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Physical and Numerical Model Studies on Cavitation Phenomenon-A Study on Nagarjuna Sagar Spillway

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***Abstract*— The Spillway of Nagarjuna Sagar dam across Krishna River was severely eroded during the floods of 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. In the present study, an attempt has been made to assess the cavitation damage due to negative pressures in terms of their magnitudes and locations on the spillway of Nagarjuna Sagar dam using the physical model studies on it. At the same time, to check the consistency and the reliability of the results obtained from the physical model studies, numerical models were applied to the problem thus ensuring the accuracy of the results. Further, the output from the numerical models improves the adequacy of the results to obtain the data for more number of points which may not be possible physically. Moreover, the numerical model can be applied to study the similar problems in future to any dam by merely changing the profile equations of the spillways. There is still a lot of scope for the future studies in showing the possible, applicable and most economical remedial measures to reduce the damage caused by cavitation.**

***Keywords*— Cavitation, Model Studies, Vapour Pressure, Piezometer, Cumec, Curvilinear flow.**

I. INTRODUCTION

Cavitation is defined as the formation of a bubble or void within a liquid. If the void is filled primarily with water vapor, the process is further classified as vaporous cavitation. If the void is filled primarily with gasses other than water vapor, the process is called gaseous cavitation. The development of cavitation in a liquid flow is characterized by a phase change from liquid to vapor at almost constant temperature.

In hydraulic structures, water contains air bubbles and various types of impurities of many different sizes.

The microscopic air bubbles or impurities in the water are necessary to initiate cavitation. However, once started, vaporization is the most important factor in the cavitation bubble growth. The presence of air bubbles in the flow also has an effect on damage [4] and noise produced by the cavitation. In addition to describing cavitation by the contents of the void; that is, by vaporous or gaseous, cavitation also can be described by its occurrence. For instance, if the pressure of flowing water is decreased through increases in the flow velocity, a critical condition is reached when cavitation will just begin. This critical condition is called incipient cavitation. Similarly, if cavitation exists and the flow velocity is decreased or the pressure is increased, a critical condition is reached when the cavitation will disappear. This condition is called desinent cavitation. Incipient cavitation and desinent cavitation often do not occur at the same flow conditions. The distinction is especially important in laboratory investigations, but can usually be ignored for all practical purposes in hydraulic structures. Finally, a set of critical flow conditions exists for which the individual cavitation bubbles suddenly transition into one large void. Condition under which the large void occurs is called variously as cavity flow, developed cavitation, or supercavitation.

II. CAVITATION INDEX

The cavitation index is a dimensionless measure used to characterize the susceptibility of a system to cavitate. The general expression for cavitation index, CI is:-

$$CI = [P_o - P_v] / [\rho V^2/2] \quad \text{………………..Eq. 2.1}$$

Where,

P_o = reference pressure
P_v = vapour pressure
V = reference velocity
ρ = density of fluid.

The expression for cavitation index on a spillway surface is given by:-

$CI = [y\cos\theta \pm (yV^2/gR_c)+P_b+P_v] / [V^2/2g]$……….Eq.2.2

Where,

y = Depth of flow
θ = Angle of chute with horizontal
R_c = Radius of curvature of chute,if any
P_b = Barometric pressure in m of water,usually 10.3 m
P_v = Vapor pressure in m of water,usually 0.233 m
V = Velocity of flow m/s

Radius of curvature R_c is taken negative for convex surface and positive for concave surface.

The values of CI_s for different systems differ markedly depending upon the shape of the flow passages, the shape of objects fixed in the flow, and the locations where reference pressure and velocity are measured. If a system operates at a CI above CI_s, it will not cavitate. If CI is below CI_s, cavitation will occur; in fact, the lower the value of CI, the more severe the cavitation. It has been confirmed experimentally that, in a given system, cavitation will begin at a specific CI_s, no matter which combination of pressure and velocity yields that CI_s. Since, in theory, a system having a given geometry will have certain CI_s, despite differences in scale; CI_s is a useful concept in model studies.

A. *Formation of Cavitation*

When cavitation bubbles grow and travel with the flow to an area where local pressure is higher, they can no longer be sustained and collapse. When a cavitation bubble collapses or implodes close to or against a solid boundary, an extremely high pressure is generated that acts on an infinitesimal area of the surface for a very short time period. Falvey [8] has described the mechanism of collapse of an individual bubble. The bubble collapse consists of phases in which the bubble diameter decreases, reaches a minimum, and then grows or rebounds, as shown in Figure 3.1. The process is repeated for several cycles, with the bubble diameter decreasing during each cycle until it finally becomes microscopic in size. During the rebound phase, a shock wave forms, with a velocity equal to the speed of sound in water. It has been estimated that the pressure intensity due to this shock wave is about 200 times the ambient pressure at the collapse site. Countless impacts due to such collapses erode the metal and concrete, which is known as cavitation pitting.The damage mechanism in concrete is more complicated due to the presence of micro fissures in the surface and between the mortar and coarse aggregates.

Compression waves in water fill such interstices and may produce tensile stresses that loosen pieces of the material. The elastic rebounds from a sequence of such blows may cause and propagate cracks and other damage, causing chunks of material to break loose. Once cavitation damage has substantially altered the flow regime, other mechanisms begin to act on the surface. These are mechanisms such as high water velocities striking the irregular surface and mechanical failure due to reinforcing steel vibrations. At this point, cavitation is only a minor contributor to the ensuing damage. The erosion may then continue through the whole mass or over the foundation. This discussion is mainly concerned with the cavitation on spillway chutes, stilling basins, and other structures such as sidewalls, buckets, and energy dissipating appurtenances.

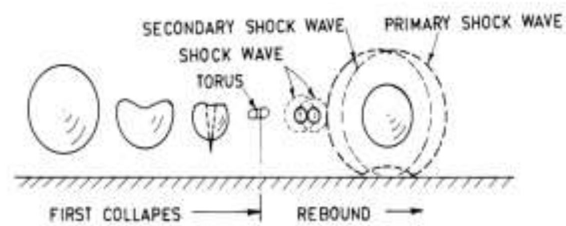

Fig. 1 Collapse of an individual bubble near a boundary (shown in Falvey [8]).

B. *Causes of Cavitation on spillways*

Falvey [13] has discussed in detail the damage that occurred to the free-surface tunnel spillways of Blue Mesa, Glen Canyon, Hoover and Yellowtail Dams, U.S.A., and the design of aerator slots used as remedial measures. Based on his research the principal causes of cavitation damage on spillway surface can be classified in structural or geometrical features such as:

- Inadequate design.
- Misalignment of boundary [2][97.
- Surface roughness [1] on the boundary associated with flow conditions involving flow separation and reattachment.

III. REMEDIAL MEASURES AND REPAIRS

For existing structures that suffer repeated cavitation damage, the cause of cavitation must be ascertained in order to determine remedial measures. Misalignments and surface irregularities can probably be rectified; such as design profile deviation, which can be corrected, or roughness, such as offsets, which can be grinded to permissible values. However, inadequacy in design and certain types of irregularities cannot be rectified. In such cases, aeration is the best remedial measure.

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Karun Spillway, Iran, is an example where aerators have been used after experiencing cavitation damage.

Conventional concrete typically performs poorly where the property of resistance against cavitation, abrasion, fatigue, and impact is important. Therefore, a variety of material and material combinations is used for the repair of concrete. Installing stainless steel liner plates on concrete surfaces subject to high velocity flows has been a generally successful method for protecting against cavitation erosion. Stainless steel is found to be about four times more resistant to cavitation damage than ordinary concrete. Its drawbacks are high cost, sensitivity to vibration, and fatigue breakdown. There are several instances where steel plates have been ripped off, adding to the severity of the problem. Therefore, this alternative is gradually being replaced by special concretes such as epoxy, fiber-reinforced concrete, etc.

A major factor that is critical to the success of a repair is the relative volume change between the repair material and the concrete substratum. Many materials change volume as they initially set or gel; others change volume due to changes in moisture content or temperature. If a repair material's volume relative to the concrete decreases sufficiently, cracks perpendicular to the interface will develop. In such situations, epoxy compounds that provide a durable bond between the fresh concrete and epoxy concrete are generally used. Epoxy compounds have been recently developed that bond to damp concrete, even to concrete under water. However, there is no unanimous opinion regarding the effectiveness of epoxy treatment against cavitation damage. For example, Lowe et al. [9] reported unsatisfactory results from the application of epoxy mixes on the Tarbela spillway structure, yet they reported positive results from the application of fibrous concrete and polymerized fibrous concrete. Meanwhile, Corlin et al. [5] reported that epoxy coating on the stilling basin of Morforsen Dam, Sweden, had a satisfactory performance. Fiber-reinforced concrete (FRC) utilizes randomly oriented, discrete fiber reinforcement in the concrete mixture. The superiority of FRC in comparison to conventional and polymerized concretes has been demonstrated by Lowe et al., [9] with the help of erosion tests on concrete specimen. It is claimed that FRC is resistant to the combined effects of cavitation and abrasion erosion.

Polymers are also incorporated into concrete to produce a material with improved properties. These are polymer-impregnated concrete (PIC), polymer portland cement concrete (PPCC), and polymer concrete (PC).

PIC is a hydrated portland cement concrete that has been impregnated with a monomer, which is subsequently polymerized in situ. PPCC is made by adding water-soluble polymer to fresh, wet concrete. PC is a mixture of fine and coarse aggregate with a polymer used as the binder. These materials are used as concrete repair materials for damaged surfaces.

ALAG anti-abrasion concrete is a recent advancement. This is a special concrete made of calcium aluminate cement and calcium aluminate reactive synthetic aggregate. Because both the cement and the aggregates have the same physical and mineralogical characteristics, two types of bonds, i.e., physical bonds as well as chemical bonds, are ensured to give it mechanical strength to resist abrasion. It has also been tested with velocities up to 110 m/s in cavitation conditions.

However, more study is required to ascertain its suitability for protection against cavitation damage.

IV. Physical Model Studies

A. *Description of project[6]*

Nagarjuna Sagar Dam, the giant among the masonry dams across River Krishna in Andhra Pradesh State with a maximum height of 124.66m (409 ft) above the deepest foundation level and with a total volume of 5.61 million cu m (199 million cu ft), is the highest and largest rubble masonry dam in the The Reservoir formed upstream of the dam, with a widespread area of 285 sq km (110 sq miles) and a gross storage capacity of 1.20 million ha m is again the largest man-made lake in the country and the third largest in the world.

B. *Problem Encountered in the Dam*

The Spillway of Nagarjuna Sagar dam across Krishna River was eroded severely during the floods of 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. Figures 2 and 3 shows the damaged occurred on the spillway of prototype.

Fig. 2 Cavitation Damage on Nagarjuna Sagar Dam.

Fig. 3 Erosion of Nagarjuna Sagar Spillway.

V. DESCRIPTION OF MODEL

A. Selection of Site

A site suitable for the construction of 2D Model of Nagarjuna Sagar Dam was selected in the out-door field laboratory of Hydraulics Laboratory, Andhra Pradesh Engineering Research Laboratories (APERL), Hyderabad and the ground was cleared-off an old existing model, leveled tray prepared and made ready for the construction of the model.

B. Selection of Site

The Infrastructure required for the model i.e., flumes, sumps, channels, honeycomb walls, shutters to regulate the water into the model and Tail channels connecting back to the main flume for re-circulation of water were constructed at the model site.

Necessary quantum of water and Motors/Pumps (Electrical/Diesel) were also arranged and kept ready for running of model experiments.

C. Selection of Site

A geometrically similar two-dimensional model to a scale of 1:80, as shown in the figures 4 and 5 representing all the design features of the Nagarjuna Sagar dam across river Krishna near Nandikonda village in Miryalaguda taluk of Nalgonda district was constructed in the outdoor field laboratory duly representing the very first five vents (which were found to be more cavitated) from the right end of the spillway based on the relevant technical information provided by the concerned agency.

Before starting the actual construction of the model, plots were made for all the vents by reducing the horizontal and vertical coordinates of prototype to that of model with the pre-fixed scale ratio.

Fig. 4 Features Of Model.

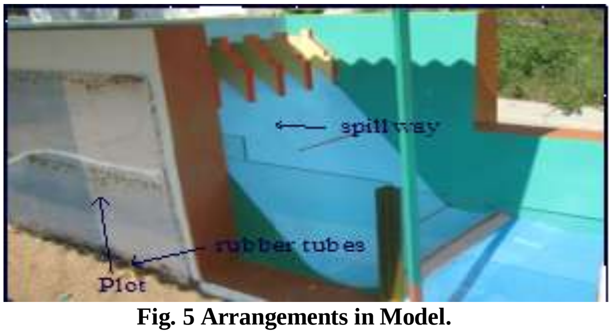

Fig. 5 Arrangements in Model.

The horizontal coordinates for prototype are taken with reference to the upstream face of the dam whereas vertical ordinates are taken from the R.L.s taking foundation as the reference.

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Then, using the plots the profiles of all the five vents were reproduced thus ensuring that all the design features of dam are well represented. On each vent, a few points were chosen where the pressures are expected to be negative and at each point holes are made for which the piezometers are connected to measure the corresponding pressures. All the piezometers are connected to the holes by means of rubber tubes and the piezometers were erected against the plots made corresponding to each vent respectively to observe the pressures at those points.

VI. Experiments

The proposed experiments were broadly divided into two setups as series-I and series-II. Each setup is explained in sequential order with the main focus of the studies on the following hydraulic Parameters-

- To measure the pressures at all the points of observation.
- Check whether they are positive or negative.

The elevations at which the piezometers were provided are given in the following table

TABLE I
Pressure Tube Points on Spillways

	VENT NO-1	VENT NO-2	VENT NO-3
CREST LEVEL	+166.422 m	+166.422 m	+166.422 m
I. PRESSURE TUBE POINTS			
P_1	+165.186 m	+165.235 m	+165.22 m
P_2	+163.866 m	+163.821 m	+161.919 m
P_3	+159.431 m	+159.311 m	+156.299 m
P_4	+152.705 m	+152.533 m	+148.422 m
P_5	+144.32 m	+143.986 m	+139.962 m
P_6	+135.76 m	+135.486 m	+131.44 m
P_7	+75.864 m	+122.81 m	+118.636 m
P_8	+73.366 m	+109.649 m	+110.104 m
P_9	+76.197 m	+88.81 m	+101.666 m
P_{10}	--	+74.665 m	+73.804 m
P_{11}	--	+73.948 m	--

A. *Series I - All Vents are 'Fully Opened'*

In the first instance, the experiments were carried-out by keeping all the vents of the dam fully open i.e., free flow for various discharge conditions. Initially a discharge corresponding to MFD i.e., 43,600cumecs was allowed into the model. After stabilization of flow throughout the model, observations were noted.

Similarly, experiments were carried out to measure the pressures on the spillway with three-fourth of maximum flood discharge and half of maximum flood discharge i.e., 32700cumecs and 21800cumecs respectively.

B. *Series II – Gated Condition*

In this series of experiments, discharge is varied and gates are operated by maintaining FRL. Firstly one-fourth of maximum flood discharge i.e., 10900cumecs is allowed through the model and the pressures on the spillway were noted. Similarly, experiments were carried out to measure the pressures on the spillway with half of maximum flood discharge, three-fourth of maximum flood discharge and three-fourth of maximum flood discharge i.e., 21800cumecs, 32700cumecs and 43600cumecs.

VII. Results

The following were the results obtained from the physical model studies (shown in table 2)

Gated Condition: Under gated conditions following results were obtained –

- Under one fourth discharge condition (10,900cumecs), negative pressures were observed at pressure tube points P_1 and P_7 in vent-1, P_1, P_2, P_7 and P_9 in vent-2 and P_1, P_2 and P_9 in vent-3.
- From the experiments, it is found that under half discharge condition (21,800cumecs), negative pressures were occurring at P_7 in vent-1, P_2, P_7 and P_9 in vent-2 and P_1, P_2 and P_9 in vent-3.
- Negative pressures under three-fourth discharge condition (32,700cumecs), were observed at P_7 in vent-1, P_2, P_7 and P_9 in vent-2 and P_1, P_2 and P_9 in vent-3.
- In full discharge condition (43,600cumecs), no negative pressures were observed in vent-1. But negative pressures were observed at P_2, P_7 and P_9 in vent-2 and P_1, P_2 and P_9 in vent-3.

TABLE II

RESULTS OBTAINED BY PHYSICAL MODEL STUDIES

DISCHARGE	GATED CONDITION			FREE FLOW CONDITION		
	Vent-1	**Vent-2**	**Vent-3**	**Vent-1**	**Vent-2**	**Vent-3**
1/4 of MFD (10900cumecs)	P_1	P_1	P_1	P_7	P_9	P_2
	P_7	P_2	P_2	--	--	--
	--	P_7	P_9	--	--	--
		P_9	--	--	--	--
1/2 of MFD (21800 cumecs)	P_7	P_2	P_1	P_7	P_7	P_2
	--	P_7	P_2	--	P_9	--
	--	P_9	P_9	--	--	--
3/4 of MFD (32700 cumecs)	P_7	P_2	P_1	--	P_2	P_1
	--	P_4	P_2	--	P_7	P_2
	--	P_7	P_9	--	P_9	--
	--	P_9	--	--	--	--
Full discharge (43600 cumecs)	--	P_2	P_1	--	--	--
	--	P_7	P_2	--	--	--
	--	P_9	P_9	--	--	--

FreeFlow Condition: Under free flow conditions following results were obtained:

- Under one fourth discharge condition (10,900cumecs), negative pressures were observed at pressure tube points P_7 in vent-1, P_9 in vent-2 and P_2 in vent-3.
- From the experiments, it is found that under half discharge condition (21,800cumecs), negative pressures were occurring at P_7 in vent-1, P_7 and P_9 in vent-2 and P_2 in vent-3.
- Negative pressures under three-fourth discharge condition (32,700cumecs), were observed at P_2, P_7 and P_9 in vent-2 and P_1, P_2 in vent-3. No negative pressures were observed in vent-1.

VIII. Numerical Model Studies

A. *Program Description*

In physical model studies, pressures measured on at different elevations of spillway using piezometers have been used to predict the occurrence of cavitation with free water surface flows. If the pressures are positive or if pressure fluctuations never drop below atmospheric pressure (scaled to model dimensions), hypothetically, cavitation damage will not occur on the surface.

The results obtained from the physical model studies can be verified by developing a numerical model [3]. The prediction of cavitation occurring at a boundary can best be accomplished by calculating the flow's cavitation index at the boundary and comparing this to the cavitation indices of surface irregularities which may be anticipated. To calculate the flow's cavitation index, the velocity and pressure conditions in the vicinity of the irregularities must be known.

Although the simplifications are somewhat crude, the algorithms produce results having sufficient accuracy for engineering analysis purposes. The use of these algorithms keeps the computational time within reasonable limits.

The program output includes the flow parameters as well as the cavitation characteristics of the structure. The computer program is written and compiled in C language.

B. *Algorithm used in Program*

Pressure Distribution on steep slopes: A hydrostatic pressure distribution is a good assumption for flow on mild slopes. However, as slope increases, the pressure distribution no longer remains hydrostatic (see fig. 7.1). Therefore, a pressure distribution correction must be made on steep slopes to obtain an accurate energy balance. The wall pressure head on steep slopes is given by:

$$h_w = d\cos\theta_i \;\ldots\ldots\ldots\ldots\ldots\ldots\text{Eq.8.1}$$

where:

d = flow depth measured normal to channel slope
h_w = wall pressure head
θ_i = angle of profile relative to horizontal

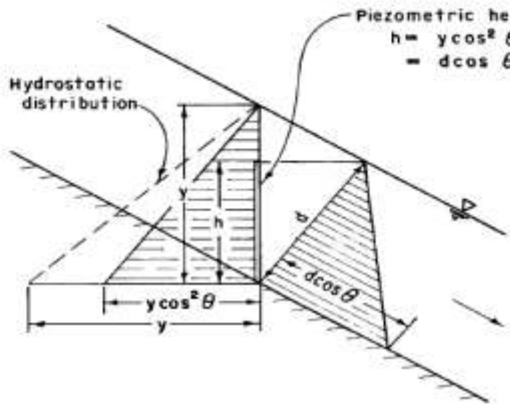

Fig. 6 Pressure Distribution on Steep slope.

Curvilinear Flow: The piezometric pressure at the boundary assumes a constant slope between computational points. If the streamlines have a substantial curvature in the vertical plane, the piezometric pressure at the boundary must be corrected by an appropriate factor. This factor is equal to the force produced per unit area of a mass of water undergoing centrifugal acceleration. For the channel invert, the factor is determined from the relationship:

$$C_g = \frac{d\,V^2}{g\,R_b}$$ Eq.8.2

Where:

C_g = centrifugal acceleration factor
d = flow depth
g = gravitational constant (acceleration)
R_b = radius of curvature at the boundary
V = flow velocity

If the flow tends to move into the boundary (concave curvature), the factor is positive. For flows moving away from the boundary (convex curvature), the factor is negative as shown on figure 7.

The radius of curvature is given by:

$$R_b = \frac{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\frac{d^2y}{dx^2}}$$ Eq.8.3

For circular curves, the radius of curvature is constant and is equal to the radius of curve.

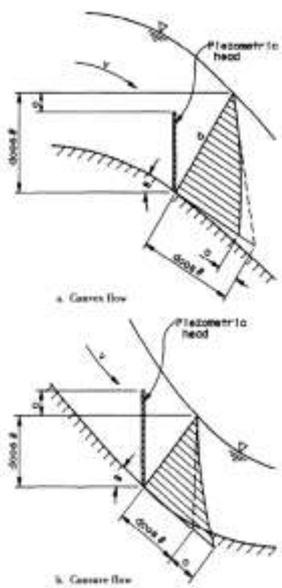

Fig. 7 Piezometric Pressure with curvilinear flow.

Cavitation Index Computation: The expression for cavitation index on a spillway surface is given by:-

CI = [$y\cos\theta \pm (yV^2/gR_c)+P_b+P_v$] / [$V^2$/…………..Eq.8.4

Where,

y = Depth of flow
θ = Angle of chute with horizontal
R_c = Radius of curvature of chute,if any
P_b = Barometric pressure in m of water,usually 10.3 m
P_v = Vapor pressure in m of water, usually 0.233 m
V = Velocity of flow m/s

Radius of curvature R_c is taken negative for convex surface and positive for concave surface.

The incipient cavitation index for the flow over spillway surfaces is 0.2. If the cavitation index at any point on the spillway surface is less than 0.2, then that point has the potential to be damaged due to cavitation.

C. *Program Description*

The input file consists of barometric pressure (P_b), vapor pressure of water (P_v), height of dam above silted level (h), effective span of spillway (L), coefficient of discharge (C), design discharge (Q), profile elevations with respect to upstream face for the first three vents.

The equation for existing downstream Ogee profile and for bucket portion is obtained from Origin Pro7.5 package. The equations are:-

For downstream Ogee

$$Y = -0.03031 - 0.03464 X + 0.03197 X^2 \quad .....Eq.8.5$$

For bucket region

$$Y = 301.31308 - 4.99918 X + 0.02739 X^2 ....Eq.8.6$$

The given input profile is calculated with respect to the crest. The program is developed for gated and free flow conditions. Under each condition, for every vent, at every 3m interval in x-coordinate, program calculates velocity at that particular elevation, radius of curvature, static pressure, dynamic pressure and cavitation index for various discharges.

The program output includes cavitation index and based on this value relative to incipient cavitation index of spillway surface (i.e.,0.2), it shows whether that particular elevation cavitates or not.

D. Assumptions

The following assumptions were made in the numerical model:

- The vapor pressure of water is assumed to be 0.233m and the barometric pressure is taken as 10.3m which are constant for all discharges.
- The incipient cavitation index for spillway surfaces is taken as 0.2. This assumption is based on the research done by Falvey.
- All gate openings are assumed to be of uniform size. So equal amount of discharge is assumed to be flowing through each vent.
- The gate openings for various discharges in gated conditions were taken approximately from the physical model studies.

E. Program Output

Output of the numerical model consists of discharge, vent number, X-coordinate, RL of elevation, cavitation index. If cavitation index is less than 0.2 then it gives 'yes', which implies that, that particular point has the potential to get damaged, and 'no', if more than 0.2.

F. Results

Gated Condition: Under gated conditions following results were obtained:-

- Under one fourth discharge condition (10900cumecs), negative pressures were occurring at an elevation corresponding to the x-coordinate of 36m with respect to upstream face for all three vents and continuing till the end of bucket.
- From the experiments it is found that under half discharge condition (21800cumecs), negative pressures were occurring at an elevation corresponding to the x-coordinate of 42m with respect to upstream face for all three vents and continuing till 69m.
- Negative pressures under three-fourth discharge condition (32700cumecs), were occurring at an elevation corresponding to the x-coordinate of 6m with respect to upstream face for all three vents and continuing till 18m. Also they were occurring at 45m at continuing till 69m.

In full discharge condition (43600cumecs), negative pressures were occurring at an elevation corresponding to the x-coordinate of 6m with respect to upstream face for all three vents and continuing till 18m. Also they were occurring at 48m at continuing till 69m.

Freeflow Condition: Under free flow conditions following results were obtained:-

- Under one fourth discharge condition (10900cumecs), negative pressures were occurring at an elevation corresponding to the x-coordinate of 45m with respect to upstream face for all three vents and continuing till the end of bucket.
- From the experiments it is found that under half discharge condition (21800cumecs), negative pressures were occurring at an elevation corresponding to the x-coordinate of 51m with respect to upstream face for all three vents and continuing till 69m.
- Negative pressures under three-fourth discharge condition (32700cumecs), were occurring at an elevation corresponding to the x-coordinate of 54m with respect to upstream face for all three vents and continuing till 69m.

In full discharge condition (43600cumecs), negative pressures were occurring at an elevation corresponding to the x-coordinate of 57m with respect to upstream face for all three vents and continuing till 69m.

IX. CONCLUSIONS

The following conclusions can be done from the results of the present study:

A. *Major Contribution from physical model studies*

The following were the major contributions from the two dimensional model studies:-

- In the first vent, pressure tube point P_7 (i.e., RL +75.864m) is the critical damage point where maximum negative pressure was observed for many discharges.
- Pressure tube points P_2 (RL +163.821m), P_7(RL +122.81m) and P_9(RL +88.81m) are the critical points in vent number 2 as negative pressures were observed for many discharges in both gated and free flow conditions.

Vent number 3 has P_1 (RL +165.22m), P_2 (RL +161.919m), P_9 (RL +101.666) as critical points of damage as negative pressures were observed for all discharges in gated conditions. In free flow conditions P_2 (RL +161.919m) is the only point where negative pressures were observed.

B. *Major Contribution from Numerical model studies*

The following were the major contributions from the numerical model studies:

Gated Condition: Under gated conditions following results were obtained:-

- Under one fourth discharge condition (10,900cumecs), negative pressures were occurring at an elevation corresponding to the X-coordinate of 36m with respect to upstream face for all three vents and continuing till the end of bucket.
- From the numerical model it is found that under half discharge condition (21,800cumecs), negative pressures were occurring at an elevation corresponding to the X-coordinate of 42m with respect to upstream face for all three vents and continuing till 69m.
- Negative pressures under three-fourth discharge condition (32,700cumecs), were occurring at an elevation corresponding to the X-coordinate of 6m with respect to upstream face for all three vents and continuing till 18m. Also they were occurring at 45m and continuing till 69m.

In full discharge condition (43,600cumecs), negative pressures were occurring at an elevation corresponding to the X-coordinate of 6m with respect to upstream face for all three vents and continuing till 18m. Also they were occurring at 48m and continuing till 69m.

Freeflow Condition: Under free flow conditions following results were obtained:-

- Under one fourth discharge condition (10,900cumecs), negative pressures were occurring at an elevation corresponding to the X-coordinate of 45m with respect to upstream face for all three vents and continuing till the end of bucket.
- From the model it is found that under half discharge condition (2,1800cumecs), negative pressures were occurring at an elevation corresponding to the X-coordinate of 51m with respect to upstream face for all three vents and continuing till 69m.
- Negative pressures under three-fourth discharge condition (32,700cumecs), were occurring at an elevation corresponding to the X-coordinate of 54m with respect to upstream face for all three vents and continuing till 69m.

In full discharge condition (43,600cumecs), negative pressures were occurring at an elevation corresponding to the X-coordinate of 57m with respect to upstream face for all three vents and continuing till 69m.

C. *Research Contributions from Present study*

The research contributions from the present study include the following points:-

- In vent-1 under gated conditions, from both physical and numerical model studies, for one-fourth of MFD (10900cumecs) and half of MFD (21800cumecs), P_7(i.e., RL +75.864m) is the point where maximum negative pressure was observed. For three-fourth of MFD (32700cumecs) and MFD (43600cumecs), P_1 (i.e., RL +165.186m), P_2 (i.e., RL +163.866m) and P_3 (i.e., RL +159.431m) were the points with maximum negative pressure.
- For all discharges in free flow conditions, P_7 (i.e., RL +75.864m) is the only point with negative pressures in vent-1.
- Under gated conditions, in vent-2, P_2 (i.e., RL +163.821m), P_7 (i.e., RL +122.81m) and P_9 (i.e., RL +88.81m) were the points with negative pressures for all discharges.

- In vent-2, P_7 (i.e., RL +122.81m) and P_9 (i.e., RL +88.81m) were the only points with negative pressures under free flow conditions for all discharges.
- In vent-3 under gated conditions, for all discharges P_1 (i.e., RL +165.22m), P_2 (i.e., RL +161.919m) and P_9 (i.e., RL +101.666m) were the points where negative pressure was observed.
- In vent-3 under free flow conditions, no points were observed with negative pressures of noticeable magnitude.

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 etc. In order to design the aerator and its location it is required to know the magnitude of negative pressures and their points of occurrence. Hence the conclusions obtained from the present study can be used to design an aerator for the Nagarjuna Sagar spillway.

D. A Scope for Future Study

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 etc. Hence the scope for the future study on the cavitation phenomenon on Nagarjuna Sagar spillway includes the following:-

- In the present study, experiments were conducted to observe the magnitudes of negative pressures and their points of occurrence. Hence using these results, further, experiments can be conducted on the physical model with an aerator by varying its location and size. From those experiments the best location of aerator and its size can be obtained so that the negative pressures were eliminated economically.

The numerical model developed in the present study can further be improved to include other cavitation parameters such as damage potential and damage index. Also, a numerical model can be developed for the air entrainment quantities.

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