



Department of Digital Business

Journal of Artificial Intelligence and Digital Business (RIGGS)

Homepage: <https://journal.ilmudata.co.id/index.php/RIGGS>

Vol. 4 No. 4 (2025) pp: 4995-5003

P-ISSN: 2963-9298, e-ISSN: 2963-914X

Analysis of Erosion Mitigation on Bridge Pillars

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Abstract

Scour on bridge piers is a major problem in hydraulic engineering, reducing structural stability and accelerating foundation failure. This phenomenon occurs due to the interaction between airflow and bridge structural elements, resulting in the formation of scour holes that potentially reduce the bearing capacity of the soil around the piers. In areas with strong currents, seasonal changes in discharge, and unstable riverbed conditions, the risk of scour is even higher. The impact of scour damage not only reduces the operational lifespan of bridges but also leads to high rehabilitation costs and increases the potential for structural failure, which can endanger user safety. This study aims to analyze various scour mitigation methods that can be applied to bridge piers, including the use of protective materials such as riprap, gabions, and geotextiles; a geotechnical engineering approach that includes soil stabilization and riverbed contour modification; and the development of pier structural designs that are more adaptive to variations in flow patterns. The study was conducted through an in-depth literature review of previous research, an analysis of the effectiveness of each method under various hydrodynamic conditions, and an evaluation of the cost. The results of this study are expected to produce comprehensive recommendations regarding the most effective, efficient, and environmentally friendly mitigation strategies to reduce the rate of scour. Furthermore, this study provides direction in planning bridge designs that are more resilient to changes in flow and sedimentation, thereby extending the service life of the structure, reducing long-term maintenance costs, and improving user safety.

Keywords: Scour, Flow Velocity, Planning

1. Introduction

Bridges are a crucial infrastructure that supports smooth transportation and inter-regional connectivity. Bridge piers, which serve as the primary supports for bridge structures, are highly susceptible to damage due to scour or erosion caused by water flow [1]. Scour on bridge piers can occur due to the force of water currents continuously eroding the material around the piers, ultimately reducing the piers' stability and shortening the bridge's lifespan. This phenomenon is more common on bridges located in river basins with strong currents or unpredictable changes in hydrological conditions [2].

Scour mitigation on bridge piers is crucial to maintaining the bridge's continued function and preventing potential damage that could endanger the safety of users [3]. Various methods have been developed to protect bridge piers, but their effectiveness varies depending on environmental conditions and water flow characteristics [4]. Therefore, research related to the analysis of scour mitigation on bridge piers is highly relevant and needed to identify more optimal and efficient solutions [5], [6]. Based on this background, the present study aims to evaluate the effect of curing temperature variations on the mechanical properties of paving blocks produced with partial cement substitution using fly ash (0%, 10%, 15%, and 20%) and the addition of 2% coconut fiber [7]. The study is expected to produce an optimal mixture composition that meets the requirements of SNI 03-0691-1996 and supports more sustainable paving block production [8].

Problem Formulation

Based on the above background, several problems that arise in mitigating scour on bridge piers are:

1. What factors influence scour on bridge piers?
2. What is the most effective method for reducing or preventing scour on bridge piers?
3. Evaluating the effectiveness of solutions for mitigating scour on bridge piers.

This study aims to analyze the causal factors, available mitigation solutions, and evaluate their effectiveness, in order to provide more appropriate and applicable recommendations for reducing the impact of scour on bridge piers.

2. Research Methods

Research Stages [9]

Year 1: Water Resources Assessment and Mapping

1. Collecting accurate data
2. Methods [10], [11]:
 - Data Collection: Conducting field surveys to obtain data on river conditions.
 - Water Resources Modeling: Developing mathematical models to estimate water potential and demand by incorporating variables such as rainfall, water use, and population distribution, which are used for long-term planning.

Year 2: Management Innovation/Solutions [12]

1. Developing new technologies to optimize the handling of existing problems.
2. Outputs:
 - Developing buildings suitable for existing conditions.
 - Evaluating the success of system implementation.

Year 3: Climate Change Impacts and Adaptation [13].

1. Identifying the impacts of climate change on existing river conditions [14], [15].
2. Methods:
 - Climatological Modeling: Using climatological models to predict changes in rainfall and temperature patterns in the study area. The data obtained is used to identify potential threats to water resources.
 - Vulnerability Assessment: Analyzing vulnerability to the management system

3. Results and Discussions

Hydrological studies are based on hydrological design criteria. Hydrological design criteria encompass various factors used to design drainage systems, dams, or other infrastructure related to water flow and water resource management [16].

Mulusari Station is located at coordinates 4°34'1.69S; 104°41'51.1E, and Tanjung Agung Station is located at coordinates 4°29'46.75S; 104°42'34.27E, in Lampung Province. Available data ranges from 2010 to 2023.

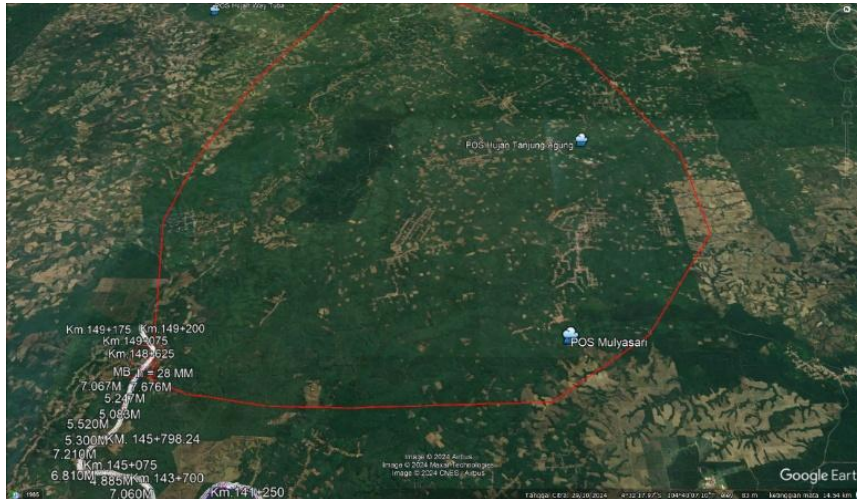


Figure 1. Research Location

Planned Rainfall Analysis

The Gumbel method is a frequency analysis method used to estimate extreme values, such as maximum flooding, maximum rainfall, or the amount of scour due to extreme flow events [17].

The Gumbel method is widely used in hydrology because it is able to describe the distribution of peak values of extreme events in a certain time period.

Table.1. Planned Return Period Rainfall Gumbel Method

Return Period years (Tr)	Yt	$K = (Yt - Yn) / Sn$	S	\bar{X}	$XT = \bar{X} + (S \cdot K)$
2	0,3665	-0,136	24,69	96,77	93,42
5	1,4999	1,058	24,69	96,77	122,89
10	2,2502	1,848	24,69	96,77	142,40
25	3,1985	2,846	24,69	96,77	167,05
50	3,9019	3,587	24,69	96,77	185,34
100	4,6001	4,322	24,69	96,77	203,50
500	6,2140	6,022	24,69	96,77	245,46
1000	6,9190	6,764	24,69	96,77	263,79

The Normal Method is a frequency analysis method that uses the Normal Distribution (Gaussian Distribution) to estimate the value of a hydrological variable—such as maximum rainfall, maximum discharge, or other hydraulic parameters—based on the assumption that the data follows a normal distribution.

The Normal Distribution has a bell-shaped curve and is widely used due to its simplicity, symmetry, and often appropriateness for natural data that are not too extreme.

Table.2. Planned Return Period Rainfall Normal Method

Return Period years (Tr)	Kt	S	\bar{X}	$XT = Xrt + Kt \cdot Sd$
2	0,000	24,69	96,77	96,77
5	0,840	24,69	96,77	117,51
10	1,280	24,69	96,77	128,37
25	1,708	24,69	96,77	138,94
50	2,050	24,69	96,77	147,39
100	2,330	24,69	96,77	154,30
500	2,880	24,69	96,77	167,88
1000	3,090	24,69	96,77	173,07

The Log Pearson Type III method is one of the most frequently used frequency analysis methods in hydrology, particularly in the United States (used by the US Water Resources Council), and is also widely used in Indonesia for design flood analysis. This method is particularly suitable for hydrological data with skewed distributions, such as maximum flood discharge or extreme rainfall.

Table.3. Planned Return Period Rainfall Log Pearson Type III Method

Return Period years (Tr)	Kt	LOG Xi	S	LOG XT	XT
2	-0,330	2,002	0,023	1,994	98,692
5	0,574	2,002	0,023	2,015	103,607
10	1,284	2,002	0,023	2,032	107,638
25	2,240	2,002	0,023	2,054	113,315
50	2,970	2,002	0,023	2,071	117,850
100	3,705	2,002	0,023	2,088	122,600
500	5,542	2,002	0,023	2,131	135,323
1000	6,200	2,002	0,023	2,147	140,199

Frequency analysis will be conducted using several methods, namely the Gumbel Method, the Normal Method, and the Log Pearson III Method, as well as a distribution harmony test using the Smirnov-Kolmogorov Method. The following are the results of the frequency analysis.

From the three calculation results above, a data consistency test was carried out and the following results were obtained.

Table.4. Planned Return Period Rainfall

No	Return Period years (T)	Planned Rainfall Frequency Analysis (mm)		
		Gumbel	Normal	Log Pearson III
1	2	93,42	96,77	98,69
2	5	122,89	117,51	103,61
3	10	142,40	128,37	107,64
4	25	167,05	138,94	113,31
5	50	185,34	147,39	117,85
6	100	203,50	154,30	122,60
7	500	245,46	167,88	135,32
8	1000	263,79	173,07	140,20
DISTRIBUTION		Eligible	Not Eligible	Not Eligible

A summary of the results of the planned rainfall calculations using these three methods is summarized in the following table. Several methods were used to determine the respective return periods for each method. Based on the results obtained from each method, the return period used was the Gumbel method.

The method used for flood discharge analysis in this work is Nakayasu. The base flow used for the empirical and regression methods uses parameters such as river basin area and river density.

$$Q_B = 0.4751 \times A^{0.6444} \times D^{0.943}$$

Table.5. Results of the calculation of the planned flood discharge using the Nakayasu method

T (hour)	Q2	Q5	Q10	Q20	Q50	Q100	Q500	Q1000
Jam	(m3/det)	(m3/det)	(m3/det)	(m3/det)	(m3/det)	(m3/det)	(m3/det)	(m3/det)
0,000	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
1,000	9,65	12,70	14,72	17,26	19,15	14,02	15,51	27,26
2,000	64,20	84,46	97,86	114,81	127,38	93,22	103,11	181,29
3,000	194,48	255,83	296,44	347,76	385,84	282,39	312,34	549,14
4,000	426,95	561,62	650,78	763,46	847,04	619,94	685,70	1205,54
5,000	785,71	1033,55	1197,62	1404,99	1558,80	1140,86	1261,89	2218,55
5200	863,26	1135,56	1315,83	1543,66	1712,66	1253,47	1386,44	2437,53
5,479	978,45	1287,09	1491,40	1749,64	1941,18	1420,72	1571,44	2762,78
6,000	862,71	1134,85	1315,00	1542,69	1711,58	1252,68	1385,56	2435,99
6,500	764,61	1005,80	1165,47	1367,27	1516,95	1110,23	1228,01	2158,99
7,000	677,67	891,43	1032,94	1211,79	1344,46	983,99	1088,37	1913,49
7,500	600,61	790,07	933,34	1074,00	1191,58	872,10	964,61	1695,91
8,000	532,31	700,23	827,21	951,87	1056,08	772,93	854,92	1503,06
8,500	471,78	620,60	733,14	843,63	935,99	685,04	757,71	1332,15
9,000	418,14	550,03	649,78	747,70	829,56	607,14	671,55	1180,67

T (hour)	Q2	Q5	Q10	Q20	Q50	Q100	Q500	Q1000
10,000	328,45	432,06	521,42	587,33	651,63	476,92	527,51	927,42
10,466	293,53	386,13	455,51	524,89	582,35	426,22	471,43	828,83
11,000	269,34	354,30	416,15	481,63	534,35	391,09	432,57	760,52
11,500	248,51	326,90	383,62	444,39	493,04	360,85	399,13	701,71
12,000	229,30	301,63	353,96	410,03	454,91	332,94	368,26	647,45
12,500	211,57	278,30	326,59	378,32	419,74	307,20	339,79	597,39
13,000	195,21	256,79	301,34	349,07	387,28	283,45	313,52	551,20
13,500	180,12	236,93	278,04	322,08	357,34	261,53	289,27	508,58
14,000	166,19	218,61	256,54	297,17	329,71	241,31	266,91	469,26
14,500	153,34	201,71	236,70	274,20	304,21	222,65	246,27	432,97
15,000	141,48	186,11	218,40	252,99	280,69	205,43	227,23	399,49
16,000	120,45	158,44	188,47	215,38	238,96	174,89	193,45	340,10
17,000	102,54	134,89	160,45	183,36	203,44	148,89	164,69	289,54
17,946	88,06	115,84	137,58	157,47	174,71	127,87	141,43	248,65
17,000	98,71	129,85	147,99	176,52	195,84	143,33	158,54	278,73
18,000	87,49	115,08	135,95	156,44	173,57	127,03	140,51	247,03
19,000	77,54	102,00	120,49	138,65	153,83	112,59	124,53	218,94
20,000	68,72	90,40	106,79	122,89	136,34	99,79	110,37	194,05
21,000	60,91	80,12	94,65	108,91	120,84	88,44	97,82	171,98
22,000	53,98	71,01	83,89	96,53	107,10	78,38	86,70	152,43
23,000	47,84	62,94	74,35	85,55	94,92	69,47	76,84	135,09
24,000	42,40	55,78	65,89	75,82	84,13	61,57	68,10	119,73

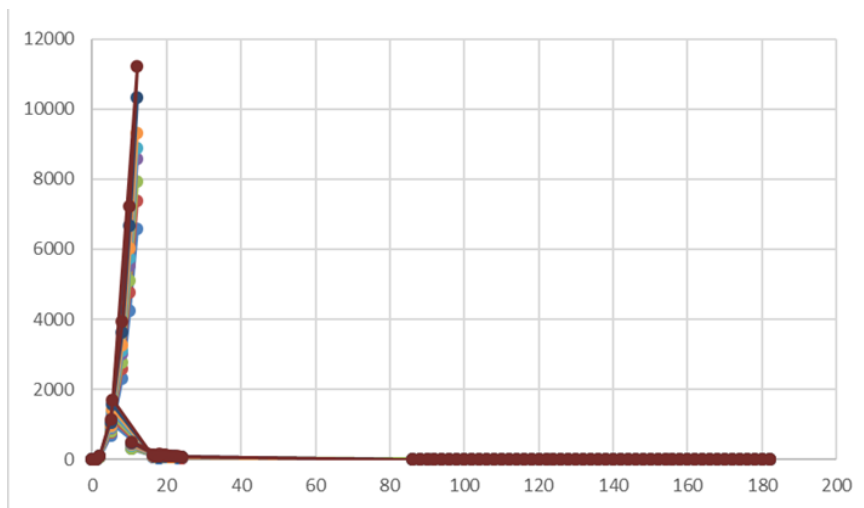


Figure 2. Flood Discharge Hydrograph

Hydraulic Analysis
 Flood water level (FWL) calculation

DOI: <https://doi.org/10.31004/riggs.v4i4.3888>
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Hydraulic design criteria focus on the design and management of water flow through channels, dams, and other hydraulic structures.

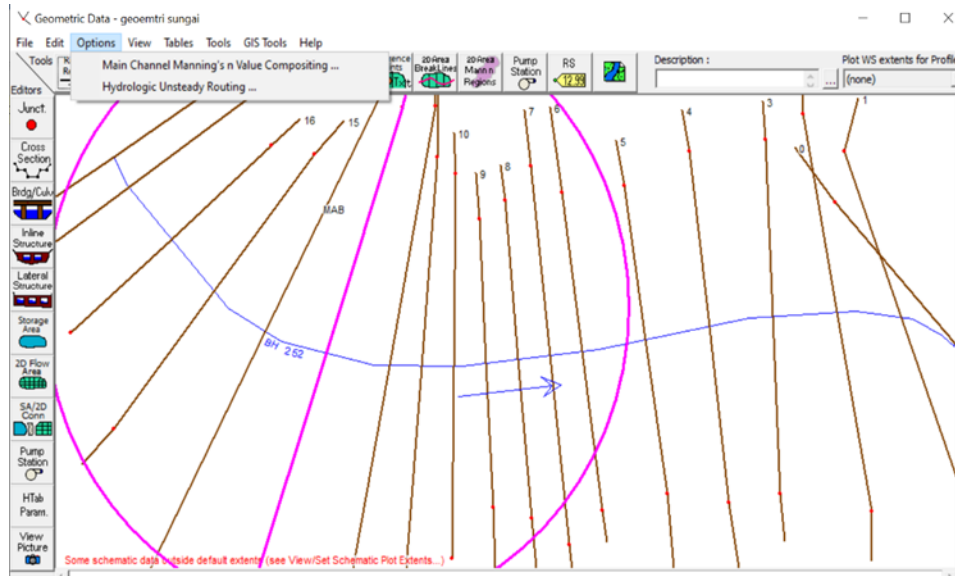


Figure 3. Cross-section of the river channel

Flood Water Level for the location using the Q50 return period flood discharge Hydrograph with the Nakayasu HSS method as follows:

Flood water levels obtained using Hec-ras software from the downstream, middle and upstream sections are as follows:

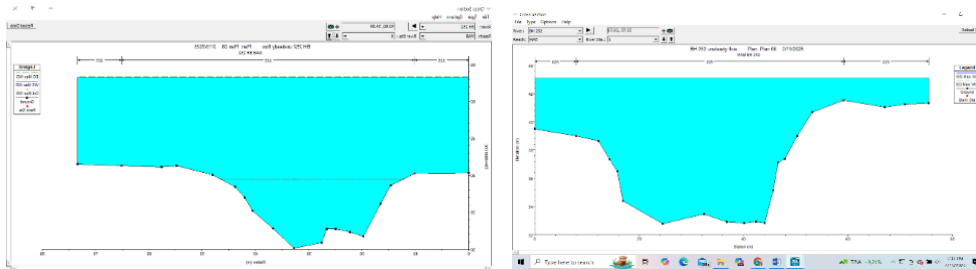


Figure 4. Downstream Position of the River

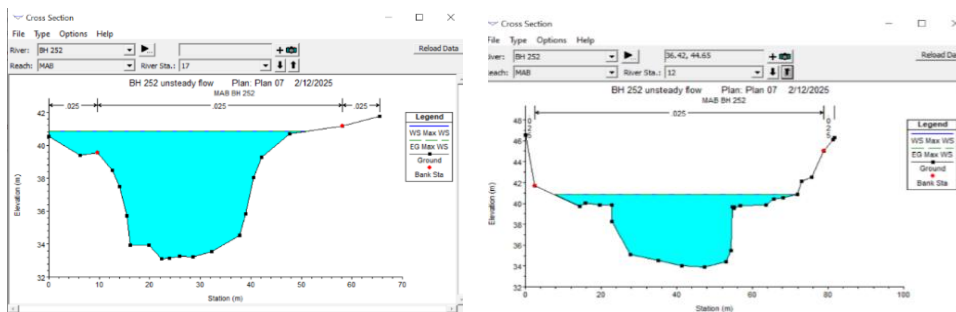


Figure 5. Position of the River Head

From the modeling results in the Hec-Ras software, verification was carried out with conditions at the research location. The Flood Water Level (MAB) conditions at the bridge location in existing conditions were obtained by looking at the signs on the bridge pillars and the existing environment and based on topographic measurements at an elevation of +42.5 m.

There is a difference between the conditions in the field and the results obtained from Hec-Ras but it is still within the tolerance limits of the calculations and factors in the field.



Figure 6. Position of MAB on the bridge structure

Meanwhile, the MAB obtained from Hec-Ras was at +43.10 m, with the channel base at EL +33.641 m. There was a difference between the field conditions and the Hec-Ras results, but it was still within the calculation tolerances and factors in the field.

Given the flood water level, the minimum clearance to the bridge deck was 1.5 meters, and considering that the bridge location still had sufficient clearance.

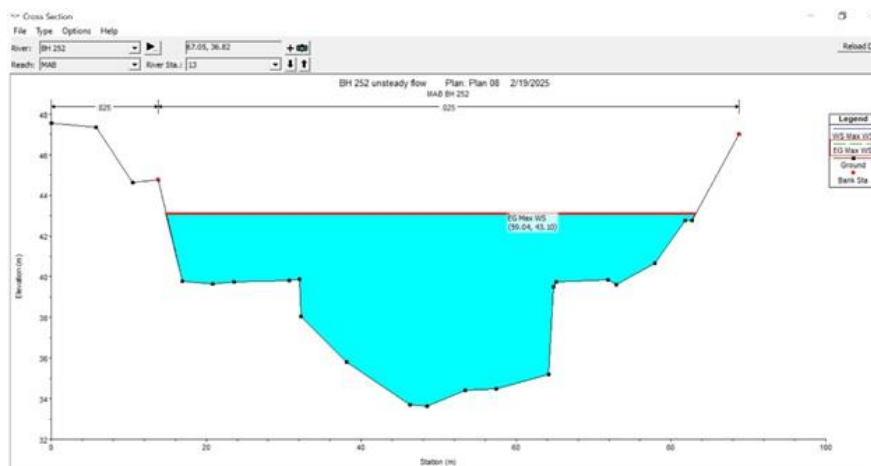


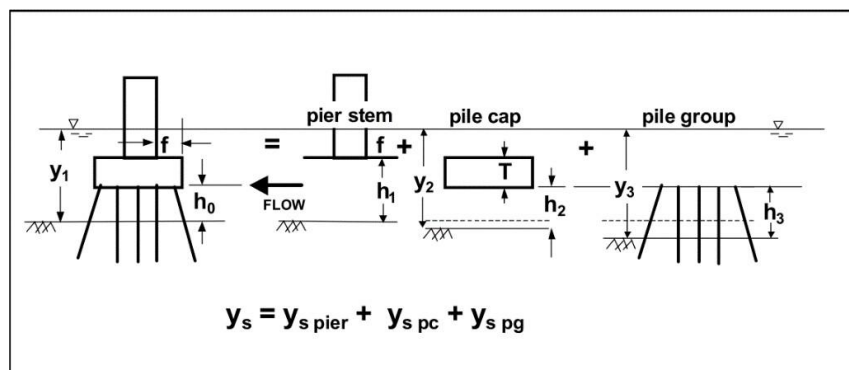
Figure 7. MAB results on Hec-Ras software at Elevation +43.10 m

SCORAGE ANALYSIS

Given the characteristics of the proposed bridge site, which is underlain by a river, the hydraulic analysis in this case focused on identifying the potential for local scouring that might occur in the soil layer supporting the bridge structure, both the abutment and the piers.

This allows us to determine that the foundation elevation of the bridge abutments and piers must be lower than the estimated river scour depth.

Once all data and parameters are known, the scour analysis can be calculated by examining the scour component characteristics of the bridge's pier group formation, based on HEC 18 FHWA NHI 01-001. The calculation for the pile group can be seen in the illustration below.



Source: HEC 18 FHWA NHI 01-001

Figure 8. Illustration of Scour Components on a Pillar

Conclusion

In the calculation of the scour table on pillars with a flood discharge of Q50 years, the scour amount was 0.1 meters or 10 cm, thus the bridge pillars are categorized as safe from scour. The floodwater level in a river with a 50-year return period (Q50) will impact the surrounding environment, causing runoff to land. This condition significantly disrupts the stability of the soil structure surrounding the railroad ties. The following image depicts the impact of the floodwater level around the abutment, necessitating the need for a gabion structure to protect the railroad ties. With MAB at an elevation of +43.10 with Q50 years, the water that will enter the riverbank at the bridge position will enter the bank as far as 54.02 meters so that it is necessary to protect the body of the railway track tire by using a retaining wall structure to prevent subsidence on the railway track due to water seepage on the body of the train tire

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