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Fuzzy Predicting Model for Cavitation in Chute Spillways

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ABSTRACT

Cavitation damage is one of the complex and prevalent process that occur in spillways. Cavitation damage is derived by magnitude and interaction of several effective parameters. These operative parameters are pressure, flow velocity and surface strength, operative time and air content. For evaluating the cavitation, a traditional method is computing the cavitation index. In this research the damage levels were adjusted using fuzzy logic, then damage intensity was predicted, and the fuzzy modeling results based on velocity and cavitation index was compared with the real damage levels. The verified numerical modeling data of Karun1 old spillway was used as input and the cavitation damage to Chute 1 of Karun 1 dam spillway in 1977 flood has been used for calibrating model. Finally the fuzzy prediction model was tested for Chutes 2 and 3 of this flood and showed a good compatibility.

Keywords: *Spillway, Cavitation damage, Fuzzy prediction model, Membership function.*

INTRODUCTION

Cavitation can produced holes and damage in hydraulic structures. Sometimes in a hydraulic system local pressure decreases and probably reaches to fluid vapor pressure because of high velocity. Also due to surface roughness, stream lines separate from their bed and local pressure reduces to the vapor pressure. Therefore in the disruption of continuity in the liquid, fluid boils and the vapor bubble is formed. These vapor bubbles (or cavities) after collapsing generate shock waves that produce high impact forces on adjacent surfaces and cause work hardening, fatigue and cavitation pits. The impact pressure of cavity imploding sometimes reaches to 1500MPa [0], and as the bubble face surface is so small, the produced force is very high on structures bed.

In long spillways the velocity is extremely high, hence small roughness in millimeters can produce cavitation. The damage in some structures is so severe, that it hardly can function safely and properly again with repairing.

Based on the researchers' many years of investigations it proved that the process of cavitation damage is very complex due to various factors, and their interaction, influences on cavitation damage. The investigations and the result of prototypes lead to a traditional method using cavitation index dependent on pressure and velocity to prevent cavitation. In this method the aim is to reach an index bigger than the critical cavitation index $\sigma > \sigma_c$. The following function is used to achieve the cavitation index in flow.

$$\sigma = \frac{p - p_v}{\rho V^2/2} \qquad (1)$$

, where p is local pressure, p_v is water vapor pressure, V local velocity, ρ is water density and σ is cavitation index [0]. Other methods for controlling this damage also exist. By considering velocity and cavitation index Wang and Chou (1979) supposed that long operation will leads to a stabilized depth for damage [**Error! Reference source not found.**]. Falvey (1990) considered cavitation index and cavitation damage potential as damage prediction parameters. Damage potential includes cavitation damage, velocity and operation time [0].

Cavitation damage is controlled by several factors, including cavitation index, flow velocity, pressure material strength, time, geometry and air content in flow. Selecting critical index even for one special case is not obvious. Changes in operation conditions, different construction techniques, variations in materials incline researchers to seek for new ways in controlling damage. Scale effects and errors from observations due to human and instrument abilities, in physical modeling and prototypes enroll in accuracy of achieved data. Hence the complexity of cavitation damage seems to represented difficulty by classic methods.

Lee and Hoopes (1995, 1996) made a fuzzy predicting model for cavitation damage using cavitation index and velocity as effective parameters [**Error! Reference source not found.** and **Error! Reference source not found.**]. They used data from Glen Canyon dam tunnel spillways for building it up and tested it for three other dam tunnel spillways and Karun 1 dam chute spillways. The predictions were in very good agreement for tunnels but didn't agree for chutes. The aim of this work is to introduce a new fuzzy prediction model specialized for chute spillways, by inspiration of Lee and Hoopes' work.

The data from Karun 1 dam chute spillway was applied. The parameters has been used for this model is velocity and cavitation index. The new damage levels, new rules and system, and new damage membership function have been developed. Due to lack of site monitoring of the case, the flow data was obtained from verified numerical modeling of it, although the damage observed data was achieved from the Karun 1 site investigation report, after 1977 spring flood.

1. *Fuzzy Logic*

1.1. Basic Concepts and Fuzzy Sets Theory

The word of Fuzzy means vague, misty and uncertain. In classical Mathematics' sets and boundaries assumed to be well defined. Well defined means the ability to conclude that a statement is right or wrong. But in real world, sets and boundaries are introduced with a kind of uncertainty, due to lag of precise and strong bordering of concepts. This impreciseness is not dependent on indefiniteness of a statement's occurrence as there is in probability theory. It's because of vagueness of language concepts, so is not included in probability theory [**Error! Reference source not found.**]. These sets and statements get out of working domain; wide range of natural phenomenon couldn't be modeled properly. Fuzzy logic theory is a precise theory itself, even though the fuzzy systems explain uncertain phenomenon basically [**Error! Reference source not found.**].

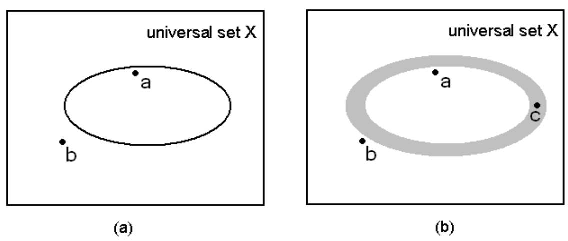

Figure 1. Comparison classic set (a), with fuzzy set (b)

The crisp set is defined in such a way that can divide universe of discourse into two groups: members and nonmembers. But fuzzy set can be mathematically defined assigning to each possible individual in universe of discourse a value representing its grade of membership [**Error! Reference source not found.**, 0] (Fig. 1).

For instance:

1. Let set X be water and A be a subset of ice. In general form and standard condition, for equal and under zero centigrade degrees, x belongs to A, and for more than zero it is not. This sub set has well defined and sharp boundary.
2. If the X is blood and A is group O, then x could belong to A or not after blood grouping. So this is subset with well defined boundary and membership of an element is probable chance.
3. Consider set X as weather and let A be a subset of sunny. If the sky covered precisely 100% with cloud or 80%, it is not sunny and 0% means x belongs to A. But what about 1% cloud cover? In order for a term such as sunny to accomplish the desired introduction of vagueness, however, we cannot use it to meaning precisely 0% cloud cover. We can accept certain intermediate states, such as 10% and 20% of cloud cover, as sunny. But where do we draw line? [**Error! Reference source not found.**].If any cloud cover under 25% is considered sunny, what about 26%? The subset A has boundary with imprecise definition; although it exist in language concepts.

1.2. Fuzzy Set, Membership Function, Relation and Operation

The capability of fuzzy sets to express gradual transitions from membership to nonmembership and vice versa has a broad utility [**Error! Reference source not found.**]. Membership function shows the membership degree of each element and ranging between zero and one [0]. For example the membership function, $\mu_E(x)$ represent the membership degree of x in fuzzy set E, and belonging to the range [0,1], $\mu_E : X \to [0,1], x \in X$. The closer $\mu_E(x)$ to one is, the stronger membership of x in E.

All operations that would be defined for fuzzy sets are converged form of classic set operations. The standard operations include intersection, union and complement operations which are presented below [0]:

1. Intersection, which is minimum value of two functions or intersection membership function of two fuzzy sets. $\mu_{D \cap E}(x) = \min\{\mu_D(x), \mu_E(x)\}$;
2. Union, which is maximum value of two functions or union membership function of two fuzzy sets. $\mu_{D \cup E}(x) = \max\{\mu_D(x), \mu_E(x)\}$; and
3. Fuzzy complement, which is membership functions of elements being in universal set but not in mentioned set. $\mu_{A'}(x) = 1 - \mu_A(x)$.

In addition there are other operations, which have these standard operations' characteristics, but being used with a different form.

1.3. Fuzzy Inference System and Model

The goal of a fuzzy inference system is to achieve the relation between input and output parameters with the set of if-then rules. This system can be used as a predicting model when parameters are imprecise and have some uncertainties. Fuzzy implication operations and fuzzy relations combination would be used for developing the model [0].

In general, any fuzzy system contains the following steps:

1. Inference system definition based on data: Analysis operation is applied by fuzzy inference engine. There are several fuzzy inference systems which can be utilized for this purpose, such as Sugeno and Mamdanifuzzy inference systems which are two of the most important ones;
2. Membership function definition: Input information is made as fuzzy data by membership functions. This step is known as fuzzification;
3. Inference rules definition and combination; and
4. Obtaining result and defuzzification if being needed.
5.

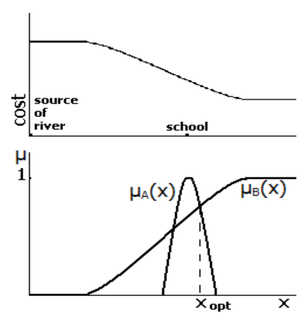

Figure 2. Optimum decision

Here a decision making example is described. For building a library in a village near a school, that the village contains a river, where is the best place, if the places near the source of the river would be more expensive. If the goal has a membership function such as $\mu_A(x)$ (building a library near the school) and the membership function of limitation is $\mu_B(x)$ (building in a cheaper place), then $\mu_C(x)$ is the decision, satisfying both aim and limitation.

$$\mu_C(x) = \min\{\mu_A(x), \mu_B(x)\} \quad (2)$$

The optimum decision is:

$$\mu_C(x_{opt}) = \max\{\min[\mu_A(x), \mu_B(x)]\} \quad (3)$$

, which is based on Mamdani inference method (the maximum of minimums) See Fig. 2.

Here the importance of aim and limitation are equal. If assumption says one of them is more important, the weights, w_A and $w_B = 1 - w_A$, could be used. $\mu_C(x)$ would be written then:

$$\mu_C(x) = \min\{w_A \mu_A(x), w_B \mu_B(x)\} \quad (4)$$

Further, if the decision is represented by level with a range, then $a_n \le \mu_C(x) \le b_n$, where a_n and b_n are the bounds of the n th decision. For example: $0.6 < \mu_C(x) \le 1$, good; $0.3 < \mu_C(x) \le 0.6$, fair; $0 \le \mu_C(x) \le 0.3$, poor [**Error! Reference source not found.**].

There is another parameter of weight that would be applied to each rule, defining the strength (power) of each rule in combination (aggregation of rules). These weights' summation is not equal to one, certainly.

2. *Model Development*

The application of comprehensive decision making model for prediction of cavitation on a spillway is considered in this section. As mentioned before, damage process is complicated, and representing all existing uncertainties is out of classic Mathematics' ability. Relativeness and graduality of cavitation formation condition, imprecise definitions of cavitation damage levels, involving various factors in the process, such as surface roughness and strength, and varying for each case due to material, construction, flow, operation and maintenance conditions make the choice of σ_c and other criteria difficult.

Factors 1. cavitation index (σ), 2.velocity (v), 3.air content (C), 4.material strength(S), and 5.time(t) contribute to cavitation damage. Although their combination and relative influence are not known, damage occurs for small pressures (or small cavitation index), increases with v (e.g. v^6), and decreases with C increases (up to 8%). A fuzzy comprehensive decision making model can combine the factors by considering their interactions with weight W. In presented work cavitation damage intensity and its place is predicted, using fuzzy Mathematics. Five damage level from none to major damage and two factors σ, v (naturally containing two other factors S, t is considered [**Error! Reference source not found.**].

2.1. Applied Membership Functions

Lee and Hoops (1996) proposed the following membership function for cavitation index. This membership function for σ can vary between 0 (no damage) and 1 (major damage). As cavities emerge when $\sigma < \sigma_i$ and major damage occurs for $\sigma > \sigma_{dh}$, μ_σ can be represented as following [**Error! Reference source not found.**]:

$$\mu_\sigma = \begin{cases} 0 & \sigma \le \sigma_{dh} \\ \frac{1}{2} - \frac{1}{2}\sin\frac{\pi}{\sigma_i - \sigma_{dh}}\left(\sigma - \frac{\sigma_i + \sigma_{dh}}{2}\right) & \sigma_{dh} < \sigma \le \sigma_i \\ 1 & \sigma_i < \sigma \end{cases} \quad (5)$$

, in which σ_i is the cavitation index for initiation of cavitation and σ_{dh} is the cavitation index for major damage. The membership function for v also can vary between 0 (no damage) and 1 (major damage). Let v_0 and v_m be limiting v values (namely, no damage for $v < v_0$ and major damage when $v > v_m$ over a sufficiently long operation time). As research shows that cavitation damage intensity is proportional to v^6 [**Error! Reference source not found.**], following membership function for v also was proposed by Lee and Hoops (1996) [**Error! Reference source not found.**]:

$$\mu_v = \begin{cases} 0 & v \le v_0 \\ \frac{(v - v_0)^6}{(v_m - v_0)^6} & v_0 < v \le v_m \\ 1 & v_m < v \end{cases} \quad (6)$$

Values of σ_{dh}, v_0 and v_m are expected to depend upon S and t since: stronger material and good construction practice can tolerate a smaller σ and a larger v before damage begins or researches a major level; S decreases (e.g., stress cracks, leaching, and deposits); and v and σ at any location depend upon spillway discharge that changes with t through a flood [**Error! Reference source not found.**].

The fuzzy set for cavitation damage intensity will be divided into five levels to show how damage changes with σ, v, S, and t. Thus, the fuzzy set is {no damage, light damage, moderate damage, serious damage, major damage}.
Quantification of each level is based upon the risk of spillway failure as well as the cost to repair [**Error! Reference source not found.**]. Values of the membership functions for each of the five levels are given in Table 1. The Value μ_d is considered as a membership function of damage intensity, $\mu_d : X \rightarrow [0,1], x \in X$.

Table 1. Cavitation damage level intervals

Damage membership function intervals	Damage level
$\mu_d(x) \leq 0.5$	no
$0.5 < \mu_d(x) \leq 0.55$	light
$0.55 < \mu_d(x) \leq 0.61$	moderate
$0.61 < \mu_d(x) \leq 0.67$	serious
$0.67 < \mu_d(x)$	major

2.2. Rules and Predicting Cavitation Model

Experiences have shown that there is no cavitation damage on a concrete surface if $v \leq 5 m/s$, that damage might or might not occur when $5 < v \leq 16 m/s$, that damage occurs when $v > 16 \sim 18 m/s$, and the major damage occurs when $v > 40 \sim 45 m/s$ [1, 2]. Thus $v_0 = 17$ and $v_m = 42$.

This expression is also exist: $0.076 \leq \sigma_i \leq 1.2$. So σ_i and σ_{ch} assumed to be in the range of 0.8~1.2. The selective weights w_1 and w_2 assumed to be 1, because there is no reason to consider relative importance for any of v and σ on the cavitation phenomenon. But with giving weight to the rules the cavitation index's influence assumed to be more important. The prediction model is prepared with $\sigma_i = 1.0$ and $\sigma_{ch} = 0.2$, and the result would be compared with real damages.

The Mamdani fuzzy inference system is used for the problem inputs cavitation index and velocity (Fig. 3). For the implication, the minimum and for the aggregation the maximum are used. The operation used instead of intersection in the rules is multiply.

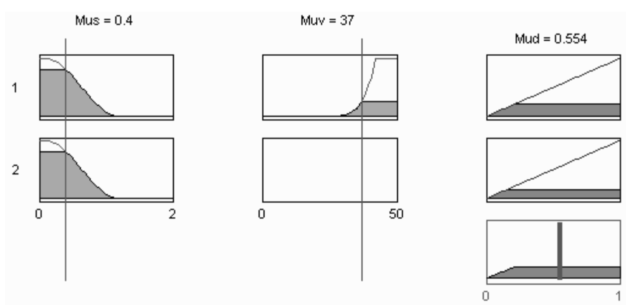

Figure 3. Rules combination in the Mamdani method

Two rules govern on the model: 1- If the membership function of cavitation index is μ_σ and the membership function of velocity is μ_v, then the damages' membership function is μ_d, with weight of 1. 2- If the membership function of cavitation index is μ_σ, then damage membership function is μ_d, with weight of 0.199. It must be mentioned that the weights here are for rule not for membership functions.

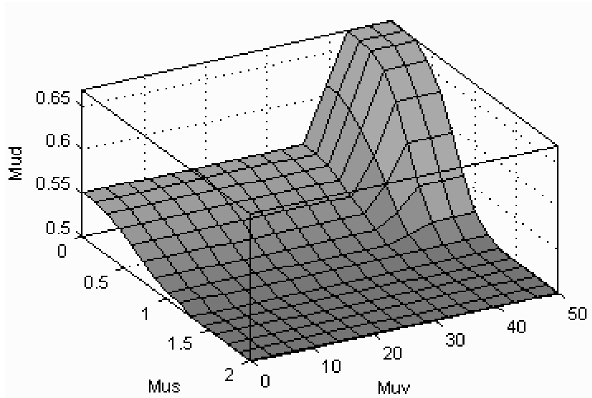

Figure 4. Model surface

On the last step, for defuzzification the method of area center is used. The surface is developed by this fuzzy modeling for membership function, which is shown in Fig. 4.

3. The Application to Damaged Case

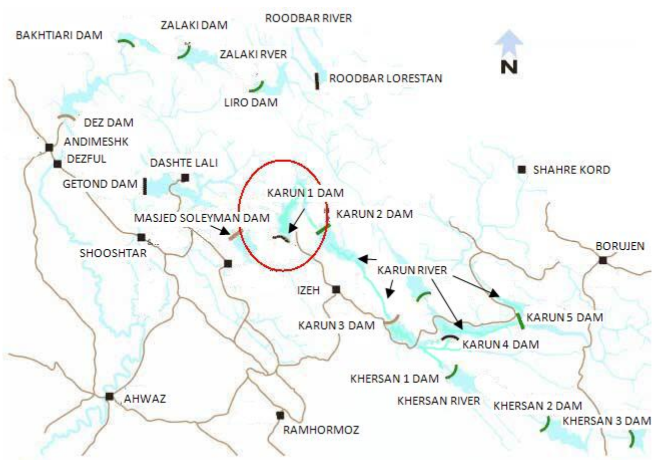

Figure 5. Site plan: dam location

Karun1 Dam is the first great storage project done on largest river of Iran, Karun. Its spillway has three chutes with a total capacity of 16200m^3/s and a head of 30m in this discharge [**Error! Reference source not found.**, **Error! Reference source not found.**] (Fig. 5). The spillway was operated initially in spring 1977. To pass the 1977 flood, spillway gates 2 and 3 were opened releasing between 350 and 750m^3/s each day. On Dec. 24, 1977, site personnel noted unusual and excessive turbulence and "rooster tails" in the flow over the lower parts of these chutes, which were found later to be severely damaged. Damage in Chute 2 was from station 2+35 to 2+55 and was the most serious. Damage in Chute 3 was from station 2+10 to 2+80 with one hole extending 4 meters upstream underneath the slab. On Dec. 24, 1977, because of heavy rains, Chutes 2 and 3 remained open and Chute 1 was opened. Chute 1 discharged a maximum flow of 1160m^3/s (average flow of 700m^3/s) for approximately 5 days. Damage was occurred from station 2+10 to 2+75. Most damage was initiated by construction joints. The maximum observed erosion in the chutes was approximately 0.5 meters [**Error! Reference source not found.**].

Investigation indicated weak plates in concrete and not fine covering of bars in the spillway involved in the damage procedure. For rebuilding and repairing the spillway a new design was selected to placing new bucket higher above the old bucket and two aerator ramps in the chutes to preventing cavitation damage at the chutes' surfaces [**Error! Reference source not found.**].

3.1. Initial Test for Chute 1

In this research the data from numerical modeling was used that had been evaluated in [**Error! Reference source not found.**]. The numerical data such as velocity and cavitation index at spillway's surface used as fuzzy model inputs. The precise inputs were changed to defuzzified outputs by the inference system. The output span can be changed due to different parameters fuzzy systems and in this research the output is changing between 0.5 and 0.67 along the spillway(Figure 6).

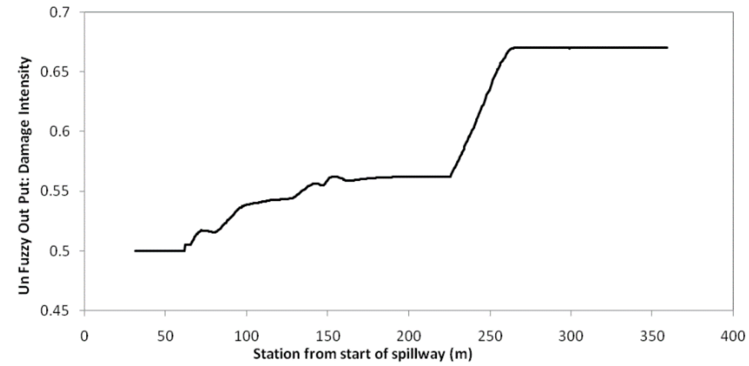

Figure 6. Defuzzified predicted damage at stations for Chute 1

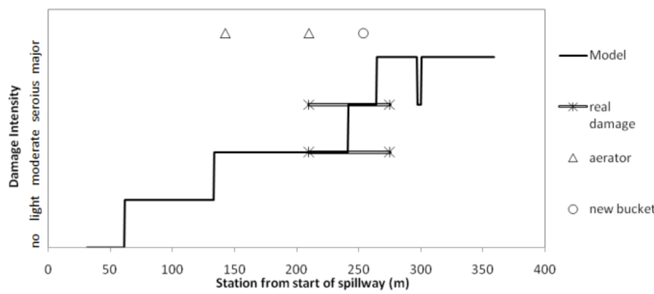

Figure 7. Predicted damage level at stations compared to real damage for Chute 1

Considering levels in Table. 1 and the results in Fig. 6, damage prediction in language concepts form was made and compared with real one. These and redesigning changes for Chute1 would be seen in the Fig. 7.

The comparison between real and predicted damage has been shown in Fig. 7. Also the station of repairing works had been done on spillway by designers in the past, could be seen in the figure. The first aerator placed close to the damage's changing from light to moderate (station 1+34). Replacing the bucket was done near the station 2+41, which the damage changes to serious and before the station 2+64 which damage reaches to the major intensity level. The real observed damage is between the station 2+10 and 2+75 with moderate or serious intensity as mentioned before.

For damage management, the controlling conditions below would be represented:

- Light damage does not definitely have the meaning of damage danger.
- Necessity of adding aerator can be represented by moderate damage level.
- Redesigning and some changes in design details have to be considered in serious damage level
- The geometry plan and whole design could be rejected in the major damage level.

This damage management could be changed due to different velocity and cavitation index limitations in different cases.

3.2. Testing Results for Chute 2 and 3

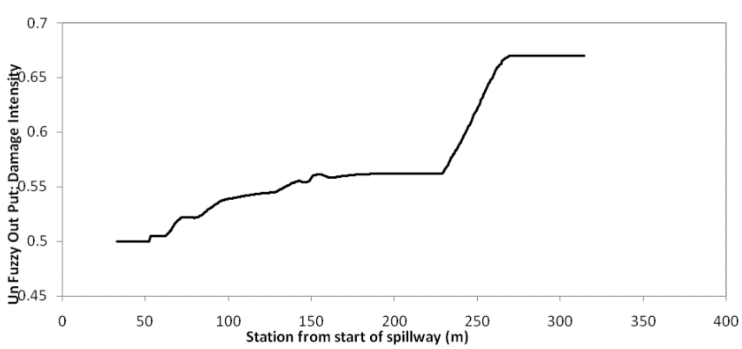

Figure 8. Defuzzified predicted damage at stations for Chute 2 and 3

All steps above have done for Chute 2 and Chute 3 too, with a flow discharge different from Chute 1 as mentioned in the site investigating report (Fig. 8). The repairs were the same as the Chute 1. So a comparison could be done here too. (Fig. 9 and Fig. 10)

Karun 1 Spillway	Actual Damage Station (m)	Actual Damage Intensity	Lee and Hoops Result for Station (m)	Lee and Hoops Result for Intensity	Predicted Damage	
					Damage Intensity	Station
Chute 1	2+10~2+75	moderate or serious	-	light	light	0+62~1+34
					moderate	1+34~2+41
					serious	2+41~2+64
					major	2+64~End
Chute 2	2+35~2+55	serious or major	-	light	light	0+53~1+35
					moderate	1+35~2+46
					serious	2+46~2+70 2+98~3+00
					major	2+70~2+98 3+00~End
Chute 3	2+10~2+80	serious or major	-	light	light	0+53~1+35
					moderate	1+35~2+46
					serious	2+46~2+70 2+98~3+00
					major	2+70~2+98 3+00~End

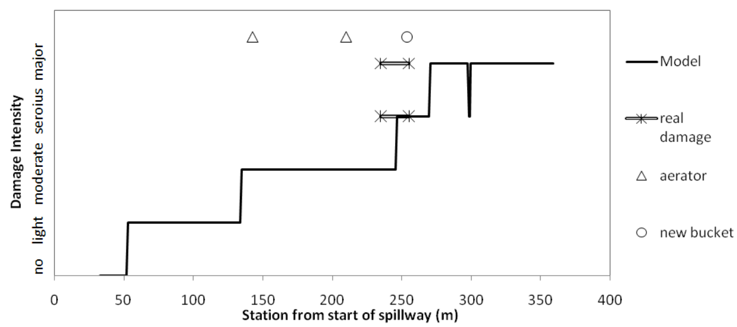

Figure 9. Predicted damage level at stations compared to real damage for Chute 2

Table 2. The predicted damage compare to real damage and past research's result

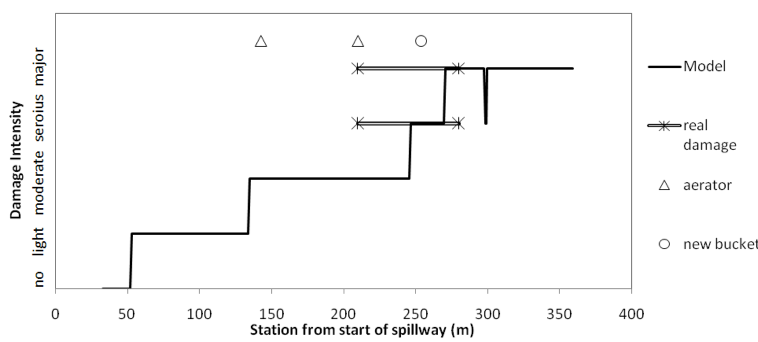

Figure 10. Predicted damage level at stations compared to real damage for Chute 3

The damage's changing from light to moderate is occurred at station 1+35. The damage changes to serious at the station 2+46, and the damage reaches to the major intensity level at station 2+70.

For Chute 2 the real observed damage is between the station 2+35 and 2+55 which is serious or major. For Chute 3 it is between 2+10 and 2+80, with the intensity of serious or major. A comparison between predicted damage and observed damage could be done by Table. 2. The past work prediction also has been given by the Table.

CONCLUSION

The comparisons between real and predicted damage have shown good compatibility as would be seen in the figures. The repairing works done by designers has shown a meaningful relation with the fuzzy results, so we could make the management plan. The fuzzy model with above damage management has shown a weaker prediction for the Chute 2 and Chute 3 even dough the result is accepTable. A few weaknesses in this model and the work done before may be cause of some problems in the materials and construction which mentioned in report.

Considering the ability of the fuzzy model in damage controlling and management, necessity of the following investigations could be understood:

- Establishing the fuzzy criteria and limitations for the influencing factors in cavitation damage.
- Evaluating the new models with considering more factors such as concrete surface strength, the effect of operation time duration on the strength and air entrainment factor.

Investigating the damage occurred in the case, if prototype exists, for identifying the real reason of damage. Sometimes the cavitation is not the only reason; also the designing or constructing mistakes, materials or geotechnical problems affect the damage occurrence or damage intensity.

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