Energy Dissipation on the Ogee Spillways by Using Direction Diverting Blocks

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ABSTRACT

The purpose of this study is to evaluate the hydraulic performance and efficiency of using direction diverting blocks, DDBs, fixed on the surface on an Ogee spillway in reducing the acceleration and dissipating the energy of the incoming supercritical flow. Fifteen types of DDB models were made from wood with a triangulate shape and different sizes were used. Investigation tests on pressure distribution at the DDBs boundaries were curried out to insure there is no negative pressures is developed that cause cavitation. In these tests, thirty six test runs were accomplished by using six types of blocks with the same size but differ in apex angle. Results of these test showed no negative pressures developed at the boundaries of these blocks. A physical model for a part of Mandili Dam spillway system was constructed with a scale ratio of 1:50. Thirteen runs were carried out to obtain the rating curve of the ogee weir of Mandili Dam Model. Four hundred and seventy test runs were carried out to investigate the performance of the DDBs in reducing the energy of the flow. In these test runs, nine types of blocks with different sizes and different apex angles installed with different configurations on the spillway surface. Thirteen configurations of DDBs were tested. The Froude Number and the location of the hydraulic jump were used as indicators for the efficiency of these DDBs. Results indicated that when using the DDBs on a spillway surface, less Froude Number downstream the spillway is obtained and the hydraulic jump occurs at a much shorter distance from the spillway toe compared to same spillway without DDBs. Depending on the DDBs type, configuration, and the applied discharge, the obtained reduction in Froude Number varied between 4.4 to 19.3% and the reduction in the hydraulic jump distance measured from the spillway toe varied between 54% and 76% compared with that of the standard design of Mandili Dam.

Key words: energy dissipation, ogee spillway, stilting basin.

تبديد الطاقة على المطافح نوع اوجي باستخدام كتل تغيير الاتجاه

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الخلاصة

هدفت هذه الدراسة الى اختبار اداء وكفاءة استخدام كتل تغيير الإتجاه مثبتة على سطح مطفح مائي نوع اوجي في تقليل تعجيل وتشتيت طاقة المياه ذات الجريان فوق الحرج. تم اختبار خمسة عشر نموذجا من هذه ألكتل مصنعة من الخشب ذات اشكال مثلثة وباحجام مختلفة. اختبر توزيع الضغوط على جوانب هذه ألكتل لاختبار فيما اذا كان هنالك ضغوط سالبة متولدة يمكن أن تؤدي إلى حدوث ظاهرة التكهف. اجري ستة وثلاثون اختبارا بتصاريف مختلفة وباستخدام ستة أنواع من كتل تغيير ألاتجاه ذات حجم ثابت وتختلف بمقدار ألزاوية ألراسية. بينت نتائج هذه ألاختبارات عدم تولد ضغوط سالبة على جوانب هذه الكتل. انشئ نموذج فيزيائي للتصميم الأساسي لسد مندلي وبمقياس 50:1 وثبت في قناة مختبريه وحددت علاقة التصاريف المارة فوق الهدار بمنسوب الماء على اساس نتائج ثلاثة عشر اختبارا. اجري أربعمائة وسبعين اختبارا لتحديد اداء

كتل تغيير اتجاه الجريان باستخدام تسعة أنواع من ألكتل بأحجام وزوايا رأسية مختلفة وتم توزيعها و تثبيتها على سطح ألمسيل ألمائي بتسعة انماط مختلفة. اعتمد رقم فرود مؤخر المطفح ومقدرا بعد مسافة تولد القفزة الهيدروليكية عن اسفل المطفح كمؤشرات لتحديد كفائة الاداء. بينت نتائج الاختبارات المختبرية كفاءة هذه ألكتل في تقليل رقم فرود للجريان أسفل ألمسيل ألمائي وتقليل طول حوض ألتسكين. اعتمادا على نوع الكتل وطريقة توزيعها على سطح المطفح فان نسبة التقليل في رقم فرود تراوحت بين 4.5 و 19.3% ولمسافة تولد القفزة الهيدروليكية تراوحت بين 54 و76% مقارنة بالتصميم الاساس لمنظومة مطفح سد مندلي.

1. INTRODUCTION

High kinetic energy of water flowing over a spillway should be dissipated in stilling basins before reaching the downstream channel to eliminate scour of downstream river bed. Different common designs of stilling basins are available. These basins are usually equipped by a combination of chute blocks, baffle blocks, and end sills. Spillway surface was used to dissipate the energy in the ancient past by constructing a stepped spillway. This study attempts to make use of the ogee spillway surface by fixing energy dissipaters on it to reduce the acceleration and energy of the flow over a spillway. A new type of blocks was used as energy dissipaters that are known by direction diverting blocks, DDBs, **Fig. 1**. These blocks have a triangular shape with a different apex angle. The direction of incoming flow over the spillway of high kinetic energy is diverted by triangular shape DDBs to both sides. The diverted flow of two adjacent blocks having an opposite velocity component across the flow direction will meet at a point downstream the blocks. If more than one row of DDBs were used on the spillway surface, then the diverted flow from the previous row hits the side of the blocks at the next row. This causes a reduction in the acceleration of the incoming flow along the spillway and a high turbulence increases the energy dissipation. This study attempts to evaluate the hydraulic performance and efficiency of using DDBs in reducing dissipating the energy downstream ogee spillways.

2. PHYSICAL MODELS OF THE DDBS AND THE SPILLWAY

Fifteen type of triangular shape DDB models were used with different shapes and sizes. The main details of these blocks models are shown in **Fig. 2** and their dimensions are presented in **Table 1**. These models were made from wood and coated with varnish to protect them from damage by water. The DDBs were fixed by using special glue. The first six of these blocks were used for pressure distribution tests, and the last nine were used for energy dissipation tests.

To make comparisons between the energy dissipation with and without using DDBs, the system of Mandili Dam Spillway was selected to be modeled. Mandili Dam has the following characteristics, **General Directorate for Dams and Reservoirs, 2006**:

- Dam Height: 14*m*.
- Dam length = 1150*m*.
- Dam crest level =184*m.a.m.s.l*.
- Maximum water level=182.5*m*.
- Maximum Discharge =1724m^3/s.
- Spillway length =250*m*.
- Maximum head over spillway=2.5*m*.
- Maximum design discharge is 1724m^3/s
- Spillway crest elevation=180 *m.a.m.s.l*.

Mandili spillway was designed as an uncontrolled ogee weir. Its stilling basin floor level was set to 165*m.a.m.s.l* with a length of 21.5*m*. Chute blocks and dentated sills were provided in the stilling basin. The chute blocks have a width of 0.5*m* and height of 0.5*m*; the dentate sill has a height of 1*m*, a top width of 0.1*m*, distance between teeth is 0.75*m*, and an out slope of 2:1. A slopping hump was located at the end of the stilling basin at an elevation 169.00*m.a.m.s.l*. This hump is of 7*m* in length with an inclination of 1.5V:5H.

The hydraulic model of Mandili Dam Spillway system was constructed with a scale of 1:50. Based on the Laboratory channel width of 30*cm*, a part of the weir of 15*m* was modeled and tested. **Fig. 3** shows the longitudinal section in the physical model of Mandili Dam Spillway. The spillway model was constructed from wood, and was coated with plies of varnish.

3. CONFIGURATIONS OF THE DDBS

Laboratory tests were carried out to investigate any development of negative pressures at the boundary of the DDBS and the efficiency of these blocks in dissipation of the flow energy. In negative pressures investigation tests, DDBs were fixed in one row perpendicular to the flow direction of a flume of 30*cm* in width. Six types of DDBs, blocks of type 1, 2, 3, 4, 5, and 6, were used in these tests. The blocks were fixed on a wooden plate installed in the flume with a longitudinal slope of 1:30 in the direction of the flow. Eight piezometers were installed with their openings are located at the base of the blocks as shown in **Fig. 4**.

The energy dissipation tests were carried out with DDBs of type 7, 8, 9, 10, 11, 12, 13, 14, and 15, arranged in thirteen different configurations that are shown in **Figs. 5** to **13**. In these configurations, blocks were used in one or multi rows on the spillway surface with varying distances between the blocks and rows, with and without a stilling basin. In addition, these tests were carried with a modified length of the stilling basin of Mandili Dam Spillway or without a stilling basin. **Tables 2** and **3** present the details of these thirteen configuration and the types of DDBs used in each configuration, respectively.

4. RESULTS AND DISCUSSION

The piezometers readings were recorded in each pressure investigation test when using the six types of DDBs and discharges varied between of 2.5 and 8.8*l/s*. **Fig. 14** shows the variation of pressure head readings of the piezometers with discharge for each type of DDBs. At the upper limit of the applied discharge of 8.8*l/s*, the maximum value of pressure head varied between 4.2 and 4.6*cm* that was obtained when using DDB of type 6 and the minimum value of pressure head varied between 3.4 and 3.7*cm* that was obtained when using DDBs of types 1 and 2. At the lower limit of the applied discharge of 2.5*l/s*, the maximum value of pressure head varied between 1.5 and 3*cm* that was obtained when DDB type 6 was used, and the the minimum value of pressure head ranged between 1 and 1.7*cm* that was obtained DDB types 1 was used. It was found that the measured pressures at these eight points were positive for all the range of the used discharges and for all block types.

The rating curve of Mandili Dam Weir model was obtained and was used to obtain the discharge during other the tests. **Fig. 15** shows a comparison between the obtained rating curve in this research, design, the rating curve of the hydraulic model of Mandili Dam, **Rafidain State Company for Dams Construction, 2008**, and that obtained according to Chow's charts, **Chow, 1959**. Discharges reading using the obtained rating curve are higher than other rating curves. This may be referred to the accuracy working in lab conditions and to high smoothness of model surface.

To show the effectiveness of the DDBs in dissipation of energy, the energy dissipation in the standard design of Mandili Dam was investigated then the DDBs of type 1 to 12 were installed at its spillway with configurations Number 1, 2, and 3. In these tests, the applied discharges varied between 200 and 1725m^3/s (0.68 and 6*l/s* in the model) and in each test, the flow depths at 20*cm* upstream the weir model and at a distance of 100*cm* downstream of the spillway toe were measured to obtain the discharge and the Froude Number.

It is logical to adopt the downstream Froude Number as the dimensionless parameter as a criterion in assessing the hydraulic performance of stilling basins, **Eloubaidy et al., 1998.** The occurrence of the hydraulic jump, as well as the sequent depth ratio and the dimensionless energy loss, are functions of the approach Froude Number, **Sturm, 2001**.

Figs. 16 to **18** show the variation of the Froude Number with discharge obtained downstream the standard design of Mandili Dam when carrying out the investigation tests by using blocks type 7 to 12 and configuration 1, 2, and 3. **Table 4** summarizes the obtained extreme values of the Froude Number during these tests. The maximum value of Froude Number was 0.86 which was recorded at the maximum design discharge of 1724m^3/s with configuration number 1 and DDBs of type 7. This value of Froude Number is less by 10.4% than that obtained without using DDBs. At this design discharge, the minimum value of Froude Number was 0.77 which was recorded when using DDBs of type 9 and configuration number 2. This obtained value of Froude Number is less by 19.3% than that obtained without using and DDBs. For the applied minimum discharge of 200 m^3/s, the maximum value of Froude Number was approximately the same for all configurations with all type of blocks, it was about 0.68 and is the same when no DDBs were used. For the same discharge of 200m^3/s, the minimum value of Froude Number varied between 0.63-0.65 for all configurations with all blocks types, with a reduction of 7.4-4.4% than that obtained when no DDBs were used. Froude Number value for configuration number 3 was less than the Froude Number with configurations number 1 and 2. This indicates that the Froude Number decreases by increasing the number of blocks, number of blocks rows, and as the block apex angle decreases.

As a conclusion from results mentioned above, as the Froude Number is reduced when using the DDBs, the flowing water will reach the stilling basin with less kinetic energy. Accordingly, shorter stilling basin can be used at the downstream of the spillway. Modification was made by reducing the length of the stilling basin of the standard design of Mandili Dam and then effectiveness of the DDBs in dissipating energy was tested. The length of the stilling basin was reduced to half and one fourth the length of the stilling basin of the standard design of Mandili Dam. Tests runs were carried out with configurations number 4, 5, 6, 7, 8, and 9. Tests runs with configurations number 4, 5, and 6 were carried out with half the length of the stilling basin of the standard design of Mandili Dam. While, configurations number 7, 8 and 9 have one fourth of the length. Three types of DDBs with small apex angles were selected and used in these tests. DDBs type13 were tested with configurations number 4 and 7, blocks type 14 were tested with configurations number 5 and 8, and blocks type 15 were tested with configurations number 6 and 9. **Figs. 19** and **20** show the variation of the Froude Number with discharge for all configurations with the modified design of the stilling basin of Mandili Dam and the extreme values of the Froude Number are summarizes in **Table 5.** At the maximum design discharge of 1724m^3/s, the maximum value of Froude Number was 0.91 which was obtained with configuration number 8. It is 5.2% less than that obtained with standard design of Mandili Dam. At the same discharge, the minimum Froude Number of 0.86 was obtained with configurations number 5 and 6 with a reduction of 10.4% compared with standard design. At the minimum applied discharge of 200m^3/s, the maximum value of Froude Number was about 0.68 in configurations number 4 and 7, which is the same as in the standard design of Mandili Dam. For the same discharge, the minimum value of Froude Number was the same value of about 0.63 for configurations number 5, 6, and 8, with a reduction of 7.4% compared with standard design of Mandili Dam. In general, the Froude Number values for configurations with a half stilling basin were less than with one fourth length stilling basin. Also, the Froude Number values with these configurations were less than that obtained with standard design of Mandili Dam in all tests within the range of applied discharges.

Based on the above discussion the length of the stilling basin of the standard design of Mandili Dam can be reduced when using the DDBs, without effecting the energy loss and Froude Number values. To investigate the effects of using the DDBs on the Froude Number, and the location of the hydraulic jump, any other energy dissipaters were eliminated, ie. the stilling basin was removed. Experimental runs were carried out on configurations number 10, 11, 12 and 13. **Fig. 21** and **22** show the variation of Froude Number and the distance of hydraulic jump with discharge with configurations number 10, 11, 12, and 13. **Table 6** summarizes the Froude Number and the hydraulic jump distance from the toe of the spillway that were obtained at extreme discharges. the Froude Number values with configuration number 10 vary with a steep slope between discharge values of about $650 m^3/s$ and $900 m^3/s$ and the flow was supercritical over a discharge of $750 m^3/s$. With configurations number 11, 12, and 13, the flow was sub critical with Froude Number less than unity. Under these configurations the flow has approximately the same Froude Number values for all the range of discharge. At the minimum applied discharge of $200 m^3/s$, the free hydraulic jump was obtained with configuration number 10 at a distance of 5*m* from the spillway toe with a Froude Number of 0.36. While, a submerged hydraulic jump occurred at the toe of the spillway for configurations number 11, 12, and 13, with a Froude Number varies between 0.17 and 0.18, depending on the block type. The Froude Number reduction in configurations number 11, 12, and 13 is about 49% to 52% compared with configuration number 10. At the maximum applied discharge of $1724 m^3/s$, the free hydraulic jump for configuration number 10 was at a distance of 105*m* from toe of the spillway and a high Froude Number of 4.21. The minimum Froude Number of 0.51 was recorded with configuration number 13, with a reduction of 700% compared with configuration number 10. The maximum value of Froude Number was 0.54 recorded with configuration number 11, with a reduction of 660% than configuration number 10. The hydraulic jump distance from the spillway toe was about 48*m*, 40.5*m*, and 25*m* for configurations number 11, 12, and 13, respectively. Compared with configuration number 10, the reduction in the hydraulic jump distance from the spillway toe was 54%, 61%, and 76% for configurations number 11, 12, and 13, respectively, which indicates that the hydraulic jump in test runs with configuration number 13 have the shortest distance from the spillway toe compared to configurations number 10, 11, 12, for all the applied range of discharge. This indicates that increasing the number of blocks rows leads to more dissipation of the energy of the flow.

5. CONCLUSIONS

The results of the laboratory investigation test runs that were carried in this study indicated that the DDBs fixed on the surface of an ogee slipway can be used effectively to reduce the energy of the flow downstream the spillway and accordingly, shorter stilling basin can be used. More energy is dissipated when increasing the number of blocks, number of blocks rows, and as the block apex angle decreases.

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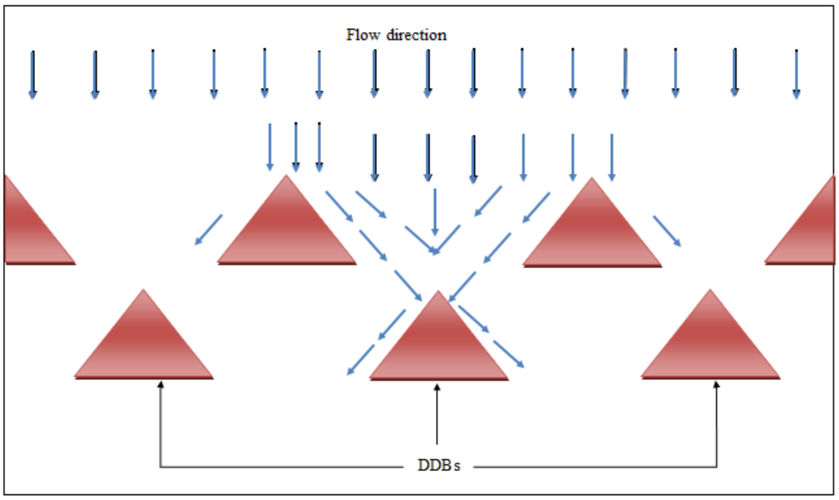


Figure 1. A schematic diagram showing a top view of the DDBs on an ogee spillway surface.

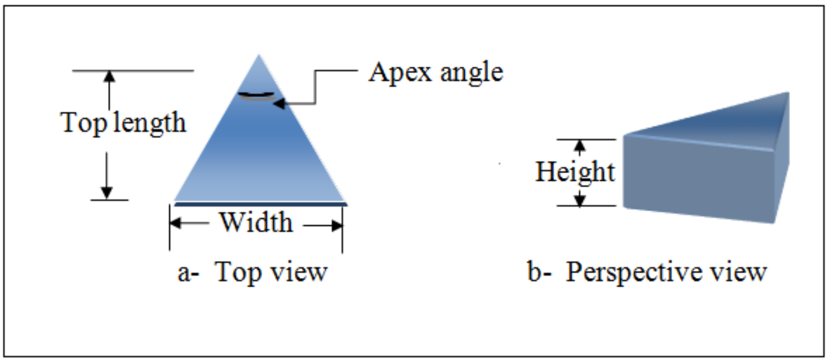


Figure 2. **D**etails of the triangular shape DDBs.

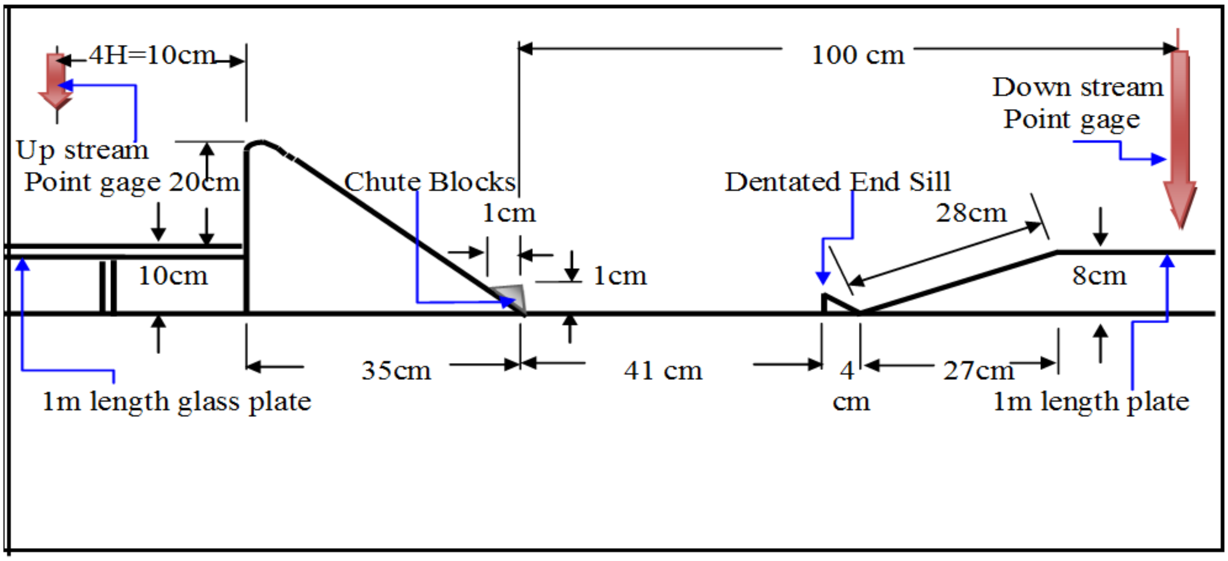
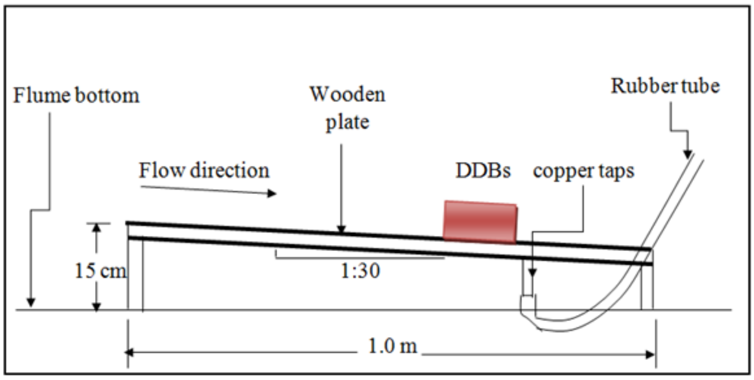
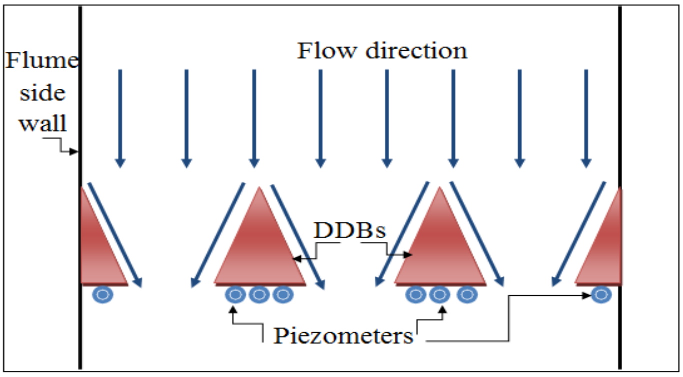


Figure 3. Longitudinal section in the physical model of Mandili Dam Spillway.



a- Side view



b- Top view

Figure 4. Schematic diagram showing the configuration of the pressure tests.

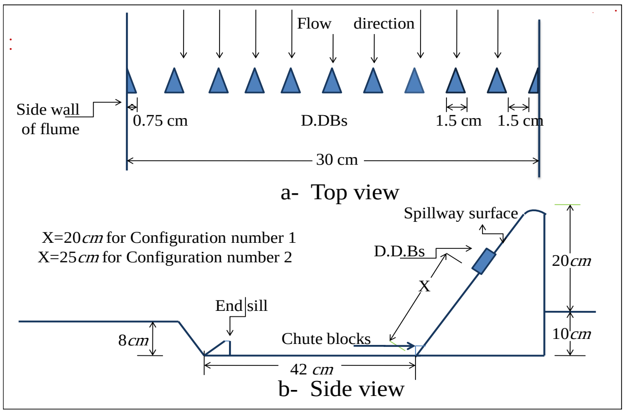


Figure 5. Configurations number 1 and 2.

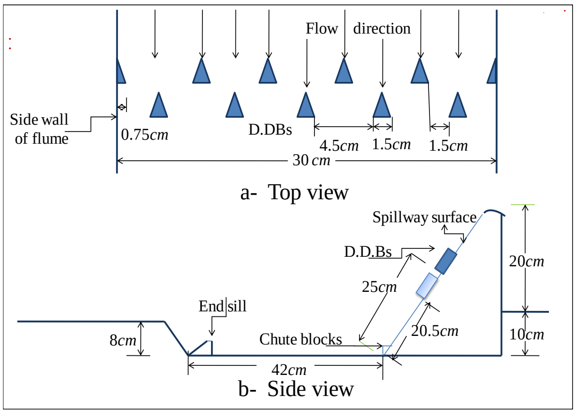


Figure 6. Configurations number 3.

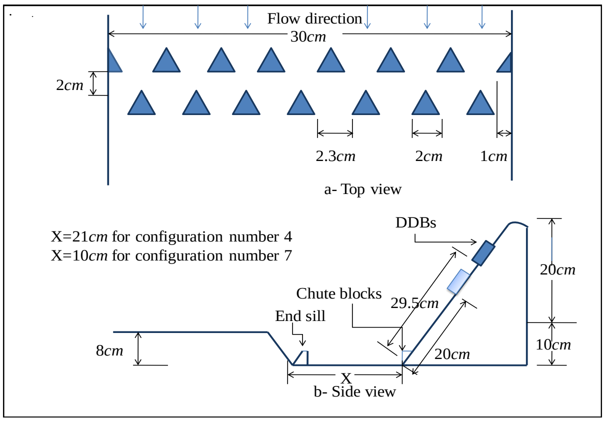


Figure 7. Configurations number 4 and 7.

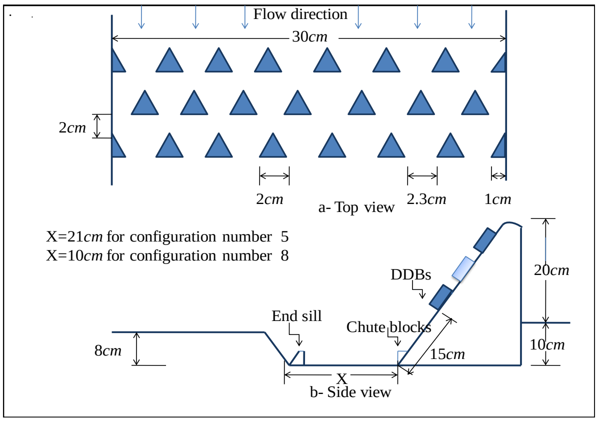


Figure 8. Configurations number 5 and 8.

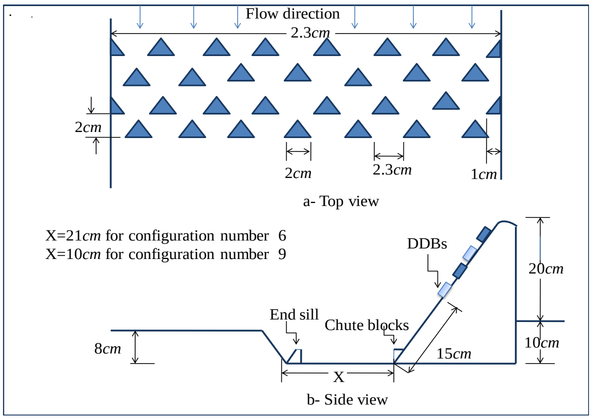


Figure 9. Configurations number 6 and 9.

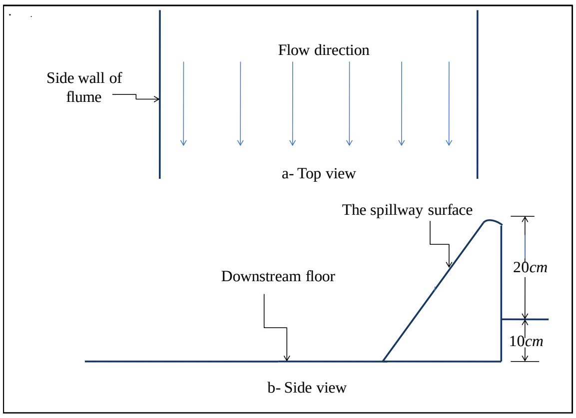


Figure 10. Configuration number 10.

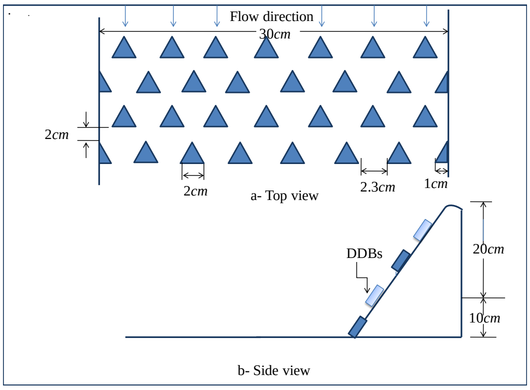


Figure 11. Configuration number 11.

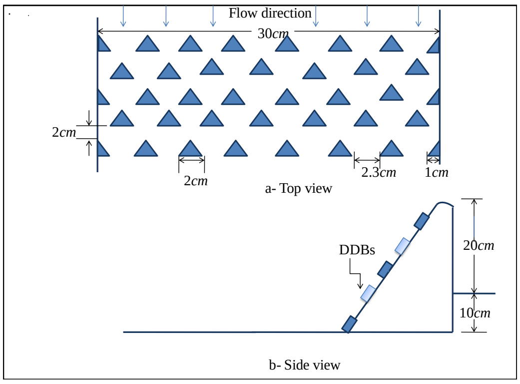


Figure 12. Configuration number 12.

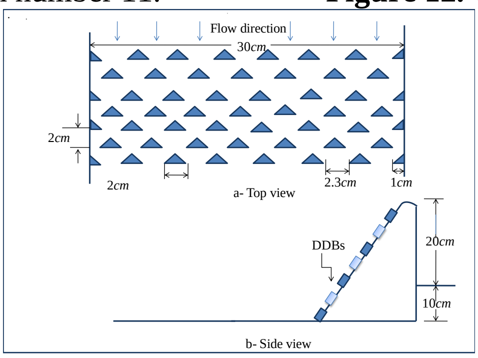


Figure 13. Configuration number 13.

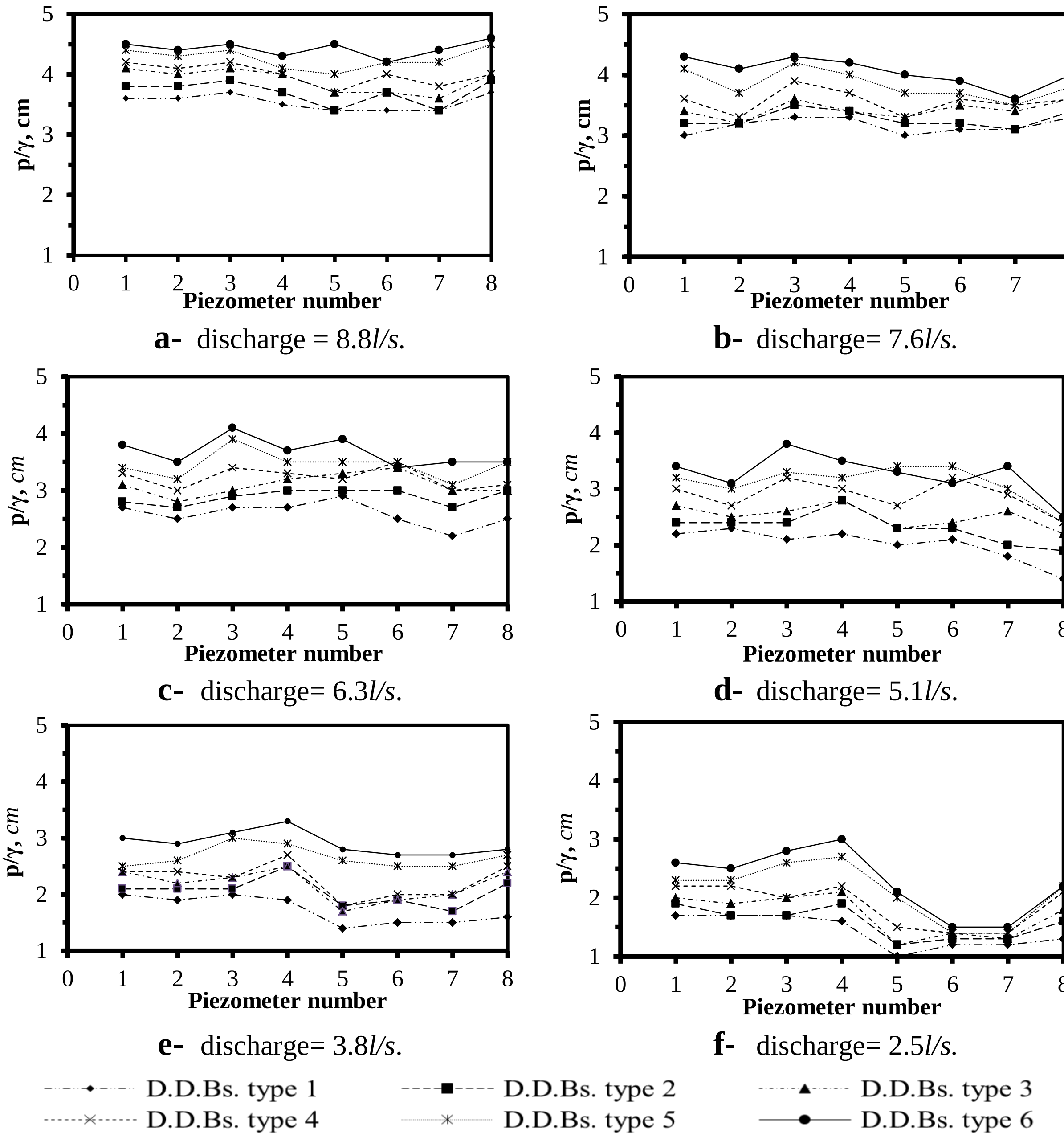


Figure 14. Variation of pressure heads with the applied discharges for each type of blocks.

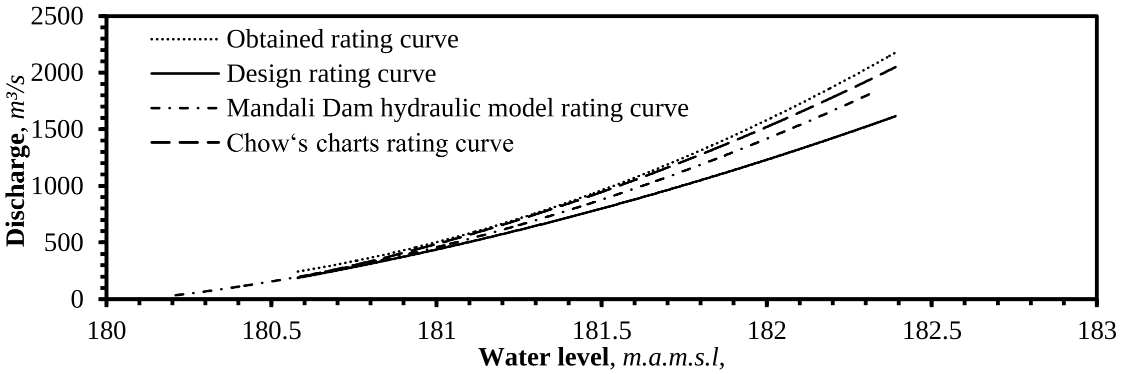


Figure 15. The rating curve of Mandili Dam Weir.

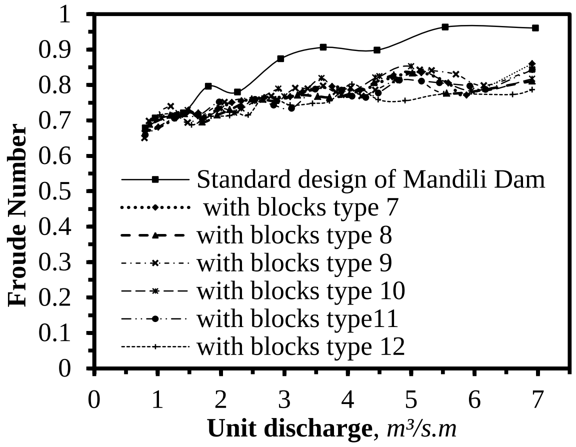


Figure 16. Variation of the Froude Number with the applied discharges for configuration number 1.

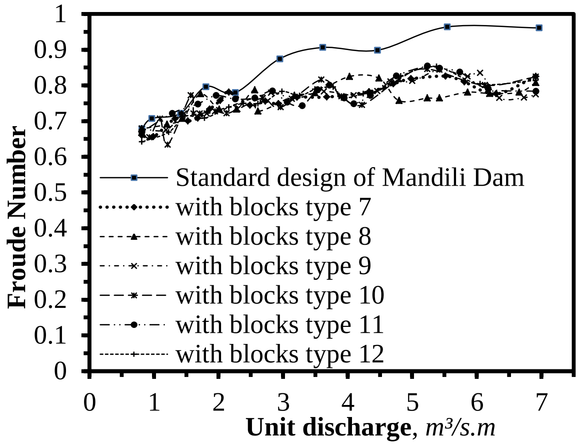


Figure 17. Variation of the Froude Number the applied discharges for configuration number 2.

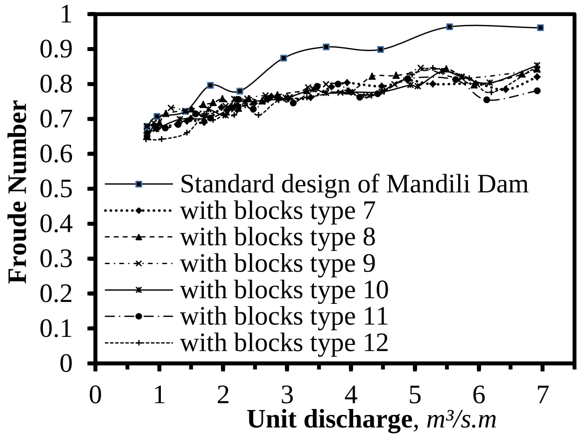


Figure 18. Variation of the Froude Number with the applied discharges configuration number 3

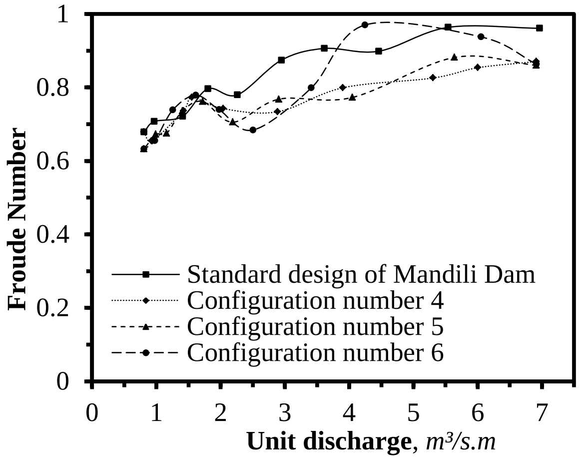


Figure 19. Variation of the Froude Number with the applied discharges, half the length of the stilling basin.

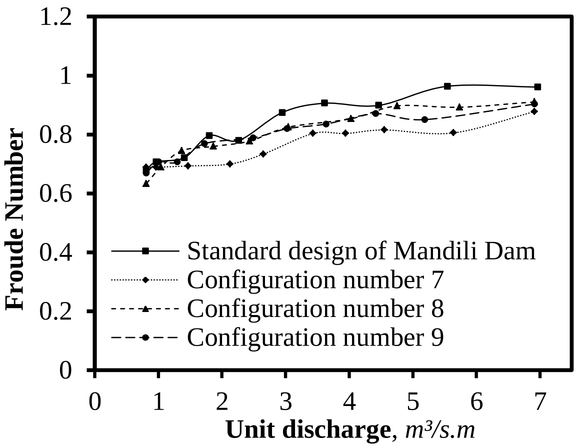


Figure 20. Variation of the Froude Number with the applied discharges, one fourth the length of the stilling basin.

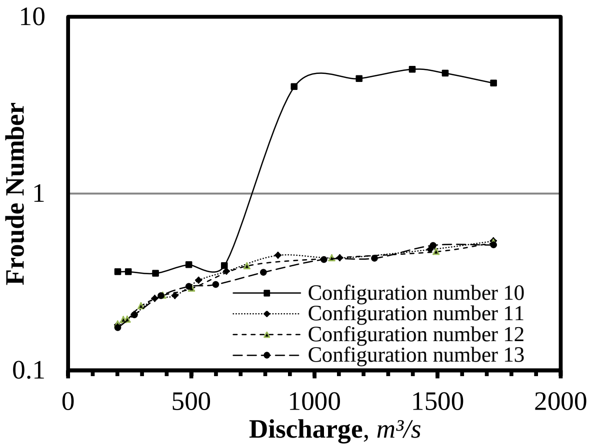


Figure 21. Variation of Froude Number with the applied discharges, no stilling basin.

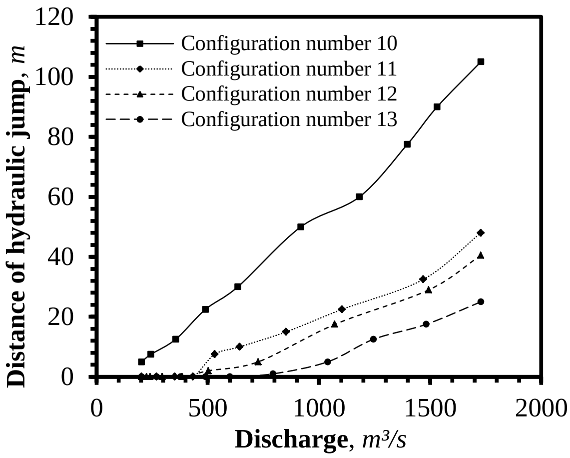


Figure 22. Variation of the distance of hydraulic jump with the applied discharges, no stilling basin.

Table 1. Dimensions of the used DDBs models.

Type of DDBs	DDBs dimensions			
	Width *cm*	**Height** *cm*	**Apex angle** *degree*	**Top length** *cm*
1	5	3.9	30	9.3
2	5	3.9	45	6
3	5	3.9	60	4.3
4	5	3.9	90	2.5
5	5	3.9	120	1.4
6	5	3.9	180	5
7	1.5	1.5	20	4.25
8	1.5	1.5	30	2.8
9	1.5	1.5	45	1.8
10	1.5	1.5	60	1.3
11	1.5	1.5	90	0.75
12	1.5	1.5	180	1.5
13	2	2	15	7.6
14	2	2	20	5.7
15	2	2	30	3.7

Table 2. Details of the configurations used for the energy dissipation test.

	Configuration Number												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Number of rows	1	1	2	2	3	4	2	3	4	-	4	5	7
Spacing between blocks, *cm*	1.5	1.5	4.5	2.3							2.3		
Distance of 1st row from weir toe, *cm*	20	25	20.5	20	15		20	15		-	0		
Distance of 2nd row from weir toe, *cm*	-	-	25	29.	-		29.5				-		
spacing between rows for more than two rows, *cm*	-	-	Variable*	2						-	2		
Number of blocks in each row	10	10	5	7						-	7		
Length of stilling basin, *cm*	42			21			10			No stilling			

*depends on the block dimensions.

Table 3. The types of DDBs that were used in each configuration.

	Configuration Number												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Type of blocks	7, 8, 9, 10, 11, 12			13	14	15	13	14	15	Without blocks	13	14	15

Table 4. The extreme values of the Froude Number, standard design of Mandili Dam Spillway.

	Discharge *m³/s*	Froude Number	
		Max.	**Min.**
Configuration number 1	200	0.68, with block type 8,10, and 12	0.65, with blocks type 9
	1724	0.86, with blocks type 7	0.79, with blocks type12
Configuration number 2	200	0.68, with blocks types 8, and 9.	0.64, with blocks type 12
	1724	0.825, with blocks type 7	0.77, with blocks type 9
Configuration number 3	200	0.67, with blocks type 9	0.64, with blocks type12
	1724	0.85, with blocks type10	0.78, with blocks type11

Table 5. The extreme values of the Froude Number, modified design of Mandili Dam Spillway.

	Discharge *m³/s*	Froude Number	
		Max.	**Min.**
Configuration number 4, 5, and 6.	200	0.68, configuration number 4	0.63, configuration number 5 and 6
	1724	0.87, configuration number 4	0.86, configuration number 5and 6
Configuration number 7, 8, and 9.	200	0.68, configuration number 7	0.63, configuration number 8
	1724	0.91, configuration number 8	0.88, configuration number 7

Table 6. The extreme values Froude Number and the distance of the hydraulic jump, no stilling basin.

Configuration number	**Discharge** *m³/s*	**Froude Number**	**distance of hydraulic jump** *m*
10	200	0.36	5
	1724	4.21	105
11	200	0.18	0
	1724	0.54	48
12	200	0.18	0
	1724	0.53	40.5
13	200	0.17	0
	1724	0.51	25