The following is a report on the development of two unique and separate cofferdam systems used in the construction of the marine foundations for the I-205 Columbia River Bridge at Portland, Oregon for the Oregon Department of Transportation. The first of these two systems utilized interlocking H-pile 100 feet long to form a cofferdam 145 feet by 58 feet in plan and 100 feet deep. The second system consisted of two immense bell shaped steel forms. The larger of the two forms was 83 feet by 66 feet in plan, 62 feet high and weighed 450 tons. This form was externally stiffened for a designed hydrostatic head of 54 feet. Both forms were designed, except for the top 14 feet, to be set and stripped in one solidly welded unit. The supporting geological formation for the bridge foundations is the Troutdale, a cemented sand and gravel. This formation is at the ground surface on the Washington Shore and slopes downward to a depth of 115 feet below normal high water at about mid-channel. In this area the Troutdale formation is covered with a layer of fine to medium sand 90 to 100 feet thick. It was the variable depth of the Troutdale which determined the two types of foundations and the corresponding to the two cofferdam systems.

INTERLOCKING H PILE SYSTEM

The first two piers off the Washington shore, Piers 12 and 13, flank the main 600-foot navigation channel. Both of these piers were designed to bear directly on the Troutdale. The design depth of the foundation at Pier 13 was 100 feet below normal high water. Because of this extreme depth, it was originally designed as a concrete caisson. After the notice of contract award, a study was made to determine the feasibility of using a cofferdam approach. Again, due to the extreme depth, conventional sheet piling were ruled out primarily because of the numerous levels of bracing which would have been required for the hydrostatic head of 62 feet at Pier 13.

Two alternate sheeting systems were evaluated. The first of these was an interlocking pipe pile system offering a section modulus as high as 469 cubic inches per foot of wall compared to the 46.3 cubic inches for the highest capacity Z sheet pile manufactured. The second system was Arbed interlocking H-pile system manufactured in Luxembourg which offered a section modulus as high as 555 cubic inches. The final selection was the Arbed HZ-600-LA sheet pile with a section modulus of 243 cubic inches. (See Figure 1.) These high strength sheets required only the seal and one wale support point to resist the designed hydrostatic head of 62 feet. The final design used two wale frames, but the purpose of the top frame was to provide support during threading and driving of the sheet pile and to carry the wall loadings as struts were removed on the main frame to allow continuation of the pier shaft. (See Figure 2.)

Figure 1: Arbed HZ 600 LA Sheet Piling System
An additional advantage of the interlocking H pile over conventional Z pile is the closed pocket formed by the interlocking flanges. These pockets when filled with a silty sand mixture not only increased the water tightness of the cofferdam walls, but also increased the total dead weight of the cofferdam by 2,450 tons. This increased weight allowed a corresponding decrease in the seal concrete volume by 1,250 cubic yards. In order to ensure that this weight could be considered in the balance of forces on the seal, two steps were taken. First a concrete plug was inserted into each of the pockets and lowered down to the bottom of the pile where it wedged against the reinforced pile tips. This plug ensured that the weight of the sand fill was transferred to the sheet pile. The second step consisted of installing a vertical shear key on the inside face of each pile to insure the weight of the cofferdam and sand fill were transferred to the seal. The shear key was designed so that the seal could not move upward relative to the sheet pile, but the sheet pile could move upward relative to the seal. This allowed pulling of the sheet pile after the pier was completed.

The use of only one load carrying wale frame above the seal resulted in extremely high loadings on the lower wale frame. The wales consisted of double W-36 x 230 beams stitch welded along both flanges to form a box section 36 inches by 32 inches and carried a design loading of 26 tons per foot of wall. This section not only allowed utilization of conventional rolled shapes but provided a stable section against any rolling tendency during the driving of the sheet piles. The struts consisted of 30 inch diameter pipe with a wall thickness of .750 inch and carried a maximum design loading on the diagonal struts of 700 tons per strut. The entire bracing system when assembled weighed 350 tons, covered an area 145 feet by 59 feet and stood 24 feet high.

The initial step in the cofferdam construction after pre-assembly of the bracing frame, was to float the frame into position, and lift it clear of the barge using a 600 ton capacity catamaran gantry barge. With the bracing frame suspended by four load blocks, four 36-inch diameter spud piles were driven, and the load of the bracing frame was transferred to the piles. Threading and driving of sheet piles followed, using a Toymomenka VM2-25000A vibratory hammer. (See Figure 3.) The double interlocking system with an interlock threaded on each flange of the H section created initial threading problems due to variations of ± ¼ inch in the flange spacing at the interlock. However, the sheets were finally threaded, and driving progressed in a clockwise direction around the cell, driving each sheet 10 to 15 feet before progressing to the next.

During the third driving cycle the ground had become so compacted ahead of the piles that further attempts at driving resulted in melting of the interlocks between the piles. The piles were finally taken to the Troutdale by using a combination air and water jet down one of the pockets a few pockets ahead of the pile being driven. The jet was allowed to penetrate below the tips of the H-piles and loosened the sand so effectively that whole sections of wall began dropping as the vibratory hammer was turned on.

Figure 3: Threading Sheet Pile at Pier 13
The remaining steps in the cofferdam construction were similar to conventional cofferdams except for the size. (See Figure 4.) The seal at Pier 13 as an example, was 38 feet deep, required 11,500 cubic yards and took 72 hours to complete. Concrete for the seal pour was supplied by both a floating batch plant and a back up system of barge mounted concrete trucks. The floating batch plant was mounted on a barge 275 feet by 60 feet by 18 feet deep and equipped with a concrete plant capable of producing 180 cubic yards per hour. Mounted on the bow of the barge were two 5-inch diameter concrete pumps equipped with 103-foot articulating booms. (See Figure 5,6 and 7.)

Upon completion of the seal and footing, the shaft was poured in lifts of 10 feet up to the underside of the bottom struts. At that point, the bolts connecting the struts to the wale frame were removed and the cell was flooded to the surrounding river elevation. After allowing the disconnected struts to float to the surface, the cell was again watered to a point just below the last construction joint in the shaft, and the next lift on the shaft was completed. In this manner, the need for struts passing through the shaft was completely eliminated. This step was repeated on the top wale frame, as the shaft pour was completed to the underside of the top struts.

The transfer of the cofferdam frame from Pier 12 to Pier 13 involved increasing the plan dimensions of the cell by 4 feet. This was accomplished by bolting 24-inch by 24-cinch timbers to the outside of the wale frame. Another change made at Pier 13 was the method of pouring the seal. At Pier 12, the pour started in the middle of the cofferdam and worked towards each end. At Pier 13, the seal was started with one end and progressed to the other. This second method with only one direction of flow resulted in a much more controllable seal pour and a more even surface on the completed seal.
concrete. This method had been successfully used to construct the foundations for the Richmond-San Rafael Bridge.

The revised method of construction proposed by the Contractor, provided essentially the same pier but arrived at by a different means. The new concept was executed in six (6) stages illustrated in Figure 9. The pier site was first pre-excavated as originally designed. Piles were driven and cut off under water. Immediately after pile driving a steel form and reinforcing cage were positioned over the top of the piles and lowered to grade. The bottom 9 feet of the form was then filled with tremie concrete, sealing the bottom of the form and encasing the driven piles. After curing for about 60 hours, the interior of the form was unwatered allowing access to the top of seal. A reinforcing mat was placed on top of the seal and a void form 10 feet in diameter with reinforcing cage was set vertically inside the form. The next step was to place the remaining structural concrete from top of seal to a point 2 feet above normal high water. The final step was to stripe the form in one solid piece. These steps were the general concepts developed prior to bid opening. After notice of contract award, work began on converting the concepts into the reality of functional systems and equipment.

The forms were built as single piece cofferdam designed for a hydrostatic head of 54 feet without any internal bracing. The forms, unlike conventional cofferdams because of their sloping faces, were required to resist the hydrostatic loading in both the horizontal and vertical direction.

**Bell Pier System**

The second cofferdam system was used on the remaining 26 piers, double piers 14 through 26. The Troutdale formation at these piers varies from 105 to 115 feet below normal high water and is covered with a layer of dense to medium dense unconsolidated sands 90 to 110 feet thick. These piers were originally designed as pile supported precast bells. The original design called for setting a bottom precast segment in a pre-excavated hole. The bottom slab of this segment was to be blocked out and used as a template for driving the 50 to 100 H piles at each pier. Once the piles were driven, cut off, and the block outs grouted, three additional precast segments were to be stacked on top of the first. After sealing the joints between each segment, the interior of the bell was to be filled with tremie
STAGE 1
- Pre-dredge pier site
- Install and cut-off piles

STAGE 2
- Pre-assemble pier form
- Pre-assemble reinforcing cage
- Install cage inside pier form

STAGE 3
- Position form over piling
- Drive temporary spud piles

STAGE 4
- Lower form to grade
- Transfer weight of form to spud piles

STAGE 5
- Pour tremie seal
- Dewater form and place bottom reinforcing mat

STAGE 6
- Pour remaining concrete in dry
- Strip form in one piece
- Remove spudded support frame
The skin of the forms was 3/8 inch plate stiffened with 8 x 4-inch vertical angles. The angels were in turn supported by eleven horizontal trusses up to 7 feet in depth, banked perpendicular to the sloping faces of the forms. These trusses formed rings circling the forms and were stabilized by twelve vertical trusses along the form perimeter. The larger of the two assembled forms was 83 feet by 66 feet in plan, stood 62 feet high, and weighed 450 tons including support frame. This weight plus the 100 tons of reinforcing cage and spud piling brought the total required lift to 550 tons.

Prior to setting the form it was first necessary to install a 72-foot high reinforcing cage inside the 62-foot high form. (See Figure 11.) In order to eliminate the two week cage fabrication time from the pier construction cycle, it was necessary to pre-assemble the cage. This meant the bell shaped cage had to be installed from the bottom side of the form. Rather than build a gantry crane with a head clearance of over 130 feet, it was decided to sink the completed cage 40 feet below the river surface, and allow the floating gantry to position the form over the reinforcing cage. Once over the cage the form was lowered and the reinforcing cage raised to meet the form.

The sinking of the cage was performed by building the cage on a steel deck suspended between two pontoons. The steel deck was supported by four cables running to hydraulic winches mounted on the pontoons. The deck was also fitted with four vertical pipe columns which traveled through roller guides on the support pontoons. The purpose of the pipe and roller guides was to insure vertical alignment of the cage in the 3 feet per second river current.

After the cage was fitted up into the form, the reinforcing steel was secured to the face of the form with U-shaped clamps passing around the vertical bars and in turn bolted through the skin plate. The skin plate at these locations was backed with a water tight steel pocket to allow removal of the clips during the pouring of the structural concrete.

Before installation of the reinforcing cage and form, 50 to 100 H piles were driven into the pre-excavated pier site. The pile driving specifications required the piles to be positioned within a tolerance of ± 6 inches at a point approximately 40 feet below the river surface. This specification was met by installing an accurately placed template at a depth of 40 feet and by providing a highly accurate and stable pile driver at the surface.

The template consisted of an adjustable pipe ring positioned two feet above the pile cut off point. The ring was supported by a trussed frame held in position by four 24-inch diameter spud piles. The template was positioned by triangulation from shore using two theodolites equipped with wild DI-35 Distomats.

The heavy lift requirements of the bell pier construction were met by designing of a 600-ton capacity catamaran gantry crane. (See Figure 11

and 12.) Support of the straddle lift gantry was provided by two barges 104 feet by 30 feet by 10 feet deep, one under each framed tower of the gantry. Vertical clearance under the cross beams was 80 feet off the water, and horizontal clearance between the barges was 74 feet.
The design of the pile driver insured accurate positioned capability by providing finite articulation of the leads without moving the barge. This was accomplished by using independent hydraulic drives and controls for each of the basic motions of the leads.

The next step consisted of positioning the form, reinforcing cage, and support frame over the required pier location, lowering the entire load 58 feet to the river bottom over the top of the pre-driven piles and finally, transferring the entire load from the floating gantry to the support frame and four 36-inch diameter spud piles. It was necessary to use the separate support frame to allow the floating gantry to work with both forms. The separate support frame also provided greater positioning accuracy and stability during the seal pouring operation. The form was suspended from the support frame by four cables connected at mid-height on the form and was fixed into position by four arms jacketed to the support piles. These positioning arms were fitted with eight hydraulic rams which allowed the entire form to be repositioned within a one foot radius of its initial set position. This feature allowed a precise positioning of the form once the form had been transferred from the floating gantry to the pile supported frame.

To ensure that this did not happen, the pier site was over excavated 2 to 3 feet and a layer of 4-inch minus rock was placed. This rock layer also helped prevent contamination of the relatively thin tremie seal with the loose river bottom sand.

And additional precaution taken to insure the integrity of the seal was the installation of a 2-foot deep cutting edge attached to the bottom of the form. It was essential that the outer edges of the form be sealed tight against any water flow. The potential for this flow existed because of possible unevenness of the river bottom and also because of the possibility of scour under the edge of the form. The cutting edge eliminated both of these concerns.

After the form was in position, a single centrally located tremie pipe was used to place the 9-foot deep 1,300-cubic yard seal. The rapid pour rate and on site batching capacity of the floating batch plant helped provide a free flowing tremie around the forest of H piles. (See Figure 13).

![Figure 13: Dewatered Bell Pier and Top of Tremie Seal](image)

During the preliminary planning of the bell pier system, it was feared that as the form was lowered closer to the river bottom, the immense shape of the form would cause the river current to increase sharply at the lower edge of the form and progressively scour away the sand from below the form. After dewatering of the bell pier form and placing of the bottom reinforcing mat and void form, the remaining 2,000 cubic yards of structural concrete were placed in the dry.

The final stage in the sequence of pier construction was the removal of the bell pier form. The forms, except for their top 14 feet, were one solidly welded unit. The stripping step was the most critical of the entire bell pier operation. The bonded area of form to concrete was over 10,000 square feet.

From a deflection analysis it was reasonable to expect the form to move away from the face of the
completed pier. During the unwatered stage of construction, the form was deflected inward under a maximum hydrostatic pressure of approximately 3,000 pounds per square foot, and the only outward pressure during the casting operation was that created by the fresh concrete which, under a pour rate of 3 to 5 feet per hour, produced a maximum pressure of approximately 700 pounds per square foot. Once the pier was cast and water allowed to seep back between the steel skin and the concrete, the form was expected to rebound from the initial deflection.

There were four basic steps taken to ensure that the form would come free of the pier. The first was to use a minimum sloping surface of 1 horizontal to 6 vertical. In order to meet this criteria, it was necessary to isolate the top 14 feet of vertical form and allow this bonded area to break free separately. The second step was to grease the entire surface of the form with a special grease used in the launching of ships. This grease was reapplied after every pier casting. The third step was to provide 140 hydraulic ports on 8-foot centers over the interior face of the form. The purpose of these ports was to break the bond between the steel form surface and the face of the completed pier. This was accomplished by inducing water at a pressure of 80 psi into a smaller cylinder which jacked the face of the form away from the pier in a small localized area. At the same time, the pressurized water was allowed to fill the localized void and progressively enlarge the bond free surface. The fourth and final precaution was to provide excess lifting capacity over that required to lift the dead weight of the form. The floating gantry was designed for a maximum lift of 600 tons. The jacking system on top of the spud piles used for final grade adjustments of the form had a designed lift capacity of 600 tons, and finally two 800-ton jacks were available for setting on top of the completed pier for jacking against a reaction beam connected to the form. These three lifting systems had a combined capacity of 2,800 tons to lift a form and frame which had a maximum dead weight of only 450 tons.

On the first pier to be stripped, it became evident the excess lifting capacity would not be required. The form lifted free of the pier with less than 10 tons over the dead weight of the form. The following 25 piers in a like manner were stripped without the use of the excess lift capacity.

The 26 bell shaped piers were cast over a period of 18.5 months utilizing two bell pier forms. The average cycle time for each pier was 37 calendar days including all weather and mechanical delays. This relatively fast cycle time per pier was attributable in part to three factors. First, the installation time for reinforcing was separated from the cycle time for each pier by pre-fabricating the reinforcing cage. Secondly, the multitude of construction steps associated with conventional sheet pile cofferdams were replaced with the single step of the setting the form. And, finally, the steps of forming the footing and column were completely eliminated and the two concrete placing steps were combined into one.

In addition to the advantages of reduced construction time, the bell pier system offers the potential for substantial reductions in seal concrete volume. For the I-205 Columbia River Bridge, the bending strength of the seal determined the required seal thickness in the bell piers. For cofferdams with seals designed to provide dead weight against hydrostatic uplift of the whole cofferdam, the bell pier system can greatly reduce the required seal concrete by reducing the total uplift on the cofferdam. This can be accomplished because of the inward sloping faces of the bell pier cofferdam which reduces the cofferdam's displaced volume in water without reducing the cofferdam's base area or height.

The bell pier system also offers the potential for adaptability to greater water depths. The bell pier system has performed at a depth of 62 feet using a rectangular shaped form stiffened with heavy trusses. This same system could be used at depths in excess of 100 feet without the use of heavy stiffening trusses by designing the piers and cofferdam forms with circular across sections allowing the cofferdam walls to carry all hydrostatic loads in compression.
Conclusions

Both the interlocking H pile cofferdam system and the bell pier cofferdam system proved to be sound methods of pier construction. All 28 marine piers were safely constructed to required specification within the schedule 1,000 calendar days and within the owner’s original estimate. Both systems offer the potential for savings on future marine foundation.