest or the most economical route for a pipeline. By assigning a value to each decision alternative and result, decision theory can be employed with the aid of economic analysis to determine the route that will provide the best protection at lowest cost and risk.

APPENDIX I

ABSTRACTS

Brown, R.J. "Soil Mechanics Important in Marine Pipeline Construction". (Ref. 8)

Pipelining offshore is more complex than onshore. Sufficient wave force data is important in determining the protection necessary to provide safe offshore pipelines. A case history of a line in the Gulf of Mexico is presented showing a flotation problem.

The passage of a wave can cause a pronounced pressure differential and current along the sea bottom. Wave profile, water velocity and pressure anomaly in 40 feet of water at the submerged soil surface are plotted for a storm occurring once in 50 years.

A discussion of the flotation problem of pipeline in heavy liquid-soil mixture is given. Some portions of the sea bottom in the Gulf of Mexico are unstable and require weighting the pipe to prevent either sinking or flotation in the liquified sediments.

The best procedure is to follow a comprehensive plan of soil sediment studies. Gravity piston coring device of Hvorslev is described along with the accepted procedure of determining the engineering properties of the soil from the core. The method of Reid for determining stresses in a pipeline that traverses a soft bottom is briefly treated. Includes 5 references.

Bonar, A.J. "Research on Pipeline Flotation for the A.S.C.E. Research Council". (Ref. 5)

Model tests were conducted on pipe sections buried in four types of soil common in the Gulf of Mexico. Pipes were buried in each soil and measurements were made to determine the resistance to flotation, the unit weight of a pipe at flotation and the characteristics of the soil at flotation. The data were presented as plots of resistance to flotation versus an appropriate parameter.

The four types of soil used were Beaumont clay obtained from the Southeast Texas Gulf Coast with a Liquid Limit (L.L.) of 64 and a Plastic Limit (P.L.) of 32; a silty clay with L.L. of 46, P.L. 23; a combination of organic sandy silt and soil 2 with a L.L. of 38 and P.L. 31; and a very organic swamp soil from Louisiana that contained a lot of roots and stems. The test soils were generally in the saturated range with the water content near to, or above the liquid limit. It was found that the miniature vane shear test yielded the most satisfactory results for shear strength determination.

It was attempted to determine the effect of thixotropic hardening on six soil samples used. The results were erratic and inconclusive. It is believed that a useful field test could be developed to learn the percent increase in shear strength with respect to time and plasticity index.

Tests:

Steel pipes, 1/8-in. thick, were used in the flotation test, with inside diameters of 4, 8 and 12 inches. These pipes were buried in the various soils; data on flotation and pullout resistance were recorded. The burial depth varied from 1/2 to 2 pipe diameters, the depth being arbitrarily defined as the distance from the top of the soil to the top of the pipe. It was found that a local shear failure occurred with upward movement of the pipe and that depth of cover did not affect flotation for the diameter size range of the test.

Several pull tests were performed to determine the resistance to flotation offered by the soil. The unit weight of the pipe was varied by removing water from it until incipient flotation in the soil medium. The tests showed virtually no resistance to pull-out at this condition. Other tests not at the flotation condition were performed and the resistance to pull-out was calculated.

Results:

Data taken from tests were recorded and tabulated in the appendix. In all tests with the exception of Louisiana soil, the pipe moved to the surface at an essentially constant rate. In soil, which contained large amounts of grass and roots, the pipe rose at an erratic rate. No flotation occurred in any soil until the water content exceeded the Liquid Limit.

An expression for flotation was derived.

$$F_F = (\delta - \delta_{pipe}) \frac{\delta D^4}{4}$$

where:

F_F = flotation force

δ = unit weight of the soil

δ_{pipe} = unit weight of the pipe

D = diameter of the pipe

An expression for the resisting force was also derived as:

$$F_R = 7.2^{\frac{1}{2}} D$$

where

F_R = resisting force

C = cohesion

A set of curves was developed using the expressions for F_F and

F_{Resis} as a function of water content. These curves, under a given set of conditions, permit determination of incipient flotation.

<u>Conclusions</u>:

1. The rate of pipeline flotation was not affected significantly by varying the depth of burial between ½D to 2D.
2. The rate of upward movement of the pipe was a function of the unit weight of the pipe.
3. No flotation occurred until the soil exceeded its Liquid Limit.
4. Soil properties and pipe properties were related to flotation through expressions for flotation and resistance force.

Miller, D.R. "Marine Studies for the Design and Construction of Offshore Pipelines". (Ref. 31)

Environmental conditions that determine, to a large degree, the location, protection, and design of an offshore pipeline are described.

An overall bathymetric chart is the first requirement. A bottom sediment investigation is conducted along allowed routes as indicated by the bathymetric chart. Results can be plotted on the chart for a convenient overview of the soil and topography. It is also recommended that current and tidal characteristics be determined with particular emphasis on the vertical distribution of the currents.

Ocean outfalls require special study with regard to currents and biology of an area. These special requirements are considered in detail and final conclusions are made. Includes 23 references.

Pipeline Flotation Research Council - "ASCE Preliminary Research on Pipeline Flotation". (Ref. 1)

The primary objective of the research undertaken by this committee was to develop a set of pipeline flotation tables giving the weighting requirements for a buried offshore pipeline to resist both flotation and sinking in soft unconsolidated sediments.

Laboratory tests involving both the soil and sediment characteristics and the flotation phenomenon are described. The engineering parameters of the soil are defined as in conventional engineering practice, and the effect of agitating the sediments is studied in terms of the change of the soil's engineering properties.

Earlier experiments involving flotation studies are examined and pertinent results of each of these studies are presented.

On the basis of the earlier tests and tests run by the A.S.C.E. the research committee compiled the aforementioned tables on the weighting requirements of a submarine pipeline. These requirements were obtained only from the results of these tests so these tables are "completely preliminary and tentative in nature".

Future research efforts to improve these tables as design criteria are recommended.

Reynolds, J.M. "Submarine Pipelines" (Ref. 36)

The constituents of a submarine pipeline and original stimulus for its construction are reviewed. Methods for construction of offshore pipeline equipment are presented, including machines for burial.

Principal factors to consider in the design of an offshore pipeline are:

1. Resistance to natural phenomena (waves, currents, seabed movements).
2. Ability to withstand construction stresses.
3. Feasible method of construction and burying.

An equation from first-order wave theory is presented to determine the horizontal component of the wave force on the pipeline as a function of the horizontal component of velocity.

Flexible pipelines have been known to sink in erodible beds. On the other hand, wave-induced scour at an unburied pipeline can cause spanning over a considerable distance and subject the pipe to bending forces for which it was not designed. Caution must be used in determining the specific gravity of a pipeline as one that is too light will float in soft sediments while one that is too heavy can sink.

The stresses to be evaluated in a submarine pipeline follows normal structural analysis.

Permanent stresses are:

1. stress due to internal pressure
2. bending due to seabed contours.

Different material for pipeline constructions are considered including steel, aluminum, concrete, plastic and fiberglass. Includes 20 references.

Silvester, R. "Engineering Aspects of Coastal Sediment Movement". (Ref. 40)

Generation of wind waves and parameters important to coastal sediment processes are described.

Two coastal zones are defined with respect to sediment transport mechanics: onshore and offshore. The onshore zone is shoreward of the breaker line and the offshore zone is seaward to the point where waves no longer influence the bottom. The surging water in the onshore zone has a longshore component if the waves arrive at an angle other than 90° to the coast. The resulting current is a longshore current and readily transports material. In the offshore zone oscillating wave motion causes sediment to be moved along the ocean floor in one direction and then in a reverse direction.

Effect on beach profiles due to swell and storm waves and the importance of the offshore bar in beach cycles is discussed.

The importance of meteorological conditions, especially cyclonic, anticyclonic, and sea breeze conditions are indicated, as their study can produce certain qualitative information about the resulting waves.

A groin built perpendicularly to the coast can accelerate sediment movement because it induces a rip current.

Generation of wind waves and parameters important to coastal sediment processes are described.

Wilson, W. "Foundation Stability for a Submarine Liquid Sulphur Pipeline" (Ref. 43)

This paper describes a pipeline that will be used to retrieve liquid sulphur from a deposit offshore of Grant Isle. The design and construction of this line presented problems that needed to be answered.

The foundation for the pipeline was known to consist of extremely soft sediment deposited by the Mississippi River delta system. Behavior of the pipeline in such sediments had to be determined considering high pipe temperatures and consequent effect on sediment properties, as well as possibility of disturbance of the line by hurricane-induced forces. The entire pipeline was to be buried in a trench 6-7 feet below the mudline and the trench was to be naturally backfilled.

Pipeline buoyancy is explained and calculated for the line buried in the described sediments. Thermal stability is illustrated, and a chart showing heatflow in one particular sediment stratum is shown as an example. The author considers stresses induced by laying and pre-stressing the pipe.

Conclusions of this study are presented. Although they apply specifically to the case under consideration, the reasoning can be generalized.

APPENDIX II

ANNOTATED BIBLIOGRAPHY

Bemben, S.M. THE VERTICAL HOLDING CAPACITY OF ANCHORS IN SAND, Proceedings of Civil Engineering in the Oceans, 2nd Conference Miami Beach, Florida, Dec. 10-12, 1969, pp. 117-136.

The authors describe model tests to determine the parameters that provide holding capacity of anchors in sand. Curves are presented showing holding capacity of anchors versus imbedment depth. Several conclusions are made with respect to determining an anchor's holding power.

Blumberg, R. DESIGN FOR ENVIRONMENTAL EXTREMES, Pipeline Industry, Vol. 25, October 1966, pp. 21-34.

The author describes the basic problems associated with marine pipelining in a hostile offshore environment. Wave and current effects are treated and special problems associated with particular areas are discussed.

Brown, R.J. RATIONAL DESIGN OF SUBMARINE PIPELINES, World Dredging and Marine Construction, Feb. 1971, pp. 17-22.

Consideration of the study and design phases of the overall pipeline construction project are treated in this paper with particular emphasis on the foundation stability of a line including soil sampling tools and procedures.

Eagleson, P.S. and Dean, R.G. WAVE INDUCED MOTION OF BOTTOM SEDIMENT PARTICLES, Journal of the Hydraulics Division, ASCE, Vol. 85, Oct. 1959.

A theoretical equation is developed which yields the net velocity of a spherical sedimentary particle as a function of flow and topographic variables. The equation is verified by laboratory experiments and the work is extended to the prediction of beach equilibrium characteristics.

Eagleson, P.S. and Dean, R.G. DISCUSSION OF SUPPLY AND LOSS OF SAND TO THE COAST by S.W. Johnson, Journal of the Waterways and Harbors Division, ASCE, Vol. 86, June 1960.

A quantitative evaluation of sediment movement is made for an area off the coast of Southern California.

Eagleson, P.S., Glenn, B., and Dracup, J.A. EQUILIBRIUM CHARACTERISTICS OF SAND BEACHES, Journal of the Hydraulics Division, ASCE, Vol. 89, Jan. 1963.

Equations are developed to express the profile of a beach in equilibrium in terms of deepwater characteristics and fluid and sediment properties.

Freeman, J.C. and Bretschneider, C.C. WHAT THE GULF CAN DO TO A PIPELINE, Pipeline Industry, Vol. 4, May 1956, pp. 28-34.

The authors stress the importance of determining the engineering properties of soil on the Gulf bottom. They also discuss the effects of wave action and hurricane.

Hobbs, H. CRITERIA FOR THE DESIGN AND CONSTRUCTION OF SUBMARINE PIPELINES, Pipes and Pipeline International, July 1966.

The importance of the environment in which an offshore line will be placed is discussed. Route evaluation, sediment characteristics, pipeline stability and pipe burial are considered and discussed.

Holland, S.M. SCREW ANCHORS HOLD WANDERING PIPELINE, Pipeline Industry, Vol. 17, Dec. 1962.

A description of the anchors used by the A.B. Chance Co. to hold the Southern Union Gas Company's 14-inch pipeline is given as well as how these anchors were installed.

Kreig, J.C. CRITERIA FOR PLANNING AN OFFSHORE PIPELINE, Journal of the Pipeline Division, ASCE, Vol. 91, July 1965.

The author discusses the important considerations in the planning of an offshore line. Environmental factors such as wave forces, currents, and sediment properties are treated as well as the structural problems in pipeline design.

Palmer, H.D. WAVE-INDUCED SCOUR OF THE SEA FLOOR, Proceedings of Civil Engineering in the Oceans, 2nd Conference, ASCE, Miami, Dec. 1969.

Field studies involving sea floor scour are discussed. The study involves a photographic technique to record the changes in the sea floor as a result of an obstruction to flow.

RATIONAL DESIGN FOR PIPELINES ACROSS INUNDATED AREAS, Report of the Task Committee on Flotation Studies, Committee on Pipeline Installations, Journal of the Pipeline Division, American Society of Civil Engineers, Vol. 87, Feb. 1961.

The causes of pipeline flotation are discussed and the criteria to determine weighting and methods of weighting are reviewed. Ways to more economically and efficiently anchor pipelines are suggested.

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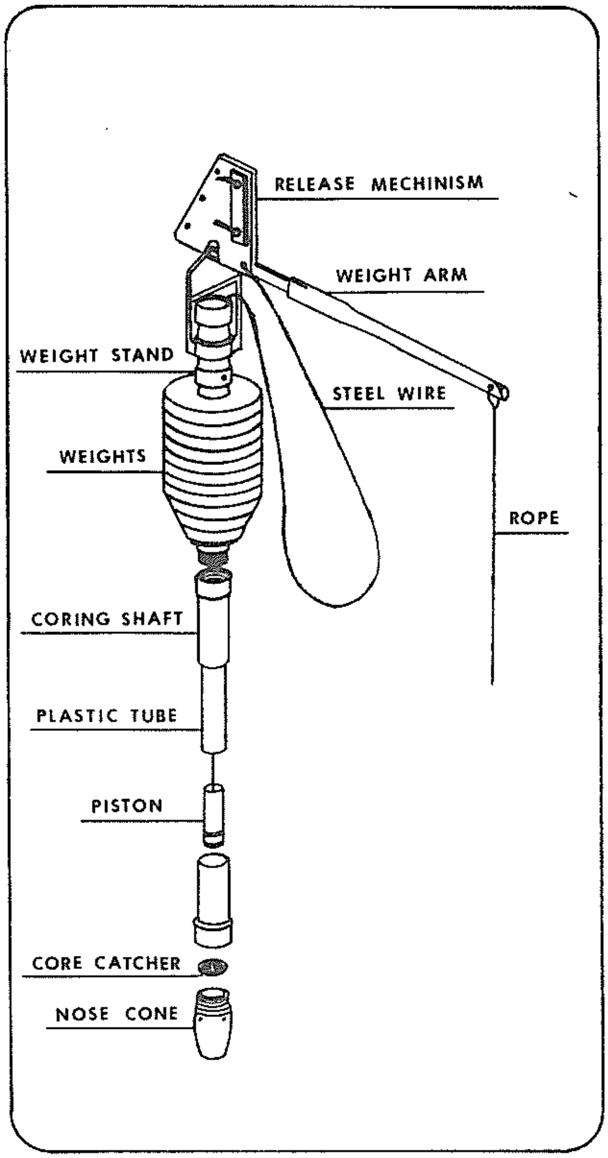

Figure 3. PISTON GRAVITY CORER

Source: Brown (9) (Fig. 1-1)

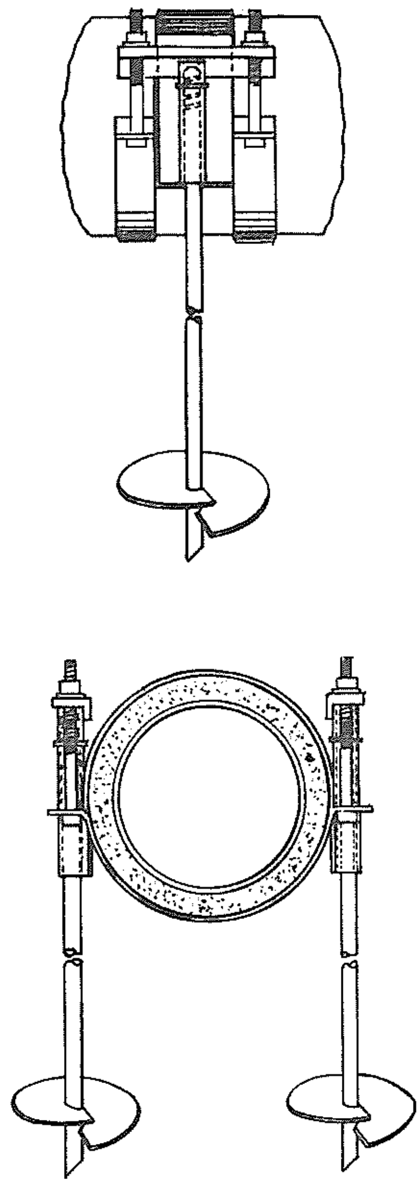

Figure 4. PIPELINE ANCHORING SYSTEM

Source: Holland (23)