Analytical and hydraulic model study of highway culvert sand-blockages

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Abstract

Culverts are essential elements of a highway system. Currently, many hydraulic engineers are facing problems of sand-blockage inside culverts along coastal highways. To establish design criteria and a maintenance policy for Hawaii coastal highways, a research program is being carried out at the Department of Civil and Environmental Engineering, University of Hawaii at Manoa, USA. In establishing the design criteria for coastal culverts, we use overland flow theory to consider the design storm, drainage area, detention basin and culvert size as a system. A computational scheme is thus created. For predicting whether a sand-blocked culvert that may be opened by floodwater or it may need manual cleaning, we built hydraulic models for two existing culverts on the Island of Oahu, Hawaii in our Fluid Mechanics Laboratory. The preliminary results of our computer model and hydraulic model are very encouraging.
Keywords: highway culverts, send-blockage, simulation model, direct runoff hydrograph, hydraulic model.

1 Introduction

Coastal highway flooding or "overtopping" by surface runoff is the concern. Mitigation measures considered herein are two-fold. The first management measure to minimize overtopping is attributed to the routine maintenance of a culvert, where the culvert is maintained free of debris to facilitate unimpeded surface runoff through a culvert. The second management measure is to assess the adequate nature of the existing culvert and detention pond combination as the

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drainage area and design storm changes. It is important to recognize that maintaining an open or clear culvert does not necessarily ensure adequate drainage from surface runoff that may occur. In addition to maintaining an open culvert, minimizing overtopping by surface runoff over a roadway is also managed by a combination of culvert size and storage capacity of a detention pond. Various combinations of the culvert size and the storage capacity of the detention pond may be appropriate to facilitate proper drainage of surface runoff. To minimize overtopping of roadways for a given design storm, (a) the ability to keep drainage culverts clear of debris and/or sand blockage; and (b) having an adequate combination of culvert size and detention pond storage capacity for a specific drainage basin, are two key criteria for long-term management. In order to establish the management criteria, two tasks are undertaken. The first task is to create a flood routing based computational scheme. This simulation model considers the design storm, drainage area, detention pond, and culvert size as a system. For predicting whether a sand-blocked culvert may be opened by floodwater or it may require manual cleaning, the second task is to build hydraulic models for existing culverts on Windward Oahu, Hawaii in the Fluid Mechanics Laboratory at the University of Hawaii at Manoa. Therefore, physical phenomena may be observed from these models.

2 The simulation model

The computer simulation model developed in this study is a flood routing based computational scheme, which considers design storm, drainage area, detention pond and culvert size as an interactive system. As indicated in fig. 1, for the drainage area, a direct runoff hydrograph may be synthesized for a given design storm. This synthesized direct runoff hydrograph from the defined drainage area is actually the inflow hydrograph to the detention pond. The dynamic routing of the inflow hydrograph through the detention pond and culvert system will result in an outflow hydrograph. This routing process is carried off by using PondPack [1].

2.1 Design storm

In accordance with Hawaii Department of Transportation's Design Criteria for Highway Drainage [2], this study uses an one-hour 50-year rainstorms or six-hour 50-year rainstorms for drainage areas less than 200 acres and drainage areas equal to or greater than 200 acres, respectively.

2.2 Synthesizing direct runoff hydrograph

Direct runoff from a drainage basin may be simulated by the Nash-Muskingum method if one assumes that inflow to the basin is a known design storm; and the drainage basin storage may be represented by one or more reservoir type storage. The Nash-Muskingum method is used to compute direct runoff of the drainage basin given the area, rainfall intensity for a 50-year recurrence interval, and the recession constant. The direct runoff hydrograph from the drainage basin is the inflow hydrograph to the detention pond. The outflow hydrograph of the drainage basin is calculated by the following relationship:

$$O_2 = C_o I_2 + C_1 I_1 + C_2 I_2 \tag{1}$$

Where O_2, O_1 are the outflow rates; I_2, I_1 are the inflow rates for time intervals 2 and 1 respectively; and C_0, C_1, and C_2 are:

$$C_2 = e^{-\left(dt/K\right)};C_1 = \left(\frac{K}{dt}\right)*\left(1-C_2\right)-C_2;C_0 = -\left(\frac{K}{dt}\right)*\left(1-C_2\right)+1$$

The Muskingum coefficient, K, is considered as a function of recession constant, K_1, of a watershed [3].

2.3 Inflow hydrograph rationale and assumptions

The inflow hydrograph used in the generalized simulation model is actually the time-dependent outflow from the drainage basin for a given design storm. For drainage areas less than 200 acres, the 50-year 1-hour design storm is used.

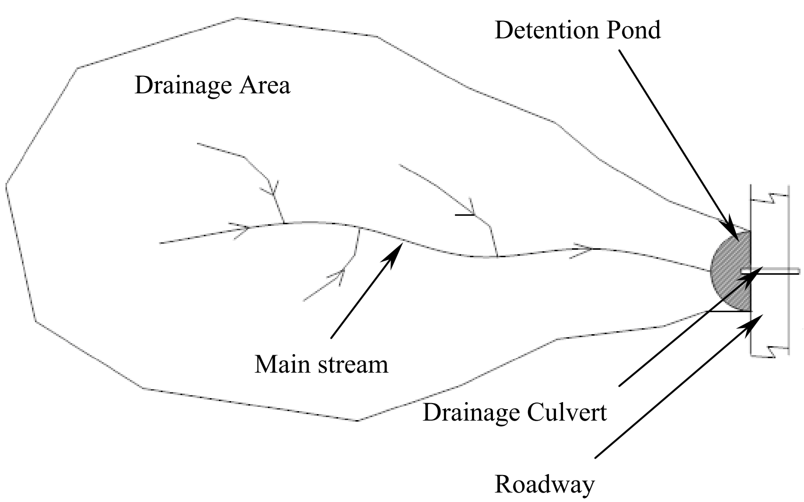

Figure 1: Conceptual simulation model.

2.4 Detention pond rationale and assumptions

Three different conceptual detention ponds were considered in this study (fig. 2). An average slope of 1%, 2% or 3% of a detention basin was used to estimate the storage capacity prior to flood routing process through a culvert. As indicated in fig. 3, the detention basin is assumed to be half of a cylindrical cone, where the center of the cone is the projection of the culvert, headwall, and roadway. The average slope represents the slope of the right cone.

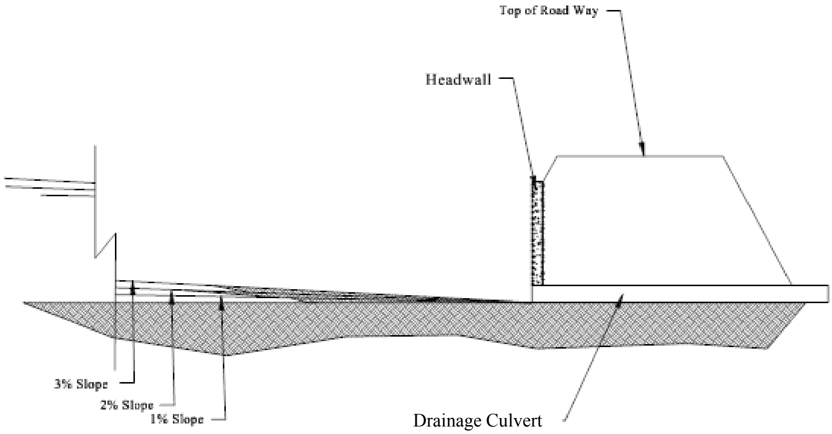

Figure 2: Details of a culvert.

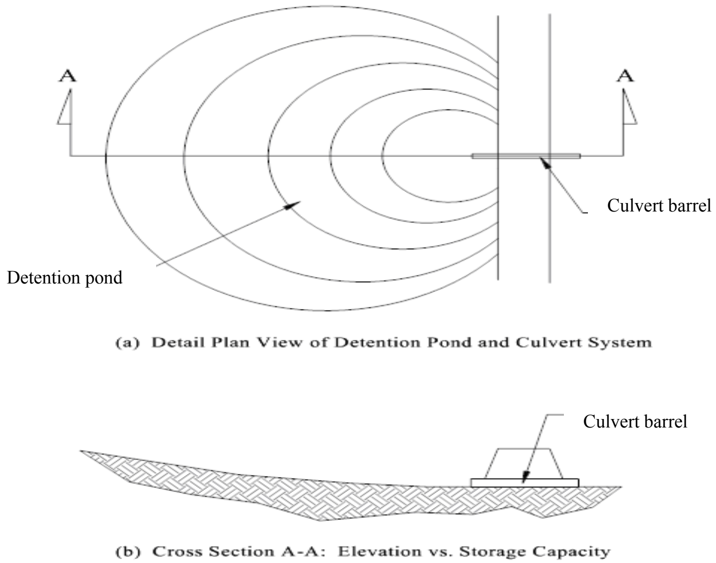

Figure 3: Schematic diagram of a detention pond-culvert system.

3 Punaluu and Hauula culverts

The Punaluu and Hauula drainage areas on the windward of Oahu, Hawaii were selected for the study by using GIS software [4] and topological maps [5]. The watershed areas Punaluu and Hauula are estimated at 262 acres and 167.3 acres, respectively. Hydraulic models of the Punaluu circular culvert and Hauula box culvert were fabricated in the Fluid Mechanics laboratory of the University of Hawaii at Manoa. The purpose of the model study is to observe the time for a culvert to self-open under various completely sand blocked conditions. The scaled models were blocked with beach sand, and experiments were conducted to evaluate the time the culvert would open as a function of water depths.

3.1 Laboratory culvert model and dynamic similitude

The model scale was calculated using the concept of dynamic similitude for open channel flow. Dynamic similitude will provide a relationship between the laboratory results and actual conditions expected in the field. For free surface flow the parameter in dynamic similitude between the model and prototype is the Froude Number, Fr. By definition:

$$Fr = \frac{V}{\sqrt{g * y}} \tag{2}$$

where V is the velocity; g is the gravitational constant; and y is the depth of the flow. Therefore, for free surface flow models, the dynamic similitude between the model and the prototype is:

$$Fr_m = Fr_p$$

$$\text{or, } \frac{V_m}{\sqrt{y_m}} = \frac{V_p}{\sqrt{y_p}} \tag{3}$$

where V_m and V_p are model velocity and prototype velocity, respectively; and y_m and y_p are the flow depths in the model and prototype.

$$\text{Since, } \frac{V_m}{V_p} = \left(\frac{y_m}{y_p}\right)^{\frac{1}{2}} = L_r^{\frac{1}{2}} \tag{4}$$

$$\text{or, } \frac{V_m}{V_p} = \frac{\left(l_m / t_m\right)}{\left(l_p / t_p\right)}$$

$$\text{Therefore, } \frac{V_m}{V_p} = L_r\left(\frac{t_p}{t_m}\right) \tag{5}$$

where the model scale $L_r = \frac{y_m}{y_p}$, and l_m and l_p are length dimensions in model and prototype, respectively.

Substituting eqn. 4 into eqn. 5 yields:

$$t_m = t_p * \sqrt{L_r} \tag{6}$$

where t_m = model time for culvert to self-open; and t_p = actual time for the culvert to self-open.

3.2 Description of Laboratory Experiment

The culverts were "packed" with beach sand to simulate complete blockages. The sand was placed in the model culvert with various compaction efforts. A constant volume of sand was placed in the model culvert for all experimental trails. The slope of the culverts was placed at 0 % for both the 9-inch by 12-inch model box culvert (fig. 4) and 6-in model circular culvert. The sand was placed in the middle of the model culvert barrel, simulating actual conditions along the coast of Windward Oahu, Hawaii.

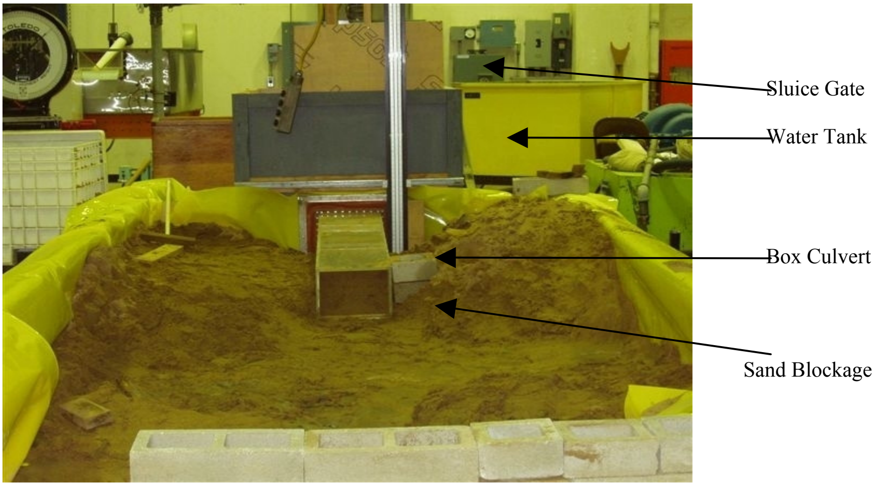

Figure 4: Photograph of model box culvert experiment for Hauula.

4 Results and discussions

A block diagram of model runs is summarized in fig. 5. This figure indicates that a total of 12 series of model runs were performed. Forty different sizes of box culverts and fifteen different sizes of circular pipe culverts were modeled for each of the three different conceptual detention ponds of 1%, 2% or 3% slopes (fig. 2) under 17 different inflow hydrograph scenarios.

Laboratory observations from model study of both the box culvert as wall as the circular culvert indicate that the time for the culvert to open varies as a function of the soil moisture and the degree of "compactness" of the sand in the model culvert. The time for the model box culvert to self-open ranged from 15 seconds to 8 minutes 39 seconds. The time for the circular culvert to self-open

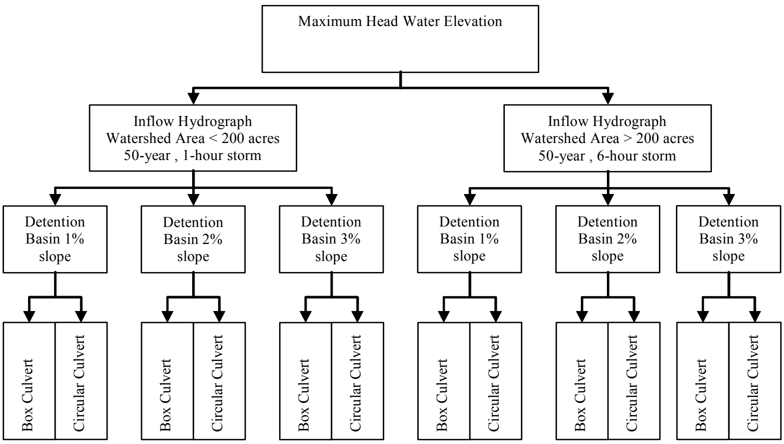

Figure 5: Block diagram of model runs.

Table 1: Values for inflow hydrograph for <200 acres with 3% average sloped detention pond.

Box Culvert Size			175 Acres					
			Time to Max Headwater (hr)		Detention Pond			
Hgt (ft) (D)	Wdt (ft) (W)	Max. Headwtr (ft) (H_1)	Closed BC t_p (hr) (1)	Open Qpeak t_p (hr) (2)	Qpeak (cfs) (3)	Max WSEL (ft) (4)	Min Vol (ac-ft) (5)	Min Area (ac) (6)
6	6	7.20	0.47	1.10	261.44	6.85	4.295	1.88
6	7	7.20	0.47	1.07	271.69	6.35	3.417	1.61
6	8	7.20	0.47	1.05	278.77	5.92	2.764	1.40
6	10	7.20	0.47	1.03	287.19	5.21	1.891	1.09
6	12	7.20	0.47	1.02	291.45	4.67	1.363	0.88

Notes:
D,W: Height and Width of a box culvert, respectively.
Col. (1): Time to reach the maximum allowable HW elevation, when culvert is completely blocked, for a given detention pond with inflow generated from a given area of a drainage basin.
Col. (2): Time to reach the peak discharge specified in Col. (3), when the culvert is fully open, in a specified detention pond.
Col. (3): Peak discharge for a fully open culvert.
Col (4): Maximum water surface elevation when the peak discharge in Col. (3) is reached.
Col. (5): The volume of the detention pond for the time and peak discharge specified in Col. (2) and Col. (3).
Col. (6): The detention pond surface area for volume specified in Col. (5).

ranged from instantaneous to 4 minutes and 5 seconds. As an example, consider the Hauula 6-ft by 8-ft box culvert described in Section 3. The storage capacity of its existing detention pond is 0.053 ac-ft and its inflow produced drainage area is 162.7 acres. The same size box culvert, with a drainage basin of 175 acres, and a 3% slope detention pond is summarized in table 1.

For a 163-acre drainage basin, the system response may be conservatively estimated with 175 acres condition in table 1. This table indicates that a detention pond with an average gradient of 3% requires a minimum of storage capacity of volume of 2.764 ac-ft, and yield a maximum surface water elevation of 5.92 ft above the culvert invert, if the box culvert is fully open. Therefore, the highway will not be overtopped. However, the completely blocked culvert would take approximately 0.47 hours (Col.1 of table 1), or 28 minutes and 12 seconds, to open before overtopping occurs at a maximum allowable headwater elevation of 7.2 ft. The range of observed time in the laboratory for the $L_r = 1/8$ Hauula model box culvert to self-open is between 15 seconds and 8 minutes and 36 seconds. By means of eqn. 6, the model time is converted to prototype time of 24 minutes and 18 seconds. This result implies that if the 6-ft by 8-ft box culvert at Hauula is completely blocked by sand, it will self-open before the detention pond is overflowed, provided the minimum storage capacity of the pond is 2.764 ac-ft. However, the existing storage capacity at the Hauula culvert system is 0.053 ac-ft, therefore, under the 1-hour 50-year design storm, the highway will be overtopped. Furthermore, the peak discharge and its surface elevation for the Hauula box culvert system with existing storage capacity under fully open conditions, were 280.22 cfs and 5.74-ft respectively. The corresponding values in table 1 are 278.77 cfs and 5.92-ft. This example illustrates the effectiveness of the simulated results. The results summarized in fig. 5 are intended for guiding decision makers in prioritizing available resources in management of existing drainage culverts along coastal highway on Windward Oahu, Hawaii.

5 Conclusions

A generalized simulation model has been demonstrated in establishing the management criteria for clearing and maintenance of culverts along the coastal highway throughout Windward Oahu, Hawaii. Results obtained from this study provide a screening tool in which decision makers are able to identify the frequency of culvert clearing, or to identify the need to study existing drainage culverts or detention ponds to minimize overtopping of the roadway for a given drainage area. The screening of an existing culvert and detention pond is intended to provide a qualitative measure for a drainage culvert. The generalized simulation model presented herein, do not reflect or simulate actual conditions of any particular drainage basin.

References

[1] Bentley PondPack 10.0, *Users manual*, Bentley Systems, Inc. New York, N. Y., 2006.

[2] State of Hawaii, *Design criteria for highway drainage*, Department of Transportation, Honolulu, HI, U.S.A., 2006.

[3] Wu, I. P., Flood hydrology of small watersheds: evaluation of time parameters and determination of peak discharge. Transactions of American Society of Agricultural Engineers, Vol. 12, No. 5, pp. 655-663, 1969.

[4] ARC-INFO, *Users manual*, Environmental Systems Research Institute, Redland, CA, U. S. A., 2006

[5] U. S. Geological Survey, Digital topographic maps for Oahu, Hawaii, Honolulu, HI, U.S.A.