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Spillway Debris Physical Model Study Morning Glory Spillway

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SPILLWAY DEBRIS PHYSICAL MODEL STUDY MORNING-GLORY SPILLWAY

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Abstract: In this 1:18 Froude scale physical hydraulic model study, woody debris was introduced into a reservoir upstream of a morning-glory spillway at different flow rates causing jams. The purpose of this study is to ascertain the frequency of woody debris clogs in the crest, mouth, transition, or a combination of the three in the morning-glory spillway over varying flow rates. Because of the random nature of debris loading into reservoirs (flux, density, species, length, diameter, branch complexity, etc.), a variety of woody species were used to represent prototype lengths of 10 feet to 35 feet and diameters of 0.5 feet to 4 feet. Flow rates in prototype ranged from approximately 500 to over 3000 cubic feet per second. Flow rate can also play an integral part in where the jam occurs, especially in the transition from weir to orifice flow into the spillway. As the flow transitions from crest control into full pipe control, the water surface elevation (WSE) becomes high enough that debris does not naturally pass through the spillway. The location of the jam can impact the degree of change in water surface elevation, causing changes of up to 25 feet prototype, or approximately a 780% increase, over the range of flow rates tested.

Keywords: Reservoir Debris, Dam Safety, Morning-Glory Spillway, Change in WSE

INTRODUCTION

The US Bureau of Reclamation (Reclamation) is responsible for over 360 high and significant hazard storage dams and dikes in the western portion of the United States (US Bureau of Reclamation). Debris entering Reclamation's reservoirs can result in clogged spillways, which reduce discharge capacity and create higher water surface elevation/s (WSE) in the reservoir. In the event of dam overtopping due to reduced spillway capacity, risk estimators elicit values for spillway capacity reduction. Prior to this research, there were no studies on the impacts to reservoirs created by debris jams in morning-glory spillway structures.

Literature Review

Morning-glory type spillways were first noted in use around 1896, making this a relatively new spillway type (Bradley, 1952). Morning-glories are typically used on sites with restricted space or where downstream flow from a reservoir needs to be restricted. Currently, morning-glories are less

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utilized than other forms of flow control due to concern around air entrainment and flow control. Specifically, while morning-glories are designed to control flow over the crest in weir flow, once the flow regime transitions into orifice control where the crest is submerged, the original discharge curves cannot be interpolated. This would result in two rating curves, one for unsubmerged weir flow and a separate curve for submerged flow, increasing the difficulty of managing the outflow of water (ACOE, 2012). Furthermore, once debris enters the throat of the control structure, it cannot be removed until flow subsides.

To understand the best configuration for utilizing piers or vortex-breakers and maximizing the coefficient of discharge over the crest Musavi-Jahromi, et al. tested 17 configurations by varying the number of vortex-breakers and the angle of the blade. The most efficient configuration was found to be six piers at an angle of 45°, increasing the discharge coefficient by approximately 545%. Furthermore, piers impact the flow at which the transition between weir to orifice flow occurs. Similarly, this hydraulic physical model based on the prototype of Foss dam in Oklahoma has six piers.

Additional literature concerning the relationship between debris loading and WSE can be seen in the previous iteration of the physical hydraulic model utilized in this study. The previous study investigated debris clogging with various openings of a radial gated ogee crest spillway (Walker, 2018). To test clogging caused by woody debris, debris pieces of various sizes were introduced to the ogee crest spillway at varying flow rates. According to this study, the woody debris caused a maximum discharge reduction of 33% with a WSE increase of 4.5 feet prototype for jams that formed under natural processes. Observations of the original tests indicated that jams with higher density are likely to occur because of the restructuring of debris pieces by wind, waves and other surface disturbances in a prototype reservoir. To provide an estimate of the upper range of debris jam impacts, after the original jam was formed, the debris pieces were manually compacted to create a very dense jam. Artificial debris jams were found to have up to a 9 foot change in WSE and a discharge reduction of 48%.

METHODS

A morning-glory spillway, seen in plan view in Figure 1 and profile view in Figure 2, also referred to as a drop inlet or bell-mouth spillway, is an inverted bell-shape that allows surface water to enter the spillway by weir-flow. After flow passes the crest of the morning glory, it then enters the bell-shaped mouth leading into a transition section that allows the flow to converge and is redirected into the conduit that passes through the foundation of the dam. Potential jams may form in the crest, mouth, transition, or any combination of the three. This physical hydraulic model is of Reclamation's Foss Dam in Oklahoma.

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Fig. 1 – Morning-glory spillway in 1:18 Froude scale physical model, plan view.

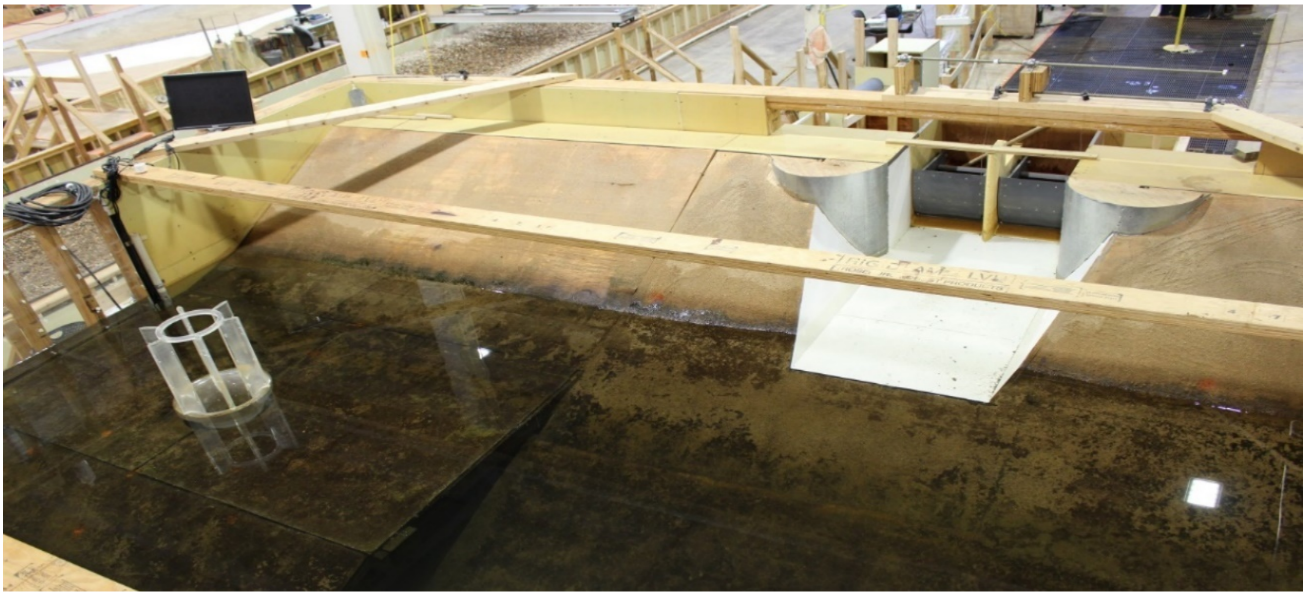

Fig. 2 – Morning-glory spillway in 1:18 Froude scale physical model, profile view.

To allow testing of debris jams with various spillway structures, a 1:18 Froude scale physical hydraulic model was constructed in Reclamation's Denver hydraulics laboratory. This included a 20-ft-wide by 20-ft-long model dimension box and a rock baffle to smooth the incoming from the laboratory pump system. The morning-glory had a model diameter of 1.35ft, with piers of 1.33ft. Model validity was established during clearwater (without debris) testing. The model afforded accurate representations of WSE, flow rates, head loss, velocities, and turbulence in prototype (Hydraulic Lab Techniques, p39). Thus, an increase in WSE caused by debris clogging is relative to the clearwater rating curve.

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Debris observed in reservoirs is variable and can include naturally occurring woody species as well as docks, boats, and debris from other structures. Variables for woody species of debris can include, but are not limited to: flux, density, species, length, diameter, and branch complexity. To represent the range of expected flood debris in the physical model, pieces used for modelling included sapling conifer trees, natural sticks, dowel rods, and simulated trees created by placing a rootball on the end of a dowel rod. The range in prototype lengths of debris was 10 to 35 feet while diameters ranged from 0.5 to 4 feet. In all, approximately 300 assorted debris samples were utilized per test.

Tested flow rates for the morning-glory physical model, given in prototype, spanned a range of 500 cubic feet per second (cfs) to 2500cfs for equilibrium tests and up to 3500cfs for the rating curve development. This represents a range of flows from crest control and into pipe control on the morning glory rating curve. Above 2500cfs, the crest of the morning-glory spillway was below the water surface, thus no debris was observed being pulled underwater into the spillway even when debris pieces were fully saturated.

The testing matrix included: generating a rating curve utilizing clearwater (debris-free water) for the morning-glory spillway (Fig. 3), debris loading a minimum of ten tests per flow rate at equilibrium, performing a simulated flood loading with a stepped hydrograph and debris addition, and loading the model with pre-formed clusters. A test for a given flow rate at equilibrium adhered to the following procedure: 1) wait for the clearwater to stabilize, 2) insert the primary log in the transition of the morning-glory spillway, 3) subject the model to randomly dispersed logs, 4) record where the original jam formed, and 5) record WSE and other parameters after the WSE stabilized with the clog.

Fig. 3- Clear water rating curve.

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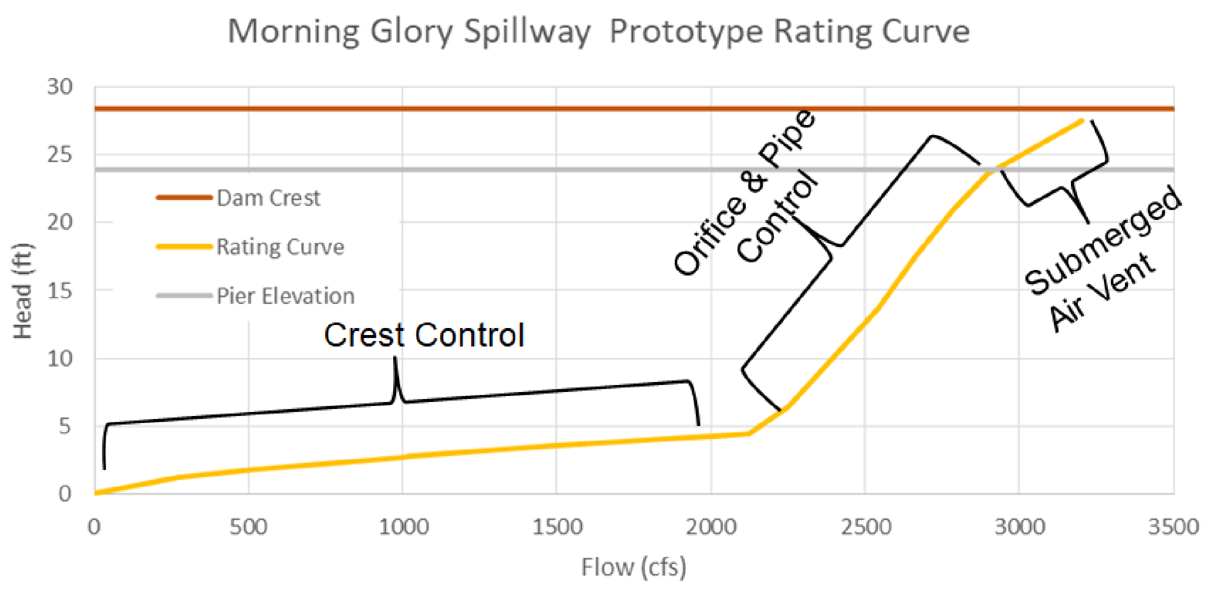
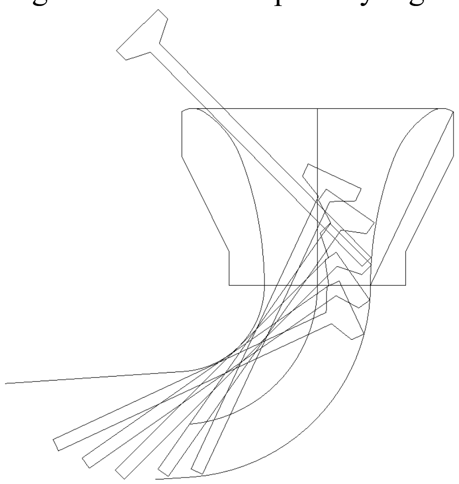


The primary log was a 22 inch long and 3/8th inch diameter dowel that was the only piece of debris designed to be too large to pass through the morning-glory when introduced individually (Fig. 4). The primary log was used to show how jams can recruit and build after a single piece of debris obstructs the passage of water. During a risk assessment, an inventory of the watershed can determine if logs are long enough to jam with the geometry of the existing morning glory. To account for the fact that the primary log ensured a jam formed, pre-constructed jam tests were also run, without the primary log, to ascertain if clogs were as likely to occur within the morning-glory. These pre-constructed jams posed a high risk of being too large to fit through the spillway. Additionally, for all tests random dispersion of the logs entailed individually placing the logs in the model at unsystematic points in an arbitrary sequence.

Fig. 4- Schematic of primary log clogging the transition.



RESULTS

Equilibrium Test

After the introduction of debris into the model, clogs in the morning-glory spillway were grouped into four primary categories: crest, mouth, transition, or a combination of the previous three. Figure 5 exhibits how these jams can potentially obstruct flow, causing an increase in WSE. Since there was a fixed flow rate into the model, the resulting change in WSE post-jam can be used to determine the corresponding flow rate on the rating curve. Then the reduction in discharge can be calculated by comparing the expected flow rate to the calculated flow rate from the rating curve. Therefore, the WSE is inversely related to the discharge capacity. Tests at a given flow rate were repeated approximately ten times or until it became apparent that clogs were occurring at only one location in the morning-glory (i.e.- crest clogs for orifice flow conditions).

Fig. 5 – Photograph of debris jamming in crest, mouth, and transition from left to right images.

Crest clogs, or jams in the piers, occurred at all flow rates for at least some of the trials and was nearly the exclusive location of jams once the morning-glory spillway entered orifice flow (Table 1). The transition to orifice flow began at approximately 2240cfs and became fully submerged at 2400cfs. Once the flow was in orifice control, the raised WSE resulted in jams having minimal impact on the WSE, if jams would occur at all (Fig. 6). Thus, the increased WSE allowed the debris to float above the morning-glory inlet in the space between the crest without getting pulled down by the water.

When in weir-flow, debris blockages tended to cause a much larger impact on WSE. This is likely because weir-flow is more efficient than orifice flow. This resulted in a larger proportion of clogs occurring in the transition and mouth portion of the morning-glory during weir flow as a higher debris load was approaching the spillway. Conversely, pier jams still occurred during weir-flow, however they were less likely because the velocity vectors diverged around a pier and allowed debris to orient into clear flow unless the debris piece formed a jam between two piers. This high passing efficiency over the morning-glory spillway contributed to the lack of combination jams at the lower flow rates.

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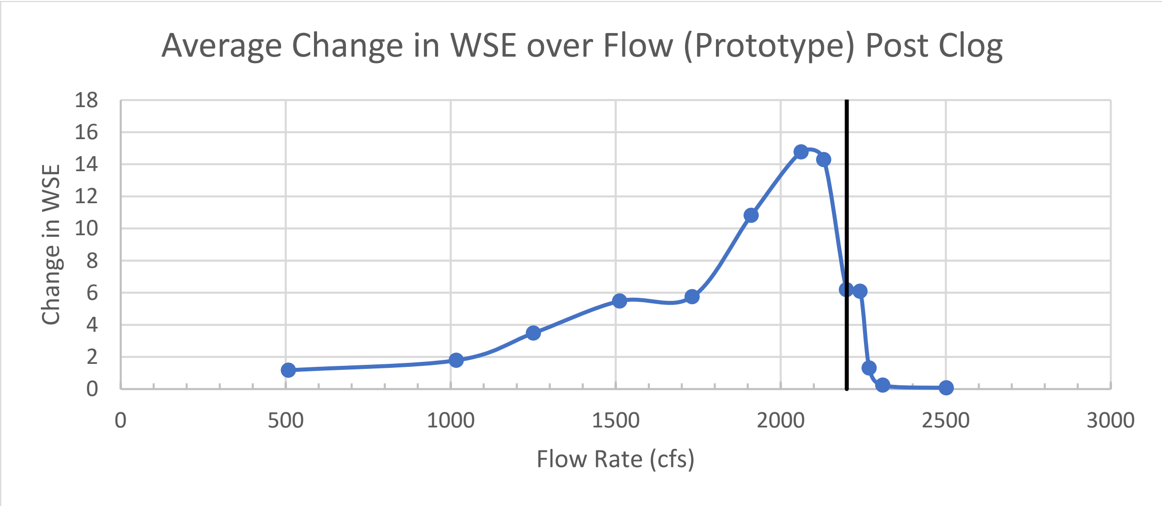
Table 1 – Average change in WSE at different jam locations in prototype for equilibrium test. The number below WSE in parenthesis denotes frequency of occurrence.

Flow Rate (cfs)	Crest (ft)	Mouth (ft)	Transition (ft)	Combination (ft)	Total Average (ft)	WSE Change (%)
500	0.954 (2)	1.278 (5)	1.128 (3)	0 (0)	1.168	69.92
1020	1.314 (4)	0 (0)	2.106 (6)	0 (0)	1.789	67.93
1250	1.701 (2)	3.87 (4)	4.5 (2)	0 (0)	3.485	115.93
1510	8.073 (2)	10.666 (6)	0 (0)	3.186 (3)	5.481	162.83
1730	2.617 (5)	13.122 (1)	10.539 (2)	7.488 (2)	5.745	154.19
1910	0.756 (3)	10.692 (2)	15.453 (2)	13.914 (3)	10.816	272.88
2060	5.13 (2)	16.608 (3)	16.44 (3)	18.09 (2)	14.764	356.00
2130	5.814 (3)	17.917 (5)	18.243 (2)	0 (0)	14.286	336.58
2200	1.458 (4)	10.179 (4)	0 (0)	16.443 (2)	6.183	122.20
2240 (Orifice flow)	6.709 (7)	0 (0)	0 (0)	5.667 (3)	6.084	95.48
2270	0.627 (7)	0 (0)	2.277 (2)	2.268 (1)	1.309	19.88
2300	0.237 (5)	0 (0)	0 (0)	0 (0)	0.237	2.86
2500	0.037 (4)	0 (0)	0 (0)	0 (0)	0.0675	0.54
Overall Average	2.774 (45)	6.024 (30)	5.049 (22)	5.229 (16)	5.386	136.71

Fig. 6 - Average change in WSE for all jam locations at varying flows.



Cluster Test

For the pre-formed cluster tests, nearly all the clusters were broken apart by the piers. Two sets of tests were utilized with pre-formed clusters. During the first test, a pre-formed cluster was introduced into the model and allowed to stabilize to ascertain the final change in WSE (Table 2, Columns 2). Out of the flow rates tested, only two clusters were able to pass the crest and form jams in the mouth or transition, highlighted in red in Table 2. When the pre-formed clusters passed the crest, flow was greatly obstructed resulting in a 200 to 300 percent increase in WSE compared to that of clusters restricted to forming jams in the crest.

The second "rapid" set of tests introduced 20 clusters per flow rate. During this test, clusters were introduced, formed a jam either at the crest, mouth, transition, or a combination of the three, and then removed from the model before being allowed to stabilize (Table 2, Columns 3-4). This test was devised to establish the frequency with which the jams would occur at the aforementioned locations. As observed in the previous pre-formed cluster test, jams were most likely to form around the piers. In both tests, the piers prevented large clusters from entering the spillway in two ways. Predominantly, piers broke apart the clusters on impact, allowing smaller pieces of debris to pass through the mouth and transition without getting lodged. Secondly, the piers restrained the larger clusters from entering the spillway. Therefore, in pre-formed clusters, risk of major changes to WSE is relatively low unless individual pieces of debris that break off from the cluster are longer than the critical dimension of the morning-glory design.

Table 2 – Average change in WSE in Prototype for cluster test. Red font denotes transition jams, black font denotes debris remained in piers.

Flow Rate (cfs)	Average Change (ft)	Number of Jams in the Crest	Number of Jams in the Transition	Percent Change in WSE
(1)	(2)	(3)	(4)	(5)
1020	1.638	20	0	64.54
1374	25.506	19	1	782.87
1910	1.332	20	0	33.94
2130	16.938	19	1	400.43
2200	2.664	20	0	61.41

CONCLUSION AND FUTURE WORK

The purpose of this study was to ascertain the risk debris clogging poses to morning-glory spillways over a range of flow rates. Furthermore, the relationship between the location of the clog and the change to WSE in the reservoir was assessed.

As changes to WSE were greatest for transition jams in pre-clustered tests and mouth jams for equilibrium tests, it can thus be concluded that debris clogs within the mouth or transition area of the morning-glory are the most restrictive to all flow rates. These jams are most likely to occur in peak efficiency of the morning-glory spillway, resulting in the largest change to WSE. Because of the proximity of the mouth and the transition, combination jams are likely to occur at both locations. Therefore, combination jams follow a similar pattern with clogs tending to occur in weir flow. Mouth jams were more likely to occur than transition jams because debris was designed to pass through the transition of the morning-glory when introduced individually. Multiple pieces of debris would need to pass simultaneously to cause a transition jam.

Current analysis suggests morning-glory spillways with piers were able to divide pre-formed clusters or prevent larger debris from entering the mouth or transition. If the jam can remain confined to the crest, this can greatly limit impacts to WSE. This is especially vital in weir-flow conditions where higher velocities will carry the debris into the mouth or transition of the morning-glory. Once the spillway enters orifice flow, debris is not as capable of entering the spillway due to the buoyancy of the debris pieces combined with higher WSE resisting the downpull of the flow velocity entering the morning glory spillway.

As every flow rate tested exhibited at least one pier jam, future testing will entail removing the piers surrounding the morning-glory and monitoring if the clogs occur in different locations at the same flow rates under regular and pre-formed cluster conditions.

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