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Investigating Causes of Highway Crossing (Bridges and Culverts) Outlet Erosion in Selected Structures of Mekelle to Adigrat Highway - Tigray, Ethiopia

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Abstract

Roads are backbones for one's country economy and play great role in public's mobility. To make these well function proper drainage systems must have; and these drainages are major causes for land degradation and gully formation. This investigation was conducted in selected road crossings; Agulae river bridge and Kehen and Betehaweriat culverts of Mekelle to Adigrat highways using hydrologic and hydraulic analysis. Hydrologic and hydraulic analysis was conducted with the help of HEC RAS 4.1.0 for bridge and HY 8 hydraulic analysis software's for culvert. Agulae river bridge has scouring problem up to 13.00 m, 13.96 m left and 18.97 m, 20.04 m right for 50 and 100 years peak flood; and overtopping 0.24 m for 50 years. Kehen and Betehaweriat culverts have high outlet velocity 6.456 m/s and 5.241 m/s and high Froude number, 3.4 and 2.92 respectively. Remedial measures were reviewed based on the hydraulic analysis result computed. Based on hydraulic analysis results; the recommend energy dissipaters are 1.204 m thickness stone riprap for bridge; and USBR type IV basin for culverts.

Keywords: Bridges; Culverts, Froude number; Hydraulic analysis; Outlet velocity, Peak flood hydrologic; Scouring

Introduction

Roads which are pervasive, persistent and potentially cumulative form of landscape; are backbone for one's country economy and play a major role for public's mobility and trade movement. In 2008, Ethiopian Road Authority (ERA) [1] state that` Regional Roads Bridge Inventory and Inspection (RRBII) project was launched in aiming dissemination of bridge management to rural road authorities and to have full data of bridge and culvert existing in the country.

As a result of Bridge asset Management Support Service, we could have 4407 bridges and 40567 culverts (opening length <4 m) registered with all kinds of geographical, physical and condition data, and regionally registered 539 bridges and 3647 culverts. The primary purpose of road crossings (bridges and culverts) are to serve as conveyance structures preventing water from pooling on the roadway surface and damage the road structure.

The analysis were done using ARC MAP 10.2.1 and excel spread sheet for the determination of the catchment area, catchment characteristics and peak flood of 50 and 100 years return period based on ERA drainage design manual [2]; and HEC RAS 4.1.0 and HY 8 were used for the hydraulic analysis of bridge and culverts respectively. Based on the obtained findings from the socio economic and hydraulic analysis, possible alternative remedial measures were drawn also according the size and type of drainage structures.

The main objective of the study is; to investigate the causes of highway crossing (Agulae river bridge and Kehen and Betehaweriat culverts) outlet erosion; using hydrologic and hydraulic analysis. And the sSpecific Objectives are;

1. To check the hydrologic and hydraulic performance of selected highway cross drainage to check whether hydraulic performance is correct
2. To suggest possible solutions and control mechanism for the erosion on the highway outlet erosions.

Research Methodology and Data Collection

Investigation and study of causes for highway crossing outlet erosion is very complex and multi-disciplinary approach; which relates with Hydraulic and Geotechnical engineering [3-5].

Nature and Source of Data: Both primary and secondary sources of data have been exploited and the major data's are:

1. Geometric data establishing the connectivity of the river system; cross section data, reach lengths, and stream junction information. Hydraulic structure data's (bridge, culverts) which are also considered geometric data's will get by surveying on selected two culverts and one bridge.
2. Metrological data (rainfall data), collected from Ethiopian Metrology Agency. Rainfall data reliability was checking using simple statistical techniques of examining average over longer periods using relative standard error is:

$$\sigma_q = \frac{\sigma_n}{Q_o} \quad (1)$$

Where: σ_q = relative standard error

σ_n = Logarithmic standard deviation

Q_o = Long term annual mean of rainfall, mm

Therefore relative standard error for Wukiro area, Agulae Bridge and Kehen culvert Is 9.91 which is less than 10%, so according ESRDF, the data series can be taken as reliable and adequate. The rainfall data for Adigrat, Betehaweriat culvert is also reliable because the: relative standard error is 7.56.

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And outliers have been checked using;

$$Y_L = Y_{mean} - K_n * stdv = 10.216 \quad (2)$$

Where: Y_L= lower outlier

Y_{mean}= mean of rainfall data series

Kn= constant

Stdv= standard deviation of rainfall data; are consistent for both areas.

Fitting distribution was checked using HEC SSP 2.0 and the best fit is Log Person III and based on this rainfall data the maximum design rainfall of Wukiro Kilte Awillalo and Adigrat have been computed.

3. Land use and soil maps of the study area are described by the Digital Elevation Model (DEM) using (ARC MAP 10.2.1) from Tekeze soil and land use map of selected culvert and bridge.
4. Drainage areas were determined from Digital Elevation Model (DEM) of Ethiopia which has 90m*90m resolution, using ARC MAP 10.2.1.
5. Time of concentration (Tc) was computed using Ethiopia Roads Authority drainage design manual [2]; for defined watercourse, channel flow occurs. The recommended empirical formula for calculating the time of concentration in natural channels was developed by the US Soil Conservation Service as shown in equation 3 [6-8].

$$T_C = \left(\frac{0.87L^2}{1000Sd} \right)^{\wedge 0.385} \quad (3)$$

Where:

T_c = Time of concentration (hours).

L = Hydraulic length of catchments measured along flow path from the catchment boundary to the point where the flood needs to be determined (km).

Sav = Average slope (m/m).

Sample size of the study

For the hydrologic and hydraulic analysis two culverts one from Kehen and the other from Betehaweriat near Adigrat and one bridge Agulae river bridge have been selected. For the bridge the hydrologic and hydraulic analysis was carried out using SCS method and HEC RAS 4.1.0 respectively and using SCS method and HY 8 for Kehen and rational method and HY 8 for Betehaweriat culverts respectively.

Hydrological model

There are many hydrologic models which have developed in the past decades due to advances in hydrologic sciences; among them the SCS method of peak discharges estimation (runoff estimation) is one. So for this study SCS method and rational method have been used. This is because it is applicable for areas which do not have sufficient rainfall and stream flow records and ERA drainage design manual recommended [9].

Rational method is estimates runoff as a function of runoff coefficient, frequency factor, rainfall intensity and area using equation 4 [1].

$$Qd = 0.278Cf * C * I * A \quad (4)$$

Where: Qd = Design discharge M^3/s

Cf = Runoff coefficient, unit less,

C = Frequency factor,

I = Intensity of rainfall, mm/hr

A = Area of the basin, ha

Hydraulic model

Hydraulic analyses of river bridge and culverts have been computed using HEC RAS 4.1.0 and HY8 respectively; from the rate of flood runoff (discharge) and the volume of runoff that will pass through the bridge.

Manning's coefficient for hydraulic analysis

Based on ERA Drainage design manual guidelines the manning 'n' value of Agulae river bridge was selected from the table given on ERA drainage design Manual. Picture of bed channels and flood plains for which the discharge has been measured and manning's n has been captured.

Calibration and validation of HEC RAS

There is no enough gauged flow data to calibrate and validate the hydraulic computation. But the HEC RAS was calibrate using recording observed flow from rating curve of depth verses discharge of Agulae river bridge (Amanual, 2008-09) with 139 observed flows of 2007, and 98% degree of freedom, the equations are given as follows;

$$ME = 1 - \frac{\sum_{i=0}^{N}(o_i - P_i)^2}{\sum_{i=0}^{N}(o_i - o_{mean})^2} \quad (5)$$

$$RRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=0}^{N}(o_i - P_i)^2}}{\frac{1}{n}\sum_{i=0}^{N}O_i} \quad (6)$$

Where: ME = Model Efficiency

RRMSE = Relative Root Mean Square Error

N = number of observations

O_i = the observed value, m

P_i = predicted value, mm

O_{mean} = is the mean observed value, m

Hence; the ME and RRMSE are 0.976295 and 0.010672 respectively which are relatively close to the 1 and 0 respectively. The model is good enough and the celebrated manning's roughness fitting with HEC RAS model is n=0.117.

Result and Discussion

Hydrologic analysis

Delineation of drainages: The longest flow path, location and elevation vary and drainage area coverage of three drainages (Betehaweriat culvert, Kehen culvert and Agulae Bridge) is as shown in the Table 1.

Computation of drainage parameters: For agulae drainage area 39.58% of the total drainage is cultivable land of which 35.67% of the total is lithic leptosoil/clay loam. 10.5% clacic vertisol and 1.53% is euteric vertisoil/siltloam. And 1.88% is eutric leptosol. and of the total 31.93% is scrublands of which 23.41% is Halpic Luvisol and 4.78% is luvic calcisol and 3.74% is halpic calcisol, 16.36% is grass land with calcric cambisol type of soil and 2.2% is natural forest with Eutric cambisol and haplic arsenol type of soil.

For Kehen drainage area 42.25% of the total drainage area is caltivable land; rainfed; cereal land cover system; unstocked (woody plantation). 41.58% of the drainage area grassland; unstocked (woody plant and 16.17% of the drainage is shurbland; open (20-50%woody cover); and for Betehaweriat drainage area 29.9% of the land covers open bushland and major soil is litho sols type D and 70.1% of the land also covers by open bushland and chromic luvisols type B The detail drainage characteristics of the areas are as shown in the Table 2.

Peak discharge computation: From the computed drainage characteristics above peak flood of the three catchment areas is computed. And the summarized and rainfall intensity and peak discharges from 5 up to 100 years return period of the three drainage areas are result as shown in the Table 3.

Hydraulic analysis

From the above computed design discharges of Agulae river bridge, Kehen and Betehaweriat culverts hydrologic analysis; the hydraulic analysis was computing using HEC RAS 4.1.0 for the river bridge and HY 8 for the culverts.

Hydraulic analysis of bridge

River cross – section data: For Agulae river bridge eight river cross section data's have been surveyed around the bridge location 150m upstream and downstream of the bridge location. The cross section data were collected at an interval of 30 m up to 57 m based on the type of river bed formation and topography to get accurate result. The downstream and upstream river cross sections are shown in Figure 1 to indicate the difference.

The existing dimensions of agulae river bridge: The hydraulic calculation was done using 50 years return period computed. Based on the computation the dimension of the existing 21 m span, 8.9 m width and 1.65m thickness bridge is not adequate for 50 years return period steady flow; which overtop by 0.24 m to the left and right farming lands due to the size of the bridge have small size in comparing to the incoming flow as indicates in Figure 2 below.

Scouring condition of bridge: In order to perform Agulae river bridge scouring analysis; first computing the mean size fraction of the bed material (D_{50}) of the river bed channel and left and right over banks using sieve method and water temperature was adjusted itself by default when the SI unit adjust to metric. The mean size fraction of the

Drainage	Drainage area Km² adjoint	Longest flow path /Km	Elevation				Tc Hr	Slope m/m
			U/S (m)	D/S(m)	@10%(m)	@85%(m)		
Agulae	422.5	45.4	2800	1990	2067.3	2724.546	10.02	0.03
Kehen	1.48	2.5	2465. 9	2267	2367	2291	0.58	0.08
Betehaweriat	0.1215	0.573	2750	2571	2701	2612	0.07	0.29

Table 1: Summarized drainage area, longest flow path, elevation, time of concentration and slope of Agulae river bridge, Kehen Culvert and betehaweriat culverts.

Drainage	Land cover	Soil type	Hydrologic soil group	Rainfall region	AMC	Normal CN	Wet CN
C1	Cultivable land	Calcic Vertisol	D	A1	Good	85	87.59702
	Cultivable land	Eutric Leptosol	D	A1	Good	85	
	Cultivable land	Lithic Leptosol	D	A1	Good	85	
	Shrub land	Haplic Luvisol	C	A1	Fair	70	
	Shrub land	Luvic Calcisol	C	A1	Fair	77	
	Shrub land	Haplic Calcisol	D	A1	Fair	70	
	Natural Forest	Haplic Aerosol	A	A1		36	
	Natural Forest	Eutric Cambisol	B	A1	Fair	60	
	Grassland	Calcaric Cambisol	B	A1	Fair	59	
C2	Cultivated Land; Rainfed; Cereal Land Cover System; unstocked (woody pl)	Calcaric Cambisol	B	A1	poor	72	87.22075
	Grassland; unstocked (woody plant)	Luvic Calcisol	C	A1	Fair	76	
	Shrubland; Open (20-50% woody cover)	Lithic Leptosol	D	A1	Good	79	
C3	Open bushed	Lithosols	D	A1	Good	71	94.9
	`Open bushed	Chromic Luvisols	B	A1	Good	89	

Table 2: Drainage characteristics of (C1) Agulae bridge; (C2) Kehen culvert; and (C3) Betehaweriat culvert.

	Return Period	5 years	10 years	25 years	50 years	100 years
C1 & C2	Rainfall intensity(mm)	75.523	85.431	93.691	102.926	108.978
C1	peak flood (M³/s)	287.558	350.875	404.996	466.632	507.549
C2	peak flood(M³/s)	17.3801	19.6602	21.5611	23.6863	25.0791
C3	Rainfall intensity(mm)	61.38	69.8	76.98	85.27	90.85
C3	0.278*Cf*C*I*A	2.07323	2.35763	2.86017	3.4562	3.8358
Where: C1 Agulae river bridge catchment; C2 Kehen culvert catchment; and C3 is Betehaweriat culvert catchment.						

Table 3: Peak flood computations of Agulae River Bridge, Kihen culvert and Betehaweriat culverts.

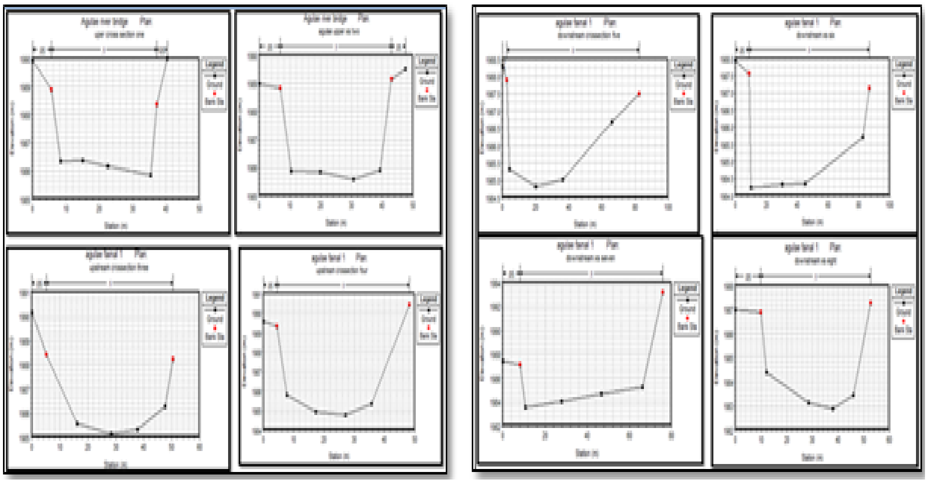

Figure 1: Upstream (left) and downstream (right) cross sections of Agulae river bridge, which have around 50 m difference.

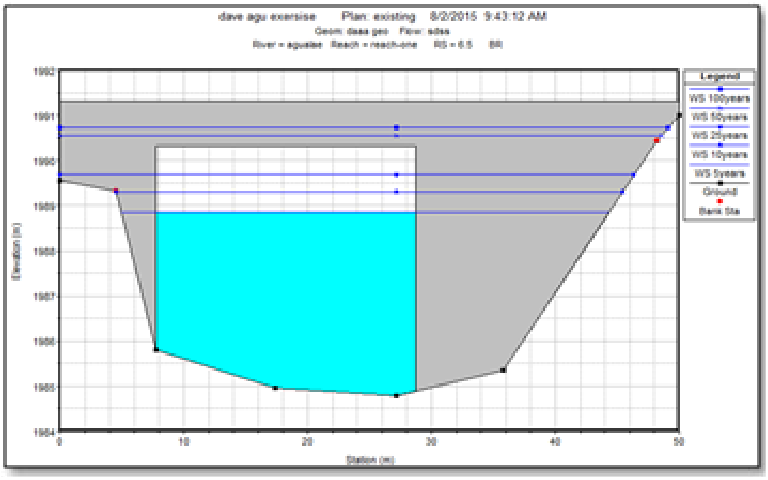

Figure 2: Peak flood profile for 21 m span upstream of Agulae river bridge 50 have not adequate for years return period which over tops by 0.24 m.

bed material/D_{50} of the river channel is 5.5 mm and overbanks 0.78 mm and the scouring conditions summarizes as follows.

Hydraulic analysis of culverts

Hydraulic performance of the existing culverts: Outlet velocity and Froude number of the two structures are very high but the structures have enough capacity to the incoming flow up to 100 years return period. Hydraulic performance of the two culverts was checked using HY 8 software and the summarized results are as shown in Table 4.

i. **Kehen culvert**: is 5m*1.8m box culvert which hydraulic design using HY-8 culvert analysis program looks as shown in the Figure 1 and full culvert analysis result is in Appendix C. The size of the culvert is fit to the incoming flow of 100 years 25.07 m^3/s and it has enough capacity up to the maximum flow of 29.36 m^3/s as shown in Table 5.

ii. **Betehaweriat culvert**: is 2m*2m box culvert in which hydraulic design using HY 8 looks as shown in Figure 2 and its computed size is fit to the incoming flow of 100 years 3.82 m^3/s and it have enough capacity up to the maximum flow of 8.34 m^3/s.

Since the maximum Froude number is 2.92 at 50 years which is greater than 1 and the outlet velocity is 5.241 m/s; for 50 years the flow change to supper critical flow, and there has been a great erosion effect.

Scouring condition at culverts: The natural channel flow is usually confined to a lesser width and greater depth as it passes through a culvert barrel. An increased velocity results with potentially erosive capabilities as it exits the barrel [10] this leads to scour at the bottom of the culvert. From the HY 8 result Kehen culverts have scour dimensions of; length 28.742 m, width 16.068 m, and depth 3.031 m and Betehaweriat culvert has scour dimensions of; length 12.343 m, width 6.411 m, and depth 1.436 m at maximum design flood and practically there is a formation of gully.

Remedial Measure

The crossing structures in the study area are highly affected by gully erosions. Due to runoff are flowing to concentration from the whole catchment to one direction and give speed to erode the soil. Erosion control practices hold soil in place and reduce soil removal by storm water. The most effective way to control erosion is to preserve existing vegetation and replant cleared or bare areas as soon as possible. Based on the drainage structure types the remedial measures have

Return Period	Contraction Scour		Abutment Scour				Combined Scour	
	Ys	Vo	Ys left	Vo left	Ys right	Vo right	Ys left	Ys right
25	3.87	1.43	6.67	1.38	11.79	1.63	10.55	15.66
50	4.5	1.46	8.49	1.32	14.47	1.58	13.00	18.97
100	4.95	1.46	9.01	1.34	15.09	1.62	13.96	20.04
1.7*100	8.415		15.317		25.653		23.73	34.068

Table 4: Scouring condition of the agulae river bridge on given return periods; all dimensions are in meter.

Culvert Name	Total Discharge (cms)	Normal Depth (m)	Critical Depth (m)	Outlet Depth (m)	Tailwater Depth (m)	Outlet Velocity (m/s)	Froude Number
Kehen	23.68	0.381	1.317	0.734	0.426	6.456	3.4
	29.36	overtopping					
Betehaweriat	3.45	0.223	0.672	0.329	0.327	5.241	2.92
	8.34	overtopping					

Table 5: Summary HY 8 result of Kehen and Betehaweriat culverts.

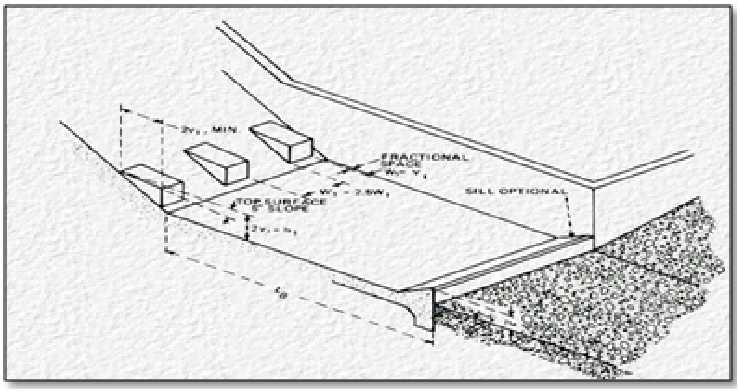

Figure 3: USBR Type IV Basin FHWA HEC 14.

been recommend. The remedial measures were recommended from hydraulic result analysis; computing from the hydraulic results of the bridge and culvert.

Rock riprap at abutments

According FHWA, 2012 the scour preventive alternative stated for existing bridges; For Froude numbers greater than 0.80 the recommended design equation for sizing rock riprap for spill-through and vertical wall abutments is in the form of the Isbash relationship from [10].

$$\frac{D_{50}}{y} = \frac{k}{(s_s - 1)} \left(\frac{V^2}{gy}\right)^{\wedge 0.14} \quad (7)$$

Where, D50 = Median stone diameter, m, V = Characteristic average velocity, m/s, Ss = Specific gravity of rock riprap (2.65), g = Gravitational acceleration, m/s^2, y = Depth of flow in the contracted bridge opening, m, K = 0.61, for spill-through abutments and 0.69, for vertical wall abutments

The rock riprap thickness should not be less than the larger of either 1.5 times D_{50} or D_{100}. The rock riprap thickness should be increased by 50 percent when it is placed under water. Based on this for Agulae river bridge it needs 1.204 m thickness.

Energy dissipaters for culverts

Energy dissipaters are devices designed to protect downstream areas of drainage structure from erosion by reducing the velocity of flow to acceptable limits. Therefore To protect the culvert and adjacent areas, it is sometimes necessary to employ an energy dissipater. From this, the culverts in Betehaweriat and Kehen have outlet velocity of over 4.6 m/s (which are 5.241 m/s and 6.456 m/s) therefore the structure needs 6.7-10.4 m length and 45.72 cm thickness of apron. For Froude number 2.5-4.5 FHWA recommend USBR type IV basin for energy dissipaters and designed using, maximum width of the chute blocks is equal to the depth of incoming flow, y1. From a hydraulic standpoint, it is better to construct the blocks narrower than y1, preferably 0.75 (y1). The block width to spacing should be maintained at 1: 2.5 with a fractional space at each wall. The top of the blocks is placed 2 (y1) above the basin floor and sloped 5 degrees downstream (Figure 3).

Conclusion and Recommendations

Conclusion

The following conclusions were drawn from the results of the investigation:

1. Lack of properly hydrologic and hydraulic design of highway drainage is major cause of downstream erosion and gully formation.
2. The existing Agulae river bridge has not enough capacity to 50 and 100 years return period flow that overtop by 0.24 m and 0.42 m respectively.
3. Kehen and Betehaweriat culverts have high velocity and Froude number and cause for highly degraded land, so they need appropriate energy dissipaters.

4. The hydraulic performance checking indicates the two culverts needs USBR type IV basin energy dissipaters; and Agulae river bridge needs 1.204 m thickness Riprap.

Recommendations

The following recommendations were drawn from this study

1. This study does not look to the dynamics of the morphology of the channels, future studies should focus to consider these.
2. There are forming a lot of gullies due to road crossing and side channel construction in many places; so researchers have to do a lot of works in this topic.
3. Construction of road and road drainages must have in consideration of hydrologic and hydraulic designs to minimize the effect of erosion and socio economic impact of these road drainages.

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