Kahului Harbor, Island of Maui

PART IV

COASTAL, ESTUARINE, AND ENVIRONMENTAL PROBLEMS

Lahaina, Island of Maui

CHAPTER 167

DESIGN PROCEDURES FOR OCEAN OUTFALLS

by

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ABSTRACT

This paper discusses procedures for designing ocean outfalls and offers the coastal engineer a practical design guide outlining the necessary steps required to plan, design, and construct an outfall. The design steps reviewed in this paper include site location considerations, environmental studies, outfall and diffuser hydraulics, pipe materials selection, pipe support systems design, and construction techniques.

INTRODUCTION

Wastewater disposal systems typically involve three components: collection, treatment, and disposal. The design of collection systems for domestic sewage and industrial wastes is generally a simple process. More difficult, but still relatively routine, is the design of primary and secondary treatment facilities to reduce the pollution impact of the wastewater. However, final disposal of the collected and treated wastewater effluent is not a routine design problem. Few disposal options are available; most are limited to land disposal, advanced wastewater treatment (AWT), or discharge to a water body. Land disposal is impractical in many regions due to poor soils and insufficient land availability. AWT is costly and consumes much energy in the treatment process. Effluent discharge to a water body, on the other hand, generally consumes little energy and requires little land. Further, the natural assimilative capacity of many water bodies is high enough to absorb wastewater discharges with no detrimental consequences. Because of these advantages, effluent disposal to the marine environment has become common practice.

Subaqueous effluent discharge occurs in four basic water bodies: river, lake, estuary, or ocean. Of these, the ocean is the ultimate receiving water. An outfall is a mechanism through which effluent is directly discharged to the ocean. The complex process a coastal engineer employs to design and construct an ocean outfall is described in this paper. The same process is applicable to outfalls in rivers, lakes, and estuaries.

OUTFALLS AND DIFFUSERS

An outfall is an underwater pipeline that discharges wastewater into a receiving water. Although the wastewater may have received extensive treatment, it is still desirable, and often necessary, to disperse the effluent to minimize possible impairment to the quality of the receiving waters near the point of discharge. This is accomplished by using a diffuser.

A diffuser is a section of the outfall, usually the deepest, most seaward portion, with relatively small holes or ports along its length (figure 1). These ports discharge the wastewater in numerous small quantities, as opposed to the entire flow being discharged at one point (figure 2). Diffuser ports may be

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simple holes in the outfall pipe wall or short tubes (risers) extending from the pipe. The type of port used depends on the particular conditions of the final installation.

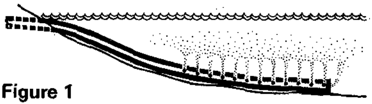

Figure 1
Outfall Diffuser

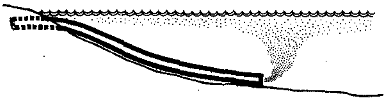

Figure 2
Outfall Without Diffuser

Designing an outfall diffuser system requires the same considerations as designing other types of underwater pipelines. However, the mechanism of discharging the effluent from the outfall to the receiving water requires additional design effort. The various elements of the outfall design process are discussed below.

OUTFALL DESIGN PROCESS

The design of an ocean outfall system is not a simple process. The design engineer must consider many factors to ensure that the outfall survives as a structural system in the ocean environment and also meets water quality requirements. The major components of the outfall design process are:

- Site selection
- Outfall hydraulics
- Dilution and mixing
- Diffuser port design
- Pipe design
- Pipe support systems
- Construction methods

Each of the above components must be evaluated during the design of an outfall. The design is normally phased into four elements: feasibility study, predesign, preliminary design, and final design. Each phase addresses the above outfall design components with increasing detail such that final design results in the preparation of construction plans and specifications. A flow diagram illustrating how the various design components and phases are integrated is in figure 3. Subsequent discussion will elaborate on each factor comprising the design process.

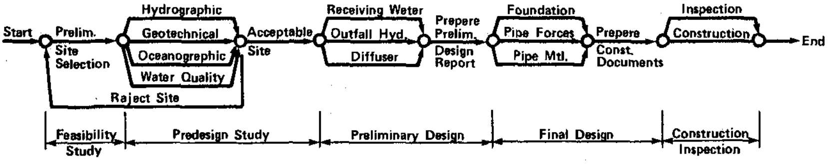

Figure 3
The Ocean Outfall Design Process

Site Selection

A discharge point for an outfall is usually located in proximity to its companion wastewater treatment plant. Therefore, the first step in the outfall site selection process is to determine the feasibility of linking the treatment plant to the nearest receiving water. This process consists of studying existing topographic maps and hydrographic charts, reviewing known literature concerning coastal processes (tides, waves, currents, geology) characteristic to the site, and obtaining available water quality data related to the proposed receiving water. If the existing information suggests that, from a construction cost and water quality viewpoint, one or more outfall routes is feasible, then additional predesign engineering studies are commenced to select a final route. If no routes are judged feasible, then relocation of the treatment plant or alternative disposal systems must be considered.

For sites judged feasible, the following outfall siting criteria are considered in detail in the predesign phase:

- Bottom topography and surf zone
- Physical oceanography
- Water quality
- Underwater soils and geology

Topography

A hydrographic survey of the general area of a proposed outfall alignment is required. An electronic recording echo-sounding device coupled with a horizontal positioning system (electronic or transit) usually produces a sufficiently accurate bottom survey. Surveys within the surf zone, however, are often difficult due to continuous wave action and often require special equipment such as helicopters to act as sounding platforms.

When reviewing the sounding data, various profiles of the bottom topography are plotted. Analysis of the profiles will reveal potential outfall routes. It is desirable to have the outfall line on a continually declining grade. This prevents potential sludge buildup in low points and accumulation of air at high points, both of which can reduce the hydraulic capacity of the outfall.

There is no ideal slope for locating the diffuser; however, a relatively flat slope is desirable. It is also desirable to have essentially equal discharge from each of the diffuser ports to facilitate equal dilutions. With a density difference between the receiving waters and the discharged effluent, a mild slope is beneficial in achieving uniform port discharge. However, a long diffuser on a steep slope can adversely modify the diffuser hydraulics. Not only will the diffuser discharge unequally from all ports, but at low flows, some ports will not flow at all.

If the topography is relatively steep, consideration must also be given to the stability of the final system. The pipeline must be secured from sliding down the slope, either slowly due to unstable soil conditions or suddenly due to natural occurrences.

Since it normally is not economically or technically feasible to significantly modify the general underwater topography of an area, the outfall must be routed and designed in accordance with the natural conditions.

Surf Zone

Penetrating the surf zone is often the most difficult and costly phase of constructing an ocean outfall. The trauma of continuous wave attack in shallow water usually limits construction to a short period during milder summer conditions. Even then, sporadic storms can shut down construction operations or damage the outfall pipe and construction equipment. Therefore, it is desirable to select outfall sites with minimum surf action. Potential sites at headlands or points of land jutting into the sea generally should be avoided because wave refraction will concentrate wave energy on these features. To minimize working in harsh conditions, surf zones extending more than about 1,000 feet offshore should be avoided if possible. Coastlines with sharp bottom dropoffs are preferable for outfall sites because the pipeline can be installed quickly in the narrow surf zone.

Physical Oceanography

Measuring water mass movements at a proposed outfall discharge site is required early in the design process. This knowledge is important because it allows the designer to predict effluent transport under all offshore current conditions. Two methods are commonly employed to measure ocean current systems: drogues and electronic current meters.

Drogues consist of a drag body positioned below the water surface with a line attached to a surface float. Movement of drogues, and therefore currents, is tracked by observing buoy movement. Current meters do not move with the water but remain fixed at a point, measuring the rate and speed of water particles as they flow past. Either system can be used to measure ocean currents, but for most ocean outfall locations both techniques are used to complement each other.

Current measurements are normally conducted over a sufficient time period to develop a comprehensive understanding of water mass movements over the outfall discharge site. This knowledge is vital so the outfall designer can predict where the effluent will be transported under all conditions. Specific monitoring periods can range from a few tidal cycles to long-term observations covering several years at sites subject to seasonal current shifts and upwelling of deep ocean waters. Careful consideration in developing a current monitoring program must be given early in the design process to allow sufficient time to conduct the studies and analyze the results.

During ocean current monitoring, physical properties of the water column, such as temperature and salinity, are also measured to calculate water density as a function of depth. Density profiles indicate the absence or presence of stratification, which can affect the dilution performance of the diffuser.

In addition to the above physical oceanographic measurements, field studies designed to measure the ocean water's natural diffusion characteristics are often conducted. Dye studies, usually employing a fluorescent tracer such as Rhodomine WT dye, help determine the ability of a potential outfall site's receiving waters to disperse and assimilate wastewater.

Measurements of ocean wave heights and periods are also desirable for outfall sites. Knowledge of the frequency and amount of wave energy passing over the pipeline route is vital to ensure its integrity as a structural system. However, measurements of wave parameters are often difficult to obtain and designers frequently rely on wave forecasting techniques to predict design wave conditions.

Water Quality

The purpose of an outfall diffuser is to disperse effluent to minimize the pollution impact on the receiving water. No matter how efficient the diffuser is in diluting effluent with ambient seawater, some change will occur in the local marine environment around the diffuser. It is a vital element of the outfall design process to accurately predict these changes, both short-term and long-term. However, to predict water quality changes due to outfall discharges, the existing water quality conditions of the receiving water must be known.

Establishing a baseline of water quality conditions within the receiving waters of a proposed outfall often requires extensive environmental monitoring. During the site selection process, it is typically found that the potential ocean outfall site has, at best, a limited record of existing water quality data. Thus, to establish a proper data bank of predischarge conditions, a water quality monitoring program is required. Baseline monitoring programs can range from a minimum of collecting one set of water samples at one location to sampling multiple stations at weekly intervals for periods of 1 to 2 years. The parameters sampled, which can also vary widely, mainly depend on composition of the effluent. The minimum parameters that should be considered for a domestic sewage outfall monitoring program are:

Water Column

- Dissolved oxygen
- pH
- Conductivity/salinity
- Temperature
- Oil and grease
- Fecal coliform bacteria
- Nutrient content
- Heavy metal content
- BOD/COD

Benthic

- BOD/COD
- Heavy metal content
- Nutrient content
- Biological organisms

Location and number of sampling stations should be carefully established to maximize data acquisition while minimizing costs. Results of physical oceanographic studies should be used to establish sampling stations within the expected water transport zones. A sampling station within the immediate dilution zone of the diffuser is a minimum requirement.

Underwater Soils and Geology

Identifying the geological conditions and their uniformity along a proposed outfall alignment is important since many of the criteria considered in outfall design depend on geologic conditions and soil types. As with most underwater soils investigations, gathering soils data for outfall design is difficult and often costly. However, the investigation must be sufficient to develop design criteria and identify the existing conditions.

Marine geophysical techniques, such as reflection and seismic profiling, are commonly used to determine subbottom stratigraphy. However, interpretation of this type of data is difficult. There is no substitute for obtaining *in situ* soil samples for laboratory analysis. The best results usually are obtained from barge-mounted drilling rigs, but soil sampling with remote or diver controlled subsurface devices has been successful (Noorany, 1971).

Analysis of Site Selection Data

Upon completion of the basic studies outlined above, one particular outfall site is normally chosen as most suitable. The next step in the outfall design process is the preliminary hydraulic design of the pipeline, including diffuser dilution and mixing characteristics.

Outfall Hydraulics

The hydraulic design of an outfall results in determining design flows, selecting pipe diameters for the outfall conduit and diffuser sections, and selecting diffuser port size and spacing.

Design Flows

Outfall design flows depend upon upstream conditions. Daily flow through a domestic sewage treatment plant can vary considerably, while most industrial discharges are more constant. Massive loads to sewer collection and treatment facilities also occur during rainy periods when runoff enters the collection system either directly (combined sanitary and storm sewers) or indirectly through infiltration (leakage at pipe joints and manhole covers). During either event, flow to an outfall can be dramatically increased. If the outfall system is not properly sized, the flow will be restricted, resulting in the backup of effluent in the outfall and possible flooding of onshore facilities.

Ocean outfalls should be designed to discharge peak flows with a gravity system. However, if the hydraulic head between the ocean and the outfall headworks is minimal, discharge of design flows through the outfall may not be possible with a gravity system. Consideration must then be given to the use of pump stations. Unfortunately, pumped outfall systems present new problems--increased costs for continual maintenance of pumps and perpetual use of energy for pumping. A sometimes satisfactory solution to both problems is the combined use of gravity and pump system. During normal flows, the gravity system handles the discharge, while during peak flow periods a pumping system augments the gravity system.

Diffuser Hydraulics

In conjunction with selecting conduit size for the outfall, the diffuser system must also be designed. The size and spacing of the diffuser's ports are determined through a series of complex iterative hydraulic calculations based upon the following parameters:

- Design flows
- Pipe diameter
- Pipe slope
- Frictional resistance of pipe material
- Effluent density
- Receiving water density
- Discharge depth
- Operating head

A computer program is typically employed to solve the manifold hydraulics problem. The program takes into account the discharge characteristics of the individual port and does a numerical integration of the hydraulic conditions port by port with a trial and error optimization of port sizes considering the various factors listed above. A complete description of diffuser hydraulic design has been reported by Rawn, Bowerman, and Brooks (1961) and the basic hydraulic requirements as reported in their paper are summarized below:

Flow Distribution. The division of outflow between the various ports should be fairly uniform. For diffusers laid on a sloping sea bottom, uniform port discharge for all rates of flow is impossible. In such cases, the diffuser should be designed for uniform distribution at low to medium flows. For higher flows, the deeper ports should be allowed to discharge more flow than the average port to prevent possible clogging of the deep end of the diffuser.

Velocity in Diffusers. The flow velocity in all ports of the diffuser should be high enough to prevent gross deposition of sludge or grease. For settled sewage, minimum velocities of 2 to 3 feet per second are required.

Prevention of Seawater Intrusion. All ports should flow full to prevent intrusion of seawater into the pipe.

Dilution and Mixing

A diffuser disperses wastewater by breaking it up into a number of smaller flows and spreading it over a large area. In essence, a diffuser changes a point-source discharge into a line-source discharge. The resulting discharge plume mixes within the receiving water to produce a diluted effluent.

The processes that cause mixing and dilution when effluent is discharged by a diffuser into receiving waters are complex, but primarily involve mixing due to kinetic energy of the initial discharge velocity, mixing caused by buoyant forces due to the density difference of the effluent and receiving waters, and, finally, mixing caused by horizontal cross currents of the receiving waters (Brooks and Koh, 1965). Normally, all three of the above processes act on the discharged effluent to produce the overall mixing and dilution.

Mixing caused by the kinetic energy occurs close to the point of discharge and is primarily a function of discharge velocity. Due to the density and viscosity of water, the energy is dissipated rapidly. Dilution is generally less than two parts of seawater to one part of effluent and occurs within a few feet of the point of discharge.

When the kinetic energy is dissipated, a mixture of effluent and receiving water exists. If the density of the effluent is less than the density of the receiving water at the point of discharge, the mixture will also have a density less than the surrounding receiving waters. This difference in density creates a buoyant force that causes the effluent mixture to rise in the receiving waters. As the mixture rises, it continues to mix with, and therefore be diluted by, receiving water.

If the receiving water is of equal density at all depths, the mixture density will always be less than the density of the surrounding waters and will continue to rise and be diluted (figure 4). Under this condition, the dilution achieved is a function of port diameter, discharge velocity, relative density, and depth of discharge.

If the density of the receiving water decreases with decreasing depth, there will be a depth when the density of the rising effluent mixture is equal to the density of the surrounding receiving waters and less than the density of overlying waters. When this occurs, the effluent mixture will not rise further and is considered trapped (figure 5). In this situation, the dilution achieved is controlled by the height of rise that, in turn, is a function of the density variations of the receiving waters. Entrapment of the effluent plume below the surface is usually a desirable objective for ocean outfall design because it helps prevent possible health and aesthetic problems common to discharges rising to the water surface.

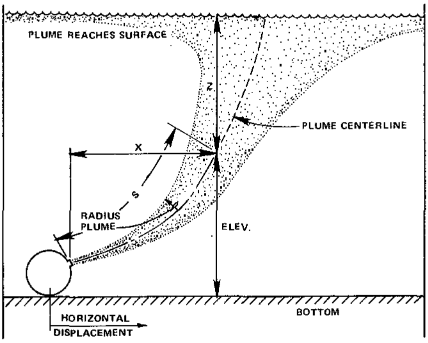

Figure 4
Effluent Plume Characteristics for Nonstratified Water

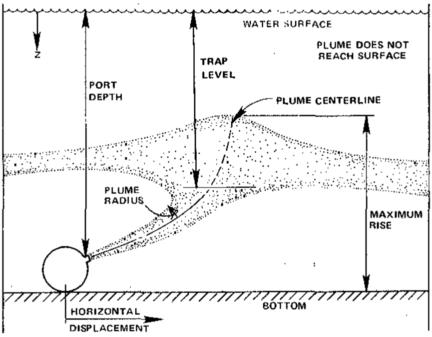

Figure 5
Effluent Plume Characteristics for Stratified Water

The previous discussion assumes that there are no horizontal currents in the receiving water. Horizontal currents will carry the effluent away from the point of discharge and cause rapid mixing and dilution. Port diameter, discharge velocity, and relative density will have little effect on the dilution achieved (Roberts, 1976). The velocity of the horizontal currents will control the dilution. Because the effluent is diluted and carried away rapidly, the effluent mixture will have little opportunity to rise, regardless of the density of the effluent or receiving waters.

Predicting diffuser plume characteristics is essential in outfall design. Computer programs are typically used to examine various discharge and receiving water conditions and predict height of rise and associated dilution. Baumgartner, Trent, and Byram (1971) have developed such a model which is used in outfall design.

Diffuser Port Design

Orientation

The flow direction of receiving water currents dictates the orientation of the diffuser. There are three basic diffuser orientations (figure 6):

- Current parallel to shore
- Current perpendicular to shore
- Variable current direction

The diffuser should be located perpendicular to the net current to maximize dilution. However, for currents that shift direction, "Y" shaped diffusers are employed to offer the greatest chance for keeping the diffuser perpendicular to the current.

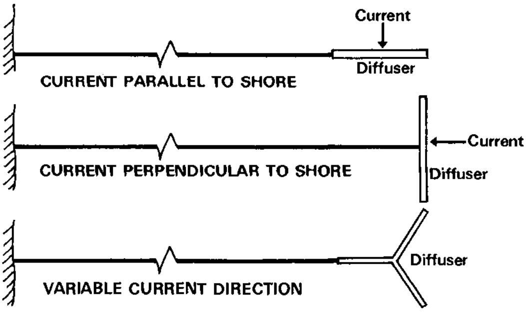

Figure 6
Alternative Diffuser Arrangements

Port Types

The two basic types of diffuser ports are pipe wall port and riser tube (figures 7 and 8). A pipe wall port system consists of holes in the wall of the pipe, at or slightly above the pipe's spring line. To prevent the pipeline filling with bottom sediments, this type of diffuser port requires that the pipe be laid on the ocean bottom rather than buried.

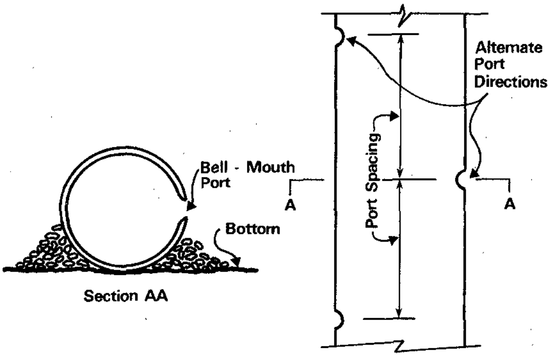

Figure 7
Pipe Wall Port Diffuser

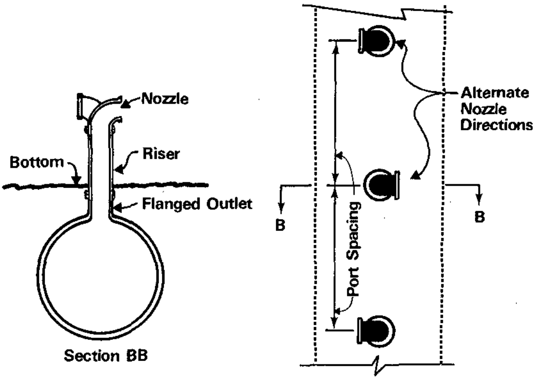

Figure 8
Riser Port Diffuser

Riser tubes are used when the diffuser pipeline must be buried (usually to prevent damage by wave action). Riser tubes project upward from the crown of the buried pipe, penetrating above the ocean bottom. The small, cross sectional area of the risers minimizes exposure to waves and current forces. However, because the riser tubes project above the bottom, they can become vulnerable to impact forces. A typical hazard common to risers--breaking of the rigid tube due to impact forces and subsequent filling of outfall pipe with bottom soils--is shown in figure 9. A satisfactory solution to this problem is the use of flexible riser tubes (figure 10). The rubber pipe wall section allows the tube to absorb impact through deflection. If the impact force is too great, the rubber section fails before the steel, allowing the pipe tube to shear off above the mud line. This type of failure minimizes the chances of filling the pipe with bottom soils and results in simple repair work.

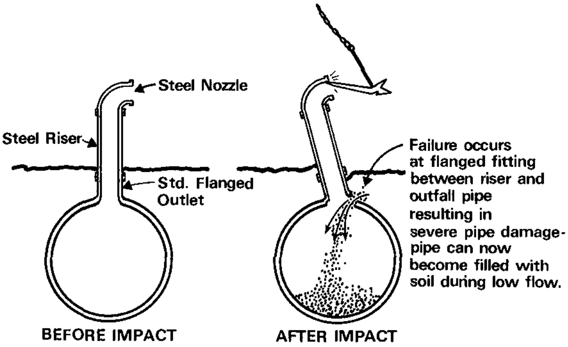

Figure 9
Rigid Diffuser Riser

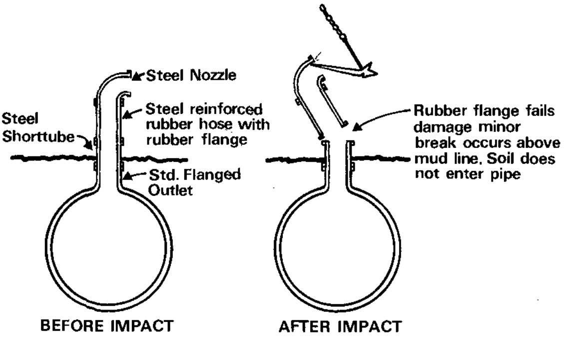

Figure 10
Flexible Diffuser Riser

Onshore/offshore and longshore drift of bottom soils must also be considered in diffuser port designs. Pipe wall ports and riser tube ports must be of sufficient height above the bottom to prevent filling of the diffuser with shifting bottom materials during low flows.

Pipe Design

Completion of the site selection process and preliminary hydraulic design results in establishing the basic outfall pipe parameters--alignment, slope, pipe length and diameter, and diffuser port sizes and spacing. The next element of the design process considers the final design of the pipeline. For ocean outfalls, the following final pipe design components must be considered:

- Foundation requirement
- Pipe forces
- Hydraulic flow properties
- Corrosion resistance
- Pipe material selection
- Pipe anchoring
- Construction methods

Foundation Requirements

Much of the actual pipe design itself depends on the soil conditions. The amount of support along the length of a pipe will influence the type of pipe that is to be used. A change in the support along a pipe will also change the type of pipe used. Some types of pipe can tolerate substantial settlement while other pipes, perhaps with closely spaced joints, would come apart if the settlement is excessive. Although soft sediments most often contribute to pipe settlement, scour and erosion from beneath a pipe can also contribute to loss of support. The support along a pipe in an ocean outfall needs to be continuous just as it does for pipes on land. Since pipes laid on rock under water may not have continuous support beneath them, the pipe may actually span two points on the rock. This can also occur in gravelly soils. Under some conditions, shifting ocean bottom materials (longshore drift) and sedimentation can contribute to the actual load on top or along the side of the pipe. In addition, consideration must be given to outfalls penetrating the surf zone where seasonal changes in beach profile will alternately scour and fill bottom materials over the pipe.

Excavation and Backfill

Outfall pipes generally need to be buried for at least part of their alignment. This requires that the conditions of excavation and backfill be evaluated. The difficulty of excavation, depth of excavation, stability of the open trench, and difficulty of actually placing the pipe in the trench all must be considered in the excavation phase. Many times the excavation must continue through a soft layer down to a firm layer. This requires that the depth of the soft layer be known and that the uniformity of the depth along the alignment be known. The disposition of the excavated material can sometimes be a problem. Most often, it will have to be loaded aboard barges and disposed of, perhaps at some distance from the excavation. It is seldom that the excavated material can also be used for backfill. Trenches excavated in loose sands or granular material often will not stand open for a long period of time since the sides will slough and material will be brought into the trench by currents and waves. In firm granular material, the trenches generally stand open well and narrow trenches can be used. Support for the pipe along the trench is important. Uniform support is often provided by placing a layer of coarse gravel in the bottom of the trench. Unless the excavated material is exceptionally clean, backfill material will usually have to be imported. Generally, coarse granular material is used for backfilling. Any material with a majority of fines in it will generally cause turbidity problems and be unsuitable. Generally, only the larger particles will reach the trench.

Pipe Forces

Outfalls must be designed to resist both internal and external forces. The internal forces are a result of hydraulic pressure imposed on the line through flow of liquid. Operating pressures in outfalls are typically low and seldom affect the structural design of the pipe. Further, since outfalls discharge at depth, there is no requirement to design the pipe to resist the hydrostatic head of the water column above the pipe. External forces include the dynamic action of waves, force from currents, impact from foreign bodies, and overburden support.

The flow of fluid around a cylinder, such as an exposed pipeline, will induce drag forces on the pipe (Priest, 1974). See figure 11. The resultant force can displace an unanchored pipe horizontally, creating large bending and shear stress within the pipe and at its connection with the shore. If the pipe is anchored or pile supported, the horizontal drag force will then be transmitted to the pipe anchor. Close spacing of the supports may be required to prevent pipe overstress due to bending. Also, closer spacing of supports may be required to eliminate vertical pipe oscillations resulting from the resonate response of the pipe to the current.

The passage of a wave over the pipe can develop large dynamic pressures on the pipeline when it is supported above the botton (figure 12). The pressures result from drag forces as well as inertial or impact forces caused by the moving fluid. Dynamic pressure can be minimized by locating the pipe in water deep enough so that it is not significantly influenced by the orbital motion of waves. However, the pipe should be buried in the surf zone to a depth sufficient to protect the line from damage.

Impact forces resulting from foreign objects striking the pipeline must also be considered. Impact from a ship's anchor and commercial fishing gear (figure 13) can result in severe damage to an outfall. Locating outfalls in anchorage zones or bottom trawling fishing grounds should be avoided. However, if the outfall alignment must be located in regions with a high probability of occurrences such as dragging anchors, the pipeline should be buried. The minimum pipe cover should be in excess of plow depth of the anchors.

Even though the main pipeline is protected from impact damage, the diffuser riser must extend above the mud line and become exposed. In such cases, the flexible riser systems should be considered as discussed above (figures 9 and 10).

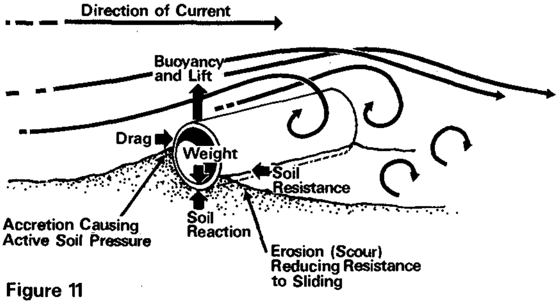

Figure 11
Current Forces

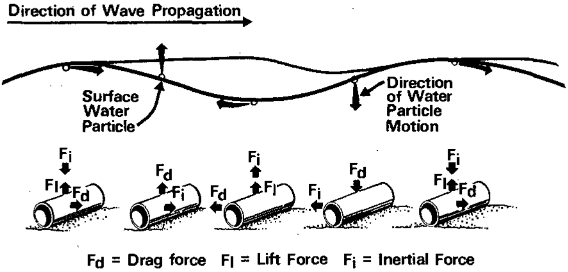

Figure 12
Wave Forces

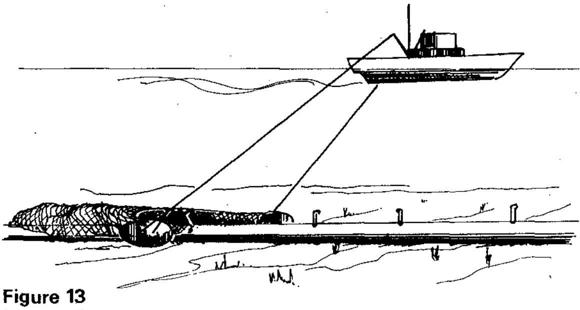

Figure 13
Impact Forces

Hydraulic Properties

An important characteristic of a pipe is its ability to transport the fluid. Various pipe materials can have substantially different frictional characteristics. Some materials, such as cast iron and steel, are subject to internal corrosion that will increase the friction and thus reduce the flow-carrying capacity over a period of time.

The range of friction factors normally applied to pipe materials commonly used for outfall construction is not sufficient to control the selection of materials or allow a reduction in outfall diameter. Since the pipeline materials cost is usually a small part of total project costs, a conservative selection of friction factors and pipe diameters is the normal procedure.

Corrosion Resistance

Saltwater can be a corrosive element for some pipe materials. The bottom sediments may also exhibit a corrosion potential so that the combination can be devastating. The technology exists to protect almost any material from excessive corrosion. The protection provided should be consistent with the design life of the facility and the protection provided associated structures. The costs for this protection are usually minimal. Therefore, corrosion is normally not a controlling factor in the selection of outfall pipe materials.

Pipe Material

A variety of pipe materials are available for ocean outfalls (table 1):

- Reinforced concrete
- Steel
- Concrete cylinder
- Corrugated metal
- Cast iron
- Ductile iron
- Fiber-reinforced plastic
- High-density polyethylene

The most common pipe material used on ocean outfalls is reinforced concrete pipe, which is a heavy and rigid pipe material that is capable of supporting large overburden loads and resisting current and wave movements. Corrosion resistance of reinforced concrete is good in the saltwater environment.

Pipe Joints

A variety of pipe joints ranging from welded to dresser couplings are available for linking outfall pipe sections together. Probably the most common is bell and spigot with a retained rubber gasket. Normally, up to 3 to 5 degrees of deflection are allowed. For greater deflections (up to 15 degrees), ball and socket joints can be used.

Outfall pipe joints are typically equipped with thrust-ties to secure the pipe joint from displacement. A bolted connection at the pipe spring line links each pipe section and restrains the joint from separating due to external forces. Stainless steel bolts are usually used in saltwater. Metallic bond straps electrically linking each pipe section together are also common features of an ocean outfall joint. Bond straps allow external electric currents to be applied to the entire pipeline to control electrolysis.

Pipe Support Systems

The wide range of pipe support systems available to the outfall designer is illustrated in figures 14 through 20. The following is a summary of each system.

Bottom Exposure. For environmental conditions with minimal current, wave, and impact potential, the outfall pipe can be laid directly on the bottom (figure 14). For this condition, only a bedding layer may be required to support the pipe. Where some current or wave action exists, an exposed outfall can be secured to the bottom with concrete anchor blocks or embedment anchors (figure 18).

Bottom Exposure With Armor. Where the pipe is subject to moderate wave attack or strong currents, it is desirable to armor a pipe laid on the bottom. Armoring usually consists of riprap and is designed in similar fashion as breakwaters (figure 15).

Buried Trench Section. Sites with heavy wave action usually require complete burial of the outfall pipe. The trench must be deep enough to ensure that scour action will not expose the pipe. Often, the pipe zone material is riprapped at the surface to reduce scouring potential (figure 16).

Table 1. CONSTRUCTION PROPERTIES OF OCEAN OUTFALL PIPE MATERIALS

Outfall Pipe Material	Composition	Range of Diameter	Nominal Length	Joint Type	Seawater Corrosion Protection	Notes
Reinforced Concrete	Concrete embedded with steel rods or fabric	12 to 120+ inches	10 feet	Bell and Spigot with thrust tie	Bond strap linking each pipe section together for induced electric currents	Very heavy and rigid pipe material; impact resistance high
Steel	Thin plates of steel welded together	Variable	Variable to 100 feet	Welded or mechanical	Pipe typically lined inside and out with mortar	Flexible pipe material; moderate impact resistance
Concrete Cylinder	Prestressed steel barrel with mortar coating and lining	12 to 40+ inches	32 feet	Bell and Spigot with thrust ties	Bond strap	Semirigid pipe material
Corrugated Metal	Rolled and bolted steel sheets, flexed or corrugated to increase stiffness	6 inches to 21 feet	12 feet	Steel band	Steel galvanized and embedded with asbestos felt, bituminous lining	May have limited use in marine environment due to corrosion potential
Cast Iron	Molded gray iron centrifugally cast on a metal mold	12 to 36+ inches	18 feet	Mechanical or ball and socket	Bond strap	Impact resistance low--brittle failure
Ductile Iron	Chemically altered cast iron	12 to 36+ inches	18 feet	Mechanical or ball and socket	Bond strap	More resistant to impact loads than cast iron
Fiber-reinforced	Fiberglass filaments bonded by resin	12 to 60+ inches	40 feet	Bell and Spigot	None. Can carry caustic effluents	Pipe is lightweight and deflects considerably under earth loads
High-density Polyethylene	Manufactured of polyethylene resin through a continuous extrusion process	12 to 48+ inches	Pipe can be continually extruded to any desired length	Butt fusion or mechanical joints	None required	Pipe is buoyant in seawater and flexible. Conforms easily with nonlinear bottom topography. Pipe wall easily punctured by sharp objects

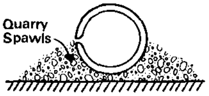

Figure 14
Bottom Exposure

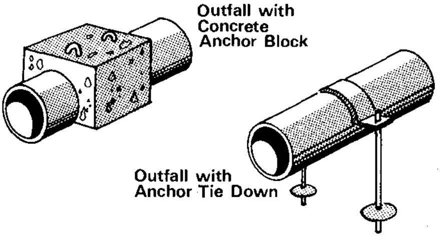

Figure 18
Alternative Pipe Anchoring Methods

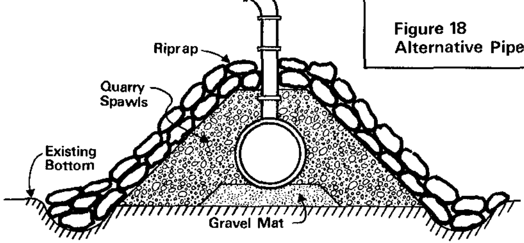

Figure 15
Bottom Exposure With Armor

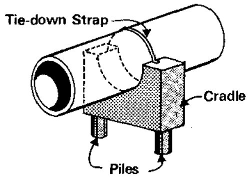

Figure 19
Pile-Supported Outfall

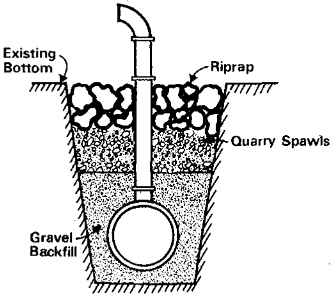

Figure 16
Buried Trench Section

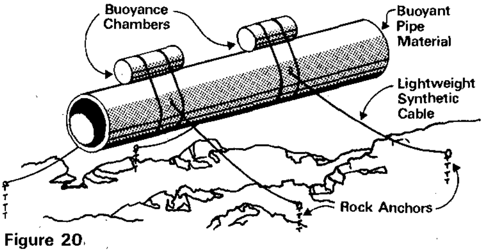

Figure 20
Floating Outfall -
Rough and Irregular Bottom

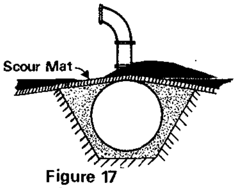

Figure 17
Shallow Trench
With Scour Mat

For some locations, scour mats can be used to eliminate the need for deep trenching. A scour mat consists of a pre-formed concrete mat that is laid over the entire exposed pipe with sufficient width to prevent undermining at its edges (figure 17).

Pile-Supported System. In some instances, the ocean bottom is composed of soft sediments, providing little, if any, bearing support for the pipe. Laying a rigid pipe material directly on the bottom in such conditions is hazardous because of potential dissimilar settlements. A common solution is the use of a pile-supported pipeline (figure 19). Piles are driven to firm bearing and a cap is attached to the pile tops. The pile caps function as a cradle for the pipe, while a tiedown strap prevents vertical pipe movements due to current-induced oscillations or positive buoyance of the pipe such as air trapped in the pipeline.

Semi-Floating Outfall. For some ocean sites, none of the previously mentioned systems is practical. An example might be a site that has minimal current action but a rough and irregular bottom (submerged coral reef). Furthermore, environmental regulations could prevent blasting a trench into the bottom. Laying the pipe directly on the bottom is not desirable because it would be damaged by sharp projections. Driving piles may be prohibitively expensive. However, floating the pipe above the bottom is a possible alternative (figure 20). A semi-floating outfall can act as a suspension bridge in reverse, keeping the pipe suspended above the problem area but below the ocean surface. Pipe material should be lightweight or, at best, buoyant. Additional buoyance chambers may be required to provide vertical uplift. Anchors and anchor cables should be sized to secure the pipe from lateral and longitudinal movements due to minor current or wave action.

Construction Methods

During the pipe design of the outfall, the designer must also consider the various construction methods available to an offshore contractor. Failure of the designer to understand outfall construction procedures can result in a difficult and costly pipe installation.

For ocean outfalls, there are three different zones that the contractor must contend with during construction: onshore, surf, and offshore. Each zone can require different construction methods. The four commonly used construction methods of outfall installation are barge lay, trestle lay, string float, and bottom pull.

With the barge lay method, the pipe is laid in relatively short lengths from a barge to the trench or bottom, similar to onshore sewer construction. The barge lay method is generally used in the offshore zone. Divers must join each pipe length to the previously installed pipe (figure 21). The cost of this method increases tremendously with increase in water depth.

The trestle lay method involves the construction of a pier through the surf zone (figure 22). The pier replaces the barge as a work platform, isolating the pipe-laying equipment from wave action. Usually steel sheeting is driven into the bottom to act as a cofferdam for the pipe trench. Pipe is laid in the trench in a similar matter as a barge lay.

John Goode Photograph

Figure 21. Diver Supervising Pipe Joint Assembly During Barge Lay Operation.

CH2M HILL Photograph

Figure 22. Outfall Construction from Trestle Through Surf Zone.

Figure 23. Launching Outfall by String Float Method.

CH2M HILL Photograph

Figure 24. Offshore Tug Preparing for Bottom Pull of Outfall.

The string float method involves floating the entire pipeline into place on the surface and then sinking the line into place on the bottom (figure 23). To provide the buoyancy necessary to float the line, the pipe and diffuser are temporarily sealed while full of air. When the line is floated into place on the water surface, the air is replaced with water, causing the line to sink. The rate of submergence can be controlled by the rate of air release.

This method is most commonly used with lightweight, flexible, plastic pipes. Additional weight is added to these lines, usually by concrete ballast collars, to provide the negative buoyancy needed to sink the line and hold it in place on the bottom. The feasibility of using this method depends on many factors, including weather and water conditions. Rough water or strong currents are of particular concern.

The bottom pull method involves pulling the line into place along the ocean bottom through the surf zone and offshore areas (figure 24). Large stresses are placed on the joints and pipe and must be considered in design and materials selection. The pipe is joined onshore and pulled seaward as assembly proceeds. A specially constructed sled is used to allow the line to be pulled without damaging the pipe material. In addition to providing a means of attaching the pulling cables, the sled will also provide a grading effect on the soils. Depending on the soils and topography, additional sleds or other supports may be needed along the pipe.

All of the above construction methods will require underwater work during installation. In all cases, diver time is required for inspection of the final installation. To ensure proper monitoring of underwater construction, the use of engineering divers as inspectors rather than commercial divers is recommended (Layton, 1976).

The appropriate method of construction for an outfall line depends on many factors, primarily soils, pipe material and size, environmental conditions, depth of construction, contractor's available equipment, and final design conditions. All of these factors are involved in determining the cost of the final installation.

Perhaps the major factor relating to costs is the amount of underwater work required, particularly work performed in deep water. Difficulty, time required, and, therefore, costs increase greatly as the depth of water increases.

OUTFALL MAINTENANCE

During the design of an outfall, provisions for inspection and maintenance of the diffuser should be considered. Even carefully designed diffusers will require occasional cleaning to remove accumulated grease, slime, and grit (Rawn, Bowerman & Brooks, 1961). These accumulations can reduce flow by increasing frictional resistance. Cleaning can be accomplished by flushing or by pulling a ball through the line.

In addition to cleaning operations, an annual diving inspection of the outfall is recommended. The purpose of the inspection is to check the outfall for structural damage to pipe and diffuser risers, pipe corrosion, changes in biological activity around diffuser, and plugging of diffuser ports due to longshore drift.

Further, it is recommended that an inspection hatch be built into the end of the outfall diffuser to facilitate flushing operations and allow divers access to the outfall's interior for removing obstructions. Also, for long outfalls, several inspection hatches should be located along the conduit and diffuser sections for easy diver access.

SUMMARY

This paper discusses the major components of the complex ocean outfall design process: site selection, outfall hydraulics, dilution and mixing, diffuser port design, pipe design, pipe support systems, and construction methods. All of these components must be evaluated throughout the design process to provide a structurally sound outfall system that meets water quality requirements.

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