CELLULAR COFFERDAMS AS PERMANENT HYDROPOWER DAM STRUCTURES

Simon Heru Prassetyo, PhD[1]
Marte Gutierrez, PhD[2]

ABSTRACT

This paper presents the results of a comprehensive study on the potential use of cellular cofferdams as basis for the design and construction of water retaining structures to sustainably and cost-effectively harness hydropower. Previously, cellular cofferdams have been widely used mainly as temporary water exclusion devices to permit dry construction of in-water structures such as dams, locks, bridge footings and piers, and hydroelectric power plants. Design and construction requirements for cellular cofferdams are less stringent than for hydropower dams. To make cellular cofferdams suitable for permanent hydropower use, different design concepts that utilize cellular cofferdams as the main or core element of the water-retaining dam structure are proposed. One particular key design concept is the so-called “dry construction technique” in which the granular fill in cofferdam cells and the downstream berm are permanently kept dry in contrast to the wet construction technique for temporary use of cellular cofferdams. The viability of the proposed permanent cellular cofferdam design concepts is demonstrated using well-established structural and geotechnical design procedures and computational modeling. The improved performance of the proposed design concepts, particularly in combination with the dry construction technique, show cellular cofferdams have the potential to be used as basis for the construction of permanent hydropower dam structures that are versatile, with less impact on the environment, and will cost less to build than conventional hydropower dams.

INTRODUCTION

Cellular cofferdams are temporary constructions consisting of interlocking steel-sheet piling driven as a series of interconnecting cells. The cells may be of circular type or of straight-wall diaphragm type, and the space between lines of pilings is filled with sand, gravel, crushed rock, concrete or other filling materials. External forces and water pressures are resisted by the weight of the cofferdam and by embedment of the cells and sheet steel piles into the ground. Cellular cofferdams have been built for different applications in dimensions up to a height of 100 ft (33 m) and maximum diameter of each cell can be as much as 90 ft (30 m). If cellular cofferdams can be adapted to permanent hydropower use, they have several attractive features (i.e., rapid construction and removal, low cost, low environmental impact, and adaptability to different field and geological conditions) that can be exploited in the design and construction of the next generation of sustainable hydropower dams.

[1] Colorado School of Mines, Golden, CO 80401, simon.prassetyo@gmail.com
[2] Colorado School of Mines, Golden, CO 80401, mgutierr@mines.edu

According to the research conducted by the Oak Ridge National Lab (2015), even though 2,200 hydropower plants have been in use to supply about 7% (80 GW) of all U.S. power generating need, there remains up to 60 GW of untapped hydropower potential that can be developed. However, development of the new potential sites entails several environmental, economic and technical challenges due to new and tougher regulations, societal reluctance to accept new hydropower constructions, and more demanding field conditions. To foster the development of new hydropower generation volume in the U.S., new technologies are required for cost-effective, environmentally sound hydropower systems that can be rapidly constructed, modified and decommissioned.

One potential way to foster the development of new low-cost and sustainable hydropower generation is to make cellular cofferdams suitable and adapted for permanent hydropower use. With their versatility in terms of speed of construction, low cost, ease of removal, and applicability to a wide range of conditions, cellular cofferdams have the potential to be adapted and used as the main component for the construction of future innovative hydropower dams. Cellular cofferdams have been widely used as temporary water exclusion devices to permit dry construction of in-water structures such as dams, locks, bridge footings and piers, and hydroelectric power plants (Figure 1). Nevertheless, cellular cofferdams have been very rarely used as the main permanent structure for hydropower dams. Consequently, design and construction requirements for cellular cofferdams are less stringent than for hydropower dams. In addition, there are risks and challenges associated with using cellular cofferdams as hydroelectric dams, particularly with respect to failure during flood events. The main hazard involves the potential that a flood exceeds the design flow and results in overtopping and failure of the dam. Other long-term design issues are failure of the foundation (i.e., sliding, overturning or bearing capacity), excessive seepage under the dam or through the cellular cofferdam fill, scouring of the foundation, corrosion of sheet piles, and structural failure of the sheet piles, supports and connections.

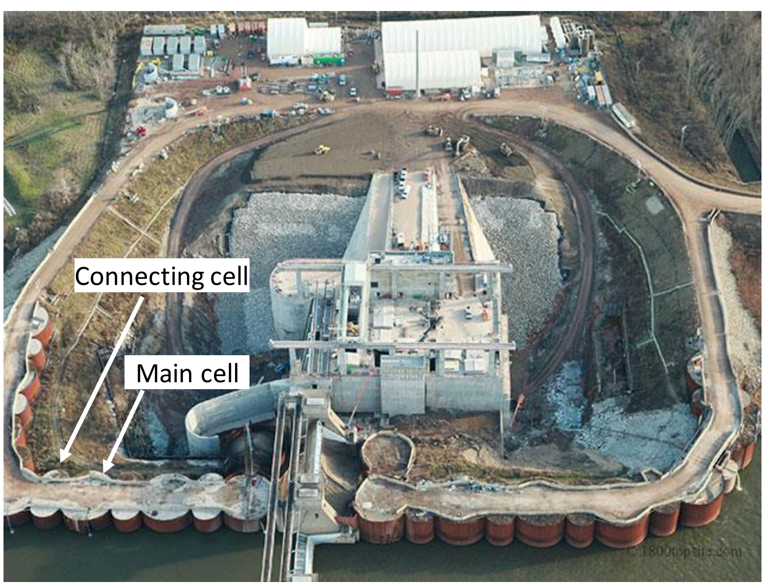


Figure 1. Willow Island Hydroelectric Project Cofferdam (HCSS, 2015).

As mentioned, the main deficiency in the use of cellular cofferdams are the less stringent requirements in their design and construction. Typically, given their short term and temporary use, subject to removal once the permanent structure they enclose is completed, is that they generally designed for much significantly lower factors of safety (FS) than hydropower dams. One of the main deficiencies in the design and construction of cellular cofferdams, is the current practice of allowing upstream water to seep into the cofferdam cells. This so-called wet construction technique induces buoyancy of the filling materials, reducing the effective weight of the cofferdam cells and lowering the factor of safety against sliding and overturning. The less stricter design and construction requirements are the main barriers for the potential use of cellular cofferdams in the construction of new hydropower plants in the U.S.

The aim of this paper is to present the results of a comprehensive study on the potential use of cellular cofferdams as basis for the design and construction of water retaining structures to sustainably and cost-effectively harness hydropower. To make cellular cofferdams suitable for permanent hydropower use, different design concepts that utilize cellular cofferdams as the main or core element of the water-retaining dam structure are proposed. One particular key design concept is the so-called “dry construction technique” in which the granular fill in cofferdam cells and the downstream berm are permanently kept dry in contrast to the wet construction technique for temporary use of cellular cofferdams. The viability of the proposed cellular cofferdam design concepts is demonstrated using well-established structural and geotechnical design procedures and computational modeling. To validate the design, computational modeling of cellular cofferdam construction and response to hydraulic loading including overtopping is developed using the two-dimensional (2-D) finite difference code Fast Lagrangian Analysis of Continua or FLAC version 8.0 (Itasca, 2016). The FLAC numerical model procedure is first numerically validated with the structural response of the St. Germans cofferdam. A comprehensive numerical analysis is then performed to evaluate the structural and geomechanical response of proposed design concepts of cellular cofferdams for hydropower use.

NUMERICAL PROCEDURE TO SIMULATE CONSTRUCTION STAGES OF CELLULAR COFFERDAM

Figure. 2 illustrates the key construction stages for the dry construction of a cellular cofferdam. The construction is simulated in the explicit finite difference program Fast Lagrangian Analysis of Continua (FLAC) version 8.0 developed by Itasca (2016). The corresponding numerical procedure in FLAC to simulate the key construction stages in Figure 2 is summarized into four steps as follow:

***Step 1*:** **Initial condition and placement of sheet pile (Figure 2a)**. Groundwater flow and adjust total stress configurations are used. The sheet piles are wished in place with the interface elements on both sides connecting the mesh and pile nodes. Beam elements are used to model the sheet piles. In situ stresses and pore pressure are initialized and pore pressure at the top of overburden is modelled by applying a uniform surcharge pressure.

***Step 2*:** **Cell excavation (Figure 2b).**
The soil inside the cell is excavated under a balanced water condition. The corresponding pore pressure is applied on the top excavated surface as a uniform surcharge pressure.

***Step 3*:** **Cell filling (Figure 2c)**.
The cell is filled under water and the pore pressure and stresses are initialized hydrostatically. New interfaces are introduced to create link between fill elements and pile nodes.

***Step 4*:** **Berm placement and dewatering (Figure 2d).**
The cell and downstream sides are first dewatered followed by soil excavation and berm placement. When the wet construction is used, dewatering of cofferdam cell and downstream berm is not performed.

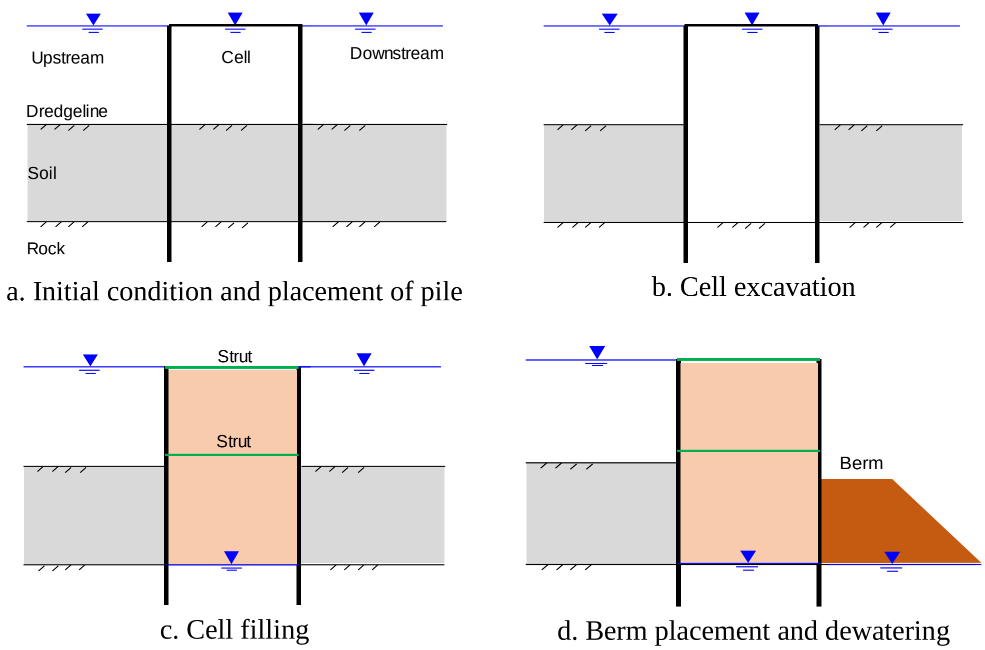


Figure 2. Main construction stages of a cellular cofferdam.

VALIDATION AGAINST STRUCTURAL RESPONSE OF THE ST. GERMANS COFFERDAM

This section will validate the numerical procedure against structural response of Cell C3 of the St. Germans cofferdam (Iqbal, 2009). This is a diaphragm type cofferdam that was built to replace the pumping station at St. Germans Norfolk, UK to pump the water from the low-level drain into the Great River Ouse as part of the drainage system south of Kings Lynn (Figure 3). The model geometry of the St. Germans cofferdam and its FLAC grids are shown in Figure 4 while the material properties are listed in Table 1 and 2. Note that in this section, the SI unit is used to ease constructing and validating the model from its original design that appeared in the literature (Iqbal, 2009).

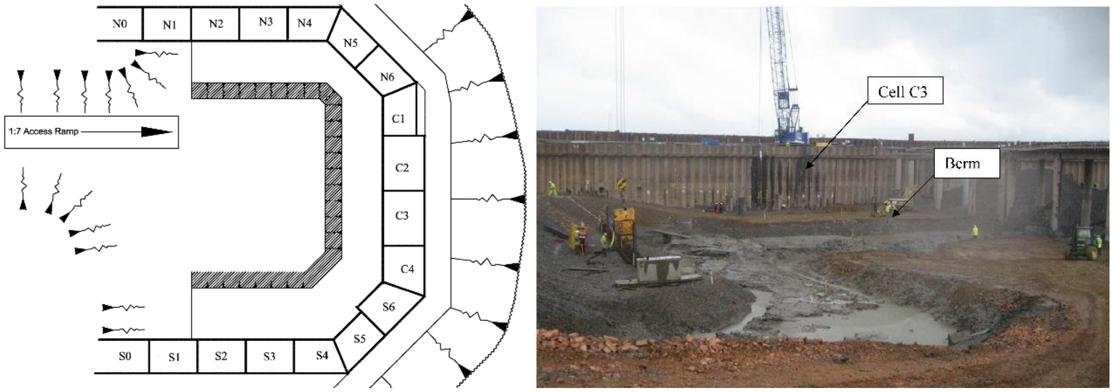


Figure 3. Construction of the St. Germans cofferdam (Iqbal, 2009).

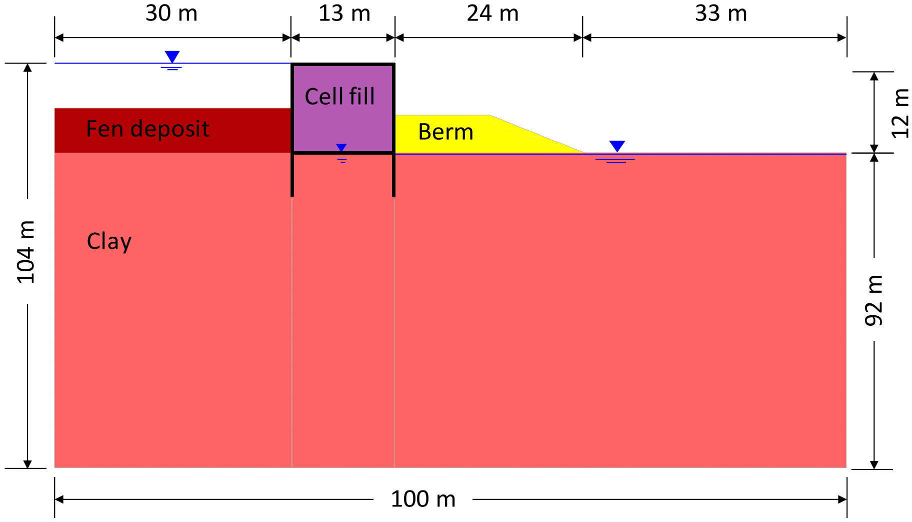


Figure 4. Geometry of the St. Germans cofferdam and its FLAC grids.

Table 1. Material properties for the St. Germans cofferdam

Parameter	Soil type				Unit
	Fan deposit	Clay	Cell fill	Berm	
Dry unit weight, γ_d	1,110	1,310	1,600	1,600	kN/m^3
Young's modulus, E	$0.7\cdot10^6$	$10\cdot10^6$	$25\cdot10^6$	$25\cdot10^6$	Pa
Poisson's ratio, ν	0.2	0.2	0.3	0.3	-
Cohesion, c	0	0	0	0	Pa
Friction angle, ϕ	30	30	30	30	…°
Dilation angle, ψ	0	0	0	0	…°
Porosity, n	0.49	0.49	0.30	0.30	-
Horizontal permeability, k_h	$1.5\cdot10^{-7}$	$1.5\cdot10^{-7}$	$1.5\cdot10^{-7}$	$1.5\cdot10^{-7}$	m/s
Vertical permeability, k_v	$1.5\cdot10^{-8}$	$1.5\cdot10^{-8}$	$1.5\cdot10^{-8}$	$1.5\cdot10^{-8}$	m/s

Table 2. Properties of the steel sheet pile and struts for the St. Germans cofferdam

Parameter	Sheet pile	Upper strut	Lower strut	Unit
Young's modulus, *E*	$200 \cdot 10^9$	$200 \cdot 10^9$	$200 \cdot 10^9$	Pa
Cross-sectional area, *A*	0.021	-		m^2
Moment of inertia, *I*	$5.9 \cdot 10^{-4}$	-		m^4
Diameter, *D*	-	0.045	0.072	m
Spacing, *s*	-	2.4	2.2	m

Comparison of Structural Response

The induced bending moment and cell deflection of the upstream sheet pile are presented. For the bending moment profiles (Figure 5 left), a rather good result from FLAC simulation is obtained for profiles above cell depth of 92 m than those below it. For the cell deflection profiles (Figure 5 right), even though FLAC simulation overestimates cell deflection from the literature, it reasonably follows the general trend of the pile displacement towards the pile tip.

Comparison of Mechanical Response

When berm is placed and factor of safety (FS) of the cofferdam is compared (Figure 6), the FS from FLAC simulation (FS = 1.1) also corresponds closely to that from the literature (FS = 1.2). The shape of failure plane, as indicated by the displacement contour and vectors, is also in good agreement. The contour suggest that the overall cofferdam cell moves on a curved surface at the base of the cell while the upstream overburden slumps in a shape of a wedge and the downstream soil is pushed upward towards the surface.

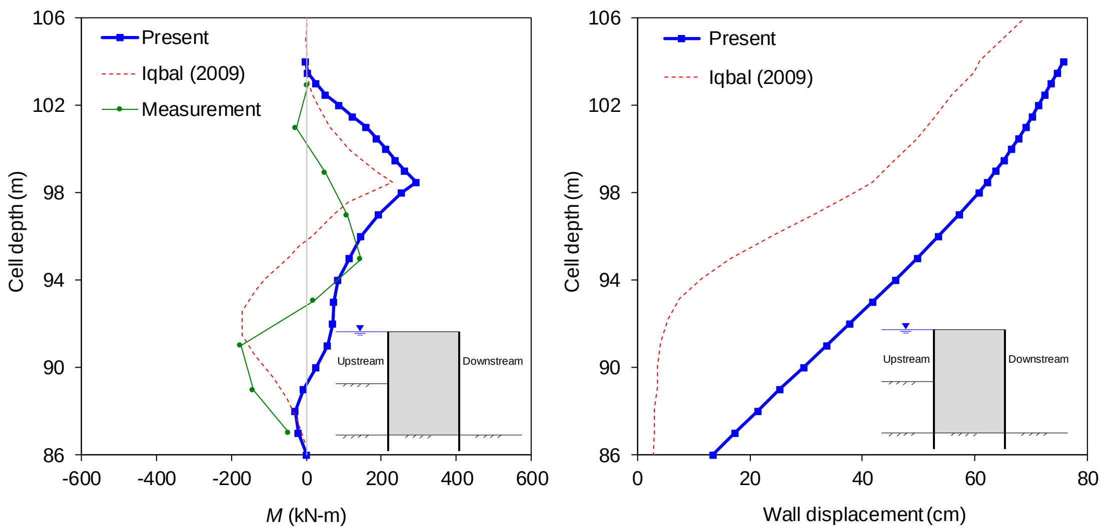


Figure 5. Comparison of bending moment (left) and cell deflection (right) for the upstream sheet pile at the end of construction for St. Germans cofferdam.

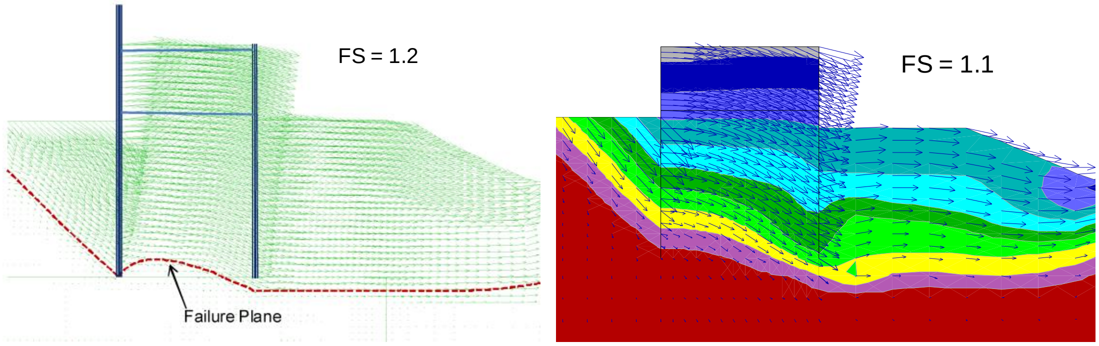


Figure 6. Comparison of deformation vector and failure plane from literature (left) and present study (right) at the time of failure for St. Germans cofferdam.

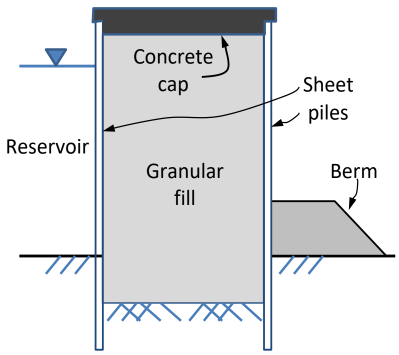
THE PROPOSED DESIGN CONCEPTS FOR DRY CONSTRUCTION TECHNIQUE OF CELLULAR COFFERDAM

Using the principle of dry construction practice, four design concepts are proposed to make cellular cofferdam more permanent for hydropower use. Unlike the wet construction technique, in the dry construction technique, the cofferdam cells and the downstream berm are permanently kept dry. The design concepts are as follow:

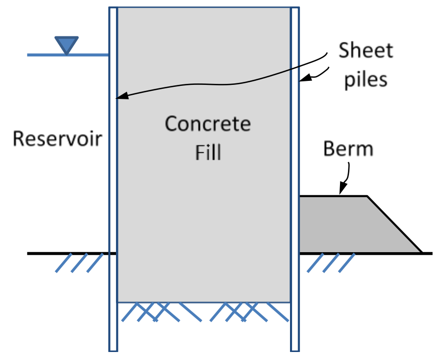
1. Design Concept #1: the cofferdam cell is filled with dry granular fill and capped with concrete to prevent overtopping from the upstream water (Figure 7a). Asphaltic liner is then installed in the inner cell.
2. Design Concept #2: the cofferdam cell is filled with dry concrete fill without capping the cell (Figure 7b).
3. Design Concept #3: the cofferdam cell is filled with dry granular fill and overtopped with downstream concrete embankment (Figure 7c).
4. Design Concept #4: the cofferdam cell is filled with dry granular fill and overtopped with rockfill embankment (Figure 7d).

The dry construction technique of the four proposed design concepts uses the Kentucky cellular cofferdam as the benchmark. This cofferdam is a part of the Kentucky Dam Lock Addition Project (Figure 8). It consisted of construction of a temporary cellular cofferdam to provide for the future construction of a new 1,200 ft lock adjacent to the existing lock. The work included construction of three 69 ft diameter circular sheet pile cells, with three connecting arc cells and a sheet pile tie-in wall. Each cell required tremie concrete base plug, the largest of which required approximately 3,000 cubic yards of concrete.

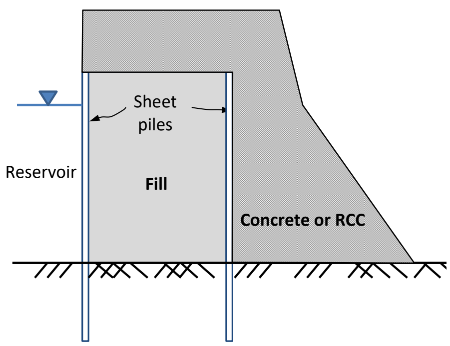
The geometry and FLAC grid of the modeled cofferdam is shown in Figure 9 while the material and sheet pile properties used in the model are listed in Tables 3 and 4. The dimension and properties for the model is taken from its original design that appears in the literature (Pile Buck, 1990). Note that, the imperial unit is used to ease constructing the model from its original design. The stability analysis of the proposed design concepts is presented for the wet and dry construction. The wet construction is still performed mainly to show how the stability from this practice will differ from the dry one.



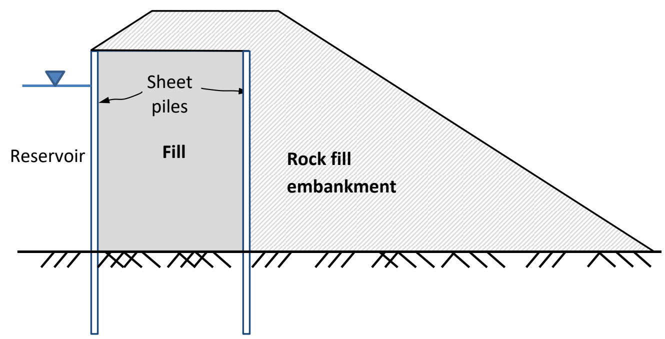
a. Design Concept #1



b. Design Concept #2



c. Design Concept #3



d. Design Concept #4

Figure 7. Four proposed design concepts for Kentucky cofferdam.

Figure 8. Construction of the Kentucky cellular cofferdam (C. J. Mahan Co., 2017).

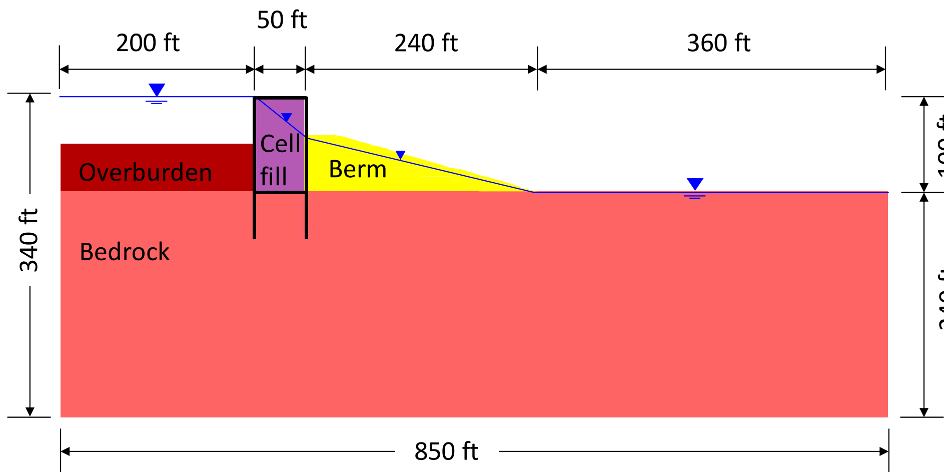


Figure 9. FLAC model of the Kentucky cofferdam.

Table 3. Material properties for Kentucky cofferdam

Parameter	Soil type				Unit
	Overburden	Bedrock	Fill/berm	Concrete	
Dry unit weight, γ_d	110	170	139	139	lb/ft^3
Young's modulus, *E*	$5.8 \cdot 10^4$	$7.3 \cdot 10^6$	$4.4 \cdot 10^4$	$2.0 \cdot 10^6$	psi
Poisson's ratio, ν	0.30	0.30	0.27	0.20	-
Cohesion, *c*	0	$1.5 \cdot 10^3$	0	$4.6 \cdot 10^2$	psi
Friction angle, ϕ	30	45	30	55	…°
Porosity, *n*	0.3	0.3	0.3	0.3	-
Permeability, *k*	$9.3 \cdot 10^{-5}$	$9.3 \cdot 10^{-7}$	$9.3 \cdot 10^{-5}$	$3.3 \cdot 10^{-12}$	ft/s

Table 4. Properties of the steel sheet pile for Kentucky cofferdam

Parameter	Sheet pile	Unit
Embedment depth	50	ft
Young's modulus, *E*	$3.0 \cdot 10^7$	psi
Equivalent width, *b*	0.26	ft
Height per segment, *h*	0.50	ft

Stability Analysis of the Four Proposed Design Concepts

As can be seen from Table 3, the berm and cell fill are the same material. Therefore, in the stability analysis of the proposed design concepts, their friction angle (ϕ) values are varied from $\phi = 60°$ to $\phi = 30°$. The FS from each simulation of reduced ϕ is then plotted into a stability graph of FS vs. ϕ to observe at what ϕ that the cofferdam will have FS > 3.0, which is the assumed FS value for permanent structure.

For Design Concept #1, the wet construction in each ϕ results in lower FS values than the dry construction does. FS = 3.0 is resulted when $\phi = 40°$ for dry construction and $\phi = 50°$ for wet construction (Figure 10).

For Design Concept #2, similar failure behavior as that in Design Concept #1 is observed when the downstream berm is present (Figure 11a). Higher FS values in Design Concept #2 are due to the use of strong concrete fill in the cofferdam cell. Interestingly, when the berm is removed, FS increases significantly by four times for dry construction with $\phi = 30°$ (Figure 11b). This is due to the failure is not controlled by the downstream berm anymore but by the failure of the cofferdam cell. When using the dry construction with $\phi = 30°$, the FS of the cofferdam with berm is 3.4, while that without the berm is 14.2.

For Design Concept #3, a more global failure involving the failure of the upstream overburden, the cell, and the concrete berm is observed (Figure 12). This type of failure is preferable for a permanent design of cofferdam than the local berm failure as shown in Concept Designs #1 and #2. Under Design Concept #3 and if the dry construction is used, FS = 6.8 is easily obtained even when the friction angle of the fill is as low as $\phi = 30°$. However, despite the increase in FS, using poured concrete as downstream berm may be less practical as it increases the construction cost and the difficulty when dismantling the cofferdam.

For Design Concept #4, even though the overtopping embankment is intended to provide additional passive force to the cell, it in fact produces lesser FS (Figure 13) than the design without the overtopping (Design Concept #1). Local failure by sliding is again observed in the downstream berm. Moreover, under this design concept, the cell fill and berm materials must have $\phi = 45°$ to obtain FS > 3.0. In other words, more compaction of the fill and berm materials is needed to achieve a stable cofferdam design.

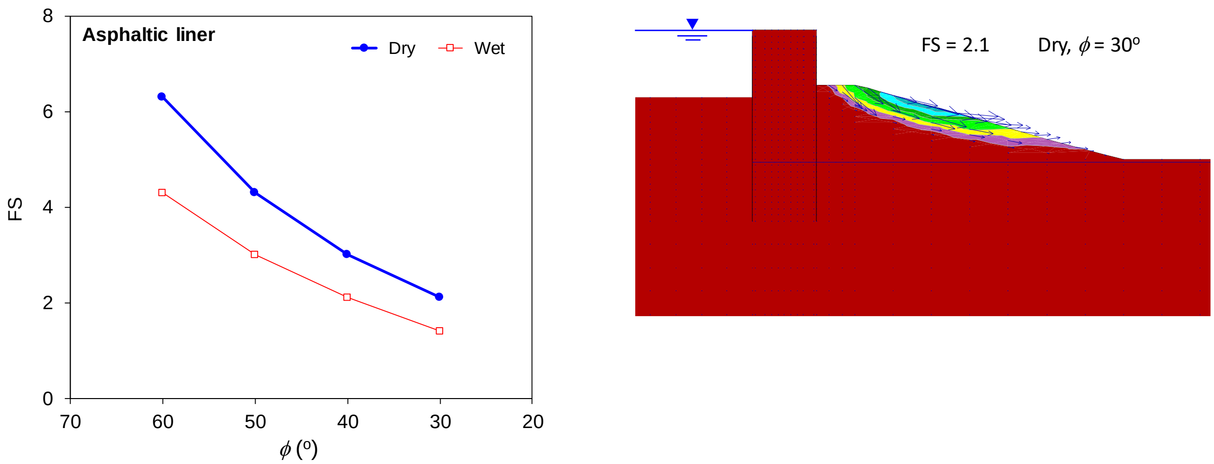


Figure 10. Stability graph for Design Concept #1.

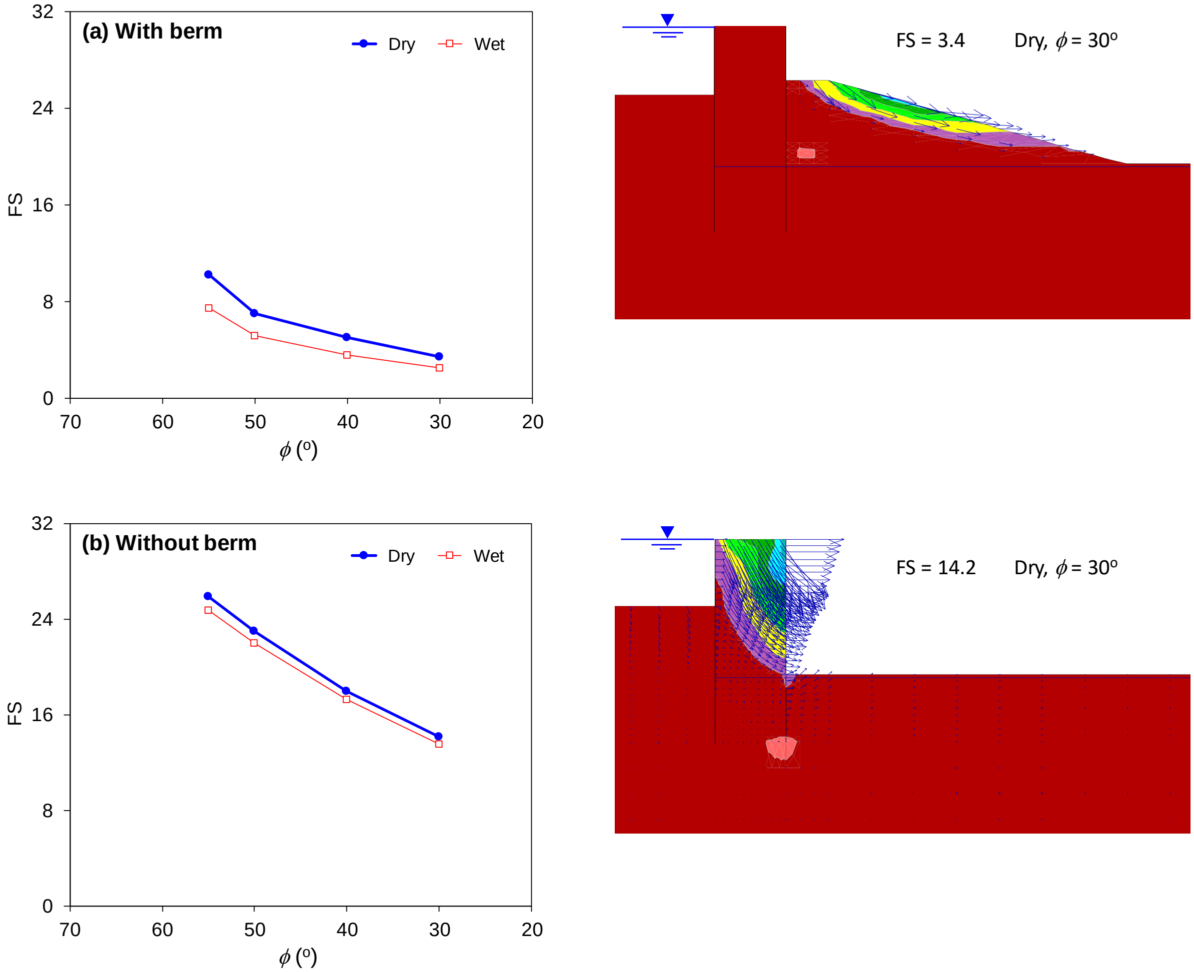


Figure 11. Stability graph for Design Concept #2 (a) with berm and (b) without berm.

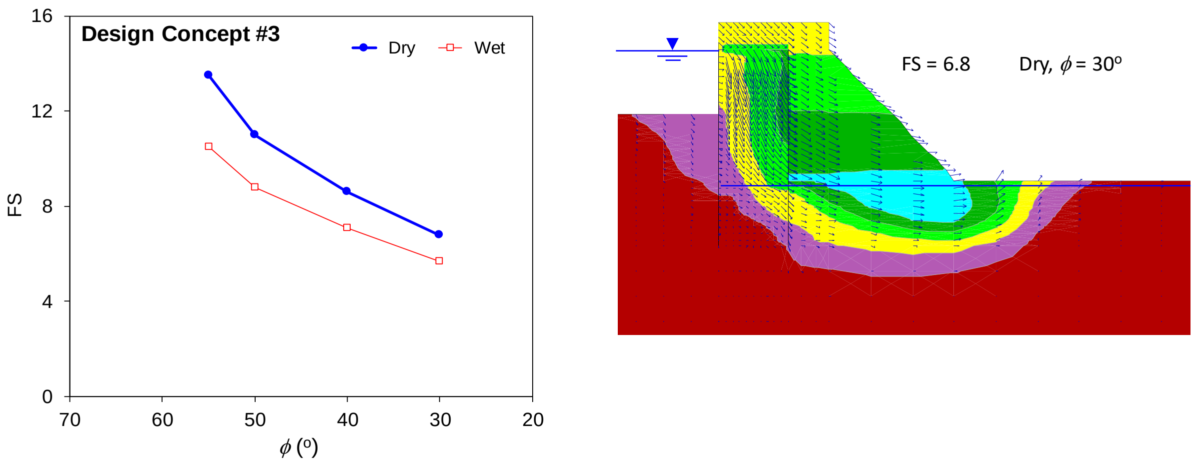


Figure 12. Stability graph for Design Concept #3.

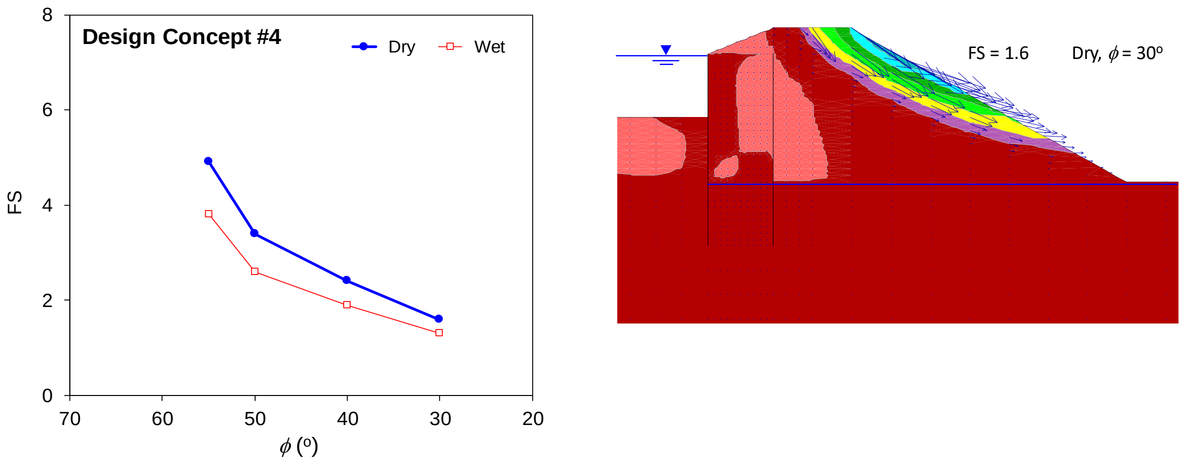


Figure 13. Stability graph for Design Concept #4.

Having analyzed the stability graphs, type of failures of the four proposed designs, and the practicality when dismantling the downstream embankment, it is then suggested to use compacted rockfill as the cofferdam fill. Downstream berm maybe added. Yet, when the stability of the cell itself is being numerically analyzed, it is suggested to perform the stability analysis separately. Including the berm into the analysis may lower the FS and underestimate the true stability of the cofferdam cell. A slope-type failure is more pronounced than a cofferdam failure when the berm is included into the stability analysis. To prevent overtopping, the concrete cap may be used, while to prevent seepage flow from the upstream river, the inner cell is lined with an elastic but impermeable asphaltic liner.

Structural Response of the Sheet Piles of the Proposed Design Concepts

Besides the stability graphs, it is also of interest to observe the structural response of the sheet piles of the proposed design concepts. Figure 14 shows the distribution of the induced bending moment (M), shear force (V), and deflection (Δx) of upstream pile for the wet and dry construction. The bending moment is considered positive when the pile's face towards the upstream side experience tension. For all design concepts, when the wet construction is used, most of the inner side of the upstream cell experiences compression while that of the downstream cell experiences tension. When the dry construction is used, the upstream pile experiences tension in the inner side of the cell. This observed response of bending moment corresponds to that appears in Iqbal (2009).

The shear force distributions also show a change in sign in the cell below the bedrock level (cell depth of 230 ft), which is the location of maximum shear force in the cell. This is the expected place where the pile can fail by shearing if it exceeds the shear strength of the pile. From the distribution of cell deflection for both constructions, the piles are pushed towards the downstream side which is an expected response. Only in the wet construction of Design Concept #4, the upstream pile seems to be move towards the river. This anomaly may be influenced by the movement of the overtopping rockfill embankment towards the upstream side (see the displacement contour in Figure 13).

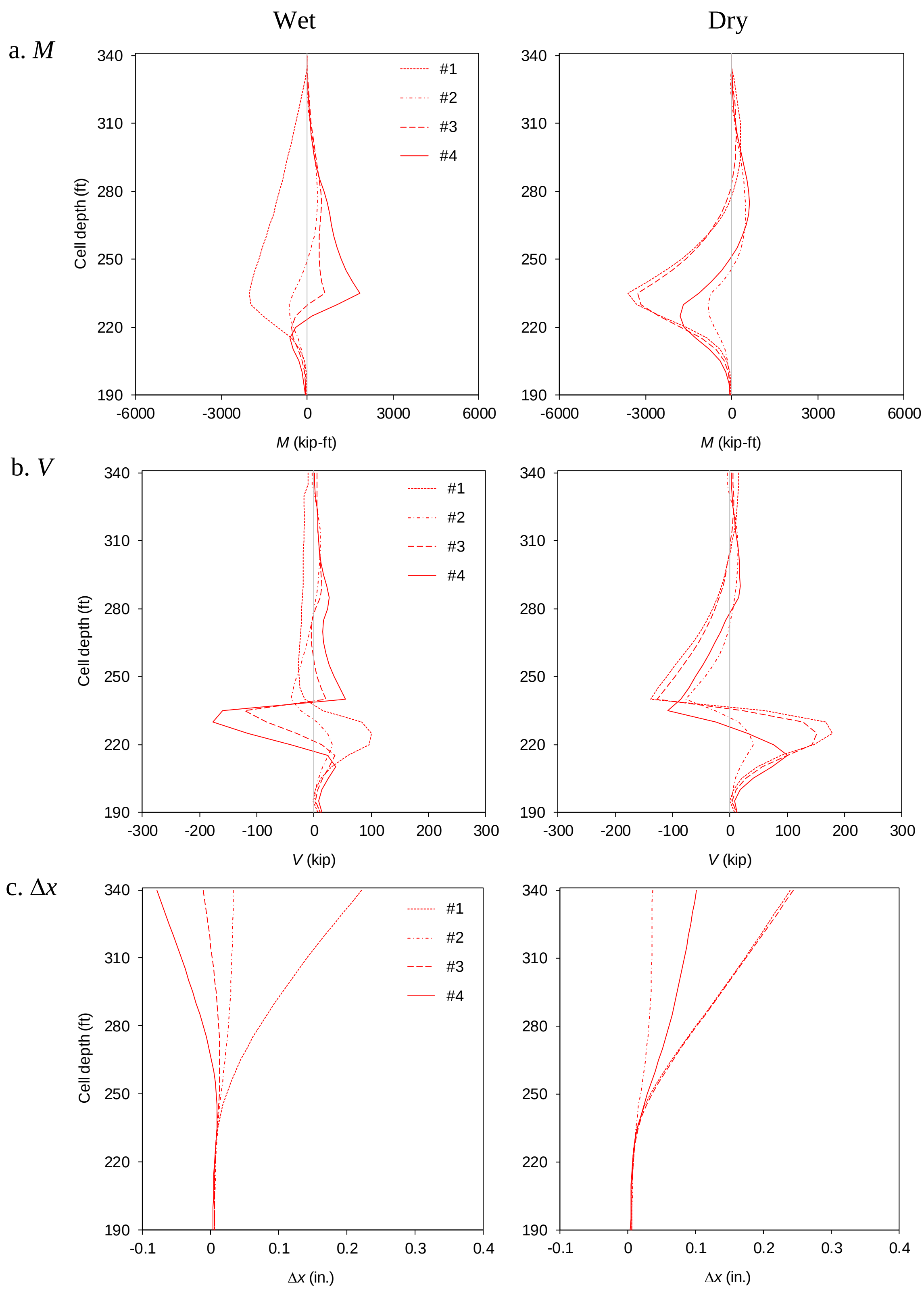


Figure 14. Comparison of (a) bending moments, (b) shear force, and (c) deflection of the proposed design concepts between the wet and dry constructions.

Seepage-Induced Displacement of the Proposed Design Concepts

Figure 15 shows the seepage-induced response of all proposed design concepts for the wet and dry constructions. In practice, the wet construction means the water from the upstream reservoir is allowed to seep into the cofferdam cell and to flow toward the downstream berm. In the long term, the fluid flow will reach the steady state pore pressure distribution. It is the mechanical effects due to the rise of the water table that is now analyzed. Figure 15 shows that, for wet construction, design concepts with rockfill berm will likely produce larger seepage-induced displacement (Design Concepts #1, #2, and #4). Compared to the induced displacement in the dry construction, displacement in the wet construction also expands towards the cofferdam cell, portending a destructive effect to the stability of the cell.

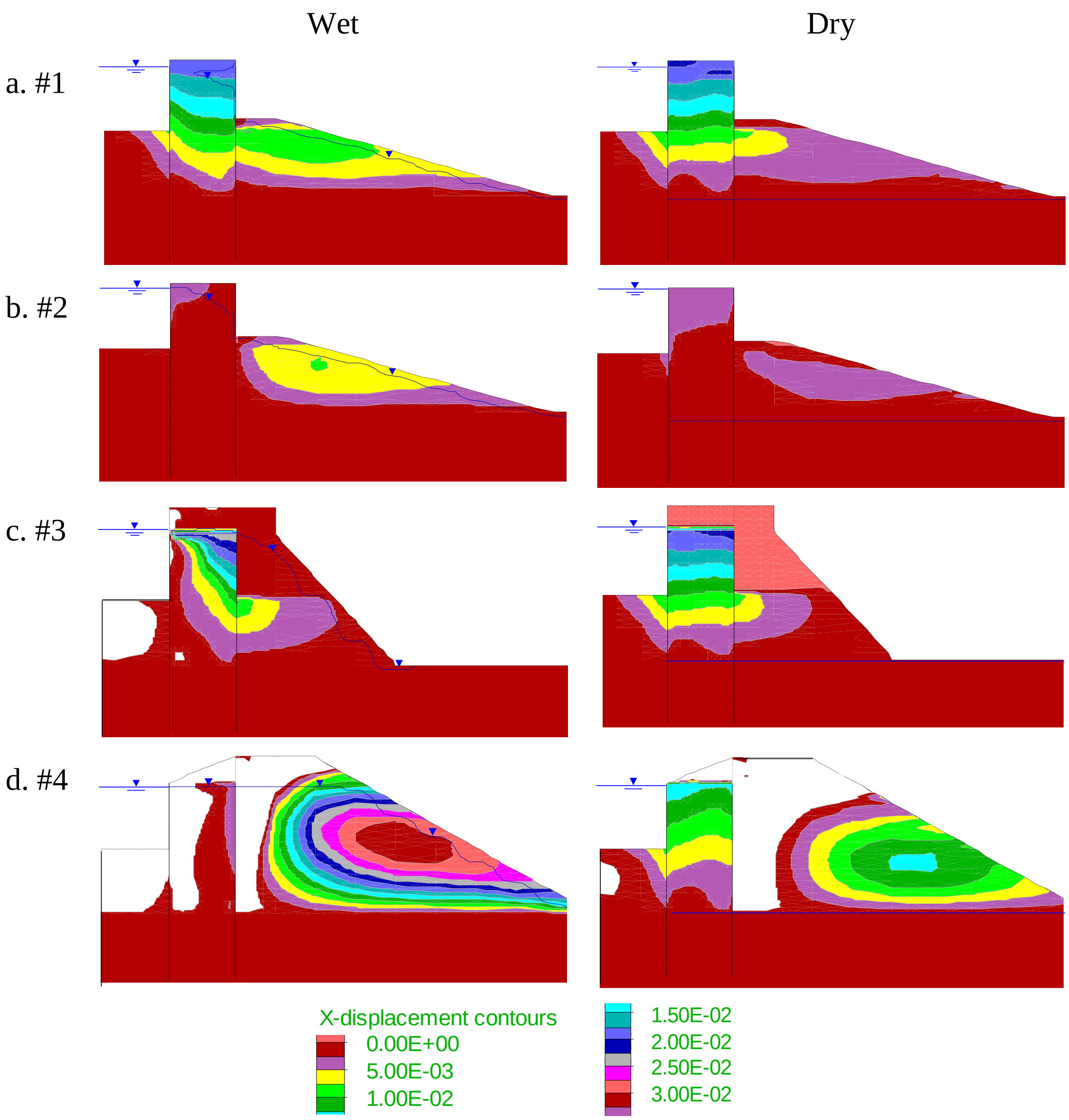


Figure 15. Seepage-induce displacement of the proposed design concepts.

CONCLUSIONS

A comprehensive study was presented on the potential use of cellular cofferdams as basis for the design and construction of water retaining structures to sustainably and cost-effectively harness hydropower. Design concepts that utilize cellular cofferdams as the main or core element of permanent water-retaining dam structures were proposed. One particular key design concept is the so-called "dry construction technique" in which the granular fill in cofferdam cells and the downstream berm are permanently kept dry in contrast to the wet construction technique for temporary use of cellular cofferdams. The viability of the proposed cellular cofferdam design concepts was demonstrated using well-established structural and geotechnical design procedures, and computational modeling using the computer code FLAC.

The dry construction technique was found to be superior in terms of cofferdam stability than the wet construction technique in all proposed design concepts. Seepage analysis has also shown that the dry construction produces lesser amount of seepage-induced displacement than the wet construction does. It is suggested to perform the stability analysis of cofferdam cell separately. Including the berm into the analysis may lower the FS and underestimate the true stability of the cell. To increase the stability of the cell, a higher friction angle of the fill must be used. Hence, compacted rockfill is recommended.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), for funding this research through grant no. DE-FE0007245. The opinions expressed in this paper are those of the Authors and not of the DOE.

REFERENCES

HCSS (2015). AMP Willow Island Powerhouse. http://mip.hcss.com/most-interesting-project/mip2015/projects/willow-island-powerhouse/. Accessed November 2017.

Oak Ridge National Laboratory (2015). National Hydropower Asset Assessment Program. http://nhaap.ornl.gov/nsd. Accessed May 2015.

Iqbal, Q. (2009). *The performance of diaphragm type cellular cofferdams* (PhD thesis). University of Southampton, Southampton, United Kingdom.

Itasca (2016). *FLAC User's Guide*. Minneapolis, MN: Itasca Consulting Group.

Pile Buck (1990). *Cellular cofferdams*. Jupiter, FL: Pile Buck, Inc.

C. J. Mahan Co. (2016). Kenctucky Dam Lock Addition Project. http://cjmahan.com/project/project-kentucky-dam-lock-addition-cells/. Accessed January 2016.

