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CONSTRUCTION OF A MATHEMATICAL MODEL FOR FORECASTING THE CONSEQUENCES OF DAM BREAKTHROUGH

Abstract. *The article is devoted to the development of a mathematical model for preventing dam breakthrough and predicting its possible consequences. The paper proposes a mathematical model of the water level in the reservoir, which allows, based on the distance from the crest of the dam to the surface of the water in the reservoir, to estimate the predicted time for the increase in the volume of the water level from the current to the critical level and inform the population about the state of the reservoir.*

Based on the solution of the model problem, the effectiveness of the developed program is shown. The practical basis for the model problem was the events that took place in the village of Kyzylagash, Almaty region of the Republic of Kazakhstan.

Keywords: *flood, dam, proran, waves, water resources, water level monitoring.*

Introduction. In the last century, more than a thousand cases of the destruction of hydraulic structures (HS) have occurred in the world, the reasons for which, among the meteorological phenomena, were also factors of a geological and geophysical nature.

So, the St. Francis dam in California was built 70 km from Los Angeles in the San Francisco canyon in order to accumulate water for its subsequent distribution through the Los Angeles water supply. All living things and buildings were destroyed under the 40 m wave wall. The valley was flooded for 80 km. More than 600 people died during this flood. The second example in Italy in 1963, a mountain range collapsed in the Vajont reservoir, as a result, ~ 25 million tons of water overflowed the dam, creating waves in the Piave river valley with a height of 70 m. 4 villages were destroyed, 4400 people died [1].

The accident at the Sayano-Shushenskaya hydroelectric power station is a man-made disaster that occurred on August 17, 2009. As a result of the accident, 75 people died, the equipment and premises of the station were seriously damaged [2].

Monitoring systems should ensure constant monitoring of phenomena and processes occurring in nature and the technosphere in order to foresee the growing threats to humans and their environment. This information is necessary for timely notification of the population and government bodies to make operational decisions to ensure environmental safety.

In Kazakhstan, the construction and construction of many hydraulic structures was carried out in the 60-80s of the last century. Their inspection today shows that the actual wear is more than 60%, the reliability and safety of strategically important hydraulic structures is sharply reduced. [3].

The tragic events in the spring of 2010 in the Almaty region and 2014 in the Karaganda region with human casualties and destruction, as well as floods in other regions of Kazakhstan served as a serious lesson in preventing similar situations in the future. Also, recent events on May 1, 2020 on the breakthrough of the dam of the Sardobin reservoir (capacity 922 million m^3) in neighboring Uzbekistan led to the flooding of 4 villages in the Turkestan region of Kazakhstan. As a result, 620 houses were damaged, and great economic damage was caused to agriculture in the region.

Materials and methods. *A mathematical model for predicting the consequences of a dam break.* When hydraulic structures break through, a hole is formed through which water is poured from the upper pool to the lower one and a breakthrough wave is formed. Breakthrough wave is the main damaging factor of this type of accidents, characterizedby wave height and speed [4-6].

In [7], it was found that the following hydroelectric complex parameters and the conditions of propagation of a breakthrough wave in the downstream most significantly affect the h_{max} values: reservoir volume before the accident (W_{water}), reservoir depth at the dam before the accident (H_0), roughness of the upstream wall (n_0), the amount of opening of the gap (B_{gap}), water flow in the downstream of the hydroelectric facility before the accident (Q_0), the distance from the damsite to the observation site (L). The dependence of the maximum flooding depth on the main influencing factors was obtained and presented in general form by the expression:

$$h_{max} = 2{,}51\ \frac{H_0^{0{,}98} n_0^{0{,}02} Q_0^{0{,}05}}{W_{water}^{0{,}05} L^{0{,}13}} \quad (1)$$

The limits of applicability of formula (1): are indicated: reservoir volume (W_{water}) – from 50 to 5000 thousand m^3; depth of water upstream of the dam (H_0) – from 2 to 20 m; water flow in the downstream of the hydraulic facility before the accident (Q_0) – from 1 to 100 m^3/s; reservoir length – from 0.8 to 2 km, if there is no backup from the downstream hydraulic structures; distance from the dam site to the considered section (L) from 0.5 to 50 km; roughness (n_0) from 0.02 to 0.2.

In addition, the formula (1) has the following disadvantages: 1) missing parameter – the amount of opening of the gap (B_{gap}); 2) the volume of the reservoir before the accident (W_{water}) is placed in the denominator, which leads to a contradiction to the basics of hydrology – «a larger volume of reservoir filling leads to a decrease in the breakthrough wave».

In [8], due to the limitations of the applicability of the formula (1), it was proposed to use the dependence (2) proposed by V.I. Volkov to determine the maximum depth of flooding:

$$h_{max} = 0{,}34H_0 \left(\frac{L}{H_0}\right)^{-0{,}13} \quad (2)$$

As a disadvantage of the formula (2), it should be noted that it does not use such important parameters of the hydraulic structures as the reservoir volume before the accident (W_{water}), the amount of opening of the gap (B_{gap}). This fact greatly narrows the applicability of this formula.

To correct these shortcomings, the article proposes the following approach. The maximum depth h_{max} is sought in the form

$$h_{max} = \alpha_0 B_{gap}^{\alpha 1} H_0^{\alpha 2} W_{water}^{\alpha 3} L^{-\alpha 4} \quad (3)$$

Then formula (3) can be rewritten in the form:

$$Y = \alpha_0 * \left(\prod_{k=1}^{3} x_k^{\alpha k}\right) * x_4^{-\alpha 4} \quad (4)$$

Formula (4) corresponds to the optimization problem, where the coefficients α_k, are unknown, which determine the influence of the k–th information parameter on the overall result.

We will take the logarithm of the expression (4):

$$ln(Y) = \alpha_0 + \sum_{k=1}^{3} \alpha_k\, ln(x_k) - \alpha_4 ln(x_4) \quad (5)$$

The coefficients α_k can be found from the minimum condition for the functional

$$S = \sum_{j=1}^{m} \left(ln(Y_j) - \alpha_0 - \sum_{k=1}^{3} \alpha_k\, ln(X_{kj}) + \alpha_4 ln(X_{4j}) \right)^2 \quad (5)$$

We introduce the set

$$A = \{0 \le \alpha_i \le 10\} \quad (6)$$

It is easy to show that A is a convex closed set in R^m space. Let's build an iterative process

$$\alpha_i^{n+1} = \Pi_A(\alpha_i^n - \gamma_n S'(\alpha_i^n)) \quad (7)$$

Here П_A – projection operator onto the set A. The coefficients $\gamma_n \ge 0$, the determine the step length at the n-th stage, can be found from the condition

$S(\text{ он } \alpha_i^n - \gamma_n S'(\alpha_i^n)) = \min_{\gamma\in R} S\,(\alpha_i^n - \gamma S'(\alpha_i^{k,n}))$ or in the process of splitting the step.

Discrepancy is sought $r = min_i\,(abs(\alpha_i^{n+1} - \alpha_i^n))$.

Based on the available information about the breakthroughs, 30 versions of parametric data were prepared. Based on this information, the following formula is obtained:

$$h_{\max} = 1{,}34 * H_0^{0{,}55} B_{gap}^{0{,}32} W_0^{0{,}04} L^{-1{,}4} \quad (8)$$

In the formula (8), the volume of the reservoir (W_{water}) is measured in millions of m^3; the water depth in the upstream wall of the dam (H_0) is in m;the amount of opening of the gap (B_{gap}) – in m; the distance from the dam site to the observation site (L) – in km.

Results and discussion. *Model problem.* All further calculations simulate the events that took place in the village of Kyzylagash of Almaty region on March 11 and 12, 2010. The 45-meter- high dam was designed to store 42 million cubic meters of water. On the night of March 10, the water level reached 30 million cubic meters. The next day, in the afternoon or in the evening, I can not say the exact time, the water level exceeded 40 million cubic meters. In other words, 15-16 million cubic meters of water was added to the Kyzylagash reservoir in 15-16 hours. The dam broke on March 11 at 10.30 p.m. Two hours later, the water gushed towards the village of Kyzylagash. The wave width of the mudflow was 1.6 kilometers, and the height was 3 to 4 meters. According to official figures, most of the village was severely damaged. 70% of the village of Kyzylagash was destroyed. The tragedy in Kyzylagash claimed the lives of 44 people.

Based on the mathematical forecasting model, the situation for March 11-12, 2010 in the village of Kyzylagash was simulated. Table 1 presents the chronicle of events. The first two columns provide information about the date and time. Information in columns 3 through 5 is obtained in automated mode. Based on the above proposed mathematical model, calculations were performed on the level of safety, reservoir occupancy and the expected overflow time over the dam crest (columns 6-8).

In the 6th column, the following security level encoding is adopted: 1– low; 2 – safe; 3 – alarming; 4 – catastrophic.

Table 1 – The simulation results of a dam break

Date	**Time**	**Water-level (m)**	**Tempera-ture**	**Precipi-tation**	**Security-level**	**Water volume (cbm)**	**Time to overflow (hour)**
1	2	3	4	5	6	7	8
11/03/2010	10.00	15	12		2	30 000,0	
	10.30	14.75	12		2	30 250,0	
	11.00	14.5	13		2	30 500,0	
	11.30	14.25	13		3	30 750,0	14.25
	12.00	14	13		3	31 000,0	14
	12.30	13.75	14		3	31 250,0	13.75
	13.00	13.5	14		3	31 500,0	13.50
	13.30	13.25	14		3	31 750,0	14.25

1	2	3	4	5	6	7	8
	14.00	13	15		3	32 000,0	13
	14.30	12.75	15		3	32 250,0	12.75
	15.00	12.5	15		3	32 500,0	12.50
	15.30	12.25	14	rain	3	32 750,0	11.75
	16.00	12	14	rain	3	33 000,0	11
	16.30	11.25	14	rain	3	33 750,0	10.25
	17.00	10.5	13	rain	3	34 500,0	9.30
	17.30	9.75	13	rain	3	35 250,0	8.75
	18.00	9	13	rain	3	36 000,0	8
	18.30	8.25	13	rain	3	36 750,0	7.25
	19.00	7.5	12	rain	3	37 500,0	6.50
	19.30	6.75	12	rain	3	38 250,0	5.75
	20.00	6	11	rain	3	39 000,0	5
	20.30	5.25	11	rain	3	39 750,0	4.25
	21.00	4.5	10	rain	4	40 500,0	3.50
	21.30	3,75	10	rain	4	41 250,0	3
	22.00	3	9		4	42 000,0	2.50
	22.30	2,5	9		4	42 500,0	2
	23.00	2	9		4	43 000,0	1.50
	23.30	1,5	8		4	43 500,0	1
12/03/2010	00.00	1	8		4	44 000,0	0.50
	00.30	0,5	7		4	44 500,0	0
	01.00	0	7		4	45 000,0	0
	01.30	0	6		4		

Figure 1 shows the hourly reservoir occupancy rate: as you can see, the emergency authorities would have been warned already at 21.00 on March 11. According to the forecast time was still 3.5 hours before the tragedy. Victims could have been avoided.

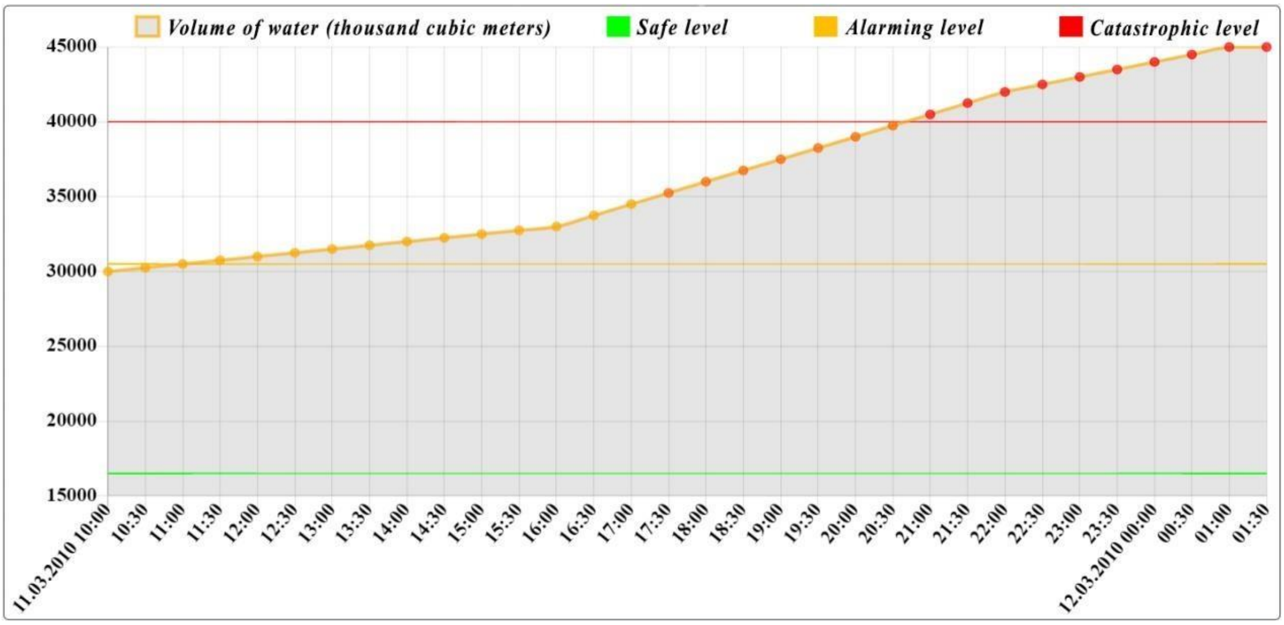

Figure 1 – Graph of fillability of a reservoir

Based on the formula (8), the situation was simulated in Kyzylagash village. Figure 2 shows a kilometer-long graph of the passage of a breakthrough wave.

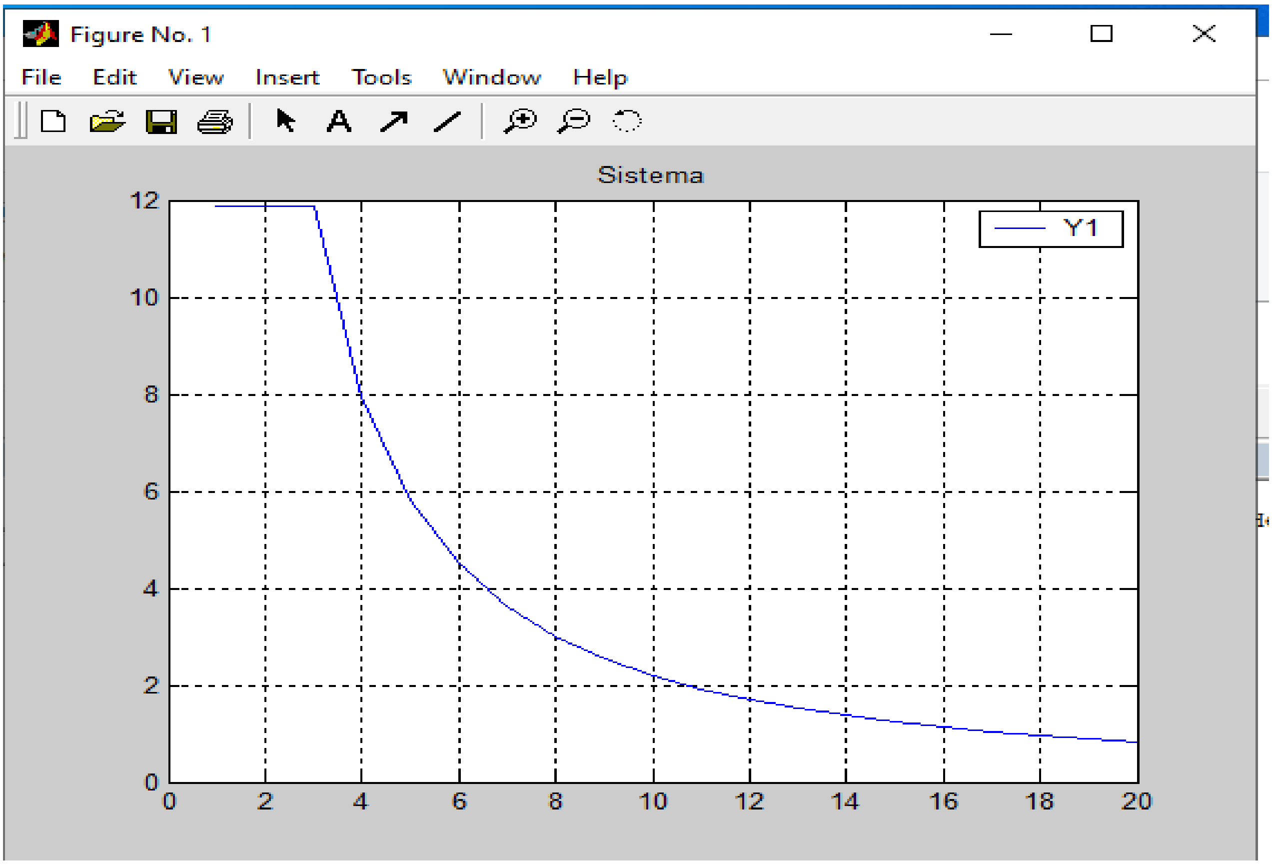

Figure 2 – Graph of maximum breakthrough wave in Kyzylagash village

As can be seen from the Figure, the wave of breakthrough came to Kyzylagash village reached a height of 4.5 meters. In Eginsu village, 16 km from the dam, the wave reached a height of about one meter.

Conclusion. In this article, a mathematical model has been developed for monitoring the state of the reservoir and predicting the consequences of a dam break. On a model problem (events that took place in the village of Kyzylagash, Almaty region of the Republic of Kazakhstan), the effectiveness of the developed mathematical model for predicting the consequences of a dam break is shown. The practical significance of the work lies in the development of a system that provides current and forecast information, contributing to the correctness of decision-making at the territorial or republican level.

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БӨГЕТТІҢ БҰЗЫЛУ САЛДАРЫН БОЛЖАУДЫҢ МАТЕМАТИКАЛЫҚ МОДЕЛІН ҚҰРУ

Аңдатпа. *Мақала бөгеттің бұзылуына жол бермеу және оның ықтимал салдарын болжаудың математикалық моделін жасауға арналған. Бұл жұмыста су қоймасындағы су деңгейінің математикалық моделі ұсынылады. Онда бөгеттің ең басынан бастап су қоймасындағы судың бетіне дейінгі қашықтыққа негізделген су деңгейінің көтерілуінің болжамды уақытын бағалауға мүмкіндік береді. Судың ең төменгі деңгейінен қауіпті деңгейге дейін көтерілуін қадағалайды және апатты жағдайдың орын алу қаупі жайында халықты дер кезінде хабардар етуге мүмкіндік береді.*

Модельдік есепті шешу негізінде әзірленген бағдарламаның тиімділігі көрсетіледі. Модельдік есептің практикалық негізі ретінде Қазақстан Республикасы Алматы облысының Қызылағаш ауылында болған апатты оқиға алынды.

Түйін сөздер: *су тасқыны, бөгет, саңылау, толқын, су қорлары, су деңгейін бақылау.*

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ПОСТРОЕНИЕ МАТЕМАТИЧЕСКОЙ МОДЕЛИ ПРОГНОЗИРОВАНИЯ ПОСЛЕДСТВИЙ ПРОРЫВА ПЛОТИНЫ

Аннотация. *Статья посвящена разработке математической модели предупреждения прорыва плотин и прогнозированию возможных его последствий. В работе предложена математическая модель уровня воды в водохранилище, позволяющая на основе расстояния от гребня плотины до поверхности воды в водоеме оценивать прогнозное время повышения объема уровня воды от текущего до критического уровня и информировать население о состоянии водоема. На основе решения модельной задачи показана эффективность разработанной программы. Практической основой для модельной задача послужили события, прошедшие в с.Кызылагаш Алматинской области Республики Казахстан.*

Ключевые слова: *наводнение, плотина, проран, волны, водные ресурсы, мониторинг уровня воды*.