

SIMULATION OF THE EFFECTIVENESS OF THE SCOURING PREVENTION STRUCTURE AT THE EXTERNAL RAIL BALLAST USING PHYSICAL MODEL

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ABSTRACT: Rail ballast is a rockfill construction that serves to bind sleepers and rail which distributes trainload to ground. The function of rail ballast is vital to the quality and strength of the rail track, but are prone to overtopping. The relationship between overtopping high and scouring has been investigated, as well as the effect of the high external prevention structure against the length of scouring. This study focuses on the effectiveness of external prevention structure at downstream in its ability to dampen and reduce the length of scouring due to overtopping by the mean the physical model. This research simulates the scouring prevention structure at downstream of ballast with several variations of type (T) and structures distance (L) so that the most effective structure is obtained, i.e. the structure which can maximum reduce the length of scouring. From the research, the most effective structure is the Type T1 at L1 distance. The modeling was carried out at the Hydraulic Laboratory of Civil Engineering Diponegoro University, with the prototype of the Mangkang-Semarang Railway KM.12 Indonesia, with the scale of 1: 5. The structure types which are simulated consist of T, T1 and T2 with the variation of structure distance L1 = 40 cm and L2 = 60 cm from downstream of toe ballast. The results of this study can be utilized by railway operator as a safety measure and especially against the danger of scouring due to flooding.

Keywords: Ballast, Scouring Prevention Structure, Effective Structure, Overtopping, Physical Model

1. INTRODUCTION

There are some important rockfill constructions in civil engineering field e.g. rockfill dam, groyne, and rail or track ballast. Railway comprises the combination of rails, sleepers, and ballast. The other complementary components are the power supply and signaling infrastructure [1]. Rail bears the weight of train directly which will be distributed to sleepers and finally distributed further to the ground by the ballast. Ballast is very important in determining the quality and the strength of railway track [2], but it is very vulnerable to scouring due to overtopping [3]. Flood will not only carry stones with small diameter [4] which will reduce ballast's strength, but the overtopping flow also will inflict scouring at downstream. Many railways undergo serious damage due to flooding [5] and flooding itself is one of the causes of fouling [6]. Overtopping, although it lasts only briefly, could potentially scour ballast and its landfill [7], [8]. The cases of failure of rockfill dams due to overtopping can be referred to [4], [5], [9] while [10] refers the failure and the scouring of railway due to flooding. The road will experience a decline in strength and large settlement in case of inundation during long time enough [11]. The author [12] mentioned that there are two important aspects of rail track design i.e.

overtopping and rapidly repetitive load. The maintenance of drainage system is highly needed since timber sleeper is very sensitive to drainage condition at its surrounding [13]. Researches on the failure of impervious upstream face rockfill dams due to overtopping conclude the importance of considering the seepage aspect which penetrates rockfill. The solutions of overtopping-induced scouring have been formulated by using wire mesh layer [14] and the author also has applied it to the design of cofferdam in the construction of Tulis Hydropower station in Indonesia (although overtopping have never occurred until the construction was finished in the span of 3 years) [15]. The research [16] based on [17] and [18] proved overtopping and/or seepage could initiate ballast aggregates to scour at a specific point from certain water level at upstream.

At the end of 2013, there was a flood which caused overtopping at the Mangkang-Semarang rail track (Indonesia) and there was an indication of scouring at station KM.12 (Fig.1). If it keeps occurring then the ballast's capacity to support and to distribute incoming load will be reduced. Furthermore, the rail track failure could occur and it would endanger the passing trains. This is why the authors feel compelled to perform this research.

The running of a hydraulic model of rail ballast scouring (without scouring prevention structure) [19] resulted in the scouring of rail ballast's downstream when the overtopping is 1 cm above the railway in the model (equal to 5 cm in the actual case). The research as in [20] performed the test to probe the effect of prevention structure to reduce the scouring on rail ballast because of flooding. The conclusion of the research is, the structure indeed reduces the scouring length under the same overtopping and the ballast only started to scour when the overtopping was 1 cm higher than the default condition (without prevention structure). The research in [20] used the structure type T and T1 located at the location L_1 .

The focus of this research is to determine the effective scouring prevention structure i.e. the construction which is able to shorten the maximum scouring length. For information, this study is the continuation of [20]. The study is performed by simulating the external scouring prevention structure with a physical model using various types of structures and distances. The structure types used are T, T1, and T2 while the structure distances are L_1 and L_2 .

The result of this study can benefit railway operators as a safety measure especially against the danger of scouring due to flooding.



Fig.1. The scouring of rail ballast after flooding

2. MATERIAL AND MODELLING METHODOLOGY

The modeling was performed at Hydraulic Laboratory of Civil Engineering Department Diponegoro University, Indonesia. The prototype of the physical model is the Mangkang-Semarang Railway KM.12.

After the flooding occurred at the prototype location, there was a sign of scouring, however, there was no accurate data regarding the water level of the overtopping occurred in Fig. 1.

2.1 Material and Instrument Setting

Fig. 2 depicts the section of the rail ballast with its dimension. Fig.4 depicts the location of the

water level measurement and the multiple locations of the prevention structure. The other instruments used are The flume with the dimension of 40 x 15 x 800 cm. The drain system from the model into the tank. The discharge-measuring instrument Cipoletti type. The *peilschaal* to measure the water level, one is positioned at the regulating valve and eight are positioned at the location of water level measurement. The ballast stones with the dimension of 0.2-1.2 cm at the model.

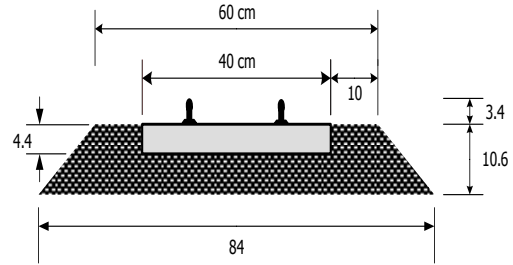


Fig.2. The section of the ballast model

The flume was equipped with the regulating valve and the spillway to release the excess water. The water from the tank will be pumped and circulated back to the model again. The stilling basin was set at the upstream of the flume so that the downstream flow became steady. The setup of the flume and the rail ballast are illustrated in Fig.3. Various sorts of prevention structure were tested i.e. T, T1, and T2 type as in Fig. 5.



Fig.3. The flume and the ballast model

2.2 Modelling Methodology

The physical model was scaled of 1:5 considering the condition of the prototype model and the laboratory [21]. The modeling started with the prototype inventorying and then collecting and sorting the previous researches as the references.

The field measurement comprised topographical survey, real elevation, the dimension of the rail ballast components, and the sampling of the rail ballast stones' dimension. The real dimension of the ballast stones ranged between 2-6 cm hence the stones used for the model ranged between 0.2-1.2 cm. The T1 structure is like the T

structure, but the former was higher by 2 cm while the T2 was higher by 4 cm. The overview of the protection structure is illustrated in Fig 5. The position of the prevention structure at L_1 (F) is 40 cm at the downstream of the ballast toe O, while L_2 (G) is 60 cm (Fig. 4).

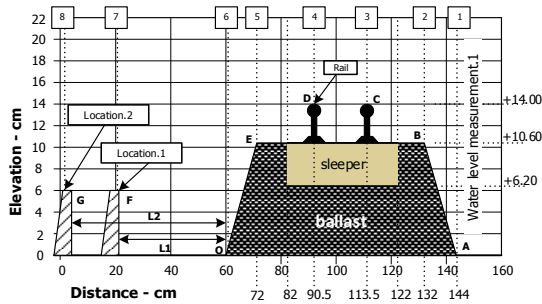


Fig.4. Eight locations of the water level measurement points and the location of the prevention structure.

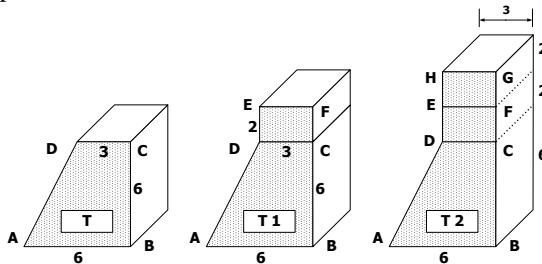


Fig.5. The T, T1, and T2 type of external prevention structures (in centimeter)

2.3 The Modelling Scenario

The modeling scenario of this study is elaborated as in Table 1.

3. RESULTS AND DISCUSSION

3.1 Modelling Results

In order to analyze the effectiveness of the prevention structure to the scouring length, it is imperative to compare its result with the results of the previous researches i.e. scouring model without protection structure [19].

3.1.1 The Results of the Previous Simulation: The Scouring of The Ballast Aggregates without Prevention Structure [19]

The simulation with various water levels $h_1 = 10, 12, 14, 15, 17, 19,$ and 20 cm produced the resulting water level h_1-h_8 as displayed in Table 2. The illustration of the water profile and the scouring profile are presented in Fig.6 and Fig. 7.

3.1.2 The Results of The Simulation of The T, T1, and T2 Structures at The L_1 Location

The simulations of the water levels $h_1 = 17, 19,$ and 20 cm are conducted similarly to the previous ones i.e. the T, T1, and T2 structures. The water levels data are presented in Table 3

Table 1. The modeling scenario

No	Setup Process	Observation	Results
1	<ol style="list-style-type: none"> The ballast stones were stacked according to the plan. The T-type structure was set at the location L_1. The water was discharged slowly until the water level reached $h_1 = 15$ cm. After the water was stable after being left for 5 minutes, the height of the overtopping was measured above the railway. Then, the water level was decreased until it was empty. The similar mechanism was replicated to other scenarios i.e.: $h_1=17$ cm; $h_1=19$ cm; $h_1=20$ cm. The simulations (number 1-3) were repeated again, but with the different structure setup i.e. T1 and T2. 	Measured: <ul style="list-style-type: none"> The water height h_1-h_8 including the overtopping height above the rail when the water had been stabilized. The water discharge when the water level had reached the planned water height (h). The elevation/profile of the ballast scouring i.e. the elevation at every 5 cm from the toe of ballast (O), upstream word and downstream word after the water was emptied. 	The data/figure: <ul style="list-style-type: none"> The water height h_1-h_8 at every scenario and the overtopping height above the railhead. The scouring profile at the different water levels in every scenario. The water discharge at the different water levels in every scenario.
2	The simulation similar to the setup above, but repeated with the T, T1, and T2 structures, but it was positioned at L_2 .	Measured : The parameters measured are exactly similar to the experiments above.	Similar as above.

Table 2. The water level of the modeling without the protection structure ($h_1 = 10-20$ cm)

Measurement point	dist from ref- cm	h_1							
		10 cm	12 cm	14 cm	15 cm	17 cm	19 cm	20 cm	
8 d/s	0	1.3	1.3	1.8	1.9	2.7	5.0	7.0	
8 u/s	3	1.3	1.3	1.8	1.9	2.7	5.0	7.0	
7 d/s	12.0	1.3	1.3	1.8	1.9	2.7	5.0	7.0	
7 u/s	20.0	1.3	1.5	2	2	2.7	5.0	7.0	
6	60.0	1.3	1.1	2.7	2	3.7	6.0	8.0	
5	72.0	4.2	4.2	7.5	7.5	7.5	9.0	10.0	
4 d/s	88.5	7	9.5	11	10.7	11.5	14.0	14.0	
4 u/s	90.5	7	9.5	11.8	12.2	14.5	16.5	18.0	
3 d/s	111.5	8.4	10.5	13	12.2	14	15.6	16.5	
3 u/s	113.5	8.4	10.5	13.4	14.1	16	18.0	18.5	
2	132.0	9	11.5	13.7	14.5	16.5	18.0	19.5	
1	144.0	10	12	14	15	17	19.0	20.0	
	160.0	10	12	14	15	17	19.0	20.0	

Notes: d/s: downstream, u/s: up stream

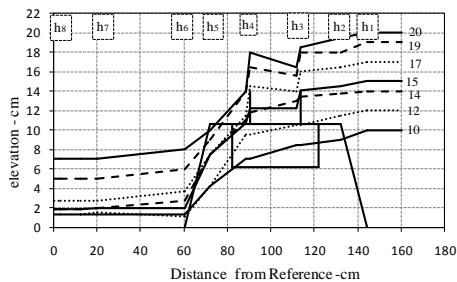


Fig.6. The profiles of various water levels simulated without prevention structure ($h_1 = 10-20$ cm)

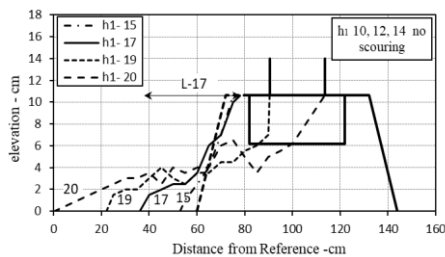


Fig.7. The scouring profile resulting from the modeling without protection structure

The water level profile for one condition as Fig.8, the others are not drawn cause of page limitation. The scouring profiles are displayed in Fig. 9 until 11. The simulation with $h_1 < 17$ cm was not conducted as scouring did not happen.

3.1.3 The Results of The Simulation of The T, T1, and T2 Structures at The L2 Location

The simulations of the water levels $h_1 = 17, 19,$ and 20 cm are conducted similarly to the previous

ones i.e. the T, T1, and T2 structures. The water level data are presented in Tabel 4.

The water level profile for one condition as Fig. 12, the others are not drawn cause of page limitation. The scouring profiles are displayed in Fig. 13-15. Resume of overtopping height and scouring length are displayed in Table 5 and Table 6.

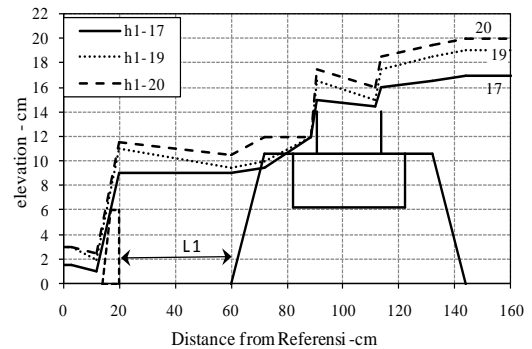


Fig.8. The water level profile variation of the T structure modeling at L_1

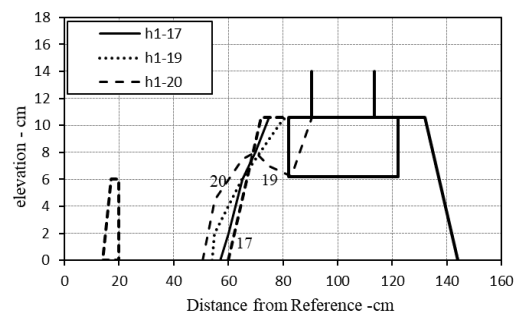


Fig.9. The scouring profile of the T structure modeling at L_1

Table 3. The water height variation at the T, T1, and T2 structures location at L₁

Measurement point	dist from ref-cm	h ₁ -T at L ₁			h ₁ -T1 at L ₁			h ₁ -T2 at L ₁		
		17 cm	19 cm	20 cm	17 cm	19 cm	20 cm	17 cm	19 cm	20 cm
8d	0	1.5	3	3	1.5	2.5	3	1	2	3
8u	3	1.5	3	3	1.5	2.5	3	1	2	3
7d	12.0	1	2	2.5	1	1.5	2	1.5	1.5	2.5
7u	20.0	9	11	11.5	11	13	13	13.5	15	15.5
6	60.0	9	9.5	10.5	11	12	12	13.3	14.5	15.5
5	72.0	9.5	10	12	11	12.5	13.5	13.5	14.5	16
4d	88.5	12	12	12	12	12	12.5	13	15	13.5
4u	90.5	15	16.5	17.5	15	16.5	17.5	15.2	17	17.5
3d	111.5	14.5	15	16	14	15.5	16	14.5	15.5	16
3u	113.5	16	17.5	18.5	16	18	18.5	16.2	18	18.5
2	132.0	16.5	18.5	19.5	16.5	18.5	19.5	16.5	18.5	19.5
1	144.0	17	19	20	17	19	20	17	19	20
	160.0	17	19	20	17	19	20	17	19	20

Table 4. The water height variation with T, T1, and T2 at L₂

Measurement point	dist from ref-cm	h ₁ -T at L ₂			h ₁ -T1 at L ₂			h ₁ -T2 at L ₂		
		17 cm	19 cm	20 cm	17 cm	19 cm	20 cm	17 cm	19 cm	20 cm
8d	0.0	1.0	1.5	2.5	1.5	2.0	2.5	1	1.5	2.5
8u	3.0	9.0	11.0	11.0	11.5	12.5	13.0	13.5	15	15.5
7d	12.0	9.0	11.0	11.5	11.5	12.5	13.5	13.5	15	16
7u	20.0	9.0	11.0	11.5	11.5	12.5	13.5	13.5	15	16
6	60.0	8.5	10.0	11.0	11.0	12.0	12.5	13	14.5	15
5	72.0	10.5	11.0	11.0	11.5	13.0	13.0	13.5	15	16.5
4d	88.5	12.0	12.0	10.5	12.5	12.5	12.5	13.5	13	14
4u	90.5	15.0	17.0	17.5	15.0	16.5	17.5	15	16.5	17.5
3d	111.5	14.0	15.5	15.5	14.5	15.5	16.5	14.5	15.5	18.5
3u	113.5	16.0	17.7	18.5	16.0	18.0	19.0	16	18	19.5
2	132.0	16.5	18.5	19.5	16.5	18.5	19.5	16.5	18.5	19.5
1	144.0	17.0	19.0	20.0	17.0	19.0	20.0	17	19	20
	160.0	17.0	19.0	20.0	17.0	19.0	20.0	17	19	20

3.2 Discussion

In the experiment without prevention structure (Fig.6), it was apparent that the stones were scoured due to the resultant of the horizontal hydraulic force which passed through the ballast and hydraulic force cause of overtopping. Moreover, the mainstream-ward force was greater than the stones' weight and friction. After the scouring, the stones would be carried away to downstream. The scouring length varied proportionally to the water height h₁ (Fig.7).

The external structure of the ballast's downstream was proven to shorten the scouring length (Fig. 9, 10, 11, 13, 14, and 15). The overtopping height varied and was correlated to the structure type and to its position (Table 5). The values of the scouring length and the damping effectiveness (the percentage of scouring length

reduction) due to the presence of the protection structure are displayed in Table 7 and Table 8.

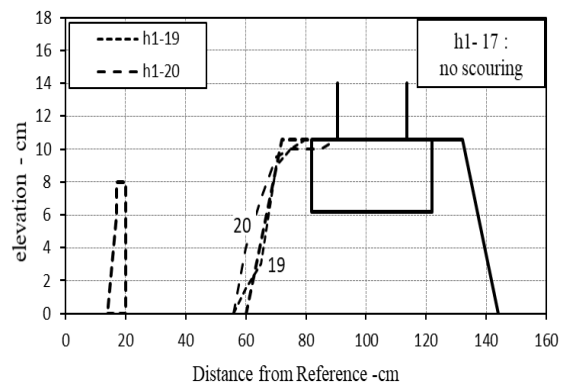


Fig.10. The scouring profile of the T1 structure modeling at L₁

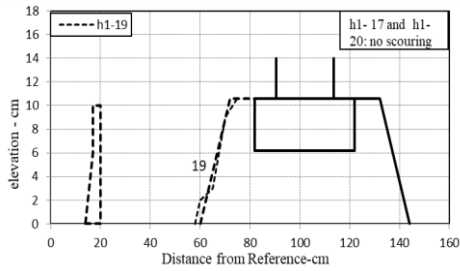


Fig.11. The scouring profile of the T structure modeling at L₂

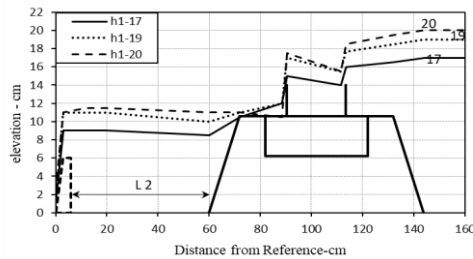


Fig.12. The water level variation of the T structure modeling at L₂

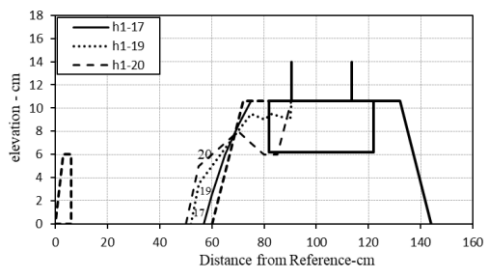


Fig.13. The scouring profile of the T structure modeling at L₂

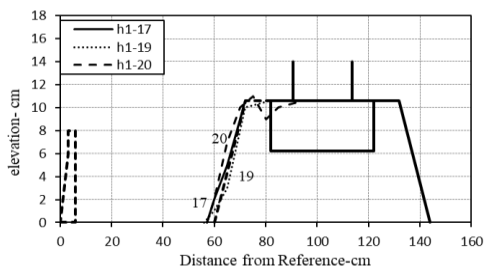


Fig.14. The scouring profile of the T1 structure modeling at L₂

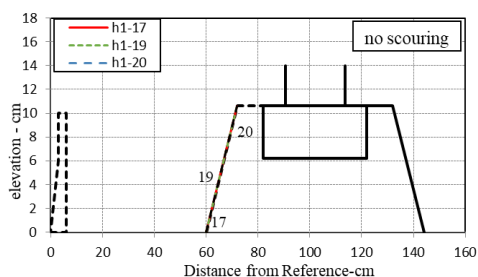


Fig.15. The scouring profile of the T2 structure modeling at L₂

From the table above, it suggests that the higher structures are more effective in shortening the scouring length given that they stand at the same location (Fig.16 and Fig.17). By comparing the average effectiveness of the scouring length's damping, the protection structure at L1 (with the similar type) is more effective than the structure at L2. The structure at L1 resulted in the shorter scouring length and the larger percentage of the scouring length's reduction. There was also a scouring case when the T2 structure positioned at L1 (Fig.11) while the precisely similar structure at L2 produced no scouring at all. However, from the data and the scouring profile, the scouring was not significant occurred. It was possibly due to the imperfect assembling of the ballast aggregates.

The water level elevation by the downstream of the rail (h₅) is very significant in damping the scouring. The downstream water level h₅ (Table 9) shows that the average h₅ for the protection structure located at L2 was higher than h₅ of the structure at L1. Due to Archimedes effect, the higher water level at the downstream would lift/reduce its self-weight of the aggregates which will reduce the shear resistance force. Thus, this mechanism would lift more stones with equal hydraulic force [17]. It can be concluded that the prevention structure being positioned at L2 or far distance will not be effective in reducing the scouring mechanism.

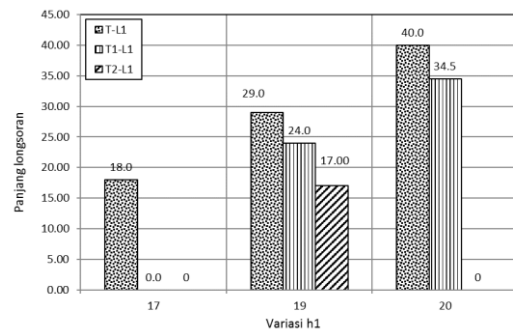


Fig.16. The scouring length structure at L1

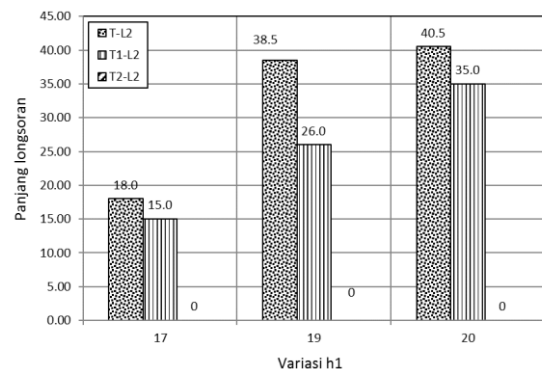


Fig.17. The scouring length structure at L2

Table 5. The overtopping height above the railway (h1) structure at L1 and L2

h ₁ cm	The overtopping height above the railway													
	Without prevention		Structure at L ₁						Structure at L ₂					
	h ₃	OT	T		T1		T2		T1		T1		T2	
15	14.1	0.1	-	-	-	-	-	-	-	-	-	-	-	-
17	16	2	16	2	16	2	16.2	2.2	16	2	16	2	16	2
19	18	4	17.5	3.5	18	4	18	4	17.7	3.7	18	4	18	4
20	19	5	18.5	4.5	18.5	4.5	18.5	4.5	18.5	4.5	19	5	19.5	5.5

Note: OT stands for overtopping height; the elevation of the railhead is +14.00; h₃ = h₃ upstream.

Table 6. The scouring length for various h1 structure at L1 and L2

Water level h ₁ cm	Without structure	L ₁ Location			L ₂ Location		
		T	T1	T2	T	T1	T2
15	22	0	0	0	0	0	0
17	42	18	0	0	18	15	0
19	68.5	29	24	17	38.5	26	0
20	113.5	40	34.5	0	40.5	35	0

Table 7. The scouring length and the damping effectiveness of the protection structures at L1

Water height h ₁ (cm)	without prevention structure (cm)	Scouring length					
		prevention structure at L1 (cm)			percentage of the scouring length's reduction		
		T	T1	T2	T	T1	T2
15	22	0	0	0	100.00	100.00	100
17	42	18	0	0	57.14	100.00	100
19	68.5	29	24	17	57.66	64.96	75.18
20	113.5	40	34.5	0	64.76	69.60	100
Average		60.33	35.50	17.00	59.85	78.19	91.73

Table 8. The scouring length and the damping effectiveness of the prevention structures at L2

Water height h ₁ (cm)	without protection structure (cm)	Scouring length					
		prevention at L2 (cm)			percentage of the scouring length's reduction		
		T	T1	T2	T	T1	T2
15	22	0	0	0	100.00	100.00	100
17	42	18	15	0	57.14	64.29	100
19	68.50	38.5	26	0	43.80	62.04	100
20	113.50	40.5	35	0	64.32	69.16	100
Average	61.50	70.00	52.67	0.00	55.09	65.16	100.00

Table 9. The water level h₅ of the structure at L1 and L2

Water level variation h ₁	Elevation h ₅ with structure at L1			Elevation h ₅ with structure at L2		
	T	T1	T2	T	T1	T2
17	9.50	11	13.50	10.50	11.50	13.50
19	10.00	12.50	14.50	11.50	13.00	15.00
20	12.00	13.50	16.00	11.00	13.00	16.00
Average	10.5	12.33	14.67	11.00	12.50	14.83

4 CONCLUSION

External structures have an effect to damp/reduce scouring length. The higher structure

is more effective in damping scouring mechanism (compared to other structures which are deployed at the same position). It is proven by Table 7 and Table 8. The structure which was located at L1 has

an average scouring damping rate by 59.85%, 78.18%, and 91.73% for T, T1, and T2 type respectively. Meanwhile, L2 position would give 55.09%, 65.16%, and 100% respectively. The Structure (with the same type) which is positioned closer at L1 is more effective in reducing scouring than being positioned longer downstream at L2. The prevention structure type T and T1 which were set at L1 is more effective in reducing scouring length relative to the structure set at L2. It is proven by the experiments where the former produced 59.85% and 78.19% while the latter produced 55.09% and 65.16%.

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