

# Hydraulic Simulation of Erosion and Scour at Cunas Bridge, Huamancaca Chico District, Chupaca-Peru

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## ABSTRACT

This study developed a hydraulic simulation to identify critical erosion zones and to propose appropriate structural protection measures. Topographic, hydrological, and sedimentological data were processed to model both historical flow conditions and climate change scenarios using QGIS, HEC-HMS, and HEC-RAS. The results indicate that, under historical conditions, maximum erosion depths reached 5.54 m, while under climate change scenarios, they increased to 7.78 m. An eroded river reach of 70.38 m was identified, with an average erosion impact of 1.81 m along the bridge, indicating a high level of structural risk, which is further exacerbated by sediment and debris accumulation in the riverbed. The analysis shows that erosion of the Cunas River has caused significant deterioration of bridge piers and abutments, adversely affecting local connectivity and the regional economy. For future bridge designs, it is proposed that maximum discharge be considered together with sediment transport effects and projected climate change. In addition, structural riverbank protection measures, such as riprap, gabions, groynes, dikes, retaining walls, or channelization works, should be incorporated into design and mitigation strategies.

*Keywords-erosion; scour; bridge; river Cunas; rainfall; Chupaca*

## I. INTRODUCTION

The primary objective of this research is to develop a hydraulic simulation of erosion and scour at the Cunas Bridge, located in Huamancaca Chico, Chupaca, Junín, Peru. To achieve this objective, the present study defines the area of influence using QGIS, models the hydrological behavior of the Cunas River with HEC-HMS, and develops the hydraulic model of the river basin using HEC-RAS. The analysis carried out includes estimating design discharges under conditions with and without sediment transport, evaluating the hydrological regime of the Cunas River basin based on historical precipitation records, peak discharges, and extreme flood events, and assessing their influence on erosion and scour processes. Additionally, the study aims to identify and characterize critical zones of erosion and scour at the Cunas Bridge, thereby demonstrating the relationship between hydrological analysis and hydraulic design. Bridges are essential components of road infrastructure, playing a key role in socioeconomic development; therefore, their design must ensure structural safety and uninterrupted traffic flow [1]. However, bridges are vulnerable to damage caused by environmental forces and design deficiencies [2]. Most bridge

failures are attributed to erosion and scour rather than to structural defects [3]. Such failures often have severe consequences, including loss of connectivity and human lives, and are primarily driven by hydraulic factors [4]. Sediment-related erosion is the dominant cause of failure. The U.S. Federal Highway Administration reports that approximately 97% of documented bridge failures are associated with hydraulic problems related to local scour, with about 25% occurring at piers and 75% at abutments. In hydraulic engineering, river discharge and sediment transport are critical considerations for infrastructure safety [5]. In Peru, bridge failures have frequently resulted from hydraulic processes intensified by extreme climatic events, particularly El Niño episodes in 1982–1983 and 1997–1998, as well as recent coastal events [6, 7], which have caused severe foundation erosion during extreme flows. Both urban and rural areas in Peru are exposed to natural hazards that threaten infrastructure, as intense rainfall can trigger floods and debris flows that compromise bridge stability [7]. The construction of a bridge alters the natural flow conditions of a river [8], and the interaction between the structure and the channel can modify local flow regimes and sediment dynamics. Consequently, understanding erosion and scour processes and their impact on

bridge stability is essential, underscoring the need for comprehensive and realistic analyses that avoid unnecessary overdesign while ensuring structural safety [9].

The influence of hydraulic behavior within a stilling basin on downstream erosion depth at a dam spillway has been analyzed, focusing on stability risks associated with flow variability and energy dissipation [10]. A physical scale model of the Krueng Kluet Dam spillway has been used at the Dr. Masimin Hydrotechnical Laboratory of Syiah Kuala University, Indonesia. A dimensional analysis approach has been applied to examine the relationships among key hydraulic parameters, including the Froude number, hydraulic jump characteristics, energy dissipation efficiency, and erosion depth. The results demonstrated a direct correlation between discharge, the Froude number, hydraulic jump intensity, and erosion depth. It was concluded that hydraulic conditions within stilling basins play a significant role in controlling erosion processes, offering insights that are also applicable to erosion mechanisms affecting bridge structures such as the Cunas Bridge. Authors in [11] experimentally evaluated the effects of geometry and installation height on reducing local scour around the slots of the rounded bridge piers. Laboratory flume experiments were performed using a cylindrical pier with a diameter of 3 cm and a maximum flow velocity of 0.23 m/s. Collar outer diameters of 2D, 2.5D, and 3D were tested at two installation heights ( $h_c = 0$  cm and  $h_c = 3$  cm). Scour depth was monitored until equilibrium conditions were reached after approximately 45 min. It was found that large-diameter collars installed at or below the riverbed surface provide an efficient and cost-effective solution for mitigating local scour around bridge piers, thereby enhancing hydraulic safety and structural durability. In addition, authors in [12] focused on the design of hydrodynamic protective layers using NACA aerodynamic profiles to address increasing erosion in bridge piles, particularly under the influence of climate change. Using a mixed methodology that combined numerical simulations and comparative analyses of various configurations, the NACA 0025 profile was identified as optimal due to its balance between structural simplicity and hydraulic performance. The results confirmed that hydrodynamic casings based on NACA profiles, especially NACA 0025, offer a practical and economical alternative for mitigating scour around bridge foundations. Authors in [3] investigated methods to reduce scour depth at short, vertical bridge abutments by modifying abutment geometry through the addition of side wings inclined at 45°, 30°, and 20°. The results showed that these geometric modifications reduced scour depth by up to 98% compared with the original abutment configuration. Authors in [5] combined laboratory physical modeling with three-dimensional numerical simulations using FLOW-3D software, employing experimental data to calibrate the numerical model. The numerical simulations overcame the inherent limitations of the physical model, enabling more representative estimates of maximum scour depth at pile foundations. These results were subsequently compared with predictions obtained from empirical equations, demonstrating the advantages of the coupled experimental–numerical approach.

Authors in [13] adopted a quantitative methodology based on an experimental database of 211 records and evaluated

model performance using statistical indicators such as the coefficient of determination, root mean square error, and mean absolute error. The results indicated that the DNN model significantly outperformed the regression model, achieving higher predictive accuracy. It was concluded that this approach provides a more efficient alternative for scour prediction by eliminating traditional trial-and-error procedures in parameter estimation. An analytical approach was used to assess how erosive processes compromise the stability of hydraulic structures and increase the risk of failure [14]. It was found that structural erosion negatively affects hydraulic safety in rural areas, increasing the vulnerability of agricultural land and nearby populations. Authors in [15] examined monitoring techniques applied in real-world cases and reviewed current bridge design criteria aimed at mitigating scour-related damage. They identified existing knowledge gaps and proposed future research directions. It was demonstrated that, despite technological advances, stronger integration between predictive modeling and monitoring systems is still required to achieve safer and more proactive bridge designs against scour. Finally, maximum scour depth depends on three main factors, including wall permeability, wall position, and wall length [16]. A general decrease in scour depth was observed as wall permeability decreased. When protective walls were placed adjacent to the channel bank, significant reductions in maximum scour depth occurred. For walls connected to the upstream face of the abutment ( $T = 0\%$ ), scour developed near the wall's downstream end; as wall length increased, the location of maximum scour shifted farther away from the abutment. Under permeable wall conditions ( $T \approx 49\%$ ), scour behavior was like that observed in unprotected configurations.

In Peru, a hydraulic simulation was conducted using maximum daily precipitation records from 1988 to 2017 obtained from five SENAMHI meteorological stations: Santa Eulalia, Autisha, Carampoma, Sheque, and Canchacalla. The model evaluated the hydraulic performance of two structures: a bridge and the associated riverbank protection works [17]. It was indicated that, for a 100-year Return Period (RP), water levels remained within design limits. However, for RPs of 139 and 200 years, flow overtopping occurred, increasing the risk of localized flooding. For more extreme events with RPs of 500 and 1000 years, the overall stability of the bridge structure was not compromised. It was revealed that extreme hydrological events substantially increase discharge levels, elevating flood risk in specific areas. In [6], an applied, quantitative, and purely experimental approach was adopted, considering the entire bridge as the population and one of its structural components as the sample. Topographic, hydrological, and sedimentological data were collected and used to develop a hydraulic model with HEC-RAS software. The results showed scour depths of approximately 1.2 m at piers 1, 3, and 4, while pier 2 experienced a greater scour depth of 2.46 m. Under these conditions, it was concluded that the use of rock fill represents an effective alternative for mitigating erosion and protecting bridge foundations. The current study emphasizes the importance of rigorous hydraulic analysis and appropriate design practices to prevent structural failures resulting from inadequate design assumptions or improper construction execution.

II. METHODOLOGY

The bridge studied in the current work was selected because its impassability directly affects local connectivity and the regional economy. The study is conducted at the Cunas Bridge, located in Huamancaca Chico, Chupaca, Peru. Its coordinates are:

- Geographic (WGS84): Latitude 12 ° 03' 25.35" S, Longitude 75° 17' 05.65" W.
- UTM (Zone 18S): Easting ≈ 469045 m, Northing ≈ 8666815 m.

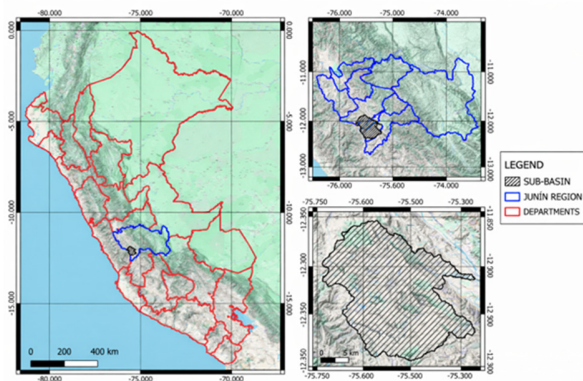


Fig. 1. Area of influence.

Figure 1 illustrates the area of influence of the study, corresponding to a basin with an area of 1657 km<sup>2</sup>, an average slope of 1.04%, and a main river length of 101.1 km. The research methodology is structured in several stages. First, the area of influence is delineated using QGIS software to define the geographic boundaries and the extent of the analyzed river reach. Next, the hydrological design is developed using HEC-HMS, through which maximum design discharges are estimated based on historical precipitation records and Intensity–Duration–Frequency (IDF) curves. Subsequently, the hydraulic design is carried out with HEC-RAS, simulating flow conditions with and without sediment transport to obtain key parameters such as water depth and flow velocity. In parallel, the hydrological regime of the basin is analyzed by processing historical precipitation series and extreme discharge records to identify interannual variability and assess its influence on erosion and scour dynamics. Finally, critical erosion and scour zones affecting bridge piers and adjacent slopes are identified and characterized by comparing the results of the hydrological and hydraulic simulations with observed evidence of structural impact. For this research, the population is defined as the communities located along the Cunas River within the reach corresponding to the Cunas Bridge. The sample is restricted to the immediate vicinity of the bridge structure, as defined by UTM coordinates and delineated using QGIS, corresponding to the established area of influence.

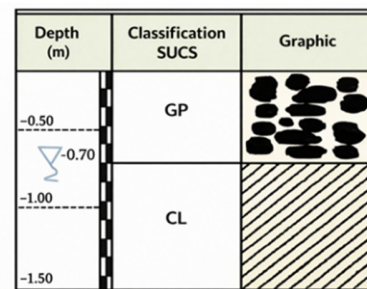


Fig. 2. Stratigraphic profile of borehole No. 01.

Figure 2 presents the stratigraphic profile of test pit No. 01 at station 000+011 upstream. According to the Unified Soil Classification System (USCS), the upper layer is classified as Poorly Graded Gravel (GP). This layer consists of moist, gray gravel with a soft consistency, containing blocks ranging from 3" to 8" in size and approximately 70% subrounded clasts. The groundwater table is encountered at a depth of -0.7 m. At a depth of -1.5 m, the underlying layer is classified as Low-Plasticity Clay (CL). This layer is saturated, dark reddish-gray in color, and exhibits a soft consistency.

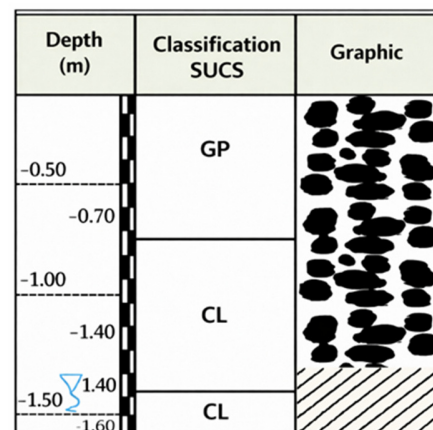


Fig. 3. Stratigraphic profile of borehole No. 02.

Figure 3 presents the stratigraphic profile of test pit No. 02 at station 000+156 upstream. According to the USCS, the upper layer is classified as GP. This layer consists of moist, gray gravel with a soft consistency, containing rock blocks ranging from 3" to 8" in size and approximately 70% subrounded clasts. The groundwater table is encountered at a depth of -1.4 m. At a depth of -1.5 m, the underlying layer is classified as CL, which is saturated, dark reddish-gray in color, and exhibits a soft consistency. The stratigraphic profiles and macro-granulometric analyses provided essential input data for the hydraulic design. This approach is consistent with recent numerical and experimental studies demonstrating that hydraulic structures alter flow patterns and sediment transport processes, leading to significant morphological changes in scour holes [19]. To determine the maximum design discharges for this study, runoff curve numbers were first established as shown in Table I. In addition, comprehensive geomorphological information for the Cunas River basin was

compiled as depicted in Table II. These datasets were subsequently used as input parameters in the HEC-HMS model to calculate the maximum design flows.

TABLE I. TABLE I. RUNOFF CURVE NUMBERS

Land use description	Hydrologic soil group			
	A	B	C	D
Cultivated land without conservation practices	72	81	88	91
Cultivated land with conservation practices	62	71	78	81
Grasslands in poor conditions	68	79	86	89
Grasslands in optimal conditions	39	61	74	80
River floodplains in optimal conditions	30	58	71	

Tables I and II present the parameters used to perform the hydrological design in HEC-HM.

Likewise, the lag time (Transformation Method) is calculated by:

$$T_l = 0.6 \times T_c \quad (1)$$

where  $T_l$  is the time lag,  $T_c$  is the time of concentration, and 0.6 is the empirical coefficient (dimensionless).

To calculate the maximum 24-h precipitation, historical records from the Huayao meteorological station were used. This station is the closest to the study area and is in the district of Huachac, Chupaca, Junín, Peru. The histogram of the historical record for the Huayao station is illustrated in Figure 4.

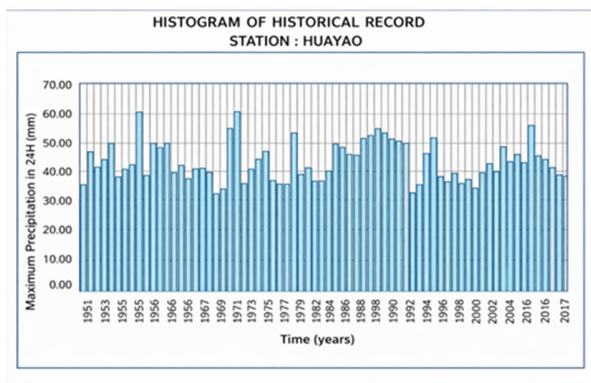


Fig. 4. Histogram of historical record, Huayao station.

For the preliminary calculations required for the use of HEC-HMS software version 4.12, the considered data are outlined in Table II.

TABLE II. CUNAS RIVER BASIN DATA

Basin data	Unit	Value
L (length)	m	101100
Upper elevation	m.s.n.m	4275
Lower elevation	m.s.n.m	3220
S (slope)	%	1.04
H (elevation difference)	m	1055

TABLE III. CALCULATION OF MAXIMUM DESIGN FLOWS FOR TWO SCENARIOS: HISTORICAL AND CLIMATE CHANGE

RP	Historical scenario - Q (m³/s)	Climate change scenario - Q (m³/s)
500	303	626.7
1000	372.2	743.2

In Table III, a notable value variation is observed, showing that under the climate change scenario, the design discharge increases during the 2-h event. For the hydrological design, the discharge data for the climate change scenario were obtained from the historical records of the Huayao station, Chupaca, Junín, Peru. It has been demonstrated that climate change alters hydrological regimes and increases the frequency and magnitude of extreme flows, directly intensifying fluvial erosion and scour processes [18].

### III. RESULTS AND DISCUSSION

Figure 5 illustrates the hydraulic simulation of a river cross-section under a climate change scenario, considering a maximum design discharge of  $Q = 743.2 \text{ m}^3/\text{s}$  and a 100-year RP. The simulation incorporates sediment transport during an extreme 2-h event, followed by a drag period of 31 days, and compares the initial riverbed profile with the eroded profile. The results show a maximum erosion depth of 7.78 m at the upstream portion of the section, near the abutment or left pier. In addition, a secondary erosion zone is identified approximately 37.84 m to the right of the bridge, with an erosion depth of about 0.9 m.

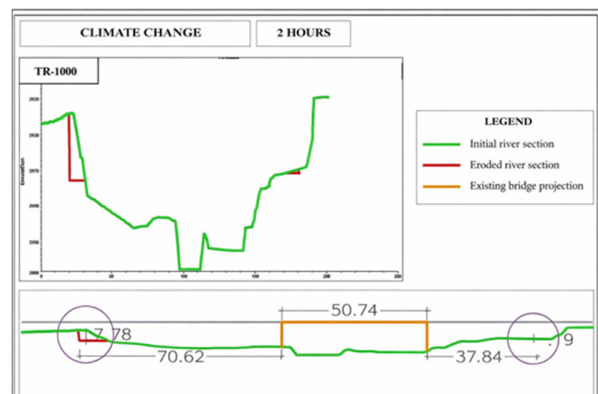


Fig. 5. Cross-section of the Cunás River,  $Q = 743.20 \text{ m}^3/\text{s}$ .



Fig. 6. Initial erosion section of the bridge.

Figure 6 illustrates the initial section of the river channel, where the erosion process is evident in both climate change and historical scenarios. Under the climate change scenario, an erosion depth of approximately 7.78 m is observed because of increased discharge and flow energy. In contrast, the historical scenario shows an even greater erosion depth, indicating progressive degradation of the riverbed near the bridge area and greater vulnerability of the structure to extreme hydrometeorological events.

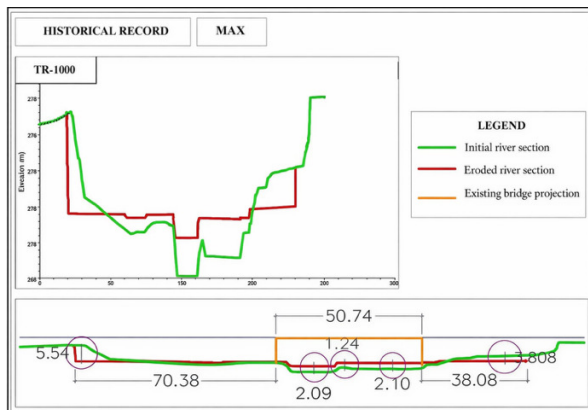


Fig. 7. Transverse section of the Cunas River,  $Q = 372.2 \text{ m}^3/\text{s}$ .

Figure 7 presents the initial river section for a maximum design discharge of  $Q = 372.2 \text{ m}^3/\text{s}$  under a historical scenario with a 100-year RP, including sediment transport. The eroded river reach can be identified, with an erosion depth of 5.54 m at the initial section. On the right side of the bridge, another eroded reach is observed with a depth of 3.81 m. Finally, the average erosion depth along the entire length of the bridge reach is 1.81 m.



Fig. 8. Eroded reach.

Figure 8 displays the eroded reach of the river described in Figure 7, with a total affected length of 70.38 m. The mathematical model of the Arturo Sandez Bridge indicates that the geometry of the tributary channel, combined with the narrowing at the bridge abutments, generates a concentration of flow toward the outer edge of the left abutment. This flow concentration intensifies shear stresses, leading to progressive scouring at the base of the structure [4]. As a result, flow velocity and sediment transport capacity increase, exposing the left abutment and compromising its structural stability. This behavior is consistent with the results depicted in Figures 5 and

7, where significant erosion is observed on the left side, with maximum depths of 7.78 m and 5.54 m, respectively.

#### IV. CONCLUSIONS

This research evaluated two scenarios: a historical scenario with a maximum discharge of  $Q = 372.2 \text{ m}^3/\text{s}$  and a climate change scenario with  $Q = 743.2 \text{ m}^3/\text{s}$ . The results show significant differences in erosion magnitude between the two cases. In the upstream portion of the eroded river, scour depths reach 5.54 m under historical conditions and 7.78 m under the climate change scenario. Downstream, scour depths range from 0.9 m to 3.808 m. These findings indicate that higher discharges associated with climate change lead to greater erosion near the bridge, increasing the risk of flooding and potential structural weakening. The Cunas Bridge exhibits considerable wear on its piers and abutments due to increased river flows. Sediment transport and accumulation further contribute to channel obstruction, elevating substructure vulnerability and the likelihood of structural failure during the rainy season. This combination of factors amplifies flooding impacts and compromises bridge safety for both pedestrians and vehicles. Therefore, future bridge designs should account for maximum discharges, including sediment transport effects and climate change impacts. Structural riverbank protection measures, such as rock riprap, gabions, groynes, dikes, retaining walls, or channelization works, should be incorporated to enhance hydraulic and structural safety.

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