Hydraulic Jump Stability of Articulating Concrete Block Systems

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Abstract

Stability of Articulating Concrete Block (ACB) systems under the influence of hydraulic jump forces has long been an unstudied and often under considered topic in ACB design. Since 2010 a series of hydraulic jump stability test runs have been conducted in an outdoor, steep slope flume at Colorado State University in Fort Collins Colorado. Data from the three separate flume installations, encompassing 7 test runs including 2 failure points and two distinct ACB systems under induced hydraulic jump conditions have been analyzed. This paper, and accompanying presentation, will detail the individual test runs, data analysis process undertaken and results developed to analyze hydraulic jump stability of ACB systems on slopes. A summary of the current abilities of this design method and future work that should be undertaken to further develop an understanding of hydraulic jumps in relation to ACB stability on steep slopes will be presented.

Introduction

A Brief Summary of ACB Testing

The earliest reference to testing an engineered system that could be considered an ACB points to the wedge block tested in Russia in the mid 1970's. There is little in the way of documented results from this testing, but anecdotal information indicates the blocks were successful in preventing erosion under fairly extreme hydraulic conditions. The earliest recorded and referenced testing of ACB systems happened in 1986 at the Jackhouse Reservoir in the United Kingdom and run by the Construction Industry Research and Information Association (CIRIA). The results are documented in CIRIA Report #116 "Design of Reinforced Grass Waterways"[1]. The study looked at various options of grass reinforced spillways and concluded that ACBs showed promise as a vegetated erosion control countermeasure.

The results of the CIRIA Study led to the Federal Highway Administration (FHWA) conducting two broad ranging studies in 1988 and 1989[2,3] at Colorado State University in Fort Collins which looked at various protection systems for protection of earthen embankments during overtopping events. Several ACB systems were part of these studies in which the results showed ACBs were an effective erosion control measure. As a result of the 1988 testing, the first accepted factor of safety method was developed by Paul Clopper of Simon & Li.

The 1990's saw an extensive testing program undertaken by Armortec (Armorflex) that centered around the untapered products. In 1999/2000 the first tapered ACB system was tested with results that showed dramatic improvement over untapered ACB systems in preventing erosion. In the late 1990's and through the 2000's several ACB manufacturers had various products performance tested in a full-scale flume. The first hydraulic jump performance testing of an ACB system was conducted in 2007 and yielded limited useful results as will be detailed later in this paper.

In 2010 Shoretec LLC (Shoreblock) embarked on a testing program designed to expand the limits of ACB design applicability. This testing program continued through 2019 [7,8,9] Test results permit an assessment of system performance when installed systems are subjected to a hydraulic jump. In addition to appropriately accounting for the lift and velocity on system stability

A Brief Summary of Factor of Safety Methods

The factor of safety (FOS) calculation for ACB systems in its most basic form is the sum of the stabilizing forces on an individual ACB block divided by the sum of the destabilizing forces acting on the individual ACB block. The first FOS method as applied to ACB systems, was developed by Clopper[14] in which measured hydraulic data taken from the tests was utilized to determine maximum shear conditions to which the tested systems were exposed. Equations were developed by evaluating the forces acting on a single block resting on a sloped embankment. Moment arms were defined, and the threshold of performance was based on incipient motion of an ACB block, like the concept utilized in riprap revetment design.

During the development of the original FOS method, it was discovered that there were too many unknowns and not enough equations for an analytical solution to be developed, so some simplifying assumptions were made. The major assumptions made in the original FOS equations included:

1. Lift and Drag forces were equal
2. The rotation point of failure was fixed based on a diagonal flow across the surface of the block

These assumptions were evaluated and a more robust, accurate method of quantifying a FOS was presented by Cox(2010) [5]. This method, referred to as the CSU Method, treats lift and drag forces independently and calculates an appropriate FOS around three natural rotation points. ACB systems are typically performance tested under ASTM D7277 and test results analyzed through ASTM D7276 as these are the current best practices in the industry. System performance can then be quantified through procedures outlined in NEH Part 628 Dams Chapter 54 ACB Armored Spillways[13]. One important addition to the practitioner designing dams is the discussion and assessment of hydraulic jump stability of ACB systems [13]

Definition and Causes of Hydraulic Jump

Froude Number (Fr) is a dimensionless parameter, defined in Equation (1), which characterizes flow conditions in open channels.

$$Fr = \frac{V}{\sqrt{g*d}} \quad (1)$$

Where:

Fr – Froude Number (dimensionless)
V – Velocity (ft/sec)
g – Gravitational Constant 32.2 ft/sec^2
d – depth of flow (ft)

Open channel flow with a Froude Number less that 1 is considered sub critical flow and is characterized by low velocity and large flow depths. When the Froude Number is greater than 1, the flow is considered super critical and is characterized high velocity and shallow depth.

Hydraulic jumps occur when open channel flow changes from super critical to sub critical as defined by the Froude Number. The simple explanation for this is that there needs to be conservation of energy before and after the jump, thus when an open channel flow slows down, the depth must increase, and energy is released in various forms.

Hydraulic jumps can by caused by several means. The list below contains some of the identified ways in which a hydraulic jump can be initiated.

- Grade change
- Plunge Pool / Tailwater
- Debris in Spillway

In general, any situation that slows the velocity of water which is in supercritical flow enough to change to sub critical flow can be defined as a cause of a hydraulic jump.

Hydraulic Jump Test Program

Numerous presentations, publications and discussions among the dam design and regulatory community indicated that there was a need to better quantify the performance of ACB systems when subjected to a hydraulic jump. A test program was thus initiated between Shoretec and Colorado State University to provide data necessary for a quantitative analysis of block performance in a hydraulic jump. The hydraulic jump test program began in 2010 and continues to the present.

The test program consisted of two distinct ACB systems and the respective Test ID associated with each

- Shoreblock SD 475 OCT placed on 4 inches of unstabilized drainage stone (2010 test Test ID #2,#3,#4 and 2015 unintended jump test Test ID #1) [7,8]
- Shoreblock EPEC SD 475 OCT placed on 6 inches of 3-dimensionally stabilized drainage stone (Test ID #5,#6,#7)[9]

Table 1 summarizes the seven test configurations extracted from previous test reports and used for subsequent analysis. Specific test details are contained in each respective test report.

Table 1. Summary of ACB Configurations

Test ID	System	Q (cfs)	q (cfs/ft)
1	OCT475	47	11.8
2	OCT475	47	11.8
3	OCT475	30	7.5
4	OCT475	15	3.8
5	EPEC	47	11.8
6	EPEC	78	19.5
7	EPEC	115	28.8

<u>Hydraulic Jump Test Description</u>

Flume Construction

The flume construction for the Shoreblock SD 475 OCT test runs followed ASTM 7277 standard procedures and is summarized below:

- 8 inches of compacted subgrade
- Propex Geotex 1201 Geotextile
- 4 inches unstabilized drainage stone (d_{50} = 1 inch)
- Synteen SR-18 microgrid
- Shoreblock SD 475 OCT ACB Revetment (cabled in place)

Flume construction for the Shoreblock EPEC SD 475 OCT test runs followed ASTM 7277 standard procedures and is summarized below:

- 6 inches of compacted subgrade
- Propex Geotex 1201 Geotextile
- 6 inches drainage stone stabilized with Presto 30V6 GeoWeb (d_{50} = 1 inch)
- Synteen ACF-35B Geogrid
- Shoreblock SD 475 OCT Revetment (cabled in place)

Both ACB systems, as described above, had hydraulic jump testing conducted after the successful completion of steady state overtopping tests. To induce the hydraulic jump, a gate with a variable opening was installed 48.5 ft from the top of the slope as shown in Figure 1. To run the test, target flow rates were selected as reported and the opening of the gate was adjusted to maintain a 3.4’ pool in front of the gate for each flow condition. Each flow rate was run for a period of two hours. Water surface elevations were taken upstream of the gate and bed elevations were recorded before and after each run. Figure 2 shows a typical hydraulic jump test in progress.

Figure 1 – Hydraulic gate installed 48.5 ft from top of slope to induce hydraulic jump Shoreblock SD 475 OCT

Figure 2 – Hydraulic Jump flume test in progress Shoreblock EPEC SD 475 OCT

Visual inspection of the revetment system was made after each run and any abnormalities noted. Figure 3 shows the result of a catastrophic failure of the Shoreblock SD 475 OCT system after Test ID #1. Classification of pass, transition or fail was used for each of the 7 conditions tested. Transition is defined as the last stable condition before catastrophic failure.

Initial analysis of the hydraulic jump data collected focused on determining the kinetic energy of the incoming flow. This idea was soon changed to evaluate specific energy SE_i as this was essentially identical to kinetic energy, a familiar term to the hydraulic engineer and readily calculated from basic flow measurement data. For each condition of hydraulic jump tested, as listed in Table 1, the entering specific energy SE_1 was calculated based on the flow data recorded during the tests. These results were analyzed and plotted as described later in this paper. Specific energy SE_s is defined in Equation (2).

$$SE_i = \frac{V^2}{2g} + d * cos\theta_0 \qquad (2)$$

Where

SE_i – Specific Energy (ft)
V – Velocity (ft/sec)
g – Gravitational Constant 32.2 (ft/sec2)
d – Flow Depth (ft)
Θ_0 – Bed Slope

Each ACB revetment system tested will have a unique SE_i threshold. It is important to note that an ACB system is not a reference to an ACB block style but rather the ACB Block style in addition to how it was installed in the flume (geotextile, drainage layer, 3-dimensional stabilization, geogrid and ACB block). The ACB system should be installed in the field identical to as it was tested in the flume for presented results to apply. Test results are summarized in Table 2 where all resulting hydraulic values calculated through procedures outlined in ASTM D7276.

Table 2. Summary of Hydraulic Jump Test Results

Test ID	System	Q (cfs)	q (cfs/ft)	D_1 (ft)	V_1 (ft/s)	Fr_1	SE_1 (ft)	Condition
1	OCT475	47	11.8	0.45	26.0	6.810	10.90	Fail
2	OCT475	47	11.8	0.44	26.9	7.190	11.63	Fail
3	OCT475	30	7.5	0.34	22.3	6.780	8.03	Transition
4	OCT475	15	3.8	0.22	17.1	6.410	4.74	Pass
5	EPEC	47	11.8	0.51	24.0	6.810	9.40	Pass
6	EPEC	78	19.5	0.66	29.6	6.540	14.20	Pass
7	EPEC	115	28.8	0.89	32.5	6.440	17.20	Pass

Figure 3 – Flume Post Failure Hydraulic Jump Test ID 2

Interpretation of Results

Figure 4 illustrates the specific energy associated with each test detailed in Table 2 and Figure 5 includes performance determination for each test. Test ID 1 & 2 in Table 2 represents the two failure points experienced by the Shoreblock SD 475 OCT ACB system. Test 1 had the jump induced by a gate installed and set to maintain a 3 ft back water level in the test flume and Test 2 had the jump initiated via a plunge pool that unexpectedly formed at the bottom of the test flume. In both cases, the failure occurred in under 5 minutes and was catastrophic as shown in Figure 3. The SE_1, entering Specific Energy was 10.9 and 11.63 ft respectively for these two tests.

Test ID's 3&4 are stable test runs from the hydraulic jump testing of the Shoreblock SD 475 OCT placed on 4 inches of unstabilized stone. While both conditions were determined to be stable, Test ID 3 with a SE_1 of 8.03 ft has been classified as a transition point, which means that is the highest stable SE_1 value for this system. This was conservatively chosen because data indicates that failure occurs somewhere between SE_1 values of 8.03 ft and 10.9 ft on a 2:1 slope.

Test ID's 5,6 & 7 represent the results hydraulic jump test for the Shoreblock EPEC 475 OCT ACB system. This system utilized the 3-dimensional stabilization of the drainage stone under the ACB revetment. All three tests were successful (i.e. the threshold of performance was not reached). Test ID 7 also represents the maximum hydraulic capacity of the flume set up and the SE_1 for this condition was determined to be 17.2 ft, thus this is the threshold of performance for the EPEC SD 475 OCT revetment system on a 2:1 slope.

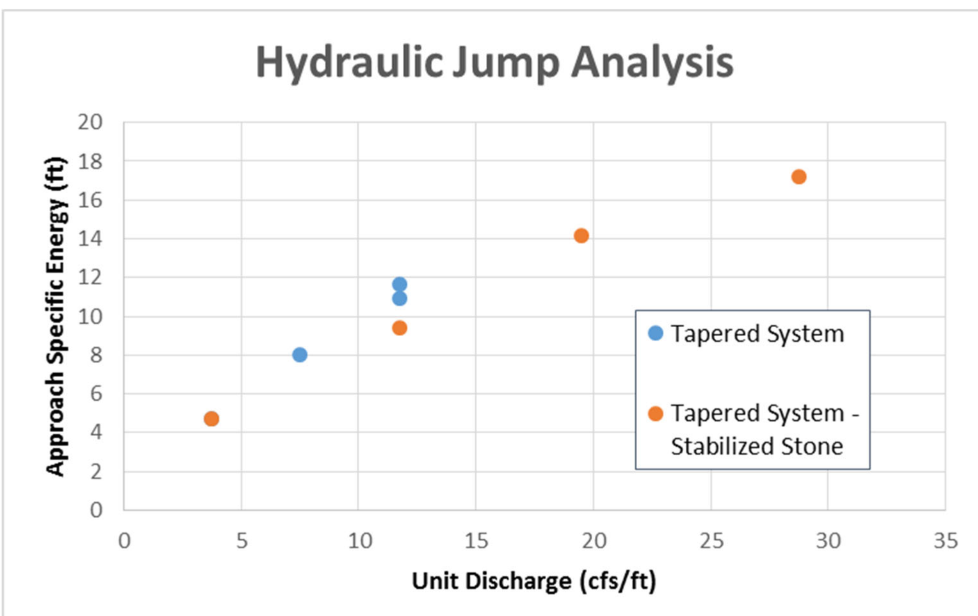

Figure 4. Specific Energy at Jump Entrance for Each Test

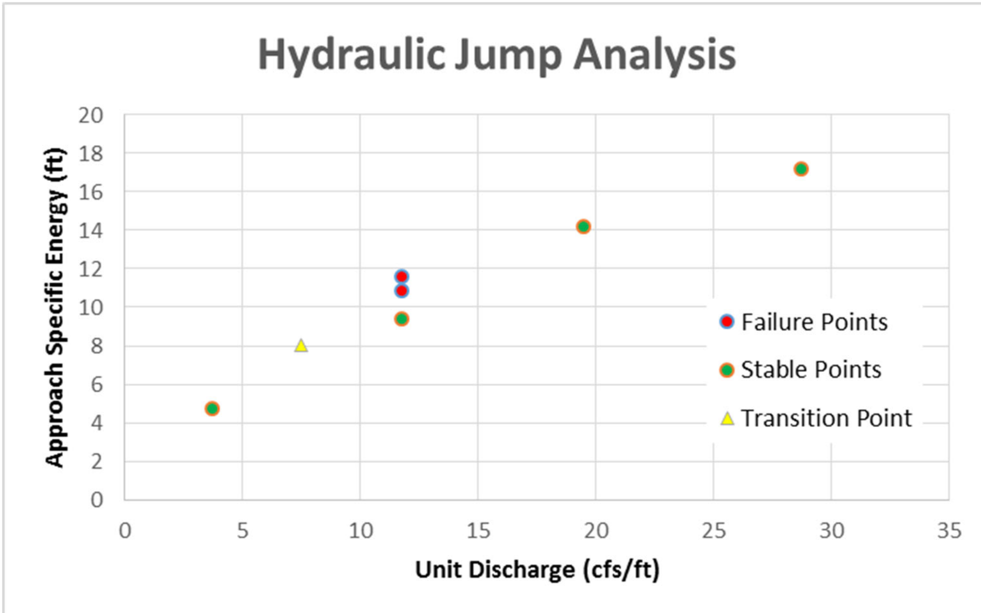

Figure 5. Summary of System Performance

Now that the two tested ACB systems have threshold stability values defined by entering Specific Energy, one can begin to look at ways to utilize this information in ACB selection and design in super critical flow applications. Figure 6 shows Specific Energy plotted as a function of Unit Discharge for three different slopes. The value of specific energy is calculated at normal flow depth as determined by Manning's equation. In addition, the threshold E_S values for the tapered ACB revetment system with the 3-dimensionally stabilized stone drainage layer and the tapered ACB revetment system with the unstabilized stone drainage layer are shown on the graph. The way to utilize this chart is to plot the E_S for the specific project one is designing and see where it falls in relation to the threshold SE_S for the two ACB systems. Designs with an acceptable FOS and an SE_S below 8.03 ft, indicate the tapered (unstabilized stone) revetment system would provide adequate hydraulic jump stability performance. Projects where the SE_S is above 8.03 ft but less than 17.2 ft would utilize the tapered ACB revetment with 3 dimensionally stabilized stone and projects with an SE_S value greater than 17.2 ft should not use ACBs as the protection system.

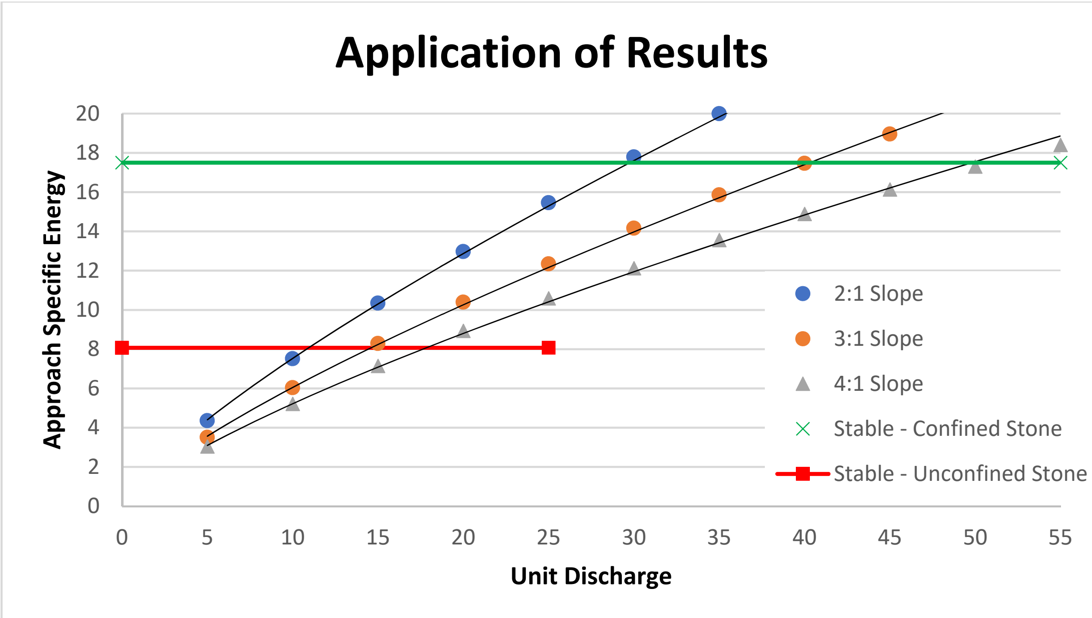

Figure 6 – Specific Energy at Uniform Flow Conditions as a Function of Unit Discharge

Conclusions

The following conclusions can be drawn from the work presented:

1. The hydraulic jump stability of an ACB system on a steep is related to the drainage layer and more specifically to the stability of the drainage layer as measured by the inclusion of physical stabilizing components added to the drainage layer under the ACB revetment system
2. The specific energy of the flow entering the hydraulic jump appears to be a good property in which to assess hydraulic jump stability of ACB revetment systems on steep slopes which have been full scale flume tested as described in this paper.

Recommendations and Future Work

The following recommendations and suggestions for more research on the topic of ACB performance under hydraulic jump conditions include

1. Re-examination of the design data used for already installed tapered ACB systems looking at both FOS with the CSU method and hydraulic jump stability based on the method outlined in this paper.
2. Continue researching hydraulic jump stability of ACB systems on steep slopes by developing a test program where the effect of the following variables are quantified, thus leading to an improved design tool
    a. ACB weight / unit weight
    b. Drainage Layer Thickness

    c. Evaluation of other 3-dimensional stabilization systems
3. Inclusion of hydraulic jump analysis (consistent with NEH Part 628 Dams Chapter 54 ACB Armored Spillways) for all ACB designs involving super critical flow conditions

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