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AGRICULTURE
Research Article

Analysis of Pressures on Nagarjuna Sagar Spillway

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Received: November 20, 2014; **Published:** December 26, 2014

Abstract

Availability of water is very important natural resource of a nation, which can be used for the development of the country. Dam is a type of hydraulic structure built across a river (or stream). At the back of this barrier; water gets collected, forming a pool of water. The side on which water gets collected is called the upstream side and the other side of the barrier is called the downstream side. The lake of water which is formed upstream is called reservoir. Thus a reservoir and a dam exist together. The present study area is on Nagarjunasagar Dam, the giant among the masonry dams across River Krishna in Telangana State. In the design of hydraulic structures, many problems of non uniform and unsteady flow, sediment motion, dispersion, density currents and cases with complicated geometry fully defy. Therefore experimental work on scale models is often the most efficient and sometimes indeed the only method for solving the problem. The experiment cannot be carried out on the full size hydraulic structures, which are proposed to be erected. It is then essential to construct a small scale replica of the structure and the tests are performed on it to obtain the desired information. An attempt has been made to find the solution to the problem encountered in Nagarjunasagar dam constructed across river Krishna in Nalgonda district, Telangana state by using the theory of physical model study. A hydraulic model study was conducted to evaluate the cavitation damage due to negative pressures in terms of their magnitudes and locations on the spillway of the dam due to the floods in 2009 using the model studies on it. The experiment was carried out for free flow and gated operations for various discharge conditions. The maximum negative pressures observed at pressure tube points in vent no 1 is 0.079 at P_7 for 1/4th of maximum flood discharge for gated condition. The maximum negative pressures observed at pressure tube points in vent no 2 is 0.031 at P_7 for 3/4th, half and 1/4th of maximum flood discharge for free flow condition. The maximum negative pressures observed at pressure tube points in vent no 3 is 0.031 at P_2 for 3/4th of maximum flood discharge for both free flow and gated conditions and1/2 and 1/4th of maximum flood discharge for gated condition.

Keywords: *Hydraulic structure; River Krishna; Nagarjunasagar dam; Cavitation damage; Negative pressures*

Introduction

Availability of water is very important natural resource of a nation, which can be used for the development of the country [1]. A spillway is a waterway provided to dispose of surplus flood waters from a reservoir after it has been filled to its maximum capacity. A spillway may be located either within the body of the dam or at one end of the dam or entirely away from the dam as an independent structure.

The required capacity of a spillway may be determined by flood routing, corresponding to a particular inflow hydrograph the maximum outflow rate and maximum rise in the water surface may be determined [2]. Spillway consists of various components such as control structure, discharge channel, terminal structures-energy dissipaters, entrance and outlet channels The Advanced technical construction methodology of roller compacted concrete dams and realization of the advantages of high degree of energy dissipation have created an interest in stepped spillways [3]. The main advantages of using a stepped spillway compared with equivalent smooth spillway are compatibility with reinforced cement concrete placement method, a significant increase in the rate of energy dissipation taking place on the spillway face, reduction of the dissipation base size and the risks of scouring, in the risk of cavitations, an increase in the discharge capacity [4]. The flow over the stepped spillway is classified in to two regimes, napped flow and skimming flow [5]. Cavitation phenomenon is a common and a complex process on spillways that threatens the stability of spillway structure and it may cause damage to the structure. Cavitation phenomenon in hydraulic structures can be a function of flow velocity, flow pressure, duration of operation [6]. Cavitation may occur at rough spots in the surface of the chute or tunnel, at local discontinuities in the finished surface such as construction joints, and at locations along critical flow profiles having significant deviations from design specifications. A lot of scope for the future studies applicable and most economical remedial measures to eliminate or further reduce the damage caused by the cavitation. The objective of present area of study is to analyze the pressure on the spillway at different points in the vents.

Review of literature

Before the present study on Nagarjuna Sagar project was taken up, some case study was studied where cavitation damage was occurred and spillways were repaired successfully. The case study on Glen canyon Dam is taken up; it is located on the Colorado River in northeast Arizona 25 km upstream of Lee's Ferry. Glen Canyon Dam is a 216 m high concrete arch dam, completed in 1964 and having a crest length of 475 m. It is the key feature of the Colorado River Storage Project. Lake Powell, formed by Glen Canyon Dam, provides 3.3x10 m^3 of storage capacity, more than all the other storage features of the project combined. Analysis of the spillway flow at Glen Canyon Dam conducted after the 1980 [7] spill indicated a high potential for cavitation damage if the spillways operated for any length of time. In late May 1983, runoff in the upper basin of the Colorado River was steadily increasing due to snowmelt from an extremely large snowpack. Several large holes were found in the tunnel invert at the downstream end of the elbow. Although some of the damage was initiated by cavitation forming on small calcite deposits along the tunnel invert caused severe damage in a very short period of time. Depending upon the extent of the damage one of two methods of repair was used. For small areas, the damaged surface was ground to a 1 : 20 (vertical to horizontal) slope in the direction of flow and to a 1 : 5 slope perpendicular to the direction of flow. For extensively damaged areas, the concrete was removed down to the first mat of reinforcing steel and then replaced with a concrete patch.

Figure 1A: *Cavitation damage on spillway profile of Nagarjunasagar Dam.*

Figure 1B: *Cavitation damage on spillway profile of Nagarjunasagar Dam.*

Problem encountered in the dam- study area

The spillway of Nagarjuna Sagar Dam across Krishna River was eroded several during the floods in 2009 due to cavitation which was resulted from the negative pressures developed over the spillway. On further investigation of the problem, it was found that there was a large deviation of the existed profile of the spillway from the design profile, which actually led to the development of negative pressures in such a magnitude that could create the problem. Figure 1A and 1B shows the Cavitation damage on Spillway profile of Nagarjuna Sagar Dam and Cavitation damage on Spillway profile of Nagarjuna Sagar Dam

Materials and Methods

The following are the two methods which gives the pressures in vent no.1, vent no.2, vent no.3 at different pressure points under various discharge conditions like Maximum Flood Discharge, 3/4th of Maximum Flood Discharge, 1/2 of Maximum Flood Discharge and ¼th of Maximum Flood Discharge.

The following are the two different conditions:

Free Flow Condition (FFC)

In the first instance, the experiments were carried out by keeping all the vents of the dam fully open i.e., Free flow condition for various discharge conditions like Maximum Flood Discharge, 3/4th of Maximum Flood Discharge, 1/2 of Maximum Flood Discharge and ¼th of Maximum Flood Discharge. Figure 2 represents the photograph of the model when all the vents are fully opened. Each discharge condition is explained with the main focus of the studies on the measuring of the pressures at all the points of observation on vent no's 1, 2 and 3.

Discharge Condition 1

Maximum Flood discharge: Initially a discharge corresponding to Maximum Flood discharge (Q_m= 3.0858 Cusecs) was allowed into the model. After stabilization of flow throughout the model, the pressure points at all the points of observations in Vent No's 1, 2 and 3 were noted. In this discharge condition, no negative pressures were observed on vent no.1, negative pressures were observed on vent no 2 at 4 locations i.e., P_2= -0.01, P_4 = -0.02, P_7 = -0.03 and P_9 = -0.04 and negative pressures were observed on vent no 3 at 3 locations i.e., P_1 = -0.02, P_2 = -0.04 and P_9 = -0.01. Table 1 represents the pressures on vent no's 1, 2 and 3 for maximum flood discharge.

Figure 2: *Photograph of the model –all the vents are fully opened.*

Pressure Point	Pressures observed on Vent No.1 in Mts	Pressures observed on Vent No.2 in Mts	Pressures observed on Vent No.3 in Mts
P_1	+0.02	+0.02	**-0.02**
P_2	+0.01	**-0.01**	**-0.04**
P_3	+0.004	+0.08	+0.01
P_4	+0.07	**-0.02**	+0.04
P_5	+0.06	+0.06	+0.05
P_6	+0.04	+0.05	+0.04
P_7	+0.17	**-0.03**	+0.04
P_8	+0.32	+0.10	+0.12
P_9	+0.28	**-0.04**	**-0.01**
P_{10}	--	+0.24	+0.30
P_{11}	--	+0.36	--

Table 1: *Pressures on Vent No's 1, 2 and 3 of MFD for FFC.*

Discharge Condition 2

Three fourth of maximum flood discharge: In this condition, three fourth of maximum flood discharge (Q_m = 2.3145 Cusecs) was allowed into the model. After stabilization of flow throughout the model, the pressure points at all the points of observations in Vent No's 1, 2 and 3 were noted. In this discharge condition, no negative pressures were observed on vent no.1, negative pressures were observed on vent no 2 at 3 locations i.e., P_2 = -0.04, P_7 = -0.04 and P_9 = -0.04 and negative pressures were observed on vent no 3 at 2 locations i.e., P_1 = -0.02 and P_2 = -0.05. Table 2 represents the pressures on vent no's 1, 2 and 3 corresponding to the three fourth of maximum flood discharge.

Discharge Condition 3

Half of maximum flood discharge: In this condition, half of maximum flood discharge (Q_m = 1.5429 Cusecs) was allowed into the model. After stabilization of flow throughout the model, the pressure points at all the points of observations in Vent No's 1, 2 and3 were noted. In this discharge condition, negative pressures were observed on vent no.1 at one location i.e., P_7 = -0.04, negative pressures were observed on vent no 2 at 2 locations i.e., P_7 = -0.04, and P_9 = -0.005 and negative pressures were observed on vent no 3 at 1 location i.e., P_2 = -0.05. Table 3 represents the pressures on vent no's 1, 2 and 3 corresponding to half of maximum flood discharge.

Pressure Point	Pressures observed on Vent No.1 in Mts	Pressures observed on Vent No.2 in Mts	Pressures observed on Vent No.3 in Mts
P_1	+0.03	+0.02	**-0.02**
P_2	+0.02	**-0.04**	**-0.05**
P_3	+0.007	+0.01	+0.02
P_4	+0.07	+0.004	+0.03
P_5	+0.04	+0.04	+0.03
P_6	+0.02	+0.03	+0.04
P_7	+0.17	**-0.04**	+0.04
P_8	+0.09	+0.07	+0.12
P_9	+0.10	**-0.04**	+0.10
P_{10}	--	+0.03	+0.07
P_{11}	--	+0.10	--

Table 2: *Pressures on Vent No's 1, 2 and 3 for ¾th of MFD for FFC.*

Pressure Point	Pressures observed on Vent No.1 in Mts	Pressures observed on Vent No.2 in Mts	Pressures observed on Vent No.3 in Mts
P_1	+0.03	+0.03	+0.02
P_2	+0.02	+0.02	**-0.05**
P_3	+0.007	+0.01	+0.02
P_4	+0.07	+0.02	+0.03
P_5	+0.05	+0.05	+0.03
P_6	+0.03	+0.04	+0.04
P_7	**-0.04**	**-0.04**	+0.04
P_8	+0.15	+0.08	+0.12
P_9	+0.18	**-0.005**	+0.10
P_{10}	--	+0.07	+0.07
P_{11}	--	+0.26	--

Table 3: *Pressures on Vent No's 1, 2 and 3 for 1/2 of MFD for FFC.*

Discharge Condition 4

One fourth of maximum flood discharge: In this condition, one fourth of maximum flood discharge (Q_m= 0.7713 Cusecs) was allowed into the model. After stabilization of flow throughout the model, the pressure points at all the points of observations in Vent No's 1, 2 and 3 were noted. In this discharge condition, negative pressures were observed on vent no.1 at one location i.e. P_7 = -0.08, negative pressures were observed on vent no 2 at 2 locations i.e., P_7 = -0.04 and P_9 = -0.004 and negative pressures were observed on vent no 3 at 1 location i.e., P_2 = -0.03. Table 4 represents the pressures on vent no's 1, 2 and 3 corresponding to one fourth of maximum flood discharge.

Pressure Point	Pressures observed on Vent No.1 in Mts	Pressures observed on Vent No.2 in Mts	Pressures observed on Vent No.3 in Mts
P_1	+0.003	+0.005	+0.001
P_2	+0.07	+0.03	**-0.03**
P_3	+0.03	+0.06	+0.02
P_4	+0.07	+0.001	+0.02
P_5	+0.05	+0.04	+0.03
P_6	+0.03	0.03	+0.04
P_7	**-0.08**	**-0.04**	+0.03
P_8	+0.09	+0.09	+0.10
P_9	+0.09	-0.004	+0.02
P_{10}	--	+0.05	+0.07
P_{11}	--	+0.16	--

Table 4: *Pressures on Vent No's 1, 2 and 3 for ¼th of MFD for FFC.*

Gated Condition (GC)

In this condition of the experiments, discharge is varied and gates are operated by maintaining Full Reservoir Level (FRL). Firstly one fourth of Maximum Flood Discharge is allowed through the model and the pressures on the Vent no's 1, 2 and 3 of the spillway were observed and noted. Similarly, experiments were carried out to measure the pressures on the vent no's 1, 2 and 3 of the spillway for 1/2 of Maximum Flood Discharge, 3/4th of Maximum Flood Discharge and Maximum Flood Discharge, Each discharge condition is explained with the main focus of the studies on the measuring of the pressures at all the points of observation on vent no's 1, 2 and 3.

Discharge Condition 1

One fourth of maximum flood discharge: In this condition, one fourth of maximum flood discharge (Q_m = 0.7713 Cusecs) was allowed into the model. After maintaining the Full reservoir level in the model, the pressure points at all the points of observations in Vent No's 1, 2 and 3 were noted. In this discharge condition, pressures were observed on vent no.1 at two locations i.e. P_1 = -0.003 and P_7 = -0.08, negative pressures were observed on vent no 2 at 4 locations i.e., P_2 = -0.015, P_4 = -0.001, P_7 = -0.03 and P_9 = -0.003 and negative pressures were observed on vent no 3 at 3 locations i.e., P_1 = -0.004, P_2 = -0.03 P_9 = -0.003. Table 5 represents the pressures on vent no's 1, 2 and 3 corresponding to one fourth of maximum flood discharge.

Pressure Point	Pressures observed on Vent No.1 in Mts	Pressures observed on Vent No.2 in Mts	Pressures observed on Vent No.3 in Mts
P_1	**-0.003**	+0.004	**-0.004**
P_2	+0.07	**-0.015**	**-0.03**
P_3	+0.003	+0.06	+0.02
P_4	+0.07	**-0.001**	+0.03
P_5	+0.05	+0.04	+0.03
P_6	+0.03	+0.03	+0.04
P_7	**-0.08**	**-0.03**	+0.03
P_8	+0.08	+0.09	+0.10
P_9	+0.09	**-0.003**	**-0.003**
P_{10}	--	+0.01	+0.01
P_{11}	--	+0.18	--

Table 5: *Pressures on Vent No's 1, 2 and 3 for ¼th of MFD for GC.*

Discharge Condition 2

Half of maximum flood discharge: In this condition, half of maximum flood discharge (Q_m= 1.5429 Cusecs) was allowed into the model. After maintaining the full reservoir level in the model, the pressure points at all the points of observations in Vent No's 1, 2 and 3 were noted. In this discharge condition, negative pressures were observed on vent no.1 at two locations i.e., P_2 = -0.003 and P_7 = -0.07, negative pressures were observed on vent no 2 at 4 locations i.e., P_2 = -0.015, P_4 = -0.001, P_7 = -0.03 and P_9 = -0.003 and negative pressures were observed on vent no 3 at 3 locations i.e., P_1 = -0.04, P_2 = -0.03 P_9 = -0.003. Table 6 represents the pressures on vent no's 1, 2 and 3 corresponding to half of maximum flood discharge.

Pressure Point	Pressures observed on Vent No.1 in Mts	Pressures observed on Vent No.2 in Mts	Pressures observed on Vent No.3 in Mts
P_1	+0.02	+0.01	**-0.04**
P_2	**-0.003**	**-0.015**	**-0.03**
P_3	+0.01	+0.02	+0.01
P_4	+0.03	**-0.001**	+0.04
P_5	+0.06	+0.01	+0.05
P_6	+0.001	+0.01	+0.03
P_7	**-0.07**	**-0.03**	+0.02
P_8	+0.01	+0.10	+0.001
P_9	+0.15	**-0.003**	**-0.003**
P_{10}	--	+0.02	+0.30
P_{11}	--	+0.05	--

Table 6: *Pressures on Vent No's 1, 2 and 3 for MFD for GC.*

Discharge Condition 3

Three fourth of maximum flood discharge: In this condition, three fourth of maximum flood discharge (Q_m = 2.3145 Cusecs) was allowed into the model. After maintaining the full reservoir level in the model, the pressure points at all the points of observations in Vent No's 1, 2 and 3 were noted. In this discharge condition, no negative pressures were observed on vent no.1, negative pressures were observed on vent no 2 at 4 locations i.e., P_2 = -0.015, P_4 = -0.001, P_7 = -0.03 and P_9 = -0.003 and negative pressures were observed on vent no 3 at 3 locations i.e., P_1 = -0.04, P_2 = -0.03 P_9 = -0.003. Table 7 represents the pressures on vent no's 1, 2 and 3 corresponding to the three fourth of maximum flood discharge.

Discharge Condition 4

Maximum Flood Discharge: In this condition, discharge corresponding to Maximum Flood discharge (Q_m = 3.0858 Cusecs) was allowed into the model. After maintaining the full reservoir level in the model, the pressure points at all the points of observations in Vent No's 1, 2 and 3 were noted. In this discharge condition, no negative pressures were observed on vent no.1, 2 and 3. Table 8 represents the pressures on vent no's 1, 2 and 3 corresponding to the maximum flood discharge.

Results

The following are the Negative pressures observed at pressure tube points along the spillway in mts under free flow condition and gated condition.

Pressure Point	Pressures observed on Vent No.1 in Mts	Pressures observed on Vent No.2 in Mts	Pressures observed on Vent No.3 in Mts
P_1	+0.03	+0.02	**-0.04**
P_2	+0.02	**-0.015**	**-0.03**
P_3	+0.007	+0.01	+0.01
P_4	+0.07	**-0.001**	+0.03
P_5	+0.04	+0.04	+0.03
P_6	+0.02	+0.03	+0.04
P_7	+0.17	**-0.03**	+0.04
P_8	+0.09	+0.07	+0.02
P_9	+0.10	**-0.003**	**-0.003**
P_{10}	--	+0.03	+0.01
P_{11}	--	+0.10	--

Table 7: *Pressures on Vent No's 1, 2 and 3 for ¾th of MFD for GC.*

Pressure Point	Pressures observed on Vent No.1 in Mts	Pressures observed on Vent No.2 in Mts	Pressures observed on Vent No.3 in Mts
P_1	+0.03	+0.03	+0.02
P_2	+0.02	+0.02	+0.05
P_3	+0.007	+0.01	+0.02
P_4	+0.07	+0.02	+0.03
P_5	+0.05	+0.05	+0.03
P_6	+0.03	+0.04	+0.04
P_7	+0.04	+0.07	+0.04
P_8	+0.15	+0.08	+0.12
P_9	+0.18	+0.15	+0.10
P_{10}	--	+0.21	+0.07
P_{11}	--	+0.26	--

Table 8: *Pressures on Vent No's 1, 2 and 3 of MFD for GC.*

Free flow condition

Under Free Flow conditions following results were obtained (Table 9):

1. Under maximum flood discharge, negative pressures were observed at pressure tube points P_2, P_4, P_7 and P_9 in vent no 2 and P_1, P_2 and P_9 in vent no.3. No negative pressures were observed in vent no1.
2. Negative pressures under three fourth of maximum flood discharge condition, were observed at P_2, P_7 and P_9 in vent no 2 and P_1 and P_2 in vent no.3. No negative pressures were observed in vent no1.
3. From the experiments, it was found that under half of maximum flood discharge condition, negative pressures were occurring at P_7 in vent no 1, P_7 and P_9 in vent no 2 and P_2 in vent no 3.
4. Under one fourth of maximum flood discharge condition, negative pressures were observed at pressure tube points at P_7 in vent no 1, P_7 and P_9 in vent no 2 and P_2 in vent no 3.

Discharge Condition	Discharge in cusecs	Negative pressures observed at pressure tube points along the spillway in mts		
		Vent No 1	Vent No 2	Vent No 3
MFD	3.0858	No Negative Pressures	P_2 = -0.01 P_4 = -0.002 P_7 = -0.03 P_9 = -0.004	P_1 = -0.004 P_2 = -0.03 P_9 = -0.003
3/4th of MFD	2.3145	No Negative Pressures	P_2 = -0.04 P_7 = -0.03 P_9 = -0.003	P_1 = -0.004 P_2 =-0.03
½ of MFD	1.5429	P_7 = -0.04	P_7 = -0.03 P_9 = -0.003	P_2 = -0.004
1/4th of MFD	0.7713	P_7 = -0.07	P_7 = -0.03 P_9 = -0.003	P_2 = -0.04

Table 9: *Shows the negative pressures observed at pressure tube points in vent no's 1, 2 and 3 for free flow condition at various discharge conditions.*

Gated condition

Under gated condition following results were obtained (Table 10):

1. Under maximum flood discharge, No negative pressures were observed in vent no1, 2 and 3.
2. Negative pressures under three fourth of maximum flood discharge condition, were observed at P_3 in vent no 1, P_2, P_4, P_7 and P_9 in vent no 2 and P_1, P_2 and P_9 in vent no.3.
3. From the experiments, it was found that under half of maximum flood discharge condition, negative pressures were occurring at P_2 and P_7 in vent no 1; P_2, P_4, P_7 and P_9 in vent no 2 and P_1, P_2 and P_9 in vent no.3
4. Under one fourth of maximum flood discharge condition, negative pressures were observed at pressure tube points at P_1 and P_7 in vent no 1; P_2, P_4, P_7 and P_9 in vent no 2 and P_1, P_2 and P_9 in vent no.3.

Discharge Condition	Discharge in cusecs	Negative pressures observed at pressure tube points along the spillway in mts		
		Vent No 1	Vent No 2	Vent No 3
3/4th of MFD	2.3145	P_3 = -0.004	P_2 = -0.015 P_4 = -0.01 P_7 = -0.03 P_9 = -0.003	P_1= -0.04 P_2 = -0.03 P_9 = -0.003
½ of MFD	1.5429	P_2 = -0.003 P_7 = -0.07	P_2 = -0.015 P_4 = -0.01 P_7 = -0.03 P_9 = -0.003	P_1 = -0.04 P_2 = -0.03 P_9 = -0.003
1/4th of MFD	0.7713	P_1 = -0.003 P_7 = -0.079	P_2 = -0.015 P_4 = -0.01 P_7 = -0.03 P_9 = -0.003	P_1 = -0.04 P_2 = -0.03 P_9 = -0.003

Table 10: *Shows the negative pressures observed at pressure tube points in vent no's 1, 2 and 3 for gated condition at various discharge conditions.*

Discussion

From the results obtained from the experiments, the maximum negative pressures observed at pressure tube points in vent no 1 is 0.079 at P_7 for 1/4th of maximum flood discharge for gated condition. Figure 3 shows the negative pressures observed at pressure tube points in vent no.1.

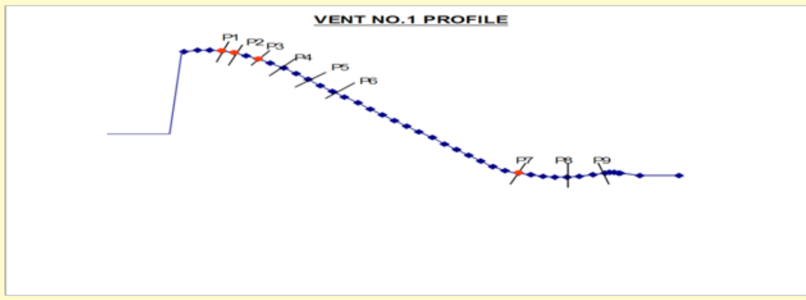

Figure 3: *Negative Pressure points on the spillway profile of Vent No 1(Model).*

From the results obtained from the experiments, the maximum negative pressures observed at pressure tube points in vent no 2 is 0.031 at P_7 for 3/4th, 1/2 and 1/4th of maximum flood discharge for free flow condition. Figure 4 shows the negative pressures observed at pressure tube points in vent no.2.

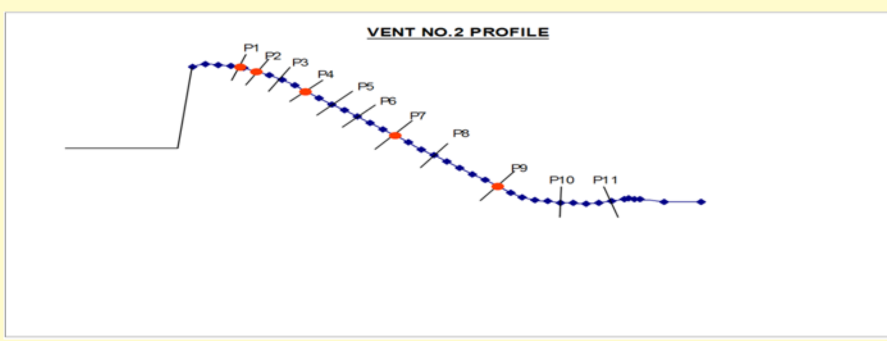

Figure 4: *Negative Pressure points on the spillway profile of Vent No 2(Model).*

From the results obtained from the experiments in case-I, the maximum negative pressures observed at pressure tube points in vent no 3 is 0.031 at P_2 for 3/4th of maximum flood discharge for both free flow and gated conditions and 1/2 and 1/4th of maximum flood discharge for gated condition. Figure 5 shows the negative pressures observed at pressure tube points in vent no.3.

According to measured flow velocities at different discharge conditions the level of cavitation damage have been predicted for Shahid Abbaspour Dam spillway, as the flow rate increases, cavitation risk increases and spillway is at risk of cavitation damage and major damage occurs at the ending of chute. Falvey has discussed the cavitation damage that occurred to the spillway of Glen Canyon, Blue Mesa, Yellowtail and Hoover Dam in United States. Occurrence of cavitation damage to a spillway can be predicted by using Cavitation index, it is a dimensionless measure used to characterize the susceptibility of a hydraulic structure to cavity [8]. There may be some uncertainty regarding spillway discharges for a given frequency flood, because of unpredictability of how the spillway will actually operate during a flood event.

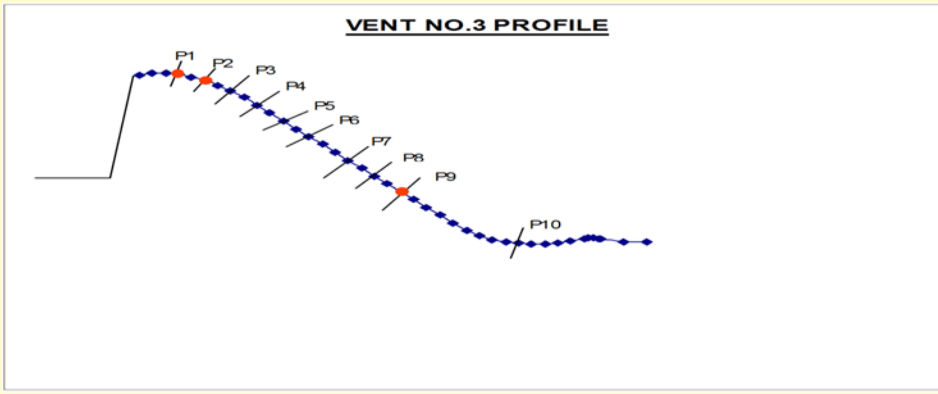

Figure 5: *Negative Pressure points on the spillway profile of Vent No 3(Model).*

Spillway capacity may be limited due to debris plugging or malfunctioning of spillway gates during a flood event, which would reduce the spillway discharge for a given frequency flood [9]. The relative energy dissipation is observed to be high at low discharges in spillways. From the Free flow condition and Gated flow condition the pressures at different discharge conditions has been analyzed and following results were obtained. Ball developed a relation between critical pressure and critical velocity while cavitation inception occurred for some typical surface irregularities. He suggested that cavitation damage could be prevented as long as the flow cavitation number was greater than the incipient cavitation number owing to surface irregularity [10]. So far, Ball's result has been still taken as a criterion to control concrete surface irregularities in the American hydraulic design [11]. Arndt and Ippen investigated the characteristics of cavitation inception owing to an isolated protrusion on smooth and rough wall surfaces [12].

Conclusion

The spillway of Nagarjunasagar dam across River Krishna was severely eroded during the floods of 2009 due to cavitation which was resulted from negative pressures developed over the spillway. On further investigation of the problem, it was found that there was a large deviation of the existed profile of the spillway from the design profile, which actually led to the development of negative pressures in such a magnitude that could create a problem. In order to provide a remedial measure to the damage occurred on Nagarjunasagar Spillway due to cavitation it is required to find the magnitude of negative pressures occurring at different elevations on the spillway. Based on the difference in elevations between the design profile and existing profile, pressure tubes were installed at points where maximum difference was observed. The model was run under gated conditions as well as under free flow conditions allowing one-fourth of MFD, half of MFD, three-fourth of MFD and full discharges. The maximum negative pressures observed at pressure tube points in vent no 1 is 0.079 at P_7 for $1/4^{th}$ of maximum flood discharge for gated condition. The maximum negative pressures observed at pressure tube points in vent no 2 is 0.031 at P_7 for $3/4^{th}$, 1/2 and $1/4^{th}$ of maximum flood discharge for free flow condition. The maximum negative pressures observed at pressure tube points in vent no 3 is 0.031 at P_2 for $3/4^{th}$ of maximum flood discharge for both free flow and gated conditions and 1/2 and $1/4^{th}$ of maximum flood discharge for gated condition. The best, economical and most practicable remedial measures to the cavitation damage occurred on any spillway is the continuous supply of air. This can be done by providing aerators such as deflectors, transverse grooves.

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Volume 1 Issue 1 December 2014