Design Loads and Construction of Tremie Sealed Cofferdams

Eugene Washington, P.E.

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This course includes a multiple choice quiz at the end.

Learning Objective

The purpose of this course is to show that cofferdam construction is a complex process of design and construction through a series of stages. The designer must consider a number of forces than just the hydrostatic water loading. The student will have a better understanding of the design and construction process involved in building tremie sealed cofferdam in open water.

Course Introduction

This course explains how the various wind, current, waves and mooring forces are applied in addition to the hydrostatic head to tremie sealed cofferdams in open water for design purposes. The course then leads the student through the construction steps and the methods successfully used in the past. The examples of past problems are employed to illustrate the importance of careful planning and proper construction methods.

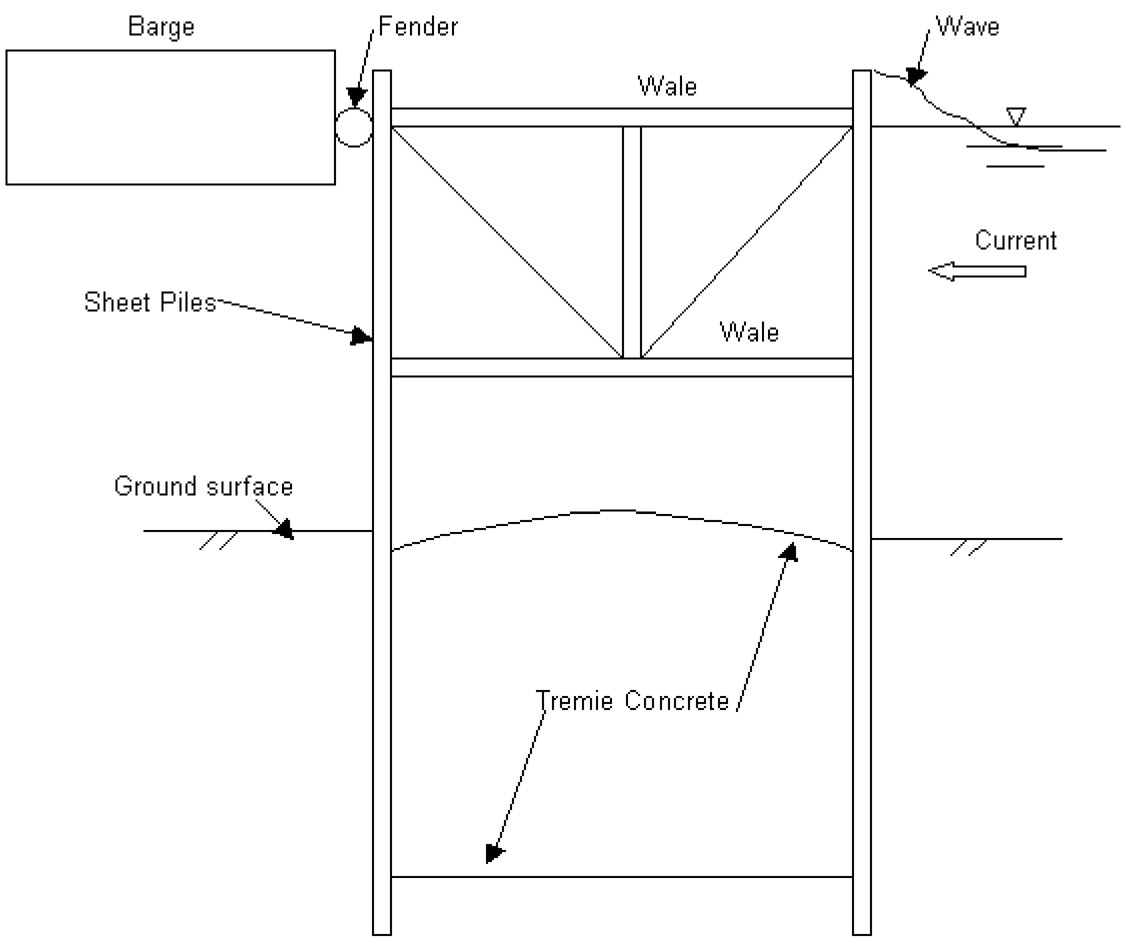
Tremie sealed cofferdams are used when construction must be preformed below the surrounding water level. Usually these cofferdams are in waterways such as lakes, rivers, and bays. In some cases, the free draining gravels will cause dewatering efforts to be less effective than a tremie sealed cofferdam. The tremie seal serves two purposes. First, it acts as a counterweight to prevent the cofferdam from floating out of the ground. Second, the tremie makes a solid foundation that will not heave or quicken from artesian water pressure.

The design of a cofferdam is a complex process that requires a detailed understanding of the various forces and construction methods that are used. The design must be compatible with the equipment and erection process. Intermediate stages of erection, internal permanent structures, and dismantling must all be considered in the design process.

Course Content

DESIGN LOADS

A typical tremie cofferdam will experience several loading conditions as it is being build and during the various construction stages. The significant forces are water pressure, buoyancy, soil active loads, water current, wave impact and mooring forces. In order to over come the displaced water buoyancy, the tremie seal thickness is about equal to the dewatered depth.



TYP COFFERDAM SCHEMATIC

The first design parameter to select is the expected high water elevation. In a river it is a question of when and how long the cofferdam will remain dewatered. If the work can be completed during low summer flow, the cofferdam and tremie will be much shorter than if it has to be able to withstand winter and spring floods. Winter weather may also cause a concern for ice pressure and spring breakup. If the cofferdam is going to be dewatered for several months a selection of high water has to be made; a one, two, five or ten-year flood are common choices. This choice will depend on what damage can be done if the cofferdam is over topped by floodwater and for how long. In bays the highest expected tide will be the design water elevation.

Above the design high water elevation the cofferdam should have at least three feet of freeboard or higher than the maximum expected wave height. Wave forces will be significant factor in large bays and lakes where the fetch is several miles. Ship and boats can also generate large wake waves. The force generated by waves is asymmetrical and must be carried to the ground through the sheet piling in shear and bending. The waler system must be designed to transmit the wave forces to the sheet piles.

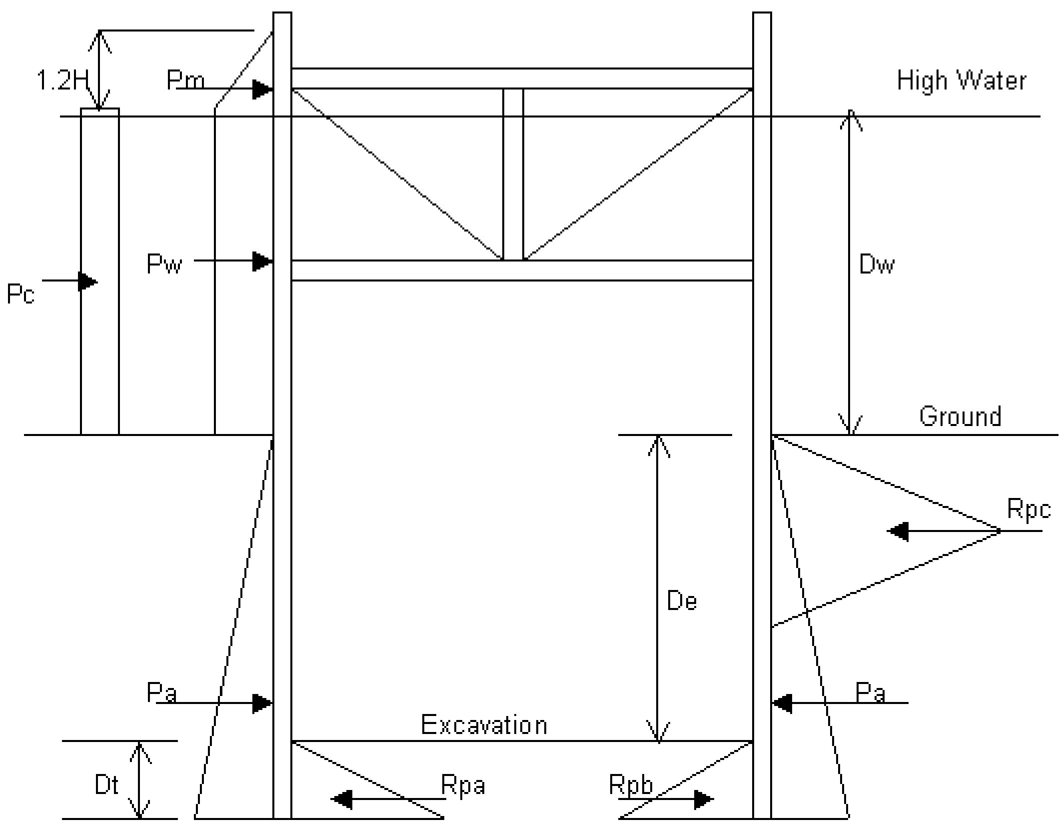
Tidal and river currents can generate significant asymmetrical forces and must be transmitted through the wale system to the sheet piles. The combination of high floodwater and fast current can result in scouring of the riverbed around the base of the cofferdam. Excessive scour can cause the cofferdam to become unstable, especially if the tremie seal is not yet in place. In loose sands and gravel scour can easily exceed ten feet deep in a matter of hours. If scour is a real possibility it may be necessary to armor the riverbed with riprap or mats to eliminate scour.

Mooring forces are derived form two separate actions. The first is the impact of the barge and tugboats as they moor to the cofferdam or the waves as they move the barges while moored. The other force is the wind pressure on the total sail area of the barge. Gale force wind is a common occurrence along most coasts and on large lakes. The combination of high wind and waves will cause major damage to the cofferdam and equipment if no preparation is made to accommodate those events.

There are at least two stages that must be designed. The first stage is when the cofferdam is fully excavated but prior to placing the tremie seal concrete ballast. Usually the cofferdam is installed and the excavation is accomplished by crane and clam bucket. The sheet piles support the excavation face. If the soil is soft and the excavation is shallow enough the piles can extend below the bottom of the excavation and the sheet piles are acting as simple beam spanning from the lowest wale to the ground below the excavation. Often the excavation is too deep and/or the soil is too stiff to allow sheet pile penetration below the bottom of the excavation. Often the stiffness of the soil requires a dig and drive operation. In this case, the sheet piles are acting in cantilever, bending around the lowest wale. The water elevation in the cofferdam is kept at least equal to the surrounding water surface elevation. Often water is pumped into the cofferdam to insure no negative differential head develops during tidal changes. The active lateral soil pressure under water is about 15 pcf. At this first stage the cofferdam the least stable and is vulnerable to wave, current and mooring forces. I have had a major cofferdam lean to the side due to soil failure during the dig and drive sequence.

The second stage is after the tremie seal is poured and the cofferdam is dewatered. The mass of tremie concrete stabilizes the cofferdam, but the system must be able to resist the water pressure, current, wave and mooring forces. In most protected bays waves will generally be five feet or less from crest to trough. The design free board should be at least 1.5 times the expected wave amplitude. The pressure of the wave can be taken as the water density times the wave height. If the cofferdam is exposed to the open ocean or large and deep lakes a thorough analysis of the anticipated wave amplitude, wave length and pressures generated is needed. The current pressure can be figured as the current velocity squared times the density of the water divided by 2 times the gravity acceleration. Mooring forces are difficult to quantify, but I use at least 1,000 lb/lf along the wale closest to the water surface. In an open ocean environment where large barges are wave and wind driven an analysis of the potential impact forces will be required. From a practical standpoint sheet pile cofferdams are not usually built in open ocean waters. This is because of the extreme natural forces that can be commonly and suddenly experienced at sea.

Sometimes to facilitate the construction inside the cofferdam the lower struts and/or wales will be removed and the new internal structure will be used to support the sheet piles. If this can not be accomplished, it is important to arrange the struts to minimize the impact on the new structure. The struts are a major interference to the interior cofferdam construction and will significantly slow nearly all productivity as forms and rebar is placed through and around the struts. Blockouts may have to be formed around the struts so that they can be removed later. It is common to need divers to dismantle the lower wale systems and plug the blockouts. This is a slow and expensive process that requires extensive support equipment and support personnel. Because of the potential danger to the divers a careful and detailed plan needs to be drafted. This plan must also address all foreseeable events that could endanger the divers and have emergency procedures in place and communicated to all involved parties.



STAGE 1 LOADING DIAGRAM

Pm = Mooring Force = 1,000 +/- ,lb/lf

Pc = Current Force = GwDwV^2/2Ge, in lb/lf

Pw = Wave Force = GwHDw, lb/lf

Pa = Soil Active Force = Ga(De+Dt)^2/2

Rpa = Soil Passive Reaction at the upstream toe

Rpb = Soil Passive Reaction at the downstream toe

Rpc = Soil Passive reaction to resist overturning

H = Wave Height in feet

V = Current Velocity if feet per second

Dw = Water depth to the ground

De = Depth of the excavation

Gw = Water density, 62.4 pcf for fresh water and 64 pcf for seawater.

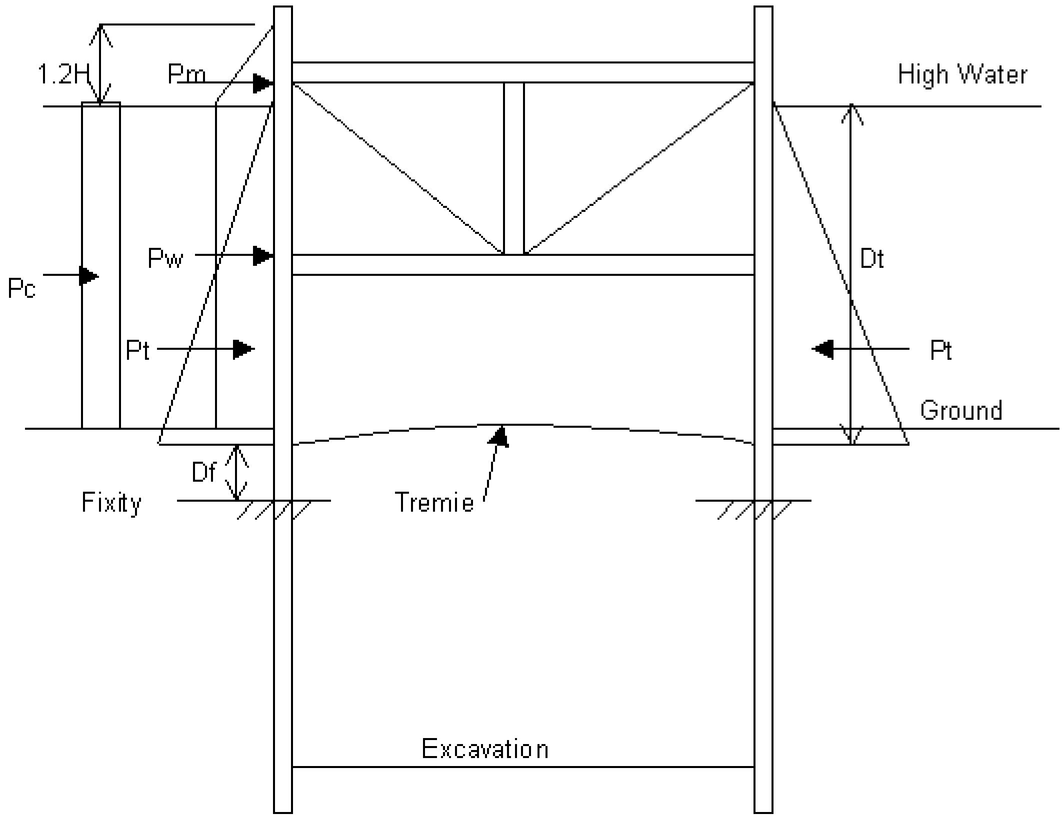
Ga = Active soil pressure, usually about 15 pcf

Ge = Gravitational Constant = 32.2 ft^2/sec

Gp = Soil Passive Pressure, usually about 300 pcf

Several assumptions must be made at this stage of design. On the positive side the duration between completing the excavation and placing the tremie seal concrete is usually a matter of only a few days, so the exposure is minimal. Both the mooring force and the wave force are short-term dynamic impact forces so the passive resistance of the soil does not need to be reduced by submergence. The current force is a steady load, but it is usually small when compared to the mooring plus the wave force. If the Rpa is set equal to Pa, then the conservation of Moments and Horizontal forces is used to readily determine the passive forces Rpb and Rpc.

The second stage loading is after the tremie seal is poured and the cofferdam is dewatered.



STAGE 2 LOADING DIAGRAM

Pt = water pressure to the top of the tremie seal = GwDt^2/2

Df = Effective Fixity below the top of the tremie concrete

It is also reasonable to assume a pinned support at the top of the tremie concrete at the sheet pile contact line.

The surface of the tremie concrete will vary about two to three feet in elevation from the high points in the center to the low point s at the sheet piles. As the tremie is poured there will be some minor segregation and water entrainment. This causes the concrete to swell from batch volume about 5% when measured in the cofferdam. This is to be expected and is not a cause for concern.

Note that all the loads are shown as point (mooring), triangular (hydraulic head) or rectangular (wave and current). This is applied to simplify the calculation process. The mooring load is an impact load that is short duration. The kinetic energy of 1,000 ton barge moving at 1mph or about 1.5 feet per second generates about 1,000 ton x 2,000 lbs/ton x (1.5 fps)^2 / 32.2 ft/sec^2 = 140,000 ft –lb. The momentum is nearly 100,000 lb/sec, if this is absorbed by the fender compression and the flexing of the cofferdam totaling one-foot the force is 100,000 lbs. Sound and heat dissipates the remainder of the kinetic energy. A 100-foot long cofferdam waler nearest the water level will transmit 1,000 lb/ft through the cofferdam. The sheet piles then must transfer the load to the ground and/or tremie seal.

Often the sheet piles are cantilevered too much to absorb that load without yielding. For this reason heavy vertical cross bracing between the upper and lower struts is required to effectively transmit the mooring load to a point where the sheet piles can safely absorb the bending load. The author prefers a cable bracing system rather than rigid steel bracing because the cables will stretch and allows lateral cofferdam movement to help absorb mooring and wave impact forces.

In rivers, the high current and high water occur simultaneously with gale force wind and wave generated impact forces. In bays where tides generate the water level fluctuations, slack tide or no current accompanies high tide. In a large bay, such as San Francisco Bay, steady storm winds can generate large waves and raise high tide by several feet.

Determining the expected wave impact is a complex procedure and there are several methods of calculation. The configuration of the body of water, depth, length of fetch, wind speed, wind direction, duration of the wind, and gusting all play a significant role. The rectangular load diagram presented above is at best an approximation. By adding the wave height to the high water elevation, a single triangular load diagram can be used to calculate the dewatered waler and sheet pile stresses.

Usually in rivers, waves are not a significant consideration. However, some river will generate very swift currents, especially during flood stage. A 7 mph current or 10 fps will cause a 200 psf differential load on the cofferdam or over three feet of water head difference from one side to the other. Often this load controls the design of the waler system cross bracing and the sheet pile selection. The rectangular configuration shown is an approximation to facilitate the calculation process.

Most major cofferdams are indeterminate structures. The design and calculation process requires the use of deflection formulas to determine load and stress distribution. For this reason the load diagrams are kept as simple as possible. There is no point in refining load diagrams to complex configurations. The mooring, current, wave and wind loads are, at best, judgmental. Usually the worst case events such as 100-year floods and storms are not used to design cofferdams. The cost would be prohibitive. For this same reason, earthquakes are not usually considered in the temporary construction. Depending on exposure, risk and cost usually a 2-year to a 10-year events are used as the cofferdam design criteria.

CONSTRUCTION

The successful cofferdam construction of depends greatly on adhering to proper procedures and sequences. The designer and builder must understand that exacting tolerances can not be maintained, with deflections and misalignments are measured in inches or feet. Piles are easily deflected off line by rocks, obstructions, and changing soil conditions. Even improper installation methods can result in major damage.

From a practical standpoint, cofferdams are limited to 60-foot long sheet piles. Manufacturing, transporting, handling, threading and driving sheets longer than 60 feet creates major problems. We have built cofferdams with 40 feet of dewatered depth by excavating below the tip of 60-foot long sheet piles. This could be done only because the ground below the sheet piles was stiff enough to stand vertically under water long enough to place the tremie concrete. We have also chemically grouted sand lens to prevent underwater cave-ins. Usually tremie sealed cofferdams are limited to about 30-feet or less of dewatered depth, plus a 30-foot deep tremie seal.

Access to the cofferdam site is by trestle or barge. Several circumstances will determine which is the better access. A trestle offers the easiest and most stable access, but deep water and great distance from the shore may cause barge access to be more economical. Ship channels may also prevent the use of an access trestle. If rough seas and high wind are common, barge access will be limited causing excessive delay while waiting for calm weather. In such cases, a trestle may prove to be more economical in the end.

The first construction step after the access is in place is to position the wale system. The wales can be assembled on a barge and floated into position. Guide piles and support frames are installed to hold the wale system in place. The barge can often be partially flooded and towed from under the suspended whale frame. The wale frame is then lowered to elevation using cranes or hydraulic jacks. The wales are then used as a guide to thread and drive the sheet piling.

Usually there are at least two layers of wales. The top and bottom layers will act as stabilizing template to control the sheet piles. In any marine environment, there will be some waves, current, and wind. Without a supporting template to guide the sheet piles it is almost impossible to maintain the vertical and horizontal alignment necessary to close the cofferdam and prevent the interlocks from splitting open. If the sheet piles are not kept plumb the interlocks will split apart in tension or the closing pair can bind up due to compressive friction and refuse to be driven.

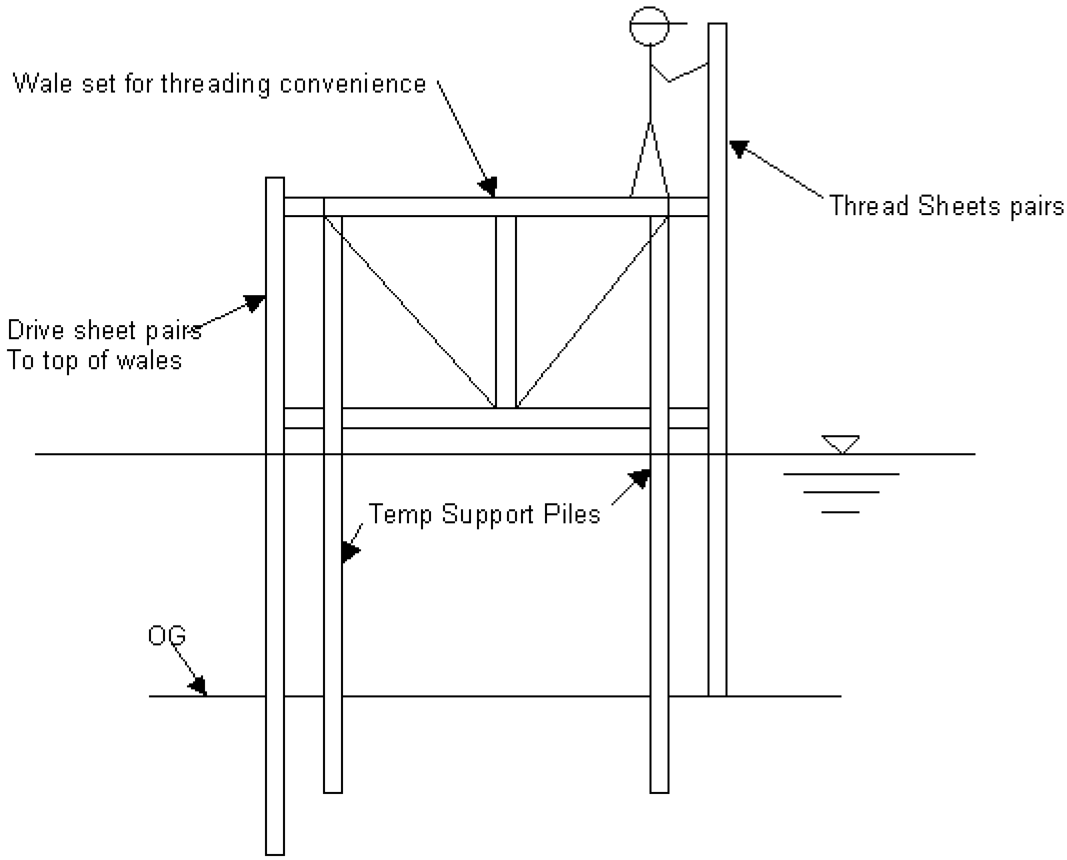
Vibratory pile driving hammers have largely replaced impact type driving hammers. The vibratory hammer is faster, quieter, and is less likely to cause damage to the sheet piles. Drilling holes for the piling is the preferred methods of installation when the soil contains cobbles or is too hard to allow pile driving.

The first step to cofferdam installation is making a driving template. Usually the waler system is used as a driving template. Someone must help thread the interlocks.

The template wales should be marked with the proper location of every sheet pile pair interlock that touches the wale. To allow for deflection and some misalignment that will occur, it is common to build the template 4" to 6" wider than the designed size. One way to accomplish this is to band 2 or 3x12 wood planks on the outside of the walers. Special care should be taken to insure the first pair is set plumb and in the proper location, since it will act as guide for the rest of the sheet piles. One real advantage of the vibratory pile hammer is the hydraulic pile grip is used to pick the sheet pile pair from stockpile and thread the interlocks. When the sheet pile pair is properly threaded and aligned, it should be driven to the top of the template wale. A C-clamp can be used to keep the free interlock from fanning out. Sheet piles will tend to tilt along the wale because of the unsymmetrical interlock friction during the initial driving, so the top should be restrained from walking along the wale.

If there is a prevailing wind or water current, start setting the sheet piles on the center of the upwind or up-current side. Complete this up wind side installation of sheets including the corner pile by alternating from left to right when adding sheet pairs. Make sure that the corner piles are truly plump in both directions. It is a lot easier to correct misalignments as the sheets are being threaded than discovering a problem when the final closure is attempted.

Final closure should never be made at a corner. The reason for this is the corner works in both directions. If either sheet wall line is out of plumb, the sheet interlock will probably split open. The other reason to be careful in initial alignment is that this will largely define the direction the piles will take as they continue to penetrate the ground. If the interlock is started off tight and out of line, it will likely split apart as it is being driven. This will damage the pile and may require a very expensive and time consuming repair procedures.



SHEET PILE TEMPLATE

When the sheet piles are fully in place and driven to the top of the upper template, the template wales can be lowered, if needed. The pairs of sheet piles should be advanced in about five foot increments. Drive alternate pairs so that the interlock friction stays symmetrical for every pair. This will help maintain pile alignment. Constantly check the sheets for plumbness and alignment. If the sheets start to walk out of plumb or alignment, extract the sheet pair and advance the pair on each side of the problem sheets. Sometimes by working the problem sheet pair up and down a few times, the pile will realign and driving can continue. This ability to extract and drive the sheets with a vibratory hammer is a huge advantage over impact hammers, which usually only can drive the pile efficiently. If the misalignment can not be corrected and is serious enough to require additional action, the only practical solution may be to excavate to the toe of the sheets and remove the obstruction. It may even be necessary to install temporary walers at unplanned elevations. This is another reason to have the design on a computer, so you can react quickly to address the problems as they arise.

Cofferdams are rarely installed as easily as they are planned and designed. You must expect and anticipate problems that will require redesign and innovative solutions. However, it is rewarding to solve the demanding construction and knowing it will help successfully complete the project.

We had one cofferdam where the crew let the sheets get out of plumb and the closure sheet pair could not be driven to the required penetration. They elected to cut the jammed sheet pair flush with the top of the adjacent sheets so nobody would notice. Unfortunately, the tip of the jammed sheet pair was above the tremie seal concrete but about ten feet into the clay bay bottom. When the dewatering was nearly complete the clay plug blew out and the cofferdam filled with water so fast that two men got wet to their waist before they could ride the crane hook out. The water rose about twenty feet in just a few seconds. It also took another month to seal the blow out and complete the cofferdam dewatering. Even a split interlock is expensive and time consuming to repair. A one-inch wide split a foot or so long will spew more water than a fire hose if it is forty feet below the water level.

In another incident, we had a major cofferdam tip to one side about 15 degrees. The cofferdam was 140 feet long, 60 feet long with 60-foot long sheet piles. The cofferdam weighed over 500 tons. The Geologist assured us the weak rock at the sheet pile tips would support the weight while the tremie excavation proceeded to further depth. It took a month to right the cofferdam using barge-mounted cranes and hydraulic jacks. The cost of the mistake cost us over $1,000,000 to fix and we still had to install the support piles to carry the weight of the cofferdam. The cost of the support piles was only $25,000. Obviously, the risk taken to save a few dollars was not a good one. Cutting corners when building major cofferdams is only begging for disaster.

With the sheets carefully driven and the wale in position, often the sheets are welded or bolted to the top wale to provide cofferdam stability during excavation operations. A crane and a clam bucket usually perform the excavation, although in some instances a backhoe can be effective.

If the soils are stiff, the ground can be "Swiss cheesed" with a crane mounted drill. This allows the bucket teeth to grip and cut through the soil rather than just scraping along the surface.

Always excavate along the sheet piles first, keeping a low hump in the middle. This allows the clam bucket to rest against the sheets and stay upright so it can stuff the bucket. If a depression is created in the middle of the excavation, the bucket will roll on its side and be unable to excavate the wedge of soil adjacent to the sheet piles. When the excavation is nearly complete, slide a steel beam spud between the wales and the sheet pile alcoves. Almost always soil will cling in the alcoves. This plug of soil can easily blow out during dewatering, causing great expense and delay. The cause of a major leak that prevents dewatering can be very difficult to even locate, often requiring divers to probe for the leak. If there is more than one plug of soil to blow, you may gain repeated experience by finding such leaks as they sequentially blow out with each attempt to dewater the cofferdam.

Tremie concreting is done in a manner so as to minimize the flowing concrete contact with the water. The method is to induce the fresh concrete under the previously placed concrete and pillow it up and out. Never allow the concrete to fall through the water, if that happens, the cement will wash out and you will have a pile of gravel with a weak cement paste icing on top. This icing or surface latents will happen to a limited extent no matter how carefully the concrete is placed. The concrete can be pumped by first filling the pump hose with concrete and weak wiring a watertight cap over the end of the hose. The hose is lowered to the bottom of the excavation and the concrete continuously pumped raising the hose only when the backpressure slows the pumping production or the concrete has risen to the desired grade. More than one pump can be employed. Pumping points should be at about 25 feet on center at the most. Tremie tubes made from 12" steel pipe can be used. These tubes act the same way as the pump hose. First the tube is lowered on the bottom and a rubber ball is pushed into the tube, forming a seal. Then concrete fills the tube forcing the ball all the way to the bottom. When the tube is completely full of concrete, it is eased up from the bottom until the concrete starts to flow. The tube is kept almost full at all times be adjusting the tube up or down to compensate for the flow rate of concrete. The tube is extracted and restarted in a new location only after the concrete pillow has reached the desired elevation.

The tremie placement is a continuous operation until completed, going 24 hours a day without interruption. Tremie pours usually involve large volumes of concrete, often several thousand cubic yards of concrete. Usually one or more concrete plant and backup are dedicated solely to the tremie pour until it is complete. One of the worst things that can be done is stopping the tremie before it is completed. Any cold joint formed will be a thick, inclined and very weak plane, which may easily fail from the weight of the structure it is designed to support.

The concrete mix design is very important. The mix design must produce a free flowing and slow setting concrete. The concrete usually contains about 7 sacks of low heat of hydration cement, rounded aggregates, high sand content and water added to achieve a six to eight inch slump. Concrete set retarding, water reducing and anti wash agents are sometimes added to the mix design. The concrete mix design is a critical element to building a successful cofferdam. It is wise to consult with an expert in tremie concrete construction before committing to the work.

We have encountered engineers and owners who think they know all about tremie placement methods. When we ceded to their method demands, it always led to major problems. One Federal agency insisted we adhere to a cofferdam construction manual that was twenty years out of date. The author of the manual, an internationally acclaimed Engineer, finally told them that that the manual was obsolete and referred to his latest work. Another time, an engineer insisted on a tremie concrete placement method that resulted in soil seams and weak cold joints. This forced us to drill and high pressure grout the tremie seal concrete. This cost the project hundreds of thousands of dollars in unnecessary lost time and expense. Refuse to comply with improper suggestions.

If an owner insists on poor procedures, document to the engineer that you believe the methods are wrong before the work is started and you will file a claim for all remedial costs and loss of time. It is usually wise to have a recognized expert review your cofferdam construction plans and methods well in advance of the work and submit the review before the owner has a chance to interfere.

When the concrete has cured enough to gain enough strength to withstand the dewatering forces (about two or three days), dewatering can begin. Two major problems can arise at this time. The first is the pH of the water in the cofferdam is going to be at least 11, very basic and often too high to permit pumping back into the bay or river without treatment. The water will be murky, containing colloidal size cement particles that will not readily settle out. The other problem is the cofferdam will leak more and more as the water is drawn down, usually generating several thousands of gallons per minute of leakage. Once the differential head of water between the outside and inside becomes great enough to push the interlocks tighter, the leakage will be significantly reduced. But initially, massive volumes of water must be quickly removed from the cofferdam until it has a chance to seal itself up. The required pumping rate is measured in several thousand of gallons per minute in order to be effective. The draw down within the cofferdam must be fast enough to detect visually, at least 1" per minute initially or the pumps will be over whelmed by the leakage through the interlocks and the draw down will cease and additional pumps will be needed.

In times past it was no problem to pump directly into the surrounding waterway. Today with strict water quality regulations in place, disposal to the pumped water can be a huge problem. Recently in Canada several weeks were lost because there was no way to dispose of the pumped water fast enough. Only by adding flocculation, buffering chemicals and circulating the water through filters could the water quality be improved enough to allow pumping into the river. Huge holding ponds must be found or created or pumping directly back into the waterway is required. The time and cost to treat the cofferdam water can cause major costs and delays. Be sure a workable and approved plan is in place before the cofferdam must be dewatered.

After the cofferdam is dewatered, the clean up process can begin. The surface will be rough and undulating. There will be layers of mud, debris, and dead fish that must be cleaned up. Once the clean up is done, the top of the tremie concrete will have about six inches of laitance. The laitance is a weak layer of nearly pure cement that has been washed to the surface of the concrete by the dynamics of the concrete tremie placement. This is one reason to have a cement rich concrete mix design. Some of the cement will be washed from the concrete and some segregation will naturally occur.

At this point, a safety precaution is inserted. No gas-powered machinery should ever be allowed inside a cofferdam. The danger for explosion and carbon monoxide poisoning is too great. Even the use of diesel powered equipment in the cofferdam should be kept to an absolute minimum. Whenever it is possible, engines outside the cofferdam should power all machinery. These actions will both reduce congestion in the cofferdam and provide for safer working conditions.

The laitance must be removed from at least the areas of contact with the subsequent structure foundation. The laitance can be removed by jackhammer; a small rubber tired backhoe mounted hoe ram, or a very high-pressure water jet. The laitance is removed until the coarse aggregate is exposed. This insures that a structurally competent bond and bearing will be achieved between the tremie mass concrete and the reinforced foundation structure.

The direct costs of clean up, laitance removal will require at least four person-hours per square yard, and the cost of the cofferdam associated equipment. Usually it takes at between a week and a month to fully prepare the tremie surface for the subsequent construction. The surface will vary in elevation approximately three feet or more. High spots usually must be chipped down. Starter forms must be custom cut and fit to the tremie surface at an expense of 2 to 4 square feet per person-hour. Often a leveling slab is placed to facilitate the construction to the subsequent structure.

While the clean up and laitance removal is progressing, the cofferdam will continue to leak and require substantial pumping. The leakage water will be contaminated by the mud and debris in the cofferdam until all remedial work and clean up is completed. All water removed from the cofferdam during this stage probably will have to be processed before returning the water to the river, lake, or bay. Sometimes barge-mounted filters are needed. At other times, a settling pond on the shore can be utilized. Pollution control measure requirements can be very extensive and costly.

As soon as the dewatering of the cofferdam is started, efforts to stop and control leaks should begin. The slower the leakage the quicker the cofferdam will be dewatered and the least amount of water will have to be handled and processed. Controlling leakage is the one major reason to adhere to strict and proper cofferdam installation methods. A properly installed cofferdam will allow quick and easy dewatering, while a badly constructed cofferdam may require weeks of work just to get to the point where it is even possible to dewater the cofferdam.

There are several ways to stop and slow the leaks. No cofferdam is totally free of leakage, but over time, the cofferdam will continue to seal up and decrease the leakage. Rust of the sheet pile steel and water borne particles will fill small gaps. After several weeks, a large cofferdam may need only a small 2” pump to keep the cofferdam dewatered. Wooden wedges can be driven into the larger seams. Fly ash can be poured on the outside over small leaks. Visqueen can be lowered on the outside to form a patch. A mixture of horse manure, sand, and sawdust is often very effective when dumped on the outside above the leak. The sand will add weight so the mixture will rapidly sink, the horse manure will add just enough stickiness to hold the mixture together, and the sawdust and sand will be sucked into the crack. The sawdust will absorb water, expand slightly to further seal the crack, and wedge itself in tighter.

Initially, an around the clock watch should be maintained to insure the pumping system does not fail. The cofferdam can easily fill overnight if the pumps fail or clog up. If that happens, then the whole process of dewatering must be started from scratch. Much of the previous leak control work will be undone and avoidable time and money will be lost. Even with a full pump watch, there should be redundancy of power source and standby pumps already in place that just need to be switched on. Sometimes automatic float switches and emergency relay gear can be used.

Removal of the cofferdam can be a single event or in stages. The single event is when all the construction below the water is completed, the cofferdam is flooded to relieve hydraulic pressure and the sheet piling are extracted and wales are dismantled. Sometimes the designer requires the sheet piling to be cut off at the ground line to enhance lateral stability of the structural foundation. That requirement will increase the cost of the cofferdam by the extra work of divers and lost salvage value of the piling.

The cofferdam will sometimes be removed in stages. The new structure is completed to just below the lower wale and backfilled between the sheets and the new structure. The lower wale and strut system is then removed. The new structure is then built to the next layer of wales and the process is repeated.

The single event allows the sheets and wale system to be removed with the hydraulic head removed, so the dismantling process is only a matter of retrieving the pieces. When the cofferdam is dismantled in stages the wale system will be under high pressure and the sheet piles will squeeze inward several inches as the gravel backfill absorbs the transferred hydraulic pressure and the piles deflect. The pressure is best transferred slowly so impact is minimized and the process is always fully controlled. The struts can be slowly cut near a wale with a torch until the remaining steel yields and the sheet piles move in. The preferred method is to heat the strut near one end with a rose bud torch until red-hot and the pressure collapses hot portion of the strut. The process can be carefully controlled and stopped at any time by cooling the steel. The bolts attaching the wale corners can be torched or driven out with an air hammer.

Every cofferdam is unique and requires thorough analysis. The designer must take into account a large number of parameters. The design must be compatible with the weather conditions, waves, currents, construction equipment, construction methods, internal permanent structures, and ground conditions. Comparable cost studies should be analyzed to determine if the cofferdam method is favored over other techniques, such as precast or caisson construction. Often the cofferdam designer must work closely with the project design engineer to arrive at a mutually satisfactory procedure.

Course Summary

Every cofferdam is unique and requires thorough analysis. The designer must take into account a large number of parameters. The design must be compatible with the weather conditions, waves, currents, construction equipment, construction methods, internal permanent structures, and ground conditions. Comparable cost studies should be analyzed to determine if the cofferdam method is favored over other techniques, such as precast or caisson construction. Often the cofferdam designer must work closely with the project design engineer to arrive at a mutually satisfactory procedure.

Once you finish studying the above course content, you need to take a quiz to obtain the PDH credits.

View/Take Quiz

Concrete down the spout

Picture at left: Tremie concreting operations on the Newport Bridge (formerly called the Narragansett Bridge) at Jamestown, Rhode Island. Conveyors were used to feed the tremie hoppers. Picture at right: A bucket and crane feed the tremie hopper during construction of the Verrazano-Narrows Bridge, New York.

Tremie concrete is the name given to the method of placing concrete under water by means of a pipe called a tremie pipe. It has been found from many years' experience that concrete of high slump, 7 to 8 inches, is necessary in order to achieve high-quality concrete with this method. Therefore, concrete is "poured" in its literal as well as its figurative sense.

The tremie method is used wherever concrete must be placed under water, and if proper care and careful control are exercised, concrete placed using this technique will be of the highest quality.

Experiments with placing concrete under water were carried out as early as 1856 and, in 1885, a timber shaft was used to place concrete under water for a bridge foundation.

Since 1894 there have been many projects constructed using the tremie method.

Up to 1940 most of this type of concreting was used for casting unreinforced mass concrete such as caissons or cofferdam seals. In 1940, however, engineers began using the tremie method for reinforced structural concrete such as bridge piers. Since that date the tremie method has been used for all types of underwater concreting.

TECHNIQUE OF TREMIE CONCRETING

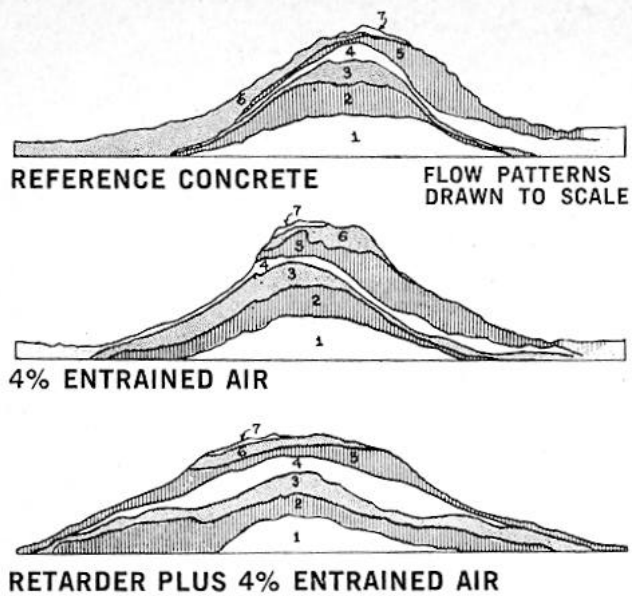
The trick in tremie concreting is to introduce concrete below the surface of the water and then to continue to introduce new concrete below the previously placed fresh concrete in a continuous operation, causing an outward and upward flow. As long as this flow is smooth and continuous and the surface is not disturbed, an extremely high-quality concrete slab will result.

A great deal of the success of this type of operation depends on the individual workmen who must be properly trained and even rehearsed, if necessary, in the procedure.

There are many advantages, as well as some disadvantages, in the use of the tremie technique. Both engineer and contractor must thoroughly appraise all alternate methods of concreting before deciding on the one specific method to be used.

Among the advantages of tremie concrete are these:

1. It is unnecessary to de-water the caisson or cofferdam.
2. It is possible to place large volumes of concrete very quickly at great depths.
3. The curing conditions are perfect.
4. Voids and honeycombs are eliminated provided the tremie seal is not broken.



Tremie flow patterns are indicated by the shaded areas. Numbers indicate sequence of batches. Tremie pipe was at center throughout. Thick end sections are laitance and poor quality concrete.

Some engineers avoid using tremie concrete, usually because they lack experience with the technique. But tremie work does have its disadvantages:

1. It is necessary to use a high slump, 7 to 8 inches, since it is not practical to vibrate tremie concrete.
2. In many cases it is difficult or impossible to inspect the results of the job.
3. The quality and strength of tremie concrete is questionable, especially at the outer edges of the job, unless the work is done by experienced workmen under proper supervision and control.
4. It is necessary to add extra cement to tremie concrete for safety. This results in increased costs and greater internal heat development. However, heat development is generally dissipated fairly quickly because of the temperature of the water above the concrete.
5. There can be an excess of laitance unless a proper mix design is used.

PRIMARY REQUIREMENTS

The two most important requirements for the successful placement of tremie concrete are the proper mix design and the proper equipment.

In designing a mix, it is generally better to use gravel than crushed rock, since the rounded shape will slide more easily down the pipe and flow more easily at the bottom. Where large masses of tremie concrete are to be placed, the gravel should be 1½ to 2-inch size. When reinforcement, or H piles are to be embedded, then ¾-inch maximum size aggregate is recommended. For jointing sections, such as precast tunnel sections, and for repair work, use pea gravel aggregate.

Sand is used as a fine aggregate and enough sand must be used for good workability, usually 40 to 45 percent.

Tremie concrete requires a high cement content and, generally, 7 bags per cubic yard are specified for average work; 6½ bags for very large masses. Slump should be 7 to 8 inches.

In most cases the use of set-retarding, water-reducing admixtures with entrained air will give much better results in the flow qualities of the concrete. It will also provide less laitance and increased concrete uniformity.

EQUIPMENT

The first item of equipment is the tremie pipe itself. Tremie pipes are usually 10 to 12 inches in diameter with a hopper attached to the top. The length must be sufficient to reach the bottom of the water and to allow for rise and fall of tides where applicable. The entire hopper and pipe usually has to be lowered and raised during the operation, so it is necessary to provide a crane or hoist for this purpose. The support for the assembly should be independent of the means of conveying concrete to the hopper because when concrete is dumped into the hopper the weight of the concrete will push the tremie assembly down. A good crane operator is, therefore, necessary to maintain the tremie assembly at the same elevation while the concrete is being placed.

Once concreting commences it is most important that the bottom of the pipe not be withdrawn above the concrete, since this causes loss of the tremie seal and can lead to voids, honeycombs, and excessive laitance. On very deep placements, the long tremie pipes must be raised as the concrete rises. For this reason most tremie assemblies are made in 10-foot sections which can be unbolted and removed one-by-one as the pipe is raised. A good watertight, quick-acting coupling must be developed for this purpose so that no water is introduced into the joints of the pipe. The pipe must also be strong enough to withstand the handling it receives, as well as any pressures from water currents.

Lastly, a plug must be made for the end of the tremie pipe to keep water out of the pipe when it is lowered. A wooden plug with a rubber gasket, attached with light wire, has proved to be one of the simplest and cheapest to make and use. When concrete starts to flow down the pipe, the weight of the concrete pushes out the plug (which may be recovered) and the concrete flows out to form a mound around the end of the pipe. This mound is the tremie seal which must be maintained throughout the operation.

The last points to consider are the batching plant, or source of concrete, and the method of conveying the concrete from the batching plant to the hopper which is usually out in deep water. The two general methods of furnishing concrete for a tremie project are:

1. Ferrying ready mix trucks from the shore to the project on a regularly scheduled basis.

2. Setting up a portable concrete batching plant on a barge moored alongside the cofferdam or caisson. This barge must be supplied with cement and aggregates on a regular basis by means of a barge ferry.

It is most important to keep the placing continuous and smooth. When there is a forecast of rough water or bad weather, the concreting operation should wait until the weather forecasts indicate sufficient clear and calm weather to enable the tremie job to be completed.

CONSTRUCTION TECHNIQUE

In designing the sequence of operations and deciding on equipment required, it is usually calculated that one tremie pipe will serve an area of about 300 square feet. The pipes are, therefore, usually spaced 15 feet on center, but this can vary depending on the thickness of the mat, the congestion of reinforcement, and the shape of the structure. The recent trend has been to increase the spacing because of the better flow afforded by the use of the proper admixtures.

Where it is not practical to set up sufficient tremie pipes to cover the whole area, it is possible to "leap-frog" the pipes ahead. However, the pipes should not be dragged through the concrete, and when taken out of the concrete, must be replugged with the wooden plug before being lowered again. When tremie concrete is being placed at great depths (70 to 80 feet or more), the empty pipe will become buoyant if the end is plugged. Therefore, when working at great depths, lower the pipe with the bottom open so that the water enters it. Then, before the concrete is placed, a plug called a "go-devil" should be pushed into the pipe ahead of the first load of concrete. The plug should fit tightly in the pipe. If it does not, it will rush through the pipe pushing the water ahead of it so rapidly that the water may scour the surface or displace the reinforcing. An inflated rubber ball makes an excellent "go-devil" and will float back to the top when released from the bottom of the pipe.

To maintain the tremie seal at all times, the pipe should be kept buried 2 to 5 feet in the fresh concrete, depending on the speed of the placing and the head of concrete in the pipe. To get flatter slopes to the seal, a deeper embedment is required. However, initial set of the lower concrete must not have taken place and, in this instance, a retarding admixture may be of some help.

When depositing the concrete from buckets into the hopper, the buckets should be opened gradually to provide a smooth continuous flow. It is bad practice to suddenly dump a bucketful into the hopper because this puts an impact load on the assembly, making it extremely difficult to control.

The delivery of concrete to the job should be timed so that there is never more than 5 minutes of delay in placing concrete in the hopper.

Tremie concreting techniques being used in the construction of a runway extension, LaGuardia Airport, New York.

If tremie concrete is being placed in cofferdam forms, the speed of the placing must be carefully adjusted to limit the pressures on the forms. Placement should proceed at 3 feet per hour to maintain safe form pressures of about 500 to 600 pounds per square foot. In this case a retarding admixture is a disadvantage because it permits a higher liquid head of concrete to be produced before initial set takes place. However, the higher cement content of the normal tremie mix often increases the temperature of the mass concrete so that initial set takes place in 1½ to 2 hours. Extra care must be taken in placing somewhat thin walls. Anchors or ties should be provided to prevent the forms from deflecting.

If the tremie concrete is being used as a foundation slab or a seat, it is desirable to finish the surface on which the superstructure is to sit. This can be done in two ways. A diver can screed the surface to remove laitance a few hours after the placement is completed, or it is possible to place sufficient tremie concrete so that the laitance will overflow the formwork and be lost, leaving sound concrete behind.

If tremie concrete is properly designed and properly placed, 28-day strengths should run in the 3,500 to 6,000 psi range. In addition to the advantage of perfect curing, no drying shrinkage can take place since the concrete remains in water. Also, since the concrete is placed under pressure, it is generally free from voids and honeycombs, is uniform in quality, and has a high density.

The slope of the surface of tremie concrete may vary from 1:3 to 1:12 with an average of about 1:6. In order to reduce the slopes it is necessary to place large masses as quickly as possible. This causes the flow to be more rapid and gives the concrete a better chance to level off.

Most of the problems or difficulties in placing tremie concrete are caused by the concrete plugging in the tremie pipe, followed by the loss of the seal. The plugs can be caused by the arching action of the concrete in the tremie pipe, delays in placing which permit the concrete to begin setting up, poor mix design, and leaks in the pipe which wash out the cement paste.

While it is possible to cure these problems, it is best to avoid them since the seal is lost each time this happens. And although the tremie pipe can be resealed by means of a "go-devil," there is always additional laitance formed in doing so.

SOME INTERESTING TREMIE PROJECTS

One of the largest and most interesting projects in recent years has been the Verrazano-Narrows Bridge, at the mouth of New York city's harbor. This suspension bridge has a clear suspended span of 4,260 feet. The towers supporting this span are supported by two caissons. The caissons were provided with 66 dredging wells, so that they could be sunk by excavating through these wells.

After the caissons were settled in their final resting place, at the bottom of the river, the dredging wells were cleaned out by rotating jets of water and by air lifts so that inspection could be made before placing the tremie seal.

A tremie seal was necessary at the bottom of the dredging wells to provide a uniform bearing over the entire area, and to support all the cutting edges and walls of the caisson. The 170-foot deep placement of tremie concrete on the Brooklyn side is one of the deepest tremie placings ever recorded. Due to the excessive length of the tremie pipe, the pipe was unbolted in its mid-section each time it was moved from one dredging well to another. It was also necessary to allow the pipe to be lowered open to reduce buoyancy. The "go-devil" type plug was used.

To place a 20-foot thick tremie seal at the bottom of these caissons, some 16,000 cubic yards of concrete was required at each caisson. The tremie seal was placed at a rate of nearly 100 cubic yards per hour.

In order to provide the concrete for this project, the contractor, Steers-Snare (a joint venture of J. Rich Steers and Frederick Snare Corporation) provided a floating batch plant on a barge adjacent to the caisson. Concrete was mixed in a pair of 3 cubic yard mixers and placed in the tremie hoppers by means of a bucket and chute.

The bridge was designed by Ammann & Whitney Engineers of New York city and built by the Triborough Bridge & Tunnel Authority.

Another interesting project was recently completed in Lake Ontario. In order to supply its Westerly water plant, Metro Toronto built an intake some 5,300 feet out into Lake Ontario. This intake shaft is connected to the shore by means of a tunnel which was driven under the lake bottom. In order to set the bell-mouth intake on a firm foundation, a tremie placement was made 60 feet deep below the surface of the lake. This job consisted of 1,200 cubic yards of tremie concrete. The area to receive the tremie concrete was a hole 20 to 24 feet deep blasted from the lake bottom. And in order to position the tremie pipe in this area, divers guided the pipe as it was lowered to the bottom.

The contractor, Anglin-Norcross Ontario Ltd., chose to use a shuttle service of transit mix concrete trucks. They were ferried out to the tremie site on barges.

The concrete used had a slump of 7 inches and was placed through four tremie pipes. The mix design used a water-reducing, set-retarding admixture to delay the setting time 7 hours. This helped to maintain very flat slopes for the final setting of the steel bell-mouth intake.

The engineers for this project were James F. McLaren Ltd. and H. G. Acres & Company.

Another unique and interesting project is the runway extension over water at New York's La Guardia Airport. In order to lengthen the runways at this airport, precast concrete decks supported on piles driven into the water were chosen. These piles were 16- to 18-inch diameter steel pipes made up in 50-foot sections and averaging 120 feet in length. The piles were driven from barges floating in the water and were afterwards filled with concrete and a spiral steel reinforcement. In order to fill the pipes to a point 10 feet below the mud line effectively, the tremie method of concreting was used. In this case the tremie pipe was 6 inches in diameter to permit its easy entry into the 16- to 18-inch diameter pipe piles. This method was used to avoid segregation of the concrete. After the pipes were filled they were capped, ready to receive the precast concrete beams and girders and finally the deck which forms the runway.

This project was built by a joint venture of Steers, Spearin, Tully & Gerwick. It was sponsored by the Port of New York Authority.

The main pier foundation of the huge San Mateo-Hayward bridge across San Francisco Bay is of special interest in that it used a patented pier design. This pier, patented by the Gerwick Company, consists of precast concrete units tied together with tremie concrete, thus eliminating the use of cofferdams. The present sections also serve as forms for the tremie concrete.

These projects show that properly controlled, properly engineered and properly executed tremie concreting can produce high-quality concrete, economically and more easily than any other method of underwater concreting.

PUBLICATION #C680247

TREMIE CONCRETE

Some useful facts about the preferred technique for placing concrete under water

Placing tremie concrete for a bridge on the Connecticut Turnpike.

Concrete is often placed beneath a water surface to seal cofferdams and caissons, to weight objects such as precast tunnel sections, and to construct numerous types of subaqueous foundations. Methods of placement on such projects include lowering the concrete in burlap or tarpaulin sacks, using special buckets to transfer the mix to the underwater floor, laying aggregate and then grouting it, and pumping concrete directly into place. These techniques have proved successful in meeting certain job requirements, but the most common and expeditious way to place large volumes of concrete to considerable thickness under water is the tremie method.

The word "tremie" comes directly from the French tremie meaning "hopper." Tremie concrete refers to placement by gravity feed from a hopper through a vertical pipe extending from above the surface to the underwater floor. As concrete flows from the bottom of the pipe, more is added to the hopper so that the tremie pipe is continuously charged with fresh mix.

The tremie pipe is constructed of extra heavy steel and usually has a minimum diameter of 12 inches. Smaller pipes can be employed, but any below 10 inches in diameter carry the risk of being plugged by the concrete.

A tremie pipe is generally lowered, raised and moved laterally by a derrick or a crane. It is possible to ride a tremie pipe in a hoist tower on the edge of a barge. It is also possible to mount a pipe on a framework spanning a cofferdam and control it with a winch.

The origin of tremie concrete is uncertain. There is some evidence of its use in the mid-19th century. Later tremie concrete was employed in the construction of the Detroit River Tunnel in 1906 and to construct a dry dock at Pearl Harbor between 1909 and 1913. Utilization of tremie pipes to place reinforced structural concrete is a somewhat recent development, furthered in great part by the construction of graving docks and dry docks during World War II. Twentieth century experience plus laboratory and field tests have indicated that tremie concrete properly used offers the following advantages: relative ease in rapidly placing large volumes of concrete at great depths; curing conditions that are excellent; avoidance of the need for dewatering before placement; and freedom from voids and honeycombing in the finished product.

The major aim in underwater concreting is to place the mix in its final position with as little disturbance as possible. A mix with sufficient slump to flow easily into place is needed. Excessive laitance is likely to result if too rich a mixture or too finely ground cement are used. Since employment of construction joints is not recommended, the concrete should be placed in one continuous pour whenever possible.

Tremie concrete need not be extra rich for if the pipe is handled properly there will be little cement loss. A 5 or 6 sack mix with a slump of from 5 to 7 inches has been found to work well. Both field and laboratory tests have shown that the addition of entrained air and a chemical retarding agent improves tremie concrete considerably, resulting in a smooth flow with good cohesion and a marked reduction of laitance and internal heat over ordinary concrete. Tests on ordinary concrete placed by tremie pipes indicated a 33.5 percent reduction in strength between the center and the extremities of the flow. Air entrained concrete with a retarding agent showed only an 8 percent difference. This type of concrete in field tests reported to the American Concrete Institute developed an average 7-day strength of 2,980 psi and an average 28-day strength of 4,620 psi.

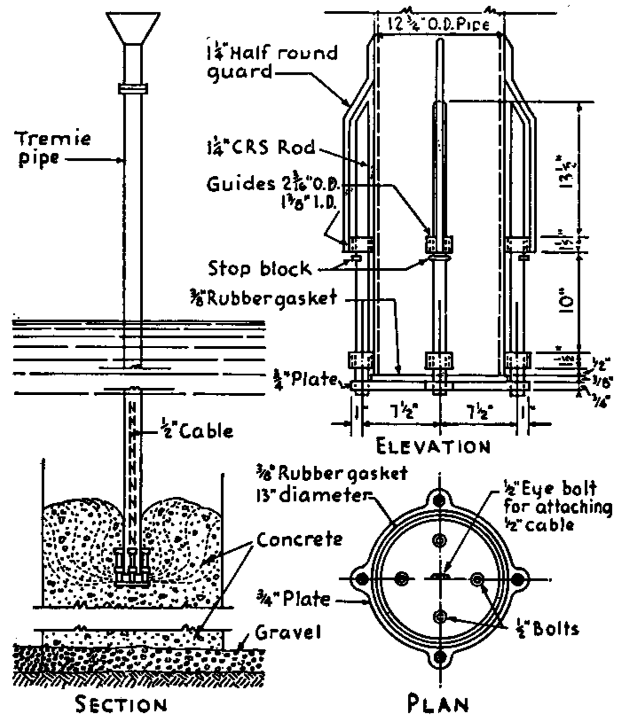
The horizontal flow of concrete under water will depend mainly on the depth at which the concrete is placed and the consistency of the mix. Concrete with sufficient head and a 5- to 7-inch slump will move as far as 100 feet from the tremie pipe. One pipe placed a third of the distance from one end and in the center transversely can make the usual bottom seal pour in a 35- by 90-foot cofferdam, leaving at the most only a few cubic yards of concrete to level off at the extreme end. One of the largest cofferdam placements of recent record occurred during the construction of the Delaware Memorial Bridge. A seal measuring 100 by 220 by 32 feet starting at a 72-foot depth was completed by 2 tremies in a continuous 172-hour casting operation. Tremie concrete of the proper consistency poured from one position will also flow around and encase steel H-piles driven in the bottom of a cofferdam, with no voids and no indication of leakage upon dewatering.

As concrete flows from the tremie pipe the end of the pipe is buried in the mass. Gradually the mix flows out toward the edges to fill the forms and as the concrete builds up, the pipe is raised sufficiently to keep its delivery end buried about 3 feet. The concrete around the end of the pipe seals it from the water and prevents aggregate segregation and washing away of cement. An important task with tremie concrete is to establish a seal before the initial pour.

Numerous devices have been used to seal the tremie pipe. They include the use of a burlap bag filled with straw, a wooden disk or plate held over the bottom of the pipe, and various kinds of mechanical valves.

A straw-filled burlap bag can be placed at the base of the hopper after the pipe has been bottomed. The weight of the concrete drives the bag down the pipe pushing water ahead. When the pipe is raised slightly to allow the concrete to flow the bag is pushed out the bottom and buried in the mix.

An objection to the use of a burlap bag as a seal maker is that it allows concrete to flow rapidly and without control down the tremie pipe and strike the underwater floor with considerable force. This action can scour and erode the floor and create turbulence. Sometimes the turbulence is great enough to damage forms. Turbulence can wash out cement, cause aggregate segregation, and damage concrete already placed should the seal need to be re-established. A burlap bag and straw also are foreign elements in concrete.



Details of tremie foot valve and section showing how valve distributes concrete under water. (Reproduced from ACI Journal by permission of copyright owner.)

Perhaps a somewhat better way to establish a tremie seal is to place a wooden disk or plate over the bottom of the pipe. The disk should be about 2 inches larger in diameter than the pipe itself and it should be fitted with a rubber gasket. As a rule a cable is attached to the disk to insure its recovery after the seal has been established.

The disk is placed against the bottom of the pipe and water pressure secures it while the pipe is lowered. The weight of the concrete introduced once the pipe is in place overcomes the water pressure and pushes the disk aside. Then the mix flows freely and forms a seal as it builds up. While an effective and fairly simple device to use, a wooden disk does carry some hazard of rapid delivery of concrete with the possibility of scouring and turbulence around the pipe opening. The use of a disk also requires complete dewatering of the tremie pipe to re-establish a seal.

A cone valve is one mechanical device that can be used to establish a tremie seal. It can be made from 1/4-inch plate with a transverse bar welded across the bottom in the vertical position and placed at the bottom of the tremie pipe. The top of the cone is cut off to create a one-inch hole through which a supporting and controlling cable is passed and fastened to the transverse bar. The cable is operated at the top of the hopper to open and close the valve.

The cone valve is closed and from 4 to 6 feet of concrete placed in the pipe before it is lowered. Once the pipe is bottomed the valve is opened to allow the mix to flow out. The use of a cone valve permits constant control of the rate of concrete flow and allows for relatively easy re-establishment of a seal whenever necessary.

Another mechanical device and one whose use requires more preparation than others is a rotary valve placed approximately midway in the pipe. A compressed air hose is connected to the pipe just below the valve. With the valve closed, the empty pipe is bottomed. Then compressed air is introduced into the lower portion of the pipe to force the water out. Once bubbles appear on the surface indicating that the pipe is free from water, sufficient concrete is allowed to flow from the hopper to slightly exceed the air pressure. The valve is then opened. The concrete forces the air ahead of it and in effect is lowered relatively gently on a cushion of compressed air.

Establishing a seal by the use of a rotary valve and compressed air offers several advantages. A gradual introduction of concrete to the floor avoids scouring and turbulence. At the same time foreign material is kept from the concrete, the need to recover a device such as a wooden disk is eliminated, and the possibility of malfunction of a device such as a cone valve is avoided. The major disadvantage is the need for special preparation of the tremie pipe.

The selection of a method to establish a seal will be influenced by job requirements and by experience. Regardless of the method chosen, the composition of tremie concrete will not usually vary.

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