Local Scour at Bridge Piers: the Case of Failure of Kulfo River Bridge at Arba Minch, Southern Ethiopia

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Abstract

The scouring of the streambed around bridge piers can be caused by the characteristics of the stream itself, due to the contraction of the flow by the bridge crossing and/or due to other human interference upstream and downstream of the crossing. Kulfo River Bridge failure in October 1997 due to excessive scour under one of the piers after a flood event is one typical case. It was known that excessive sand/gravel was being extracted for construction purposes prior to the failure. To determine the extent and specific cause of the failure, river survey, bed material sampling and simulation of the pier scour under different river bed scour scenarios were conducted. From the bed material sampling, the grain size was found to vary from very fine sand to small cobbles, showing that the bed is in the coarse-grained class – gravel bed alluvial river. Simulation of the pier scour was done using BRI-STARS (Bridge Stream Tube Model for Alluvial River Simulation) model. The model was calibrated in two phases: (i) calibration of hydraulic parameters, and (ii) calibration of sediment transport parameters. Measured water surface elevations and Manning's roughness coefficient were used as calibration parameters. Among the two gravel/sand mining scenarios (wet-pit mining from the active channel, and bar skimming or scalping above low water level) simulated, the wet-pit mining resulted in maximum scour under the bridge pier when it is followed by a 100-year flood and consequent failure. This result shows that sand/gravel extraction operations within or near the streambed have direct impact on the stream morphology and river structures.

1 Introduction

If an obstruction is placed in a stream, the flow pattern in the vicinity of that obstruction will be modified. Since the transport capacity is a function of the flow characteristics, the transport capacity pattern will also be modified. In an area where the transport capacity is not equal to the rate at which material is supplied, scour or deposition must occur (Molinas, 2000).

The maximum scour depth at a river crossing is composed of three components that, in general, are additive (Molinas, 2000).

1. General scour, due to long-term changes in the riverbed elevation, which would occur irrespective of the existence of the bridge.

2. Contraction scour, resulting from the constriction of the waterway, either natural or due to the bridge and its approaches.
3. Local scour, a consequence of interference with flow by piers or abutments, which accelerate the flow, creating vortices that remove the material around them.

Among the principal causes of general scour are (Klingeman, 1973); effect of upstream dam, dredging, or sand and gravel removal. These will cause an imbalance in the supply and transport of bed load sediments. This imbalance results from upstream interception of bed load, such that the steam mines its bed and banks downstream of the inception point whenever the discharge is sufficient to permit bed load transport and until such time as the interception has ceased or new hydraulic conditions have developed in the downstream river reach (e.g.; a flatter stream gradient with a lower sediment transport capacity that matches the reduced supply from upstream). When dredging or sand and gravel removal occurs downstream of a bridge there may also be an influence upon pier scour at the bridge. Such removal of streambed material, by lowering the streambed and increasing the cross-sectional area of the flow, will reduce the flow velocities, energy slopes, and water slopes in the zone of removal. Extending the reduced slope upstream over the dredged zone from some downstream control point for a particular backwater curve, the water elevation becomes lower than formerly, at upstream limit of dredging. This in turn steepens the energy slope across the next upstream reach and increases the amount of scour there, if the streambed is not resistant.

Contraction scour, which results from the contraction of the waterway due to the bridge and its approaches, may also be further aggravated due to debris transport during floods. Debris caught against piers increases their effective size, concentrates the local flow, causes deeper scour, and can place loads on the structure for which it was not designed. Debris caught on the superstructure, abutments, and approach spans blocks part of the waterway and concentrates the stream flow in the remainder of the bridge opening; increasing velocities, water depths, and scour.

Local scour can occur in the form of either clear-water scour or live-bed scour (Molinas, 2000). Clear-water scour occurs when there is no bed material movement at the upstream of the stream crossing, but the acceleration of the flow and vortices created by the piers or abutments cause the material to move. Live-bed scour (scour with sediment transport) occurs when there is movement of the bed material upstream of the crossing. An excess shear stress must exist to transport the sediment through the scour hole.

In contrast to general scour, contraction scour and local scour (collectively termed as localized scour) are directly attributable to the existence of the bridge (Klingeman, 1973). Local scour occurs when the capacity of the flow to erode and to transport the sediments is larger than the capacity to supply (replace) the sediments. The total scour depth at a foundation is calculated on the basis of superposition of general and localized scour at the foundation (Coleman and Melville, 2001).

In this study, the effect of sand/gravel extraction from river channel due to localized scour of the bridge pier is investigated. To determine the extent and specific cause of the failure, river survey, bed material sampling (both surface and sub-surface) and simulation of the pier scour under different bed material (sand and gravel) extraction scenarios was conducted. From the bed material sampling and analysis, the bed material grain size was found to vary from very fine sand to small cobbles, showing that the bed is in the coarse-grained class – gravel bed alluvial river. Simulation of the pier scour was done using BRI-STARS (Bridge Stream Tube Model for Alluvial River Simulation) model. BRI-STARS is generalized semi-two-dimensional water and sediment routing model with integrated graphical interface for solving river engineering problems. The model is capable of computing scour and deposition through subcritical, supercritical, and a combination of both flow conditions.

The objective of this study is, therefore, to make use of the BRI-STARS model to simulate different sand/gravel mining alternatives regarding the quantity of removal and its location and its effects on the magnitude of scour that may result at the bridge crossing and its vicinity. Knowledge of this result could help to make recommendations on sustainable use of the sand/gravel resource without impairing the bridge structure and river morphology.

2 Effect of Various Parameters on Bridge Pier Scour

The intensity of scour, and thus the scour depth, will depend on the channel flow, the sediments of the bed, and the geometry and alignment of the piers (Graf & Altinakar, 1998;

Simons & Senturk, 1992). As a result of many studies, mostly in the laboratory, there are a number of equations for predicting scour at bridge piers (Simons and Senturk, 1992; Molinas, 2000). In this study, the CSU (Colorado State University, 1975) equation is used in BRI-STARS to model the scour at Kulfo Bridge piers.

The CSU Equation for equilibrium depth of scour is given as:

$$\frac{y_s}{h} = 2K_1K_2\left(\frac{b}{h}\right)^{0.65} F_r^{\ 0.43}$$

where y_s is the scour depth; h is the flow depth just upstream of the pier; K_1 and K_2 are corrections for pier shape and flow angle of attack, respectively (given in Table 1); b is the pier width; F_r is the Froude number just upstream of the pier. The coefficients are derived from laboratory data (Molinas, 2000).

Table 1. Pier shape correction factor (K_1) and flow alignment correction factor (K_2)

K_1 for pier type		**Correction factor, K_2**			
Type of pier	**K_1**	**Angle**	**L/b = 4**	**L/b = 8**	**L/b = 12**
Square nose	1.1	0	1.0	1.0	1.0
Round nose	1.0	15	1.5	2.0	2.5
Circular cylinder	1.0	30	2.0	2.5	3.5
Sharp nose	0.9	45	2.3	3.3	4.3
Group of cylinders	1.0	90	2.5	3.9	5.0
Angle = skew angle of flow; L = length of the pier					

BRI-STARS computes sediment transport as a function of shear stress, streamflow velocity, or some other variable, and then computes contraction scour according to the sediment-transport equation selected. The sediment transport capacity computation is carried out using the following equations: Molinas and Wu (1996), Ackers and White (1973), Yang (1973, 1984), Yang, Molinas and Wu (1996), or Meyer-Peter and Mueller (1948).

Contraction scour is indicated by the amount of channel degradation computed by the model. If bridge piers are present in the study reach, one of the above equations, which are available in the model to compute local scour due to piers are used.

3 Case Study Kulfo Bridge at Arba Minch: Investigation of the Bridge Failure and Pier Scour Estimation Resulting from Gravel Mining

The scouring of the streambed around bridge piers can be caused by the characteristics of the stream itself, due to the contraction of the flow by the bridge crossing and/or due to other human interference upstream and downstream of the crossing. Among the human activities, which aggravate the scour at bridge crossings, is the removal of gravel/sand in excessive amount upstream or downstream of the bridge. Such activities were going on downstream of Kulfo Bridge for a long time. One of the worst conditions occurred in October 1997 when the bridge failed after a flood event. It was known that excessive sand/gravel was being extracted for construction purposes prior to the failure. The field evidence documented by the TCDE (Transport Construction Design Enterprise, 1999) show that the bridge has failed due to excessive pier scour. Figure 1 shows the failed Kulfo Bridge during the 1997 flood. The site investigation report by TCDE (1999) indicated that at the failed pier a downward movement of about 1m has been measured.

Figure 1. Photograph of Kulfo Bridge after its failure during the October 1997 flood (Source: Picture taken during failure)

The stability of gravel-bed streams depends on a delicate balance among stream flow, sediment supply from watershed, and stream channel form. Sand/gravel mining disrupts sediment supply and channel form, which can result in a deepening of the channel over great distances upstream and downstream of the mine site (Roell, 1999).

Kulfo River has shown changes due to various alterations made as a result of human activities. As human population expanded to the present, vegetation and land use has changed in association with agriculture, timber harvest, urbanization, and gravel mining activities, destabilizing the river system as channel adjusted to altered flow regime and eroded sediment. Due to increased population and expansion of the town, construction of roads and other infrastructure increased the demand for gravel in the past few years. At the time of this study and before, sand and gravel used to be heavily mined from Kulfo River, though the exact estimate of the magnitude of extraction is not available.

In this study the BRI-STARS model is used to simulate different sand/gravel mining alternatives regarding the depth of removal and location and its effects on the magnitude of scour that may result at the bridge crossing and its vicinity. Knowledge of this result could help to make recommendations on sustainable use of the sand/gravel resource without impairing the bridge structure and river morphology.

The most common forms of sand and gravel mining in rivers are (NMFS, 1998; Roell, 1999; Hill and Kleynhans, 1999): (1) dry-pit mining, (2) wet-pit mining in the active channel, and (3) bar skimming or scalping. Dry-pit refers to pits excavated on dry ephemeral streambeds and exposed bars. Wet-pit mining involves removal of sand or gravel from below the water table or in a perennial stream channel (that is active channel bed). Bar skimming or scalping, on the other hand, requires scraping off the top layer from a gravel bar without excavating below the low water level.

In order to estimate the relative effects of these forms of gravel mining activities, various alternatives of mining scenarios are applied, which include form of mining, location of mine site with respect to the bridge, and depth of mining in reference to the low riverbed level (thalweg) in the active channel.

In order to estimate the magnitude of scour (at the bridge, upstream and downstream of the bridge) that results from different activities in the vicinity of the bridge, the following sand/gravel extraction scenarios are projected (Nigussie, 2005):

1. Bar skimming or scalping above the low water level downstream of the bridge;
2. Sand /gravel extraction from the active channel (over the thalweg), removing material of thickness equal to 0.5 m from the reach downstream of the bridge.

In the first alternative, all bar material is removed starting from about 50 m downstream of the bridge and extending over the entire reach where sand/gravel used to be extracted.

The lowest level of gravel removal is determined from the water level in the channel during low flow. In the second alternative, for the same location as that for alternative one, material is dredged by 0.5 m from the active channel bed for the entire reach of sand/gravel extraction.

The BRI-STARS model is calibrated and used to simulate the effects of these alternatives on bridge scour and river morphology (Nigussie, 2005). The model calibration is conducted in two phases: (i) calibration of hydraulic parameters, and (ii) calibration of sediment transport parameters.

In phase one calibration, the sediment routing computation is deactivated and focused solely on hydraulic computations. Measured water surface elevations (for both low and intermediate flows) were used for comparison with model predictions. From the surface bed material size distributions of the reach and observed characteristics of the channel during the fieldwork, the range of Manning's roughness coefficients was determined using Cowan (1956) method. The roughness coefficients used in the model ranged from 0.035 to 0.040. Within this range of roughness coefficient, adjustments were made until reasonable agreement was attained between measured and predicted water surface elevations. Calibration results of hydraulic parameters for measured and simulated water surface elevations were found to be in good agreement with R^2 value of 0.93 to 0.99.

The second phase, calibration of sediment transport parameters, is undertaken by activating the sediment transport computation in the model, and providing pertinent sediment data. To calibrate BRI-STARS model for use in the study reach of Kulfo River, the hydrograph for the period of 28 to 29 August 2003 flood was routed through the study reach using the surveyed cross-section data as model input. The flood of August 2003 was selected for modeling because it was the largest flood observed in the season with corresponding significant observed changes. The resulting cross-sections were then compared with the surveyed 2003 cross-sections to determine how well the model would simulate the observed changes.

A number of model runs were made until an optimal combination of parameters was obtained. The optimal combination showed the best correspondence of the resulting model cross sections to the 2003 surveyed data. The sediment transport equation of Ackers and White (1973) and Yang (1973, 1984) were those that gave best agreement of model predictions with surveyed cross sections. However, Yang (1973, 1984) was adopted for this model based on range of bed material size distributions in the reach.

Generally, the comparison between the calibration results and the observed channel changes between 2002 and 2003 indicated that the model provides a good overall estimate of aggradation or degradation at the bridge.

After the model was calibrated, the resulting scour was calculated for the 100-year flood at the bridge site. The results of simulations are compared with the initial bed elevation. The simulation results show that the scour at the bridge and downstream are less for the case of bar skimming than channel mining. It has been found that if bar skimming is followed by a 100-year flood, the resulting maximum scour at the bridge will be 3.02 m, whereas for channel mining it will be 5.31 m. The above two alternatives and that without gravel extraction, in relation to the initial bed elevation, are shown in Figure 2.

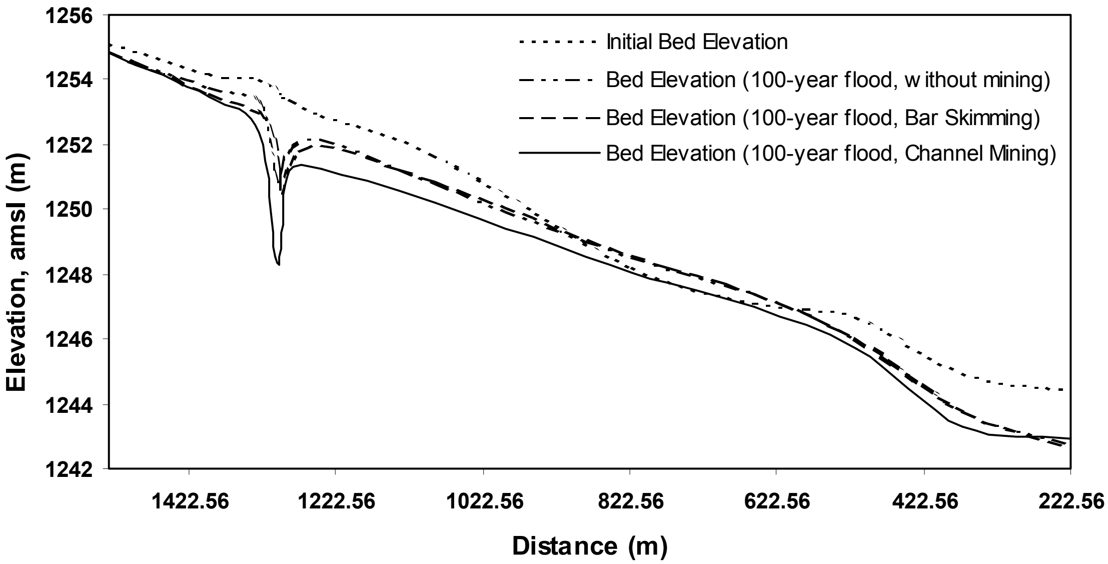

Figure 2. Simulated results of bed elevation profiles and scour at the bridge for 100-year flood and different gravel mining alternatives in relation to initial bed elevation profile (Source: Nigussie 2005).

In both cases, it is also observed that there is a considerable channel scour downstream of the bridge due to headcutting, which advances in the upstream direction from the mine sites.

Although the scour resulting from bar skimming is less than that of channel mining, care has to be taken not to cause adverse effects on the active channel and adjacent riverbanks. It is usually recommended (e.g. Roell, 1999) that a minimum-width buffer be provided that would separate the extraction site from the low-flow channel and the adjacent active channel bank. This would lessen the risk of mining-induced headcuts, but could nevertheless cause channel incision downstream of mining site.

Other problems associated with bar skimming include abrupt relocation of low-flow channel, and higher mobility of loosened sediments. Apart from these adverse effects, bar skimming is still a better alternative as compared to gravel mining from the active channel bed. It is possible to see from Figure 2 that the total scour at the bridge as well as the headcuts upstream of the mine site (or downstream of the bridge) is the highest for the channel mining alternative. Hence, this option is with the most adverse effects on the river morphology and should be totally avoided.

4 Conclusions and Recommendations

Generally, sand/gravel extraction operations within or near the streambed have direct impact on the stream morphology and on the stream's habitat. Obtaining an increased understanding of the potential impacts of these mining activities on aquatic resources will allow concerned water resources related authorities and decision makers to make more informed decisions when issuing gravel resources use authorizations.

The recommendations, which follow, pertain to the specific case of Kulfo River. However, they could also be the considerations that must always be taken into account in all sand and gravel mining operations (based on this study and by others cited above).

- Wet-pit mining from active river channel should be totally avoided;
- Sand/gravel should be removed (from gravel bars) only during low flows and from above the low water level (bar skimming);
- Berms and buffer strips must be used to control stream flow away from the mining site;
- The final grading of the gravel bar (in case of bar skimming) should not significantly alter the flow characteristics of the river during periods of high flows;
- Sand/gravel extraction operations should be managed to avoid or minimize damage to riverbanks and riparian habitat.
- Abandoned stream channels on terraces and inactive flood plains should be used in preference to active channels. Excavation should not take place from below the water table. Dry-pit mining is therefore preferable to other mining methods.

References

Ackers, P. and White, W.R. (1973). Sediment Transport: New Approach and Analysis. Journal of Hydraulics Division, ASCE, Vol. 99, No. HY11, pp. 2041-2060.

Coleman, E.S. and Melville, B.W. (2001). Case Study: New Zealand Bridge Scour Experiences. Journal of Hydraulic Engineering, ASCE, Vol. 127, No. 7, pp. 535 – 546.

Graf, W. H. and Altinakar, M.S. (1998). Fluvial Hydraulics – Flow and transport processes in channels of simple geometry. John Wiley & Sons, Chichster.

Hill, L. and Kleynhans, C.J. (1999). Preliminary Guidance Document for Authorization of Sand Mining/Gravel Extraction, in terms of Impacts on Instream and Riparian Habitats. Internet document:http://www.dwaf.pwv.gov.za/iwqs/waterlaw/discuss/sand/sandfin.htm.

Klingeman, P.C. (1973). Hydrological Evaluations in Bridge Pier Scour Design. Journal of Hydraulic Engineering, ASCE, Vol. 99, No. HY 12, pp. 2175 – 2184.

Molinas, A. (2000). User's Manual for BRI-STARS. U.S. Department of Transportation, FHWA.

Nigussie Teklie Girma (2005). Investigation on Sediment Transport Characteristics and Impacts of Human Activities on Morphological Processes of Ethiopian Rivers: Case Study of Kulfo River, Southern Ethiopia, Ph.D. dissertation, Dresden University of Technology, Dresden, Germany.

NMFS (1998). National Marine Fisheries Service (NMFS) National Gravel Extraction Policy. Internet Document: http://swr.ucsd.edu/hcd/gravelsw.htm

Roell, M.J. (1999). Sand and Gravel Mining in Missouri Stream Systems: Aquatic Resource Effects and Management Alternatives. Missouri Department of Conservation, Conservation Research Center, Columbia, Missouri.

Simons, D.B. and Sentürk, F. (1992). Sediment Transport Technology: Water and Sediment Dynamics. Water Resources Publications.

Transport Construction Design Enterprise (TCDE) (1999). ´Kulfo River Bridge Rehabilitation Report (unpublished) ´, Addis Ababa, Ethiopia.

Yang, C.T. (1973). Incipient Motion and Sediment Transport, Journal of Hydraulics Division, ASCE, Vol. 99, No. HY10, pp. 1679-1704.

Yang, C.T. (1984). Unit Stream Power Equation For Gravel. Journal of Hydraulics Division, ASCE, Vol. 110, No. HY12, pp. 1783-1797.