ISSN 0511-5728
The West Indian Journal of Engineering
Vol.38, No.2, January 2016, pp.59-63

A Road Collapse at Pont Cassé, Dominica: Hydrologic and Hydraulic Aspects

Gyan Shrivastava

Department of Civil and Environmental Engineering,, Faculty of Engineering, The University of the West Indies, St. Augustine Campus , Trinidad and Tobago, West Indies
E-mail: Gyan.Shrivastava@sta.uwi.edu

(Received 6 August 2015; Revised 9 November 2015; Accepted 5 December 2015)

Abstract: *In the early morning (about 5:30 AM) of Friday 19th April 2013 a motor vehicle fell in a 13m deep and 25m wide ravine, which had rapidly formed across a major road, at a culvert crossing at Pont Cassé in the island of Dominica (15^0N, 16^0W) in the Lesser Antilles. There were intermittent heavy rains in the preceding three days, and particularly during the preceding twenty-four hours. About 400 mm of rain is believed to have fallen on the catchment upstream of the culvert crossing. This accident unfortunately led to the death of two persons. This technical note, based on a site visit during 5th to 7th May 2013, first outlines the hydrologic and hydraulic setting of the road collapse, as well as the unavailability of event specific hydrologic data. It concludes – essentially using heuristics, judgment and transposition - that the probable causes of the road failure were twofold - firstly, a flash flood, arguably, with a return period in excess of 100 years, and secondly, an inadequate maintenance of a concrete culvert in a terrain prone to slope instability. It ends with the following recommendations (a) there is a need to expand the network of recording rain-gauges and stream-gauges in Dominica for preparing Rainfall Intensity-Duration-Frequency and Flood Frequency Curves respectively, for an optimal design of hydraulic structures; (b) the Caribbean Council of Engineering Organisation should undertake the preparation of a code of practice for engendering the same in the islands of the Commonwealth Caribbean; and (c) in the aforementioned islands, there is a need for preventive maintenance and/or retrofitting of culvert and bridge crossings.*

Keywords: *Culvert, Dominica, Flood, Rain, Road, Scour*

1. Introduction

This technical note refers to the scour of a road during a flash flood in Dominica (15^0N, 16^0W), which is an island in the Lesser Antilles (see Figure 1). Some specific aspects of this event are as follows: at about 5:30 AM on Friday 19th April 2013, a motor vehicle fell in a 13m deep and 25m wide ravine, which had rapidly formed across a major road, at a culvert crossing at Pont Cassé. There were intermittent heavy rains in the preceding three days. A non-recording rain-gauge, located about two kilometers away, indicated that during the preceding twenty four hours, about 400 mm of rain might have fallen on the small catchment upstream of the said culvert crossing. This accident at Pont Cassé unfortunately led to the death of two persons. This technical note presents a brief outline of observations made during a site visit two weeks after the incident and attempts to highlight the underlying causes. Its objective is to reinforce the need for hazard resistant design of Civil Engineering infrastructure in the Commonwealth Caribbean Region.

2. Hydrologic Setting

Dominica is a mountainous island where precipitation is dominated by its orography (see Figure 1). Indeed, it is considered a natural laboratory to study tropical meteorology (Smith et al. 2012).

Figure 1. Dominica: An island in the Lesser Antilles
Source: Macmillan (2006)

Specifically, its orographic enhancement factor, defined as the ratio of precipitation between high and low terrains, can range between 2 to 12 during a storm. Not surprisingly, its average annual rainfall shows a marked spatial variation ranging from a high of more than 7,600 mm at its highest elevation to about 1,500 mm at sea level. In such a hydrologic setting, a carefully planned network (WMO, 2008) of recording and non-recording rain-gauges and stream-gauging stations is essential for hydraulic engineering design of highway drainage structures (FHWA, 2002). In particular, there is a need for Rainfall Intensity Duration Frequency (IDF) Curves and streamflow frequency curves. However, the current data base of hydrologic information in Dominica is limited to a record of daily rainfall at only a few locations and sporadic stream flow measurements across the island.

Unavailability of hydrologic data in Dominica, as mentioned earlier, provides a well-known paradox to Engineering Hydrologists (Prakash, 1999). On the one hand there is the scale and complexity of hydrologic processes. On the other hand there is often an insufficiency of hydrologic data in terms of temporal length, spatial extent, continuity and accuracy. Moreover, engineering projects cannot wait for sufficient hydrologic data to be collected. Under such circumstances use of heuristics, transposition and judgment is therefore inevitable.

Figure 2 shows that the catchment upstream of the road breach is approximately 0.5 km^2 and is almost entirely forested (Google Earth). It seems to have an average slope of 9% and a time of concentration, t_c, of about 17 minutes. There is a 3:1 ratio between the Annual Rainfall at Pont Cassé and Melville Hall (US Army Corps of Engineers, 2004).

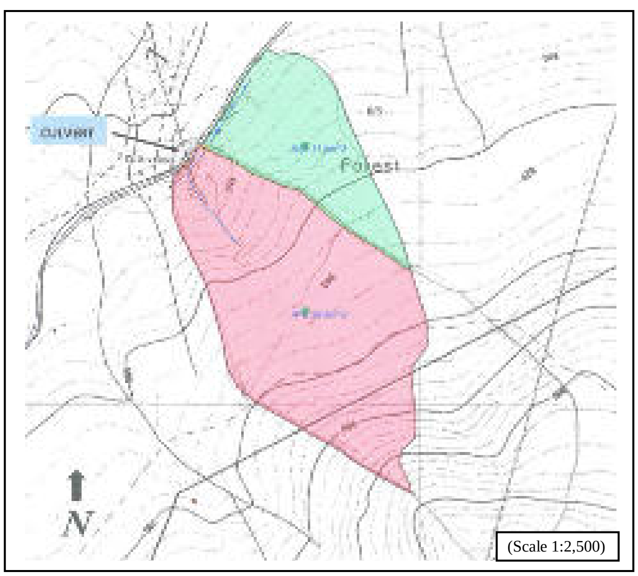

Figure 2. Estimated catchment area upstream of the road collapse Source: Cooper (2013)

Thus, if we scale the Melville Hall Daily Rainfall of 129 mm on 18th April 2013 to Pont Cassé, we arrive at figures which are close to a 100 year 24 hour rainfall at an orographically similar location in Puerto Rico (US Department of Agriculture 1961). Further, although a temporal distribution of the rainstorm is not known, a cloudburst and flash flood cannot be ruled out. Indeed, there is a record of a cloudburst rain of 198.12 mm in 15 minutes at Plumb Point in Jamaica in 1916 (WMO, 2009). However, a cloudburst (defined as rainfall intensity greater than 100 mm/h over a short duration) is almost an unknown meso-scale weather system throughout the world; since rain-gauge networks generally are unable to capture it due to its highly localised occurrence (Thayyen, 2013). Figure 3 shows a photo taken on a collapse of a road at Pont Cassé on 19th April 2013.

Figure 3. A photo showing a collapse of a road at Pont Cassé

3. Estimation of Peak Flow

In Engineering Hydrology, it is recognised that peak flood flow estimation for 50 and 100 year return period, based on extreme value probability analysis of stream flow record, is the gold standard. This is because stream flow is the output of a catchment in response to a precipitation input. However, such an analysis requires 20 to 30 years of stream flow data, which is generally not available, especially in developing countries. In the absence of a suitable stream flow record, the appropriate hydrologic method for flood peak flow estimation is the application of an event based rainfall/runoff model such as the Triangular Unit Hydrograph proposed by the Natural Resource Conservation Service (Chow et al., 1988, NRCS, 1986). This however, requires an IDF curve for the catchment in question, and land use and topographic information. When neither of these two hydrologic methods is possible, Global and Regional Frequency Analyses – which are generally used for cross checking the estimates of the previously mentioned two methods—can be applied as a primary method of estimation.

It is against the foregoing background, that this report estimates, as a first approximation, the likely return period (probability of occurrence) of peak flow which occurred during the breach of the road on the morning of Friday 19th April 2013. It does so by a combination of Global and Regional Flood Frequency Analyses (DHV Consultants, 1998, Meigh et al., 1997). Specifically, Mean Annual Flood (MAF) is estimated first and it is then scaled up for higher return periods. For estimating MAF a regression equation for West Africa ($\leq 8^0$N) is selected, since in the author's experience its hydrology is similar to that in the Caribbean. This perhaps should not be surprising, since Caribbean Weather Systems normally originate off the coast of Africa. The MAF equation includes the catchment area (AREA) as well as the Average Annual Rainfall (AAR), and gives an MAF of approximately 2 m^3s^{-1} for the stream at Pont Cassé (see Figure 4) for an AREA = 0.5 km^2 and AAR of 6,645mm.

Figure 4. The stream at Pont Cassé

Regional correlation with the Global Frequency for the stated region in Africa shows that a 50 year return period peak flood is about two times the MAF and a 100 year peak flood is about three times the MAF. Subsequently, comparison with the hydraulic capacity of the failed culvert indicates a rainstorm of return period ≥ 100 years.

An attempt can also be made, with an accurate map of the catchment and rainfall at Pont Cassé (if belatedly available), to distribute the 24 hour rainfall using Type III Distribution and compute the peak flow using the NRCS method (NRCS, 1986). The visually estimated curve number (about 50) would need to be corrected for antecedent moisture condition (AMC III) in view of about 200mm of rainfall, at Melville Hall, in the preceding two days. This estimate can act as a cross-check of the peak flow estimated earlier. This is an area for further work .

4. Hydraulic Setting

Given that the channel slope downstream of the culvert outlet is much steeper (17%) than the culvert slope of 9%, the possibility of culvert operating under outlet control does not arise. Further, in view of near vertical drop of 5m approximately 14m from the outlet, the possibility of any backwater effect downstream (which would have led to outlet control) is also ruled out.

As stated previously, a mathematical analysis of flow through a culvert under inlet control condition is difficult due to complex physics. Therefore, physical scale models are tested, for critical situations such as culvert spillways going through earth dams or in lock gates, to observe and calibrate its hydraulic characteristics. Nevertheless, an approximate mathematical analysis is possible from first principles (Prashun 1987), from the geometry of the inlet, and the original road cross section (see Figure 5).

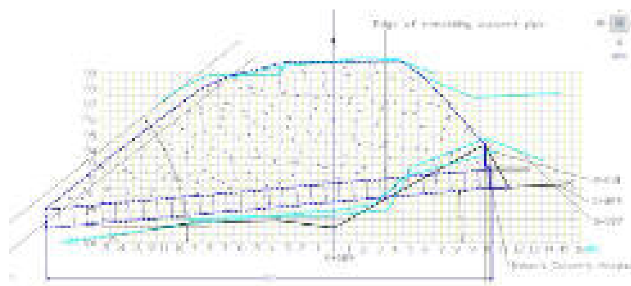

Figure 5. Reconstructed Road Cross Section
Source: Gay (2013)

Hydraulic analyses under inlet control with a headwater depth at the road crest level (i.e. 8m) gave a peak discharge, of the 1.2m diameter culvert, as $11.3m^3s^{-1}$, entrance velocity of 13 m/s, an inlet velocity of 10.5 m/s running 95% full, an outlet velocity of 10m/s with culvert flowing full. Such a velocity regime can impart a force (approximately 50 kNm^{-2}), which is about half of the atmospheric pressure at sea level on a dislocated/exposed culvert joint.

5. Failure Mechanism

The mechanism of road failure remains open to question. On one hand, there is a possibility of a peak flow exceeding the culvert capacity. This can cause failure due to combined overflow erosion and progressive jet erosion at culvert joints (through joints dislocated by traffic vibration, slope instability or seismic activity over time) commencing at the outlet (see Figure 6). On the other hand, if the culvert capacity was not exceeded, there is the possibility of failure entirely due to progressive jet erosion of dislocated culvert joints commencing at the outlet. One interim conclusion that can be made from these perspectives is that, irrespective of the failure mechanism the choice of reinforced concrete box culvert (FHWA, 2005) is clearly superior for a replacement structure.

Now some comments on field evidence: to begin with, the presence of gabion baskets at the downstream end (see Figure 7) raises the possibility that there was a downstream slope failure and dislocation of 1m long culvert pipe segments some time prior to the event. This observation underscores the need for a regular inspection, and preventive maintenance of bridges and culverts. Besides, the inlet structure (see Figure 8) and upstream segments of the culvert remained intact (see Figure 9) and give credence to the argument that an overflow did not take place.

Figure 6. A photo showing dislocated culvert joints

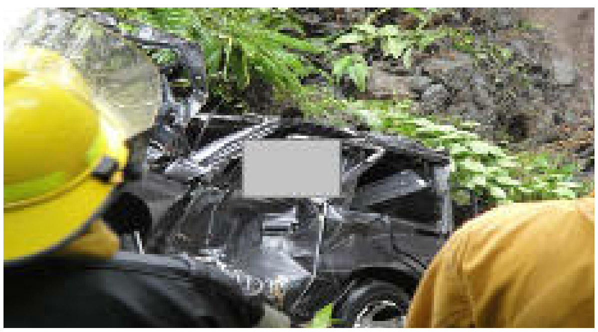

Figure 7. A photo showing gabion baskets at the culvert outlet

Figure 8. A photo showing the culvert inlet

Figure 9. Remains of the culvert at the upstream end

Furthermore, the shape of the three post failure cross sectional profiles (0+087, 0+089 and 0+091) seems to indicate an overflow. It is hoped that a geotechnical analysis/numerical simulation may resolve this contradiction. This then, is another area for further investigative work.

6. Discussion

Failure of culverts and bridges due to scour phenomenon is not uncommon across the world, and often leads to loss of life (Kala, 2014, Murillo, 1987, Polemio and Lollino, 2011). With reference to the Commonwealth Caribbean region, there seem to be four primary causes for such failures. First, uncertainty in estimating the magnitude and intensity of a rainstorm is due to insufficient hydrologic data. Second, equally unpredictable, is a catchment's response to a given rainstorm, underscoring the need for good quality information on land use, topography and geology. Third, there is, frequently, an absence of a code of practice or guidelines for the design of drainage structures, which results in subjective design criteria. Finally, there is the ever present issue of poor maintenance of infrastructure.

7. Conclusions

Admittedly, the hydraulic and hydrologic analyses lack rigour primarily due to unavailability of event specific hydrologic data. In such circumstances, methods of analyses depend more on the data available than on the nature of the problem posed. Nevertheless, it is believed that in due course more information may be obtained which can permit a deeper investigation of the event.

Meanwhile, the following interim conclusions may be made: (a) the scour failure at a culvert crossing at Pont Cassé can be attributed to concurrent occurrence of a storm of a return period in excess of one hundred years and overflow on the road embankment. These circumstances were exacerbated by dislocated joints of concrete culvert segments arising from prior slope instability; (b) there is a need to expand the network of recording rain-gauges and stream-gauges in Dominica.
Specifically, Rainfall Intensity-Duration-Frequency and Flood Frequency Curves are needed for optimal design of hydraulic structures; (c) the Caribbean Council of Engineering Organisation should undertake the preparation of a code of practice for the design of hydraulic structures in the islands of the Commonwealth Caribbean; and (d) in these islands, there is a need to regularly inspect, repair and retrofit culvert and bridge crossings.

Acknowledgements:

The author is grateful to Emile Lancelot, Kendell Johnson and Lucien Blackmoore for their kind hospitality and support with field investigations and information, and to The University of the West Indies for the financial assistance for travel. The collegial support of Vincent Cooper and Derek Gay is also acknowledged. Besides, credit is given to Kendall Johnson, for all photographs in this paper

References:

Chow, V.T, Maidment, D. R., and Mays L.W. (1988), *Applied Hydrology*, McGraw Hill

Cooper, V. (2013), Personal Communication, June

DHV Consultants, (1998), *Water Resources Management Strategy*, Delft Hydraulics and Lee Young & Partners / Government of Trinidad and Tobago

FHWA (2002), Highway Hydrology, Federal Highway Administration, Reston, Virginia

FHWA (2005), *Hydraulic Design of Highway Culverts*, Federal Highway Administration, Reston, Virginia

Gay, D. (2013), Personal Communication, June

Kala, C.P. (2014), "Deluge, disaster and development in Uttarakhand Himalayan region of India: Challenges and lessons for disaster management", *International Journal of Disaster Risk Reduction*, Vol.8, pp.143-152

NRCS (1986), *Urban Hydrology for Small Watersheds*, National Resource Conservation Service / US Department of Agriculture

Meigh, J.R., Farquharson, A.K. and Sutcliffe, J.V. (1997), "A worldwide comparison of regional flood estimation methods and climate", *Hydrological Sciences Journal*, Vol.42, No.2, pp.225-244

Macmillan (2006), Dominica: An Island in the Lesser Antilles, in: *Macmillan Caribbean Junior Atlas*, Macmillan Press

Murillo, J.A. (1987), "The scourge of scour", *Civil Engineering*, Vol.57, No.7, pp.66-69

Polemio, M. and Lollino, M. (2011), "Failure of infrastructure embankments induced by flooding and seepage: a neglected source of hazard", *Natural Hazard and Earth System Sciences*, Vol.11, pp.3383-3396

Prakash, A. (1999), "Guest Editorial", *Journal of Hydrological Engineering*, Vol.4, No.1, pp.1.

Prashun, A.L. (1987), *Fundamentals of Hydraulic Engineering*, Holt, Rinehart and Winston, New York, p.445-451

Smith, R.B., Minder, J.R., Nugent, A.D., Storelvmo, T., Kirshbaum, D.J., Warren, R., Lareau, N., E Palany, P., James, A., and French, J. (2012), "Orographic precipitation in the Tropics: The Dominica experiment", *Bulletin of the American Meteorological Society*, Vol. 93, No.10, pp.1567-1579.

Thayyen, R.J., Dimri, A.P, Kumar, P., and Agnihorti, G. (2013), "Study of cloudburst and flash floods around Leh, India during August 4-6, 2010", *Natural Hazards*, Vol.65, No.3, pp.2175-2204

US Army Corps of Engineers (2004), *Water Resources Assessment of Dominica, Antigua and Barbuda, and St. Kitts and Nevis*, Washington D. C.

US Department of Agriculture (1961), *Generalised Estimates of Probable Maximum Precipitation and Rainfall-Frequency Data for Puerto Rico and Virgin Islands*, Technical Paper NO. 42, Washington, D.C.

WMO (2008), *The Guide to Hydrological Practices*, WMO No. 168, World Meteorological Organisation, Geneva

WMO (2009), *Manual on Estimation of Probable Maximum Precipitation*, WMO No. 1045, World Meteorological Organisation, Geneva

Author's Biographical Notes:

Gyan Shrivastava *studied Civil Engineering at Indian Institute of Technology at Delhi, Imperial College in London and at The University of the West Indies (UWI), St. Augustine. Professor Shrivastava is a Chartered Civil Engineer, a Member of the Institution of Civil Engineers in London, and a recipient of IADB and BPTT research fellowships in Engineering Hydrology. In 2006, he received a Gold Award from the Caribbean Water and Wastewater Association for his teaching, research and public service. In 2015, he retired from the Department of Civil and Environmental Engineering at The UWI.*

■