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Hydraulic Performance of Inverted Siphons for Irrigation Water Supply Using Physical Modeling

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Abstract: In this paper, we investigated the performance of the Rambatan siphons in Indramayu Regency, Indonesia, via physical modeling. The model was built in the laboratory with a scale of 1:10, consisting of two siphons, each with a diameter of 0.3 m and a length of 14 m for the model scale. Several scenarios were considered for the physical modeling, of which the focus was on analyzing the discharge capacity, sediment flushing, flow pattern, and pressure. Using the (prototype) design discharge of 6.36 m^3/s and some variations of sediment size for the original configuration of the model, we observed the insufficient hydraulic capacity of the siphons. Several modifications were thus applied to the original design, namely by modifying the upstream channel and extending the upper wall of the downstream channel. The result showed that the hydraulic performance increased after applying such modification scenarios, where the siphons were able to discharge 6.36 m^3/s. In addition, we observed that the flushing pipe diameter of 0.5 m was faster to flush the sediment inside the siphons. The results of this study are useful for the related stakeholders to increase water supply productivity.

Keywords: Discharge, flushing, physical modeling, sediment, siphon

1. Introduction

In 2012 the Rambatan siphons were constructed in Indramayu, West Java Province (Indonesia), see Fig. 1, of which the main function is to supply water for the Rentang irrigation area. However, after the construction, the barrel portion of the siphons under the river bed was heavily damaged and its hydraulic structure function was completely lost. Thus, no water supply to the downstream part could be provided by these siphons due to such structure damage. In order to solve this problem, a new design has been prepared to replace the existing siphons. The total structure length of the prototype scale is 112 m, consisting of 15 m approach channel and 97 m of two inverted siphon pipes. These new siphons were designed for the maximum discharge of 6.36 m^3/s. The layout and technical drawing of the siphons are given in Fig. 2 and Fig. 3, respectively. So that this new design can work properly, several hydraulic parameters must be checked and ensured, for instances, discharge capacity, sediment flushing, flow pattern, and pressure head.

The previous research from [1]-[4] showed that the flow velocity was one of the important parameters among others, for siphon or sewer structure, whether it can be used for urban or irrigation drainage. With respect to this, an approach that can be undertaken to investigate the characteristics of the aforementioned hydraulic parameters is by means of physical modeling, where the prototype structure is built with a certain scale at a laboratory. It was shown in [5]-[8] that physical modeling can provide a detailed evaluation with high accuracy. In this paper, we investigate the hydraulic performance of inverted siphons via physical modeling.

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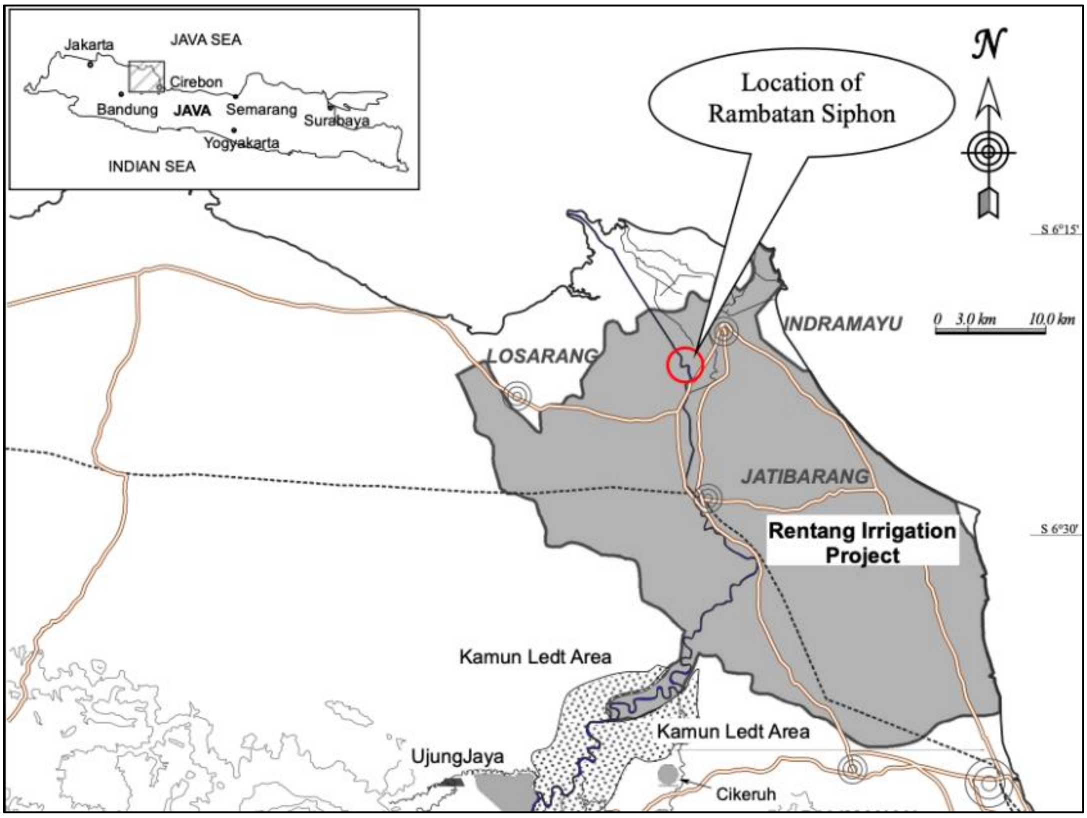


Fig. 1 - Location of the Rambatan siphons

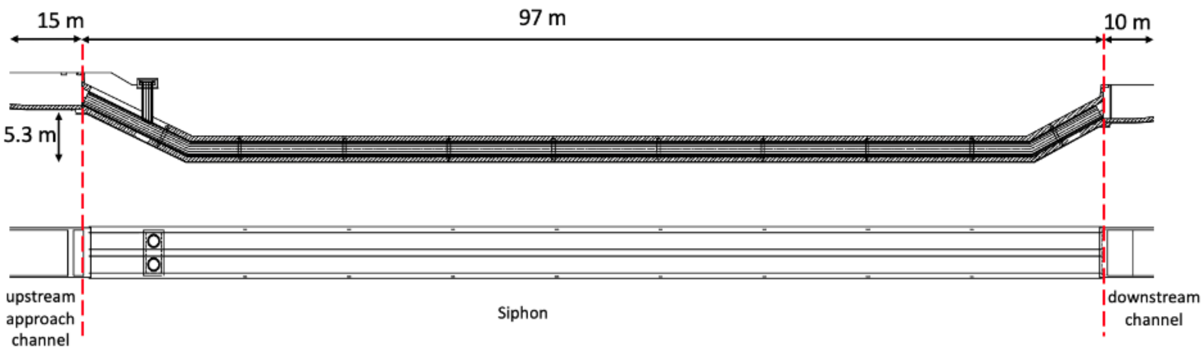


Fig. 2 - Long section of the Rambatan siphons (dimension in prototype scale)

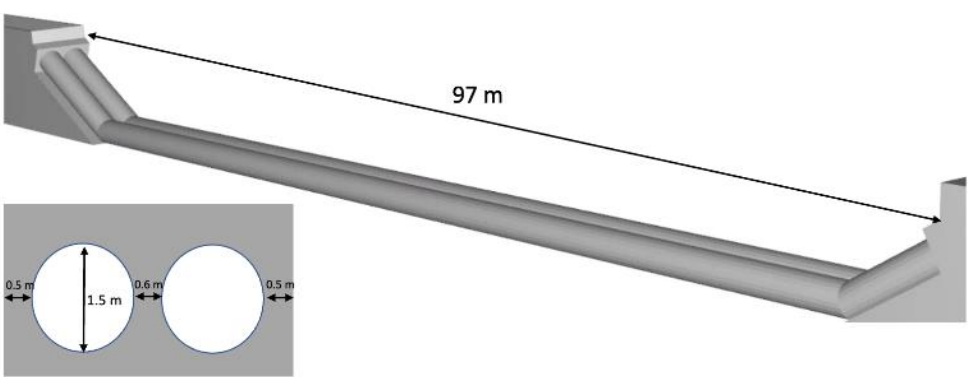


Fig. 3 - 3D view design of the Rambatan siphons (dimension prototype scale)

2. Physical Model

The physical model of the Rambatan siphons was constructed with undistorted fixed scale at the Hydraulic Laboratory of the Technical Implementation Unit for Hydraulic and Geotechnics, Ministry of Public Works and Housing, Indonesia. Due to the availability of the laboratory space and pump capacity, it was decided to use a scale of 1:10 for the model with the Froude similarity. The scaling factor used for this model is given in Table 1, where the variable n_h denotes the base scale factor for the height. The technical data of the Rambatan siphons (in prototype scale) is shown in Table 2. According to the design report, the laboratory experiment was conducted using four discharge values as presented in Table 3. These values were selected based on the actual requirement for irrigation. A point gauge was used along with the laboratory digital velocity meter to collect the observed data.

Table 1 - Scaling factor for the hydraulic parameters

Hydraulic Parameters	Notation	Factor
length, height	L, h	$n_L = n_h = 10$
velocity	v	$n_v = {n_h}^{1/2} = 3.162$
discharge	Q	$n_Q = {n_h}^{5/2} = 316.2$
Manning coefficient	n	$n_n = {n_h}^{1/6} = 1.1467$
volume	V	$n_V = {n_h}^3 = 1000$

Table 2 - Technical data of the Rambatan siphons (dimension in prototype scale)

Property	Value
Length of siphons	97 m
Diameter of siphons	1.5 m
Number of siphons	2
Upstream approach channel	15 m
Downstream channel	10 m
Inlet elevation of siphons	+2.03 m
Outlet elevation of siphons	+1.33 m
Bottom elevation of siphons	-3.33 m

Table 3 - Discharge data for the Rambatan siphons (dimension in prototype scale)

Discharge scenarios	Discharge values (m^3/s)
Low	1.58
Low medium	3.18
Medium	4.77
High	6.36

The laboratory experiment was conducted using a pump with a capacity of 7.6 l/s. First, the water was pumped from the reservoir to the forebank through a V-notch weir that was used to measure the discharge. Afterwards, the water flowed to the modeling area and then to the reservoir tank through the downstream channel. For this experiment, the siphons were made from acrylic glass, whereas the upstream and downstream channels were constructed with smooth concrete material. In the modeling area, the flow depth was measured with an analog point gauge, and the flow velocity with a digital current meter. The accuracy of these measurement instruments can be ensured to be less than 1 mm and 0.007 m/s for the depth and velocity data, respectively, which correspond to 0.01 m and 0.022 m/s for the prototype scale. The sketch of the physical model configuration is shown in Fig. 4.

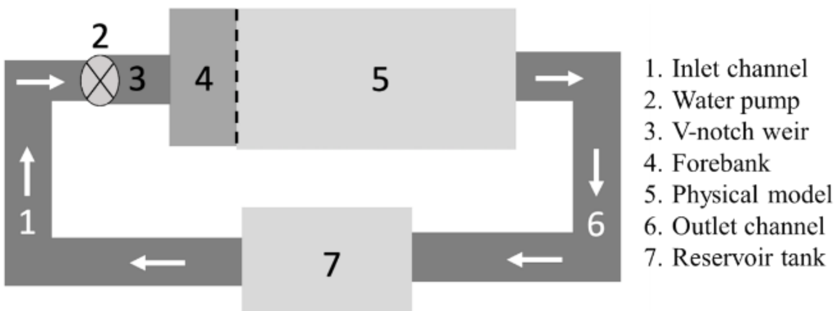


Fig. 4 - Physical model configuration

Fig. 5 - Physical model of the Rambatan siphons

The configuration of the laboratory model of the Rambatan siphons is shown in Fig. 5. The system of these siphons consists of three components of main structures, namely (i) an upstream channel (in front of the inlets of the siphons) that conveys water from the river, (ii) two pipes at the middle part, and (iii) a downstream channel (in front of the outlets of the siphons) that directs water to the irrigation channels, see Fig. 6. It was observed in the field that the sedimentation rate at the upstream part increased over the last year. Hence, if this phenomenon continues to occur, sedimentation problems inside the siphon pipes may exist, and it will be difficult to flush the sediment material outside the pipes. Therefore, it is of uttermost importance to study the flushing system for these siphons. To this regard, a diversion pipe was added to each siphon pipe for sediment flushing, see Fig. 6.

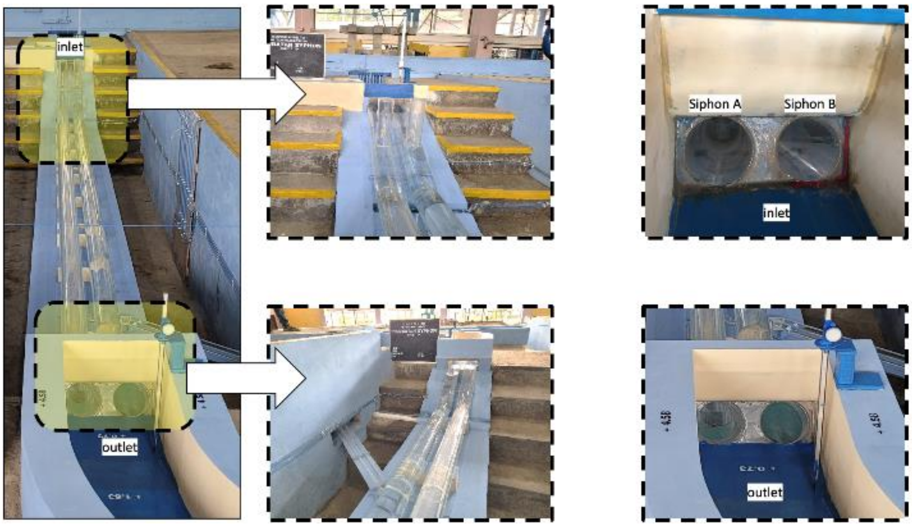


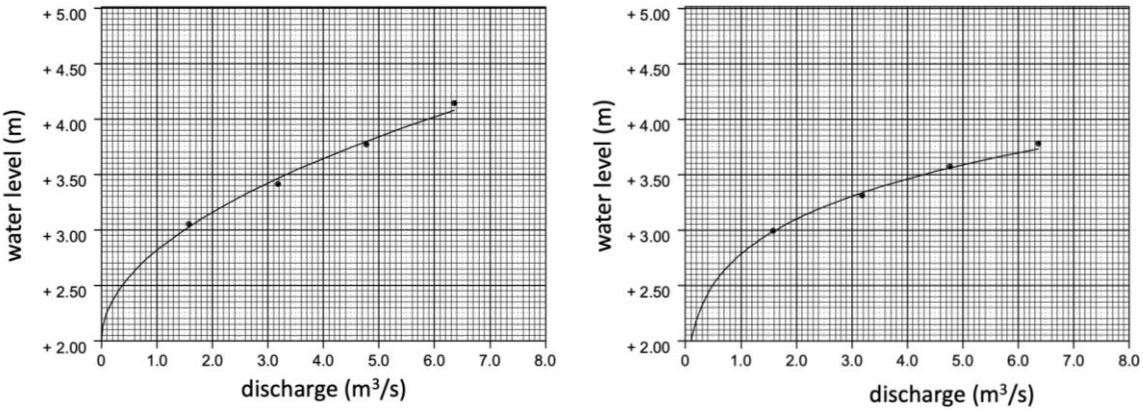
Fig. 6 - Inlet and outlet configurations of the Rambatan siphons (physical model)

3. Physical Model

In this section, we will discuss four hydraulic parameters, namely discharge capacity, sediment flushing, flow pattern, and pressure head, which were investigated during the experiment. As recommended in [9] and [10], these parameters are important to be studied in order to assess the performance of siphon. Note that all the laboratory results in the next sections are explained in the prototype scale.

3.1 Discharge Capacity

It is required to check the discharge capacity of the siphons because one must ensure that both upstream and downstream dikes for the upstream and downstream channels, respectively, are free from overtopping. As previously shown in Table 3, four discharge values were used for the physical modeling. In this regard, the discharge was adjusted according to the gauge level of the V-notch weir. Thereafter, the water levels at both upstream and downstream parts (upstream and downstream channels) were measured in conjunction with the discharge values. The results were provided as the rating curves for both channels, see Fig. 7. Note that these curves were produced with respect to the elevations of the inlet and outlet of the siphons being +2.03 m and +1.33 m, respectively, see Table 2.



(a) (b)

Fig. 7 - Rating curve (a) upstream channel, and; (b) downstream channel (dimension in prototype scale)

Based on the laboratory results shown in Fig. 7, it can be known that the upstream water level for the high discharge of 6.36 m^3/s was at the elevation of +4.17 m. Meanwhile, the downstream water level for this discharge reached the elevation of +3.81 m. Because the elevation of the upstream dike is +5.18 m and of the downstream dike is + 4.58 m, it can then be noticed from Fig. 7 that the freeboard values for the upstream and downstream channels are 1.01 m and 0.77 m, respectively. Hence, the freeboard values are sufficient for the maximum discharge. According to [7], such freeboard values already comply with the Indonesian standard that requires a value between 0.75 m - 1.5 m. These results indicate that the Rambatan siphons has sufficient capacity to flow the maximum discharge, thus preventing overtopping cases for both upstream and downstream dikes. Note that when the water level and dike crest elevation are the same (without freeboard), the maximum discharge of the Rambatan siphons is hence 16.96 m^3/s.

3.2 Sediment Flushing

In this experiment, we investigated the capability of the Rambatan siphons to flush the sediment using the diversion pipes. The first siphon (siphon A) was connected to a diversion pipe (let us say pipe A) with a diameter of 0.3 m (protype scale). Meanwhile, the other siphon (siphon B) was connected to a diversion pipe (pipe B) with a diameter of 0.5 m (prototype scale). These diversion pipes were installed on the bottom part of the siphons, see Fig. 8. For the sake of simplicity, the flushing experiment was conducted only for each pipe. To this regard, sediment materials with an approximate volume of 0.017 m^3 with four different grain sizes was prepared for the experiment. The grain size diameters were 0.02 m, 0.012 m, 0.006 m, and 0.0015 m.

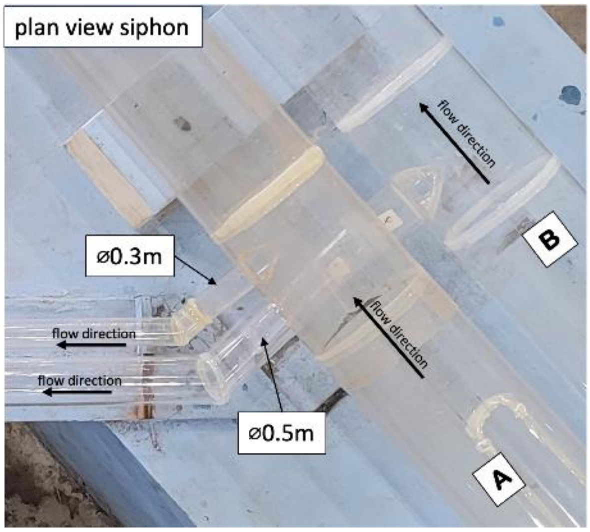


Fig. 8 - Diversion pipe for the siphons (dimension in prototype scale)

The flushing tests were conducted by sowing the sediment materials on the siphon inlet so that such materials entered a siphon (siphon A or siphon B). Thereafter, water flowed into the siphon and the time duration was recorded until the sediment material was entirely flushed, see Fig. 9, where the result was shown for a discharge value of 6.36 m^3/s. The flushing time for each siphon was documented in Table 4. We observed that for the sediment material with coarser grain size (0.006 m - 0.02 m), siphon B was able through pipe B to flush all the materials faster than siphon A with pipe A.

This is obvious because a larger pipe size causes the materials to enter it easier when the water flows. However, this is not the case for the finest material (0.0015 m).

Interestingly, no significant time difference was observed between siphon A and siphon B to flush the 0.0015 m material through pipe A or pipe B. This indicates that there is no significant effect of the diversion pipe size on the flushing time for the finest sediment size. This may be because such fine size materials dominantly acted as suspended load, which became easier transported by water. Indeed, even after all the sediment materials were flushed through the diversion pipe, it was found that there were accumulated sediment in front of the outlets of the siphons (at the downstream channel), as shown in Fig. 10. Therefore, further measure needs to be considered, for example, a modification of the downstream channel. This will be discussed in the next section.

Table 4 - Flushing duration of the siphons

Diversion pipe size	Sediment diameter	Material	Flushing duration
0.3 m (dimension in prototype scale)	0.02 m	Sand	104.3 minutes
	0.012 m	Sand	142.3 minutes
	0.006 m	Sand	173.9 minutes
	0.0015 m	Crushed bricks	79.1 minutes
0.5 m (dimension in prototype scale)	0.02 m	Sand	88.5 minutes
	0.012 m	Sand	101.2 minutes
	0.006 m	Sand	107.5 minutes
	0.0015 m	Crushed bricks	79.1 minutes

(a) (b)

Fig. 9 - (a) Before flushing simulation, and; (b) during flushing simulation to the 0.3 m pipe (dimension in prototype scale)

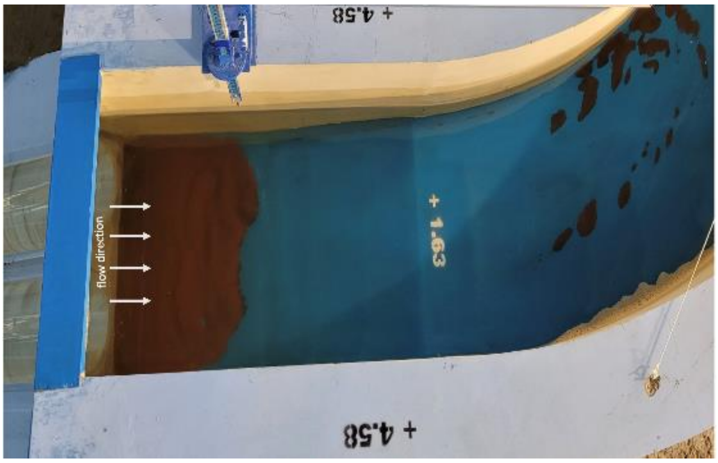
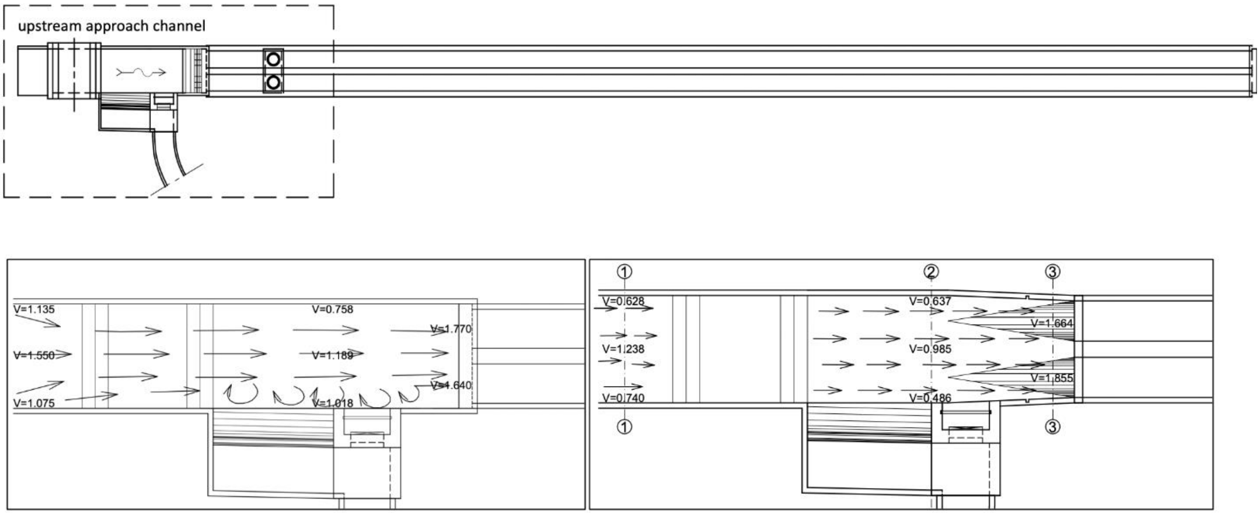


Fig. 10 - Accumulated sediment remaining at the downstream channel with the existing design

3.3 Flow Pattern

This experiment aimed to investigate the flow pattern so that uniform flow distribution from the upstream and downstream channels of the siphons could be ensured. Similar to the previous section, the results are presented here for the discharge of 6.36 m^3/s. The flow velocities at both upstream and downstream channels were measured using the current meter. In Fig. 11(a) we sketched the laboratory results of the flow pattern with the existing design. It was observed that some vortices occurred around the upstream part near the inlet of siphon A. Such vortices were caused by a sudden change from the transition channel to the siphon inlet. The shape of the transition channel was rectangular, whereas the siphon inlet was of round shape, see Fig. 12(a), so the flow could not be well distributed when the water entered the inlet of the siphon. The flow velocity was shown to be not non-uniform with the existing design of the siphons. The velocity range at the upstream part was between 1.075 m/s - 1.550 m/s, where the maximum value was detected at the middle part. Near the inlet of siphon, A, some vortices were noticed, where a velocity of 1.64 m/s was recorded.



(a) (b)

Fig. 11 - Flow pattern of upstream channel with 6.36 m^3/s discharge (a) existing design, and; (b) modified design (dimension in prototype scale)

It is understood that vortices at the siphon inlets must be avoided unless the discharge proportion to siphon A and siphon B will not be uniformly distributed. For this reason, we modified the shape of the existing design with a smooth transition from trapezoidal to round shape, see Fig. 12(b). After this modification, we noticed that the flow distribution became relatively smooth and well-distributed from the upstream channel to the siphon inlets, where no vortices were observed, see Fig. 11(b). At the upstream part, the velocity became relatively smooth with a range of 0.74 m/s - 1.238 m/s. For the inlets of both siphons, the flow distribution became uniform as well, although slightly different velocity values were still observed (1.855 m/s and 1.664 m/s for siphon A and siphon B, respectively).

(a) (b) (c)

Fig. 12 - Upstream part of the siphons (a) existing design; (b) modified design, and; (c) simulation with modified design (dimension in prototype scale)

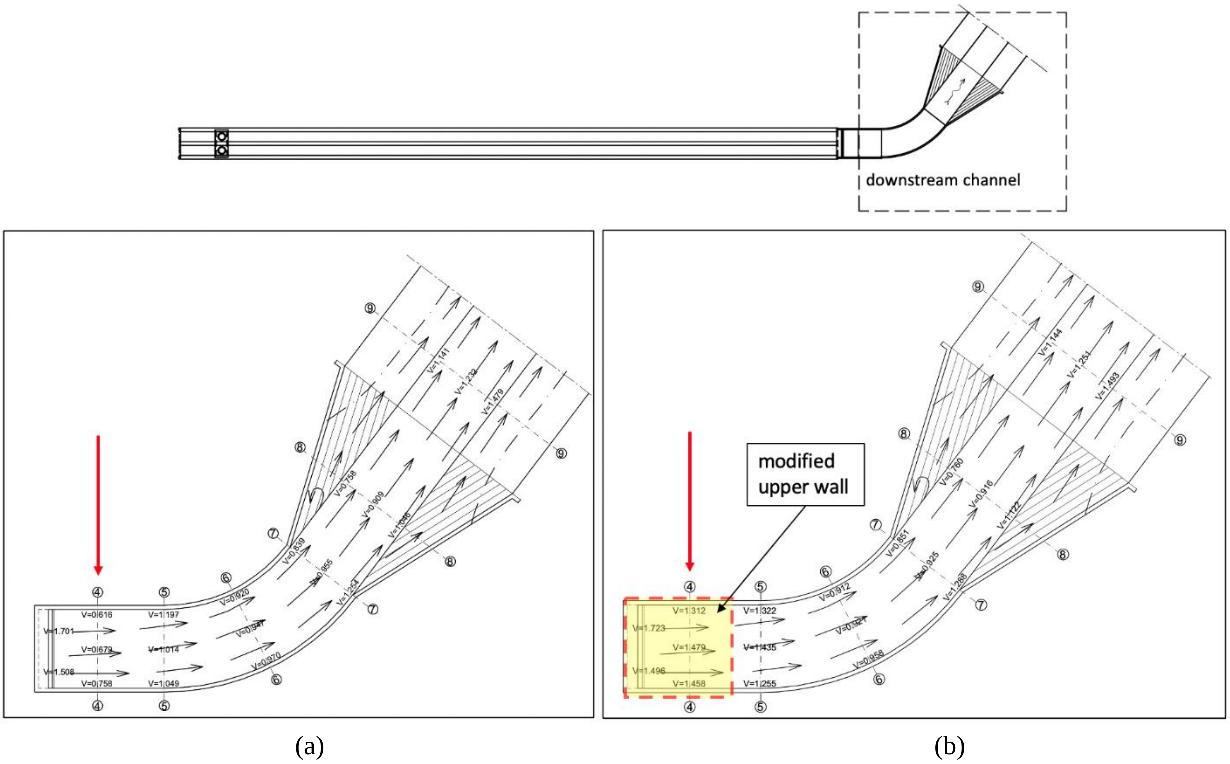


Fig. 13 - Flow pattern of downstream channel with 6.36 m^3/s discharge (a) existing design, and; (b) modified design (dimension in prototype scale)

In addition to the upstream part, we also investigated the flow pattern at the downstream channel. For the existing design, it was observed that the flow pattern was already well distributed at the downstream channel, see Fig. 13(a). However, one can see that there was a significant decrease of the velocity from 1.7 m/s (the average velocity from the outlet of the siphons) to 0.684 m/s (the average velocity at the downstream channel of section 4). This relates to the accumulated sediment materials discussed in the previous section. Such a decrease in velocity tends to cause the materials to deposit in front of the outlets of the siphons. To deal with this problem, we modified the downstream channel by extending the upper wall (near the siphon outlets) to maintain the high velocity from such outlets, see Fig. 14. In other words, this modification maintains a closed-channel flow, instead of the open-channel one, at the siphon outlets just before reaching the downstream channel. The flow pattern with the modified design is shown in Fig. 13(b). With such a modification, no significant decrease in velocity was observed between the outlets of the siphons and the downstream channel (section 4), where the average velocity at the downstream channel of section 4 now became approximately 1.416 m/s, being larger than the average velocity value before the modification (0.684 m/s). In Fig. 15 we show that with the modified design, the amount of the accumulated sediment materials in front at the downstream channel could be significantly decreased.

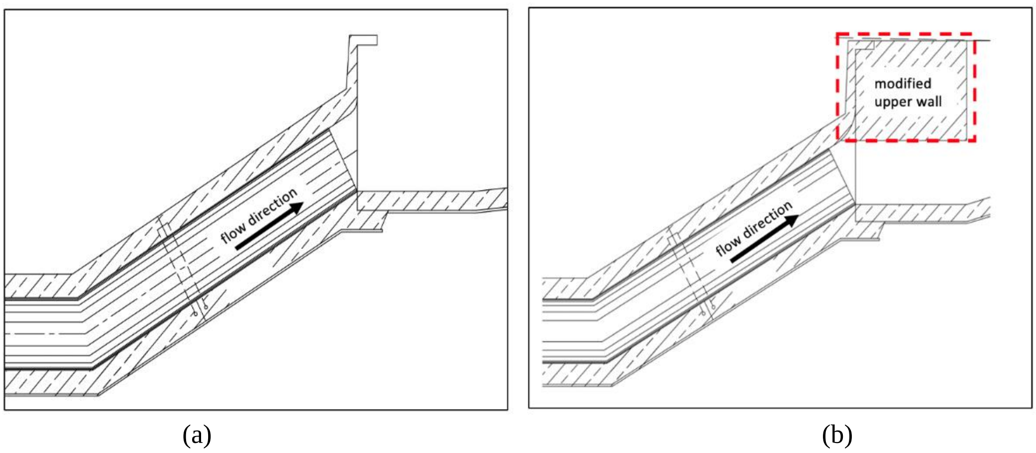


Fig. 14 - Sketch of the configuration of the downstream channel (a) existing design, and; (b) modified design

Fig. 15 - Accumulated sediment remaining at the downstream channel with the modified design

3.4 Pressure Head

The last hydraulic parameter investigated in this study was the pressure head. This aimed to check whether the pressure head in the siphons is still sufficient to convey water to the irrigation area. For this purpose, the pressure tube was installed along with both siphons, see Fig. 5. Some piezometers were also installed in the siphons in order to measure the static pressure head of the water flowing at certain section of a siphon, see Fig. 16. Here we present the results for all the discharge values tested.

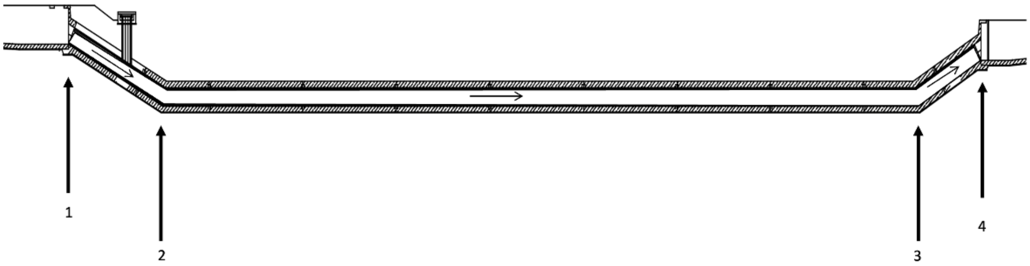


Fig. 16 - Sketch of the piezometer locations

The results of the pressure head are given in Fig. 17. In general, one can observe that higher discharge values result in higher pressure. In piezometer 1 to 2, the pressure dropped significantly due to the velocity increase on the steep gradient. In piezometer 2 to 3, a slight decrease was observed, but in piezometer 3 to 4 the pressure increased significantly due to the decrease in flow velocity near the outlets of the siphons. From the laboratory results with different discharge values, it can be noticed that the maximum head loss from the upstream to downstream parts was 0.37 m, see Fig. 18. Note that the downstream water level was +3.78 m, and thus, this elevation was still sufficient for irrigation water supply because the downstream water level requirement for the irrigation channel was lower than the outflow water level from the siphons.

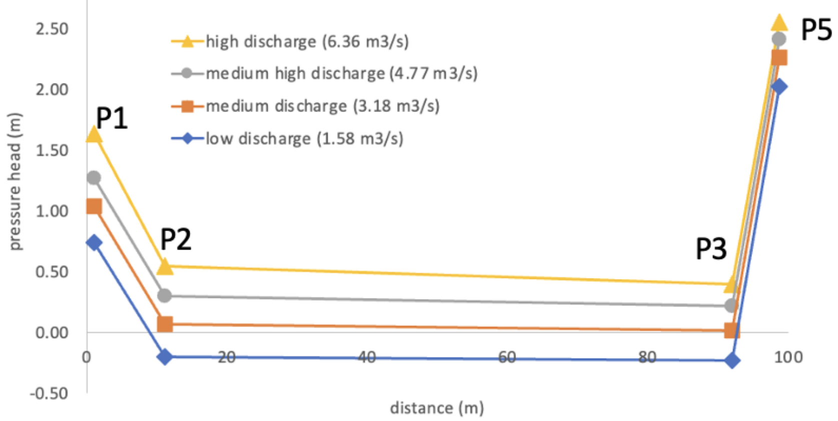


Fig. 17 - Piezometer results (dimension in prototype scale)

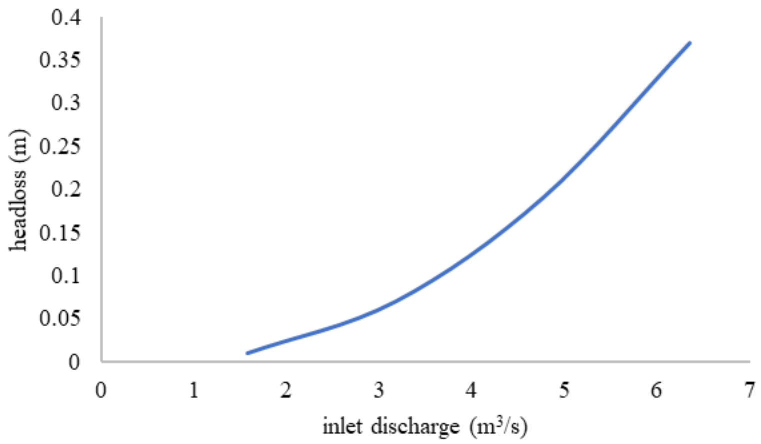


Fig. 18 - Head loss for the siphons for different discharge values (dimension in prototype scale)

4. Conclusion

An investigation of inverted siphons has been presented in this paper. This study aimed to investigate the performance of the Rambatan siphon for irrigation water supply with respect to four hydraulic parameters, namely discharge capacity, sediment flushing, flow pattern, and pressure head. We found that several modifications must be made to the original design of the siphons. For the discharge capacity, it was observed that the freeboard values of 1.01 m and 0.77 m for both upstream and downstream dikes fulfilled the standard criteria. Several modifications were made to improve the performance, namely by modifying the approach inlet channel from trapezoidal to round shape and by extending the upper wall of the outlet channel to maintain the outflow velocity to downstream area. With this modified design, it could also be ensured that the amount of the accumulated sediment materials in front of the siphon outlets (at the downstream channel) significantly decreased. The maximum head loss from upstream to downstream siphon was considered acceptable since the downstream water level requirement for the irrigation channel was lower than the outflow water level from the siphons. Finally, we present a resume of our investigation for the modified design in Table 5.

Table 5 - Resume for the modified design of the Rambatan siphons

Parameters	Status	Description
Discharge capacity	sufficient	Upstream freeboard 1.01 m
Flow pattern	well distributed	No vortex
Pressure and headloss	sufficient	Maximum headloss 0.35 m
Flushing sediment	clear	Ø 0.5 m flushing pipe is the best option

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