Deep Foundations

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2021 Outstanding Project: Retention Systems for Hydroelectric Dam

COVER STORY

2021 OPA Winner: Hydroelectric Dam Conversion With Diaphragm Walls, Retention Systems

Completed upstream diaphragm wall, intake structure (left) near existing structures

Converting Red Rock Dam in Iowa to produce hydroelectric power required extensive water- and earth-retention systems to maintain the integrity of the existing flood control dam. Construction challenges included excavations up to 70 ft (21 m) deep on the upstream and downstream sides of the existing dam and modifications to convey water from the reservoir to a new powerhouse, which ultimately amounted to "putting holes in a perfectly good dam." The extensive retention systems for the Red Rock Hydroelectric Project that received DFI's Outstanding Project Award (OPA) for 2021 included an unusually high cantilevered diaphragm wall to retain a permanent cut through the embankment dam.

Project Elements

The U.S. Army Corps of Engineers (USACE) constructed Red Rock Dam on the Des Moines River near Pella, Iowa, in the 1960s — creating Lake Red Rock, the largest reservoir in Iowa. The USACE dam is an earthfill structure with a chimney filter and blanket drain. It features a central concrete control structure consisting of 13 adjoining monolithic segments that house 14 sluice gates and 5 radial tainter gates. The dam has an overall length of 6,260 ft (1,908 m) and a height of 110 ft (34 m). A county highway traverses the length of the dam along the crest. Western Minnesota Municipal Power Agency and Missouri River Energy Services developed the hydroelectric project to diversify their electric generation portfolio. The main project elements are:

- A cantilevered concrete diaphragm wall that retains the integrity of the embankment dam along the side of a new intake channel for water entering the hydroelectric plant. The 69 ft (21 m) high diaphragm wall is one of the tallest of its type in the world.
- A second concrete diaphragm wall, which serves as a cutoff wall along the axis of the embankment dam.
- The new intake structure, which has emergency-closure gates and is founded on drilled shafts.
- Two 21 ft (6.4 m) diameter steel-lined penstocks (pressure conduits) that convey water through the dam to a powerhouse.
- Two vertical Kaplan turbine-generator units, located in the powerhouse.
- A substation on the upstream side of the powerhouse connecting to a buried transmission line.

The intake, penstocks and powerhouse were constructed next to the existing dam's spillway, where the embankment fill wraps around the end of the concrete gravity section.

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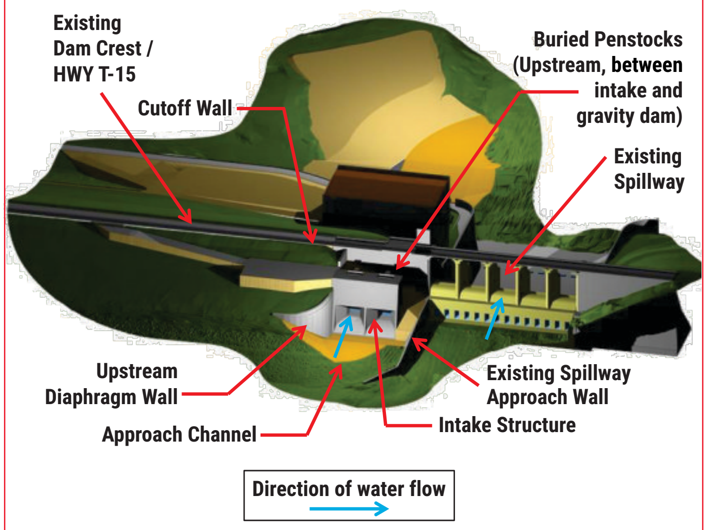
Dam Conversion

Constructability and dam safety were the main technical challenges for the project team that included Stantec as the engineer. The new hydroelectric facilities had to be constructed within the body of the existing dam while avoiding any impact to active flood control operations.

Design of the project began in 2010 with a feasibility study, followed by preliminary design and a geotechnical investigation program. Detailed design, including of the temporary works (e.g., cofferdams and retention systems), began in 2012. Although the construction contract was awarded in 2014, high water levels caused delays that meant substantial completion occurred in October 2020.

Cofferdams: Constraints were placed on the design of the upstream cofferdam due to its proximity to the dam's spillway and large fluctuations in the reservoir level. A 95 ft (29 m) high cofferdam extending 40 ft (12 m) above the normal reservoir level would have been required to ensure year-round protection of the intake structure and upstream penstock construction. Such a cofferdam was considered impractical and unrealistic for construction. Ultimately, the cofferdam for the intake structure and upstream penstock construction was designed to provide 8 ft (2 m) of protection above normal reservoir levels, which allowed extended periods of construction, but necessitated flooding of the upstream work when water levels were elevated.

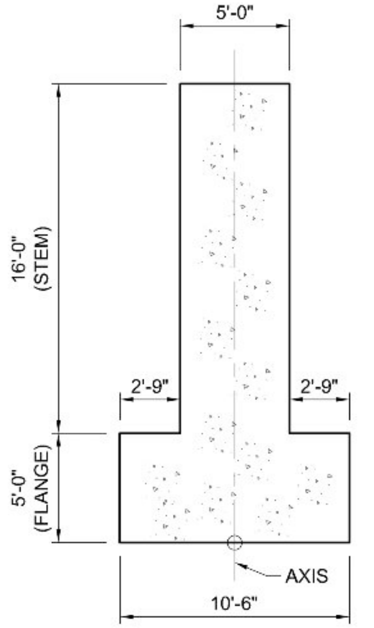
Final Design - Upstream Project Features



The upstream cofferdam consisted of a concrete work platform constructed on the sloping face of the dam and founded on steel piles. Lightweight concrete along with pre-excavation into the slope were used to minimize applying new loads to the dam's existing spillway approach wall. The temporary excavation support walls for the intake structure excavation and upstream penstock excavations formed the seepage cutoff.

The powerhouse construction area located at the downstream toe of the dam was protected by a cellular cofferdam founded directly on rock. This cofferdam was designed to provide protection against a 100-year event. Since the cellular cofferdam was founded on a unit of friable weathered sandstone, weak and fragmented rock was removed with an excavator prior to constructing the cells. A concrete base seal was placed to address the potential for the rock foundation to erode when subject to under-seepage across the base of the cells, and to seal potential gaps below the sheet piles due to the uneven rock surface.

Diaphragm Walls: The upstream diaphragm wall along the side of the new intake channel permanently supports a 69 ft (21 m) tall cut in the embankment dam. It was designed as a cantilevered wall without tieback anchors to avoid the potential for hydrofracturing or otherwise damaging the core of the embankment dam during anchor installation. The wall was effectively designed to minimize deflections and thus reduce the potential for related cracking of the clay embankment. It was constructed using abutting T-shaped elements up to 130 ft (40 m) tall. These heavily reinforced elements included 5 ft (1.5 m) wide stems that extended 16 ft (5 m) into the embankment from the back of the 5 ft (1.5 m) thick face of the diaphragm wall.



T-shaped panel geometry

Guide wall for upstream diaphragm wall construction

The stem length was established by striking a balance between the need to increase the moment arm of the structural section and the practical limits of slurry trench construction. The depth of the upstream diaphragm wall was iteratively established to minimize deformations. The final height of the most heavily loaded section was 130 ft (40 m), and included a 35 ft (11 m) rock socket.

Bedrock at the site consisted of dolomitic and argillaceous shales overlain by alternating beds of limestone and sandstone with unconfined compressive strengths ranging from approximately 3,000 to 9,000 psi (21 MPa to 62 MPa). Borehole pressure meter testing was used to measure the in situ modulus of the bedrock, which was critical for design of the wall.

The construction sequence for each T-shaped element required three overlapping excavation passes, or "bites," that were nominally 10.5 ft (3.2 m) long by 5 ft (1.5 m) wide to achieve the design geometry. The average verticality achieved for the excavation was 0.38%, using a combination of clamshell and hydromill excavation methods through soil and rock, respectively.

The diaphragm wall reinforcing cages weighed up to 90 tons (82 m tons) each, with much of the reinforcement at the end of each element's long stem. A 4,500 psi (31 MPa) tremie concrete mix with an initial set time of 16 hours and negligible bleed was developed for the extended duration that was required to place concrete for each T-shaped element.

The heavily reinforced T-shaped cantilevered elements eliminated the need for anchors to support the diaphragm wall. In addition to retaining the embankment dam along the side of the new intake channel, the wall was also utilized for temporary excavation support during construction of the intake structure and upstream penstocks.

To address risks associated with the intrusive excavations into the existing dam, a second diaphragm wall was constructed along the center line of the embankment. This 5 ft (1.5 m) thick wall extends 100 ft (30 m) off the end of the dam's concrete gravity monoliths and was designed to prevent potential excavation-induced cracking of the embankment dam from propagating through the dam (upstream-downstream). The second wall also mitigates against the potential for internal erosion of the soil due to seepage that can occur along such features.

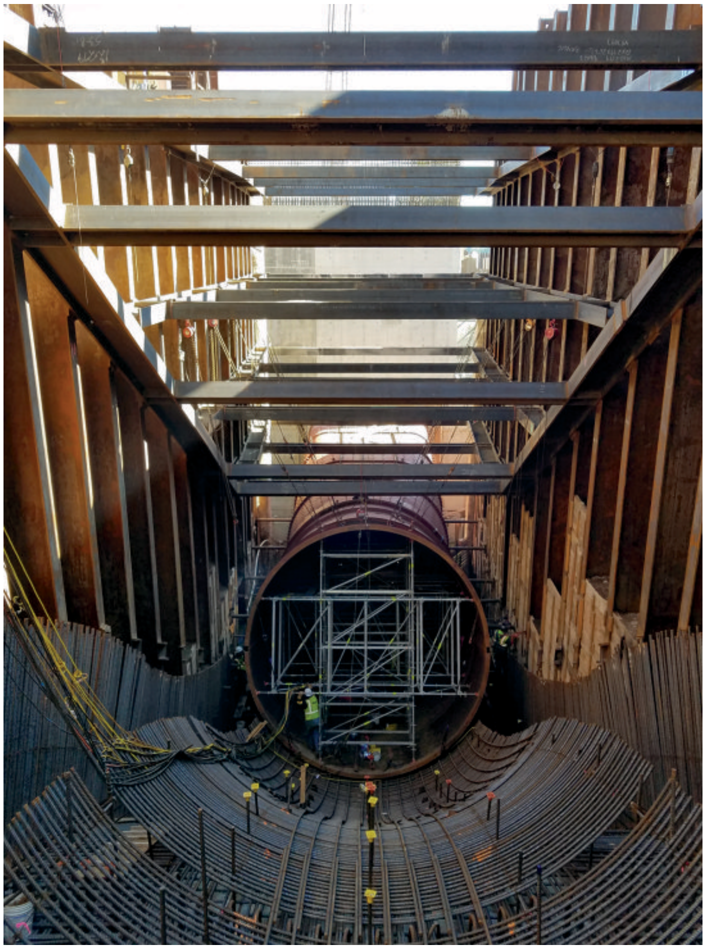
Deep Excavation Design and Analyses: The construction of the permanent works would require several excavations into the existing dam and its foundation in immediate proximity to the existing dam's spillway.

The design for the excavation support systems considered differential loading due to the embankment dam slopes and minimized deformations to maintain the integrity of the existing dam during construction.

A nonlinear staged three-dimensional finite element analysis was performed to design the excavation system for the intake structure excavation, and to confirm that the stability of the existing spillway approach wall would not be negatively impacted by the excavation. Similar analyses were conducted for the two downstream penstock excavations, which extended up to 70 ft (21 m) deep and consisted of internally braced *combi-walls* (combination walls composed of interlocked steel beams and sheet piles).

The excavation support was designed for the 2H:1V (2 horizontal to 1 vertical) embankment cross-slope acting across the penstock excavations. The bracing arrangement for the downstream penstock excavations had to accommodate the installation of 21 ft (6.4 m) diameter steel liners. This required an open area up to 30 ft (9.1 m) high and wide at the base of the excavation, which was accomplished by installing temporary intermediate struts and then removing those struts after the lowest level of struts along the bottom of the excavation were installed. The irregular geometry and staged construction were incorporated into the finite element modeling that was used to design the penstock excavations.

An anchored secant pile wall was designed to retain the downstream slope of the dam for the powerhouse excavation. This wall was designed to minimize deflections that could induce potential cracking in the embankment, and thus effectively had to be designed for at-rest earth pressures instead of active pressures.



Fall 2017 steel liner installation into penstock

Secant pile wall for powerhouse construction (at front), with diaphragm wall cage being lifted for upstream placement (background)

Due to the intrusive nature of the large excavations, the designs needed to consider construction staging to reduce potential impacts to the dam's integrity and maintain dam safety throughout construction. As a result, construction sequence drawings were developed to prescribe the upstream and downstream work. The construction sequence included coordination with the design of the braced excavations, cofferdams and other temporary structures. The sequence defined by those drawings became part of the design criteria for the excavation support systems and the basis of load cases for design of the permanent structures.

Construction

Excavation for the 7 ft (2.1 m) deep braced intake structure was supported by the upstream diaphragm wall along the embankment dam side of the excavation. The other three sides were supported by 5 ft (1.5 m) diameter secant pile walls. The primary and secondary piles were both reinforced. The piles were keyed into rock along the upstream and downstream sides of the excavation and notched into the backside of the existing spillway approach wall along the spillway side of the excavation. The intake excavation was braced by steel walers and pipe struts. The struts were arranged to avoid interfering with concrete forms for the water passages through the intake structure.

A differing site condition consisting of cobbles within the embankment fill was encountered during installation of the penstock combi-wall. The project team modified the combi-wall system to incorporate elements of a traditional lagging wall, and deep soil mixing was locally used to provide a cutoff so that progress could continue.

The upstream side of the powerhouse excavation was formed by a 63 ft (19 m) high anchored secant pile wall, which retained the downstream slope of the dam above a 40 ft (12 m) high rock cut. The rock anchors for this wall were installed at a 45-degree angle to avoid encroaching on the concrete gravity dam monoliths and the impervious fills that wrap around the end of the monoliths.

Treatment of Solutioned Gypsum Deposits: Prior to the rock excavation for the powerhouse, grouting was performed around the perimeter of the excavation site, primarily to strengthen the rock mass but also to reduce seepage inflows during construction. For much of the perimeter, the rock was fairly tight, and grout takes were relatively low. However, for a 160 ft (49 m) extent along the land-side of the excavation, extensive grouting was required to treat a 2 to 5 ft (0.6 to 1.5 m) thick zone characterized by artesian flows from grout holes. The flows were on the order of 20 gallons per minute (gpm, or 75 L/min) or higher from a voided zone in the rock that was partially filled with sand, clay and rock fragments. The voided zone was assessed to have been created by a previously undetected water-soluble evaporite (gypsum anhydrite) deposit.

Communication was observed between widely spaced grout holes during drilling in this area, indicating that there were indirect hydraulic connections in rock across distances of 50 ft (15 m) or more. Despite the large grout takes, return was seldom seen through neighboring grout holes, even when closely spaced.

The treatment of this solutioned zone ultimately entailed a combination of thick cement grout and polyurethane grout, with holes spaced as close as 18 in (45 cm) on-center; two additional rows of grout holes were required for closure in this area prior to commencing rock excavation for the powerhouse.

The observed sequences of pressure increase and release during grouting indicated that the grout was moving and/or compacting soil in the voided zone. Upon excavation, a 6 to 9 in (15 to 23 cm) seam of grout was observed in the excavation wall on the top of an approximately 18 to 24 in (45 to 60 cm) layer of soil. It appeared that the grout increased the density of the soil, with the overlying limestone acting as a confining roof above the zone.

During rock excavation, angled drain holes were drilled from the excavation face down into the voided horizon to relieve water pressures behind the grout prior to excavating through the zone. Many of the drain holes produced little to no flow. However, some had outflows up to 20 gpm (75 L/min), which flowed throughout excavation. The grouting program and drains installed during excavation were effective in controlling and monitoring the seepage flows.

Controlled Blasting: Drill and blast rock excavation for the powerhouse and tailrace channel was performed within an area protected by the downstream cofferdam after overburden excavation and consolidation grouting were completed. Approximately 26,000 yd^3 (19,900 m^3) of rock was excavated to a depth of approximately 40 ft (12 m) below the foundations of the existing spillway stilling basin wall, cellular cofferdam and anchored secant pile wall. Given the close proximity of the rock excavation to these structures, blasts were designed to achieve peak particle velocities less than 2 in (5 cm) per second and measured at multiple points around the excavation. After a successful test blasting program, blasting was successfully performed within 5 ft (1.5 m) of these structures by utilizing blast control measures such as added line drilling, boosters, reduced burden and spacing and lower pounds per delay.

The excavated rock walls were generally observed to be undisturbed by the blasting methods. Where shotcrete was placed to protect the weathered upper sandstone unit, it was similarly undisturbed by blasting. After excavation, the patterned rock bolts originally specified for excavation support were reduced to spot bolting for much of the excavation to take advantage of the quality of the vertical faces and favorable joint spacing and orientation.

Dam Safety Monitoring: A surveillance and monitoring program was used to evaluate the performance of excavation support systems, cofferdams and the existing dam during construction. By combining different instrumentation — including survey points, inclinometers, piezometers, pressure cells and strand load sensors — readings could be evaluated in multiple ways and compared with anticipated behavior.

Conclusion

The Red Rock Hydroelectric Project on Iowa's Des Moines River presented several unique challenges in the design and construction of a new hydroelectric facility within and through an active flood control dam. The potential dam safety ramifications necessitated a series of sophisticated design analyses, a range of specialty geotechnical construction methods and a robust dam safety surveillance and monitoring program – along with teamwork and coordination during construction – to enable this unique renewable energy project.

With the completion of the hydroelectric project in 2020, the dam now provides up to 55 MW (55,000 kW) of clean, reliable power to the surrounding communities and will generate approximately 178,000 MWH (178,000,000 kWH) annually.

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Downstream view of completed powerhouse, to right of spillway