DOI: 10.1051/e3sconf/20160703008

Evaluating the mechanisms of erosion for coarse-grained materials

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Abstract. Efforts are currently underway by the U.S. Army Corps of Engineers (USACE) to perform a risk assessment of all dams and levees within their portfolio. The vast majority of that portfolio is earthen structures. Findings from the assessments have shown that the major risk drivers for these earth structures are related to erosion (internal and external), overtopping, poorly designed and constructed intrusions (such as pipe crossings), and other factors to a lesser degree (such as burrowing animals). Therefore, the USACE is currently investigating several of these failure modes with emphasis on internal and external erosion. This paper will highlight efforts to investigate surface erosion, which may lead to breach formation and growth, by use of laboratory scale model testing to understand and properly capture the physics of the problem. These data are informing improvement and development of numeral methods for use in ongoing risk assessments.

1 Introduction

The U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi, is conducting research to evaluate the mechanisms of erosion for coarse-grained material, which may result in failure or loss of integrity on earthen structures. The first phase of research, described in this paper, is in the planning stage and involves laboratory tests using instruments and equipment designed specifically to replicate erosion processes. The objectives of the tests are to provide a better understanding of erosion parameters, k_d and τ_{cr}, and to identify the dominant surface erosion mechanism for coarse-grained material. The knowledge and data gained from these laboratory tests, and physical models scheduled for a second phase of research, will provide better guidance on the selection of breach modeling parameters and modeling approach, thereby supporting improved engineering analysis of flood risk arising from dam and levee erosion and breach processes.

2 Background

The U.S. Army Corps of Engineers (USACE) uses several models for evaluating breach in earthen embankments (i.e., dams and levees) and spillways. There is some uncertainty in the erosion model input parameters (i.e., erodibility coefficient, k_d, and critical shear stress, τ_{cr}) of coarse-grained materials that comprise earthen dams or levee embankments. There is also uncertainty in the type of erosion mechanism (i.e., headcutting or surface erosion) that is active during breach initiation and formation. A better understanding of k_d and τ_{cr} and the dominant surface erosion mechanism for coarse-grained material would provide a better overall understanding of the likelihood of breach (is overtopping/erosion duration sufficient to cause breach) as well as allowing for a better understanding of consequences as a result of a better estimate of breach initiation time, breach formation time, and peak breach outflow.

A widely-accepted mathematical representation that describes the physical phenomena of erosion states that the rate of erosion is proportional to the difference in effective hydraulic shear stress and critical stress as adjusted by some coefficient of erosion. The erosion rate is generally expressed as [1]:

$$\varepsilon_r = k_d\,(\tau - \tau_{cr})^a \qquad (1)$$

where:

ε_r is the erosion rate (cm sec^{-1})
k_d is the erodibility coefficient (cm/sec)/(N/cm^2)
τ is the average hydraulic boundary shear stress (Pa)
τ_{cr} is the critical shear stress (Pa), and
a is an empirical exponent assumed by Hanson to be unity [2, 3].

However, this equation may not be suitable for larger gradations where particles are moving independently. The values of erosion parameters, k_d and τ_{cr}, of coarse-grained material used in breach models are lacking in literature because of the size of testing equipment and the flow velocity required to capture these parameters are large, often cumbersome. In a laboratory setting, there are three devices most widely used to calculate k_d and τ_{cr} from a soil sample: Jet Erosion Test (JET), Erosion

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Function Apparatus (EFA), and Hole Erosion Test (HET). However, these devices are limited in size and, hence, also to the size of particles that can be tested.

In modeling a breach, some models do not consider the specific breach mechanism. For example, in some breach programs, a dam is modeled as an in-line structure in two dimensions that uses a simplified user-defined erosion rate to model breach. The model considers the breach to start near the top of the embankment and to end when negligible erosion is occurring. This period of time is referred to as the critical breach time. While this approach relates flow conditions to breach erosion rate, it does not allow for specific geometric, hydraulic, or soil conditions that would affect breach initiation and growth rate to be considered. The model may not include the process of head-cut initiation at a knickpoint that progresses towards the crest, which is associated mainly with fine-grained or cohesive materials and possibly with larger-size materials that still contain a considerable amount of fines.

3 Methodology

The approach focuses on specific requirements for risk assessments. This includes research on determining breach modeling parameters and breach failure mechanism related to coarse-grained materials that comprise the shell layer of dams. The approach is divided into: (1) *Selection of test gradations*, (2) *Laboratory tests for material characterization*, (3) *Description of physical models for testing gradations, and* (4) *Measurements and Results.*

3.1 Selection of test gradation

Dams have different zones based on design function. Example gradations for coarse-grained material placed on the downstream face of a dam are plotted in Figure 1. The figure includes gradations from the following sites:

- Townshed Dam, West River, Vermont, USA
- Hop Brook Lake Dam, Hop Brook, Connecticut, USA
- Painted Rock Reservoir Dam, Gila River Basin, Arizona, USA
- Oroville Dam, Oroville, California, USA
- West Dam, California, USA
- United States Society of Dams (USSD), Materials for Embankment Dams, 2011
- Norwegian large breach test on rock fill dam, Norway
- Levee Embankments, France

Several factors related to soil gradation affect rate and mechanism of erodibility. Previous research has shown that the denser the soil, the less erodible it is (Hanson et al., 1990). Compacted soil at its optimum yields the highest dry density, and well-graded soil has a higher compacted density than poorly-graded soil. The material will be tested at a minimum of 95% compaction (Standard Proctor ASTM D698) with ±2% of optimum water content. These values for compaction and water content are those that are typically specified in project specifications. It is possible to perform additional runs on the same gradation using different compactive efforts to assess the effect of as placed density on erodibility.

Two sets of gradations are proposed for testing; the first set (1-1 through 1-12) is shown in Figure 2 and is based on varying D50 and fines and clay content. The second set (2-1 through 2-10) is based on actual example gradations shown in Figure 1 with few changes to limit the maximum size of soils to 6 in. (Figure 3).

The total number of proposed gradations is 22. Set 1, in general, is finer than Set 2 and will enable assessing the effect of clay fraction on the erosion behavior of soils. Set 2 will address the effect of larger-size materials. A shaded area is added to both figures to highlight the band of the selected example gradations shown in Figure 1. The model tests will start with the finer gradations (smaller D50) and continue to larger D50 values. Table 1 summarizes those gradations.

3.2 Laboratory test for material characterization

The selected materials for testing will be characterized via laboratory testing, mainly sieve analysis and compaction, to control the construction of the model. The type of the laboratory test for compaction is dependent on the size of the gradation. Compaction of finer gradations with less than 30% passing 3/4 in. will be performed in the 4-in. mold following ASTM D698, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. For larger gradations, compaction will be performed in 12-in. or 18-in. molds using a mechanical rammer and the same energy as stated in ASTM D698. Where fines (finer than sieve #200) content is higher than 10%, a hydrometer test will be performed. On the erosion side, k_d and τ_{cr}, will be measured using JET and/or EFA tests for gradations that are fine enough for such tests.

3.3 Description of physical models for testing gradations

The evaluation of erosion on the selection gradations will be performed using physical models in an ERDC flume facility (Figure 4A-D). The flume has dimensions of 128 ft long, 24 ft wide, and 10 ft deep and is capable of creating flows up to 225 cfs.

Two model layouts will be used to study erosion parameters and mechanics of erosion separately although measurements from both models may be used in the final calculations. All of the gradations in Table 1 will be used in all model tests. The layouts are described as follows:

3.3.1 Model 1 (Erosion parameters)

The first model layout will focus on the measurement of erosion parameters in compacted gravelly soil materials. The materials will be compacted in a box of 3W × 6L ×

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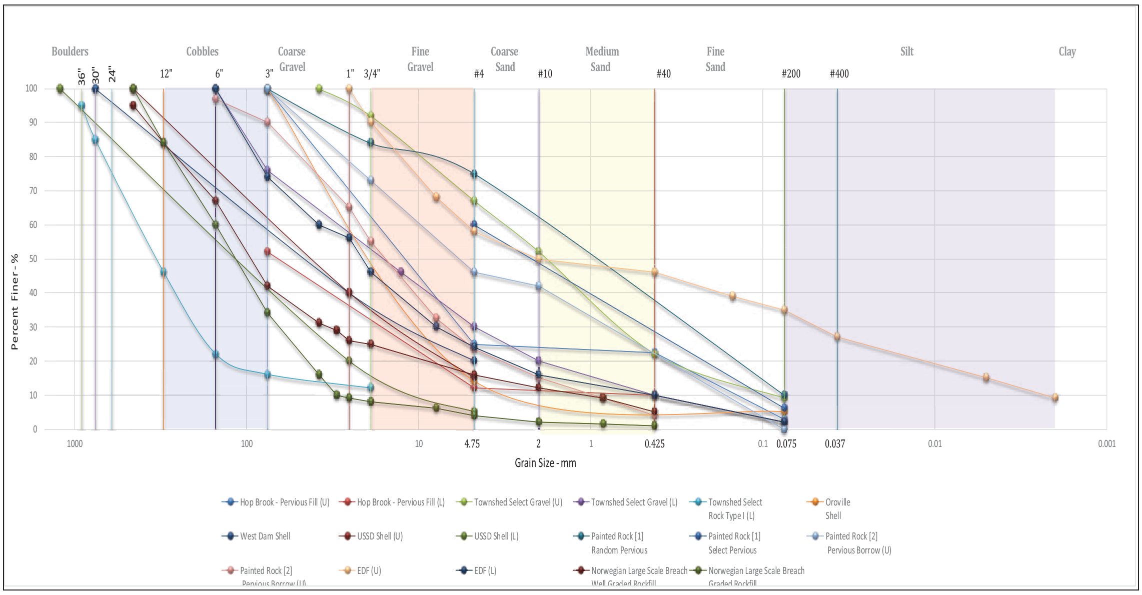

Figure 1. Gradation examples of coarse-grained materials.

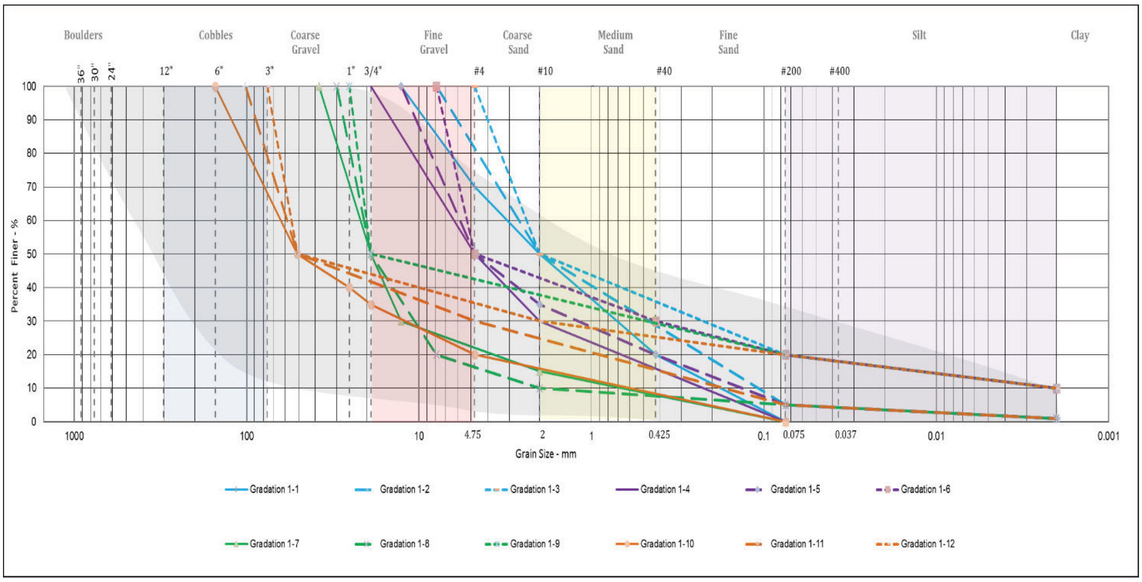

Figure 2. Proposed gradations for Set 1 of model tests.

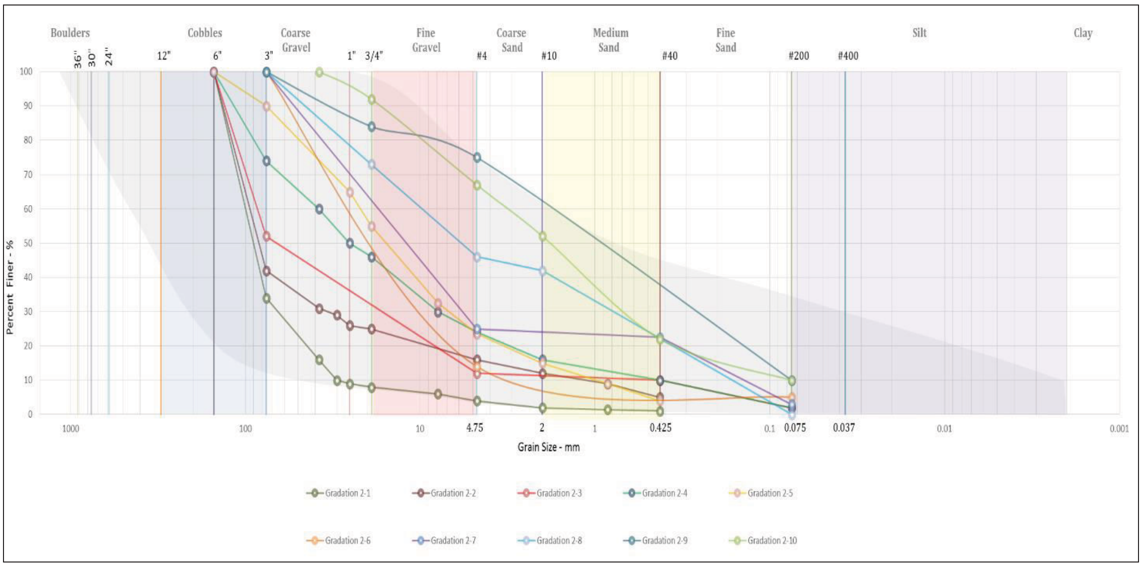

Figure 3. Proposed gradations for Set 2 of the model tests.

Gradation No.	D_{50} (mm)	Max Size (in.)	%< Gravels (3 in. – 76mm)	%< Sand (#4 – 4.75mm)	%< Fines (#200 – 0.075mm)	% Clay (2 µm-0.002mm)	C_u D_{60}/D_{10}	C_c $D^2_{30}/D_{10}.D_{60}$	Comments
1-1	2	0.5	100	70	0	-	15.8	1.0	Well graded
1-2	2	0.31	100	82	5	1	23.8	0.7	
1-3	2	0.2	100	100	20	10	1100	11	
1-4	5	0.75	100	50	0	-	28.2	2.9	Well graded
1-5	5	0.5	100	50	5	1	45.8	2.2	Well graded
1-6	5	0.31	100	50	20	10	2600	17.4	
1-7	20	1.5	100	22	0	-	36.7	10.9	
1-8	20	1.2	100	17	5	1	10.5	2.9	Well graded
1-9	20	1.0	100	42	20	10	1000	4.5	
1-10	50	6	67	16	0	-	103.3	3.9	
1-11	50	4	80	25	5	1	322.2	2.2	Well graded
1-12	50	3	100	30	20	10	27500	36.4	
2-1	90	6	34	4	-	-	3.3	1.3	
2-2	85	6	41	17	2	-	63.3	6.3	
2-3	65	6	51	11	5	1	200	9.0	
2-4	25	6	73	25	3	-	89.4	4.0	
2-5	15	6	90	25	-	-	22	2.2	Well graded
2-6	20	3	100	15	6	1	7.1	1.1	Well graded
2-7	12	3	100	26	3	-	113.3	11.9	
2-8	6	3	100	46	-	-	62.5	0.4	
2-9	18	3	100	67	10	2	40.0	2.2	Well graded
2-10	0.9	1.5	100	75	10	2	22.7	0.5	

Table 1. Summary of proposed gradations for model tests.

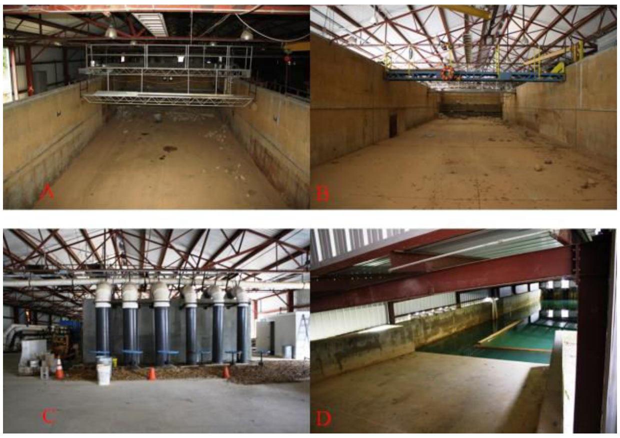

Figure 4. Flume at ERDC, Vicksburg, MS. (A) Looking upstream of the flume from the upper end of the flume, (B) Inside the flume looking upstream, (C) Pumps with capacity of 210 cfs, and (D) Reservoir downstream.

3H (ft), placed in the center of a sloped 6-ft-wide channel. A transitional area upstream of the box will be constructed using a thin layer of same tested material to simulate its roughness. Four samples of each gradation with similar density and grain size will be subjected to a number of hydraulic loadings. The weight of the material before and after each test will be measured to determine the amount of material loss during erosion. LiDAR (Light Detection And Ranging) will be used to calculate the eroded volume. During the test, the depth of eroded area will be recorded at different time intervals to determine the rate of erosion at a given hydraulic loading. Samples will be collected and laboratory tests will be conducted to determine the change in gradation due to erosion. The approach to calculating the erosion rate from the erosion parameters will be reviewed for applicability of larger gradations based on the results from the model tests.

3.3.2 Model 2 (Mechanics of erosion)

The second model layout will focus on studying the mechanics of erosion to identify the conditions that cause surface erosion or head-cut erosion. The proposed model will be 4 ft high, 4-ft crest width with an upstream and downstream slope of 1V to 2H. The base of the model will be 2 ft thick, constructed using the same material as the body of the model. The width of the model will be limited to a minimum of 6 ft for constructability. The upstream slope of the model will be covered to limit through flow and effect of seepage induced effects. A wider/taller model may be required to accommodate the larger gradations. Each model construction and test run is estimated to take approximately two weeks. Mechanism and development of erosion will be monitored via cameras recordings and LiDAR and Sonic System survey measurements.

A consideration in both models is hydraulic loading. Hydraulic loading will be varied during the test to assess the effect of hydraulic loading on the mechanism of erosion. According to the Hjulström diagram (Figure 5), a velocity of approximately 25 cm/sec is required for soils to start eroding, and about 400 cm/sec is required for particle size of 150 mm (approximately 6 in.). Figure 6 shows calculated water head and velocities at the testing model.

4 Measurements and results

For both models, the progress of erosion will be recorded using:

- Two sets of cameras, one from the side through the Plexiglas of the channel, and three from above covering upstream, crest, and downstream areas of the model. The cameras output will be useful during the test duration where the water is clear. In case of fines eroding the circulating water becomes unclear, other measurements as described below will be main source of measurements.

- The velocity profile of the flow will be measured using Laser Doppler Velocimetry (LDV), which can be moved in two axes; vertical and horizontal, upstream and downstream from the model. Placing tracers in the flow would be considered as an indication of flow turbulence.
- The energy head will be measured and recorded using manometers or Pitot tubes along the side of the channel.
- The progress of erosion will be measured using a LiDAR system; however, because of the limitation of LiDAR (i.e., to "see" through muddy water), it may only be useful to record the model geometry before and after a test. During the test progress, a multi-beam side scan sonar (Sonic System 881A Imagenix) will be used; however, because it can be used only under water, the test has to be temporarily stopped and gradually flooded.

Using observations and measurements from both models (mainly Model 1), the values of k_d and τ_{cr} will be calculated. The results will be compared to the values from erosion laboratory JET and/or EFA tests for the finer end of the tested gradations, and to EDF's developed testing equipment when data becomes available.

A set of curves will be produced for k_d and τ_{cr} for use in breach models. If possible, the relationship between the gradation shape and characteristic size with these erosion parameters will be shown in graphs and curves. Erosion rates at varying shear stresses (flow velocity and depth) will be reported.

Erosion parameters and mechanism based on Model 1 and Model 2 results will be incorporated to calibrate and validate breach modeling and compare to case histories. The measured critical stress, τ_{cr}, and erosion index, k_d, on the finer gradations will be compared to values available in literature [4, 5] in addition to the laboratory test results.

5 Conclusions

The results of the flume model tests will increase the state-of-knowledge of the erosion processes in the following areas: (1) rate of erosion and critical stress; (2) mechanism of failure: head-cut erosion versus surface erosion, (3) effects of velocity and flow conditions, (4) effects of gradation shape and fines content, and (5) progression of head-cut and growth of initial breach.

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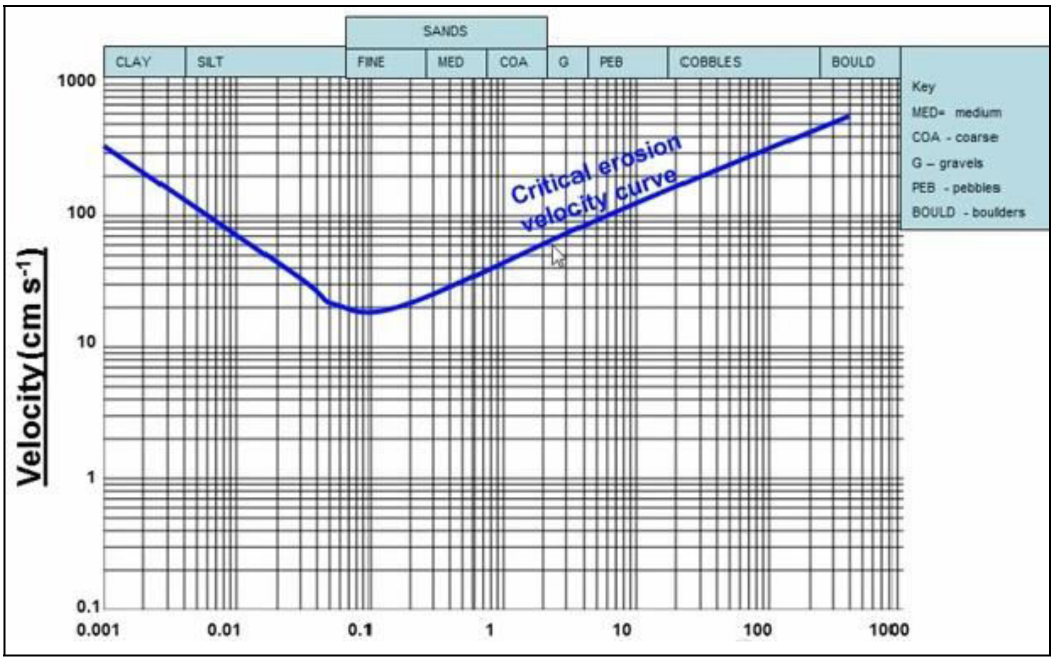

Figure 5. Hjulström diagram showing the critical erosion velocity.

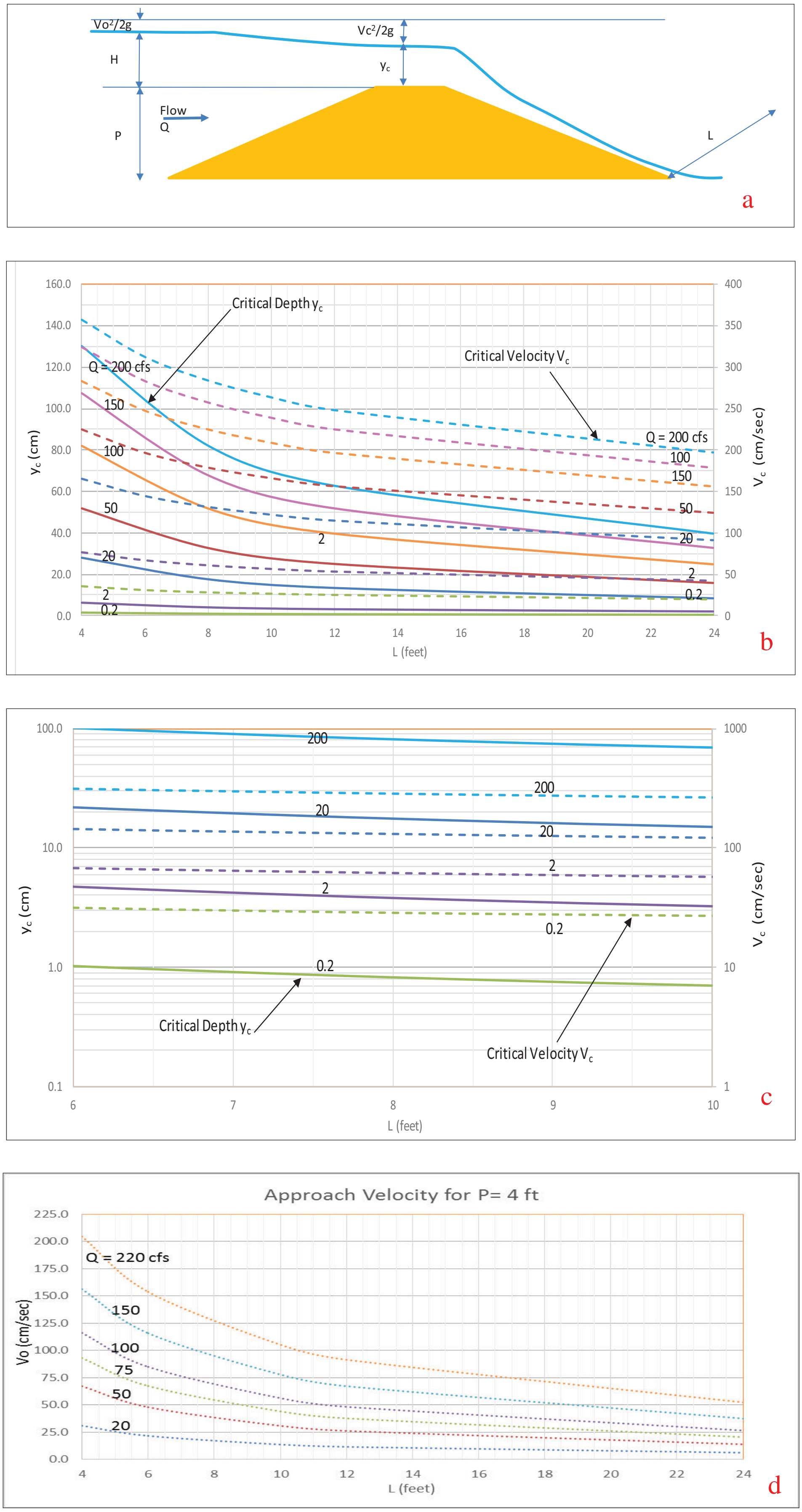

Figure 6. (a) Model Sketch, (b) Critical Depth and Velocity for Full Range of Model Width, (c) Critical Depth and Velocity for Model Width between 6 ft and 10 ft (Log Scale), (d) Approach Velocity V_o.