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MATHEMATICAL MODELING FORECASTING OF CONSEQUENCES OF DAMAGE BREAKTHROUGH

Abstract. The article is devoted to the development of a mathematical model for preventing a breakthrough of a dam and predict its possible consequences. In this work, the task of developing a single integrated approach to ensuring the safe operation of hydraulic structures, based on the notification of interested bodies in real time, was solved. A mathematical model of the state of the reservoir is developed, on the basis of which a hardware-software complex for operational notification of interested organizations (akimats) and local emergency departments is implemented. A mathematical model of predicting the consequences of a dam break is proposed. An algorithm for calculating the maximum level of the breakout wave has been formulated, taking into account many parameters of the hydraulic structures. The convergence of the developed algorithm in the form of a theorem has been proved. This method has a large practical focus, compared with existing formulas.

The Java language implements a hardware-software complex (PAC) for predicting the effects of a dam break, consisting of the following modules: 1) a module for receiving and transmitting current information about the water level, humidity and temperature on the crest of the dam; 2) a module for processing constant and operational information about the threat of dam breakthrough (server); 3) a module for predicting the effects of a dam break. Based on the solution of the model problem, the effectiveness of the developed hardware-software complex is shown. The practical basis for the model task was the events that took place in Kyzylagash village of Almaty region of the Republic of Kazakhstan.

Key words: mathematical modeling, flooding, dam, breach, breakthrough waves, water resources, water level, hydraulic structure, hardware-software complex.

Introduction. According to the report of the UN Commission, the damage from natural disasters, in particular floods, has only increased over the years, and economic losses from the consequences of floods lead to a decrease in gross domestic product. Over the past century, more than a thousand cases of destruction of hydraulic structures have occurred in the world, the causes of which, among the meteorological phenomena, were factors of a geological and geophysical nature.

Thus, 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 system. Under a wave wall of 40 m, all living things and buildings were destroyed. The valley was flooded for 80 km. More than 600 people died during this flood. The second example in Italy in 1963, a mountain massif collapsed in the Vayont reservoir, resulting in ~ 25 million tons of water overflowed through the dam, creating waves in the Piave river valley with a height of 70 m. 4 villages were destroyed, 4,400 people were killed [1-3].

The accident at the Sayano-Shushenskaya hydroelectric station was a man-made disaster that occurred on August 17, 2009. As a result of the accident, 75 people died, the equipment and the equipment and premises of the station were seriously damaged [4-6].

In Kazakhstan, the construction of many hydraulic structures was carried out in the 60-80s of the last century. Their survey today shows that the actual depreciation is more than 60%, the reliability and safety of strategically important hydraulic structures are sharply reduced [7-9].

The long service life and reduction in the last 20 years of funding for operating expenses, current and capital repairs, as well as the influence of climatic and seismic factors gradually lead to moral and physical deterioration of the entire complex of hydraulic structures. There are also objects located close to hazardous industries [10-12].

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 to prevent similar situations in the future. It is necessary to develop recommendations on equipping the hydraulic structures with modern monitoring systems, equipment and means to improve operational safety. Also, the recent events of May 1, 2020 on the breakthrough of the dam of the Sardobin reservoir (capacity of 922 million m3) in neighboring Uzbekistan led to the flooding of 4 villages in the Turkestan region of Kazakhstan. As a result, 620 houses were damaged and the region's agriculture was severely economically damaged [13, 14].

In this regard, research on the development of a mathematical model of dam breakout and the prediction of its consequences is relevant.

Mathematical model for predicting the consequences of a dam breakout. Catastrophic flooding, which is the result of a hydrodynamic accident, consists in the rapid flooding of the area by a breakout wave. Hydraulic structures can be breached due to natural forces (earthquake, hurricane, landslide, etc.), structural defects, violations of operating rules, impact of floods, destruction of the dam base, etc. During the breakthrough of the hydraulic structures, a gap (closure channel, passage) is formed, through which the water flows from the upper downstream to the lower one and the formation of a breakthrough wave. Breakthrough wave is the main striking factor of this type of accident, characterized by wave height and speed [15, 16].

In [17], 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:

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

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 [18], 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:

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

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 $\mathrm{h}_{\max}$ is sought in the form

$$\mathrm{h}_{\max} = \alpha_0 \mathrm{B}_{gap}^{\alpha_1} \mathrm{H}_0^{\alpha_2} \mathrm{W}_{water}^{\alpha_3} \mathrm{L}^{-\alpha_4} \tag{3}$$

In the formula (3) all the coefficients $\boldsymbol{\alpha_i > 0, i = \overline{0,4}}$.

Let n = 4 be the number of information parameters of hydraulic structures that affect the size of the breakthrough wave; $x = (x_0, \dots, x_n)$ – the vector whose components characterize the hydraulic structures.

For the convenience of further calculations, we will accept

$$y = \mathrm{h}_{\max};\ x_0 = 1,\ x_1 = B_{gap};\ x_2 = H_0;\ x_3 = W_{water};\ x_4 = L.$$

We introduce the following designations:

m– the number of versions (situations); X_{ij} – the value of the i-th parameter in the j-th version, where $i = \overline{0,n}\,, j = \overline{1,m}$.

Y_j – maximum breakthrough wave depth in the j –th situation, where $j = \overline{1,m}$.

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

$$Y = \alpha_0 * \left(\prod_{k=1}^{3} x_k^{\alpha_k}\right) * x_4^{-\alpha_4} \tag{4}$$

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):

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

The coefficients $\alpha_k$can be found from the minimum condition for the functional

$$S\ = \sum_{j=1}^{m}\left(ln(Y_j) - \alpha_0 - \sum_{k=1}^{3} \alpha_k\, ln(X_{kj}) + \alpha_4 l\, n(X_{4j})\right)^2 \tag{6}$$

We introduce the set

$$A = \{0 \le \alpha_i \le 10\} \tag{7}$$

It is easy to show that A is a convex closed set in R^m space.

The algorithm for finding the coefficients of functional (6).

Step 1. The minimum of functional (6) is found by the least square method, by reducing to a system of linear algebraic equations of the form

$$C\beta = d,$$

where C – (n+1)*(n+1) – the matrix, d – (n + 1) – the vector made up of values

$$ln(Y_j), ln(X_{kj}), k = \overline{0,n}\,, j = \overline{1,m}.$$

If all elements of the vector $\beta_i > 0,= \overline{0,n}$, then we take $\alpha_i = \beta_i$, $i = \overline{0,n}$ and go to step 5.

Step 2. Denote by α_i^n the n-th approximation for calculating the coefficient α_i.

As a zero approximation, we select

$$\alpha_i^0 = \begin{cases} \beta_i\,, if \beta_i > 0 \\ \varepsilon, if \beta_i \le 0 \end{cases}.$$

Here $\varepsilon > 0$ – is a sufficiently small number.

Step 3. The minimum of the functional (6) is defined on the set (7).

Let's build an iterative process

$$\alpha_i^{n+1} = \Pi_A\left(\alpha_i^n - \gamma_n S'(\alpha_i^n)\right) \tag{8}$$

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

$$S(\quad \alpha_i^n - \gamma_n S'(\alpha_i^n)) = \min_{\gamma \in R} S\left(\alpha_i^n - \gamma S'\left(\alpha_i^{k,n}\right)\right)$$

or in the process of splitting the step.

Step 4. Discrepancy is sought $r = min_i\left(abs\left(\alpha_i^{n+1} - \alpha_i^n\right)\right)$.

If $r < \varepsilon$, then go to step 5. Otherwise, increase the iteration number and go to step 2.

Step 5. Algorithm completion.

The convergence of the proposed algorithm is provided by the following theorem.

Theorem 1. Let the set A be convex and closed. Then the sequence $\{\alpha_i^n\}$, defined by the formula (8) converges to the solution of the problem of minimizing the functional (6) on the set (7).

Proof. Since the set A is convex and closed, the functional (6) is convex and differentiable, then any limit point of the sequence $\{\alpha_i^n\}$ is the minimum point [19].

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

$$\mathrm{h}_{\max} = 1{,}34 * H_0^{0{,}55} B_{gap}^{0{,}32} W_0^{0{,}04} L^{-1{,}4} \tag{9}$$

In the formula (9), 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.

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.

Results. Based on the mathematical forecasting model, the situation for March 11-12, 2010 in the village of Kyzylagash was simulated. Table 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.

The simulation results of a dam break

Date	Time	Waterlevel (m)	Temperature	Precipitation	Securitylevel	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

Table continuation

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 an hourly chart of the reservoir occupancy. As can be seen from table 1 and the graph in figure 1, the akimat (local administrations) and emergency authorities would have been alerted at 21.00 on March 11. According to the forecast time was still 3.5 hours before the tragedy. Victims could have been avoided.

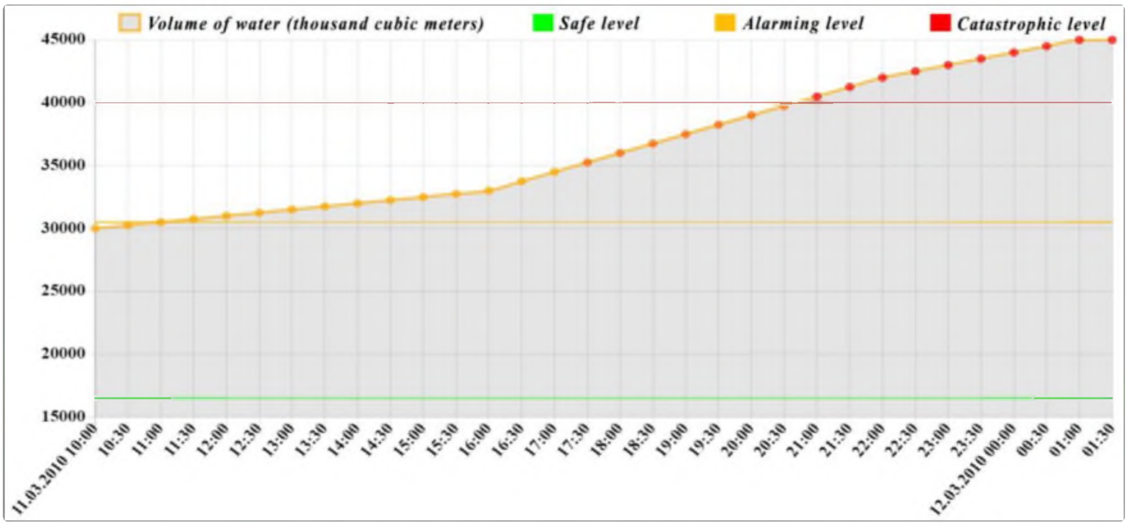

Figure 1 – Graph of fillability of a reservoir

Based on the formula (9), the situation was simulated in Kyzylagash village. Figure 2 shows a kilometer-long graph of the passage of a breakthrough wave.

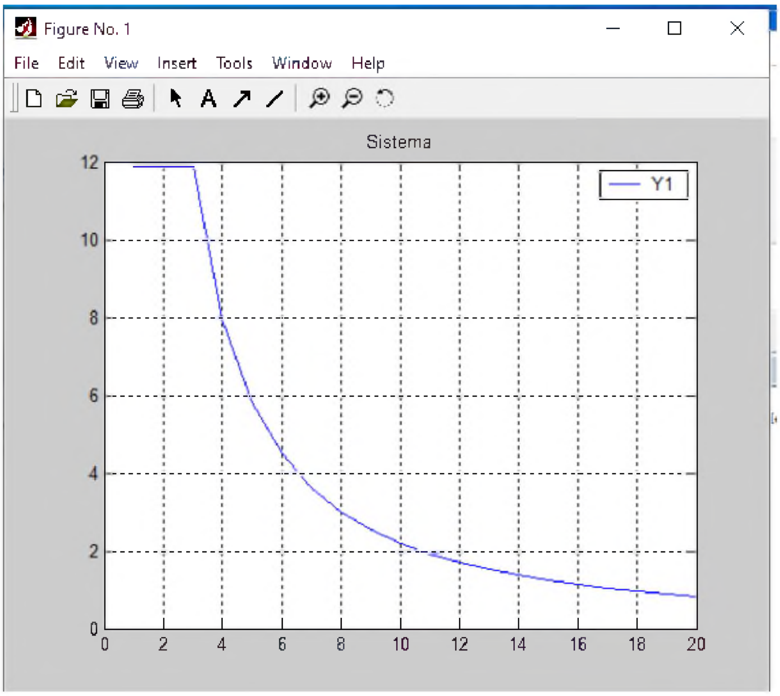

Figure 2 – Graph of maximum breakthrough wave in Kyzylagash village

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. This article has developed a mathematical model of monitoring the state of the reservoir and predicting the consequences of a dam break.

The model problem (events that took place in Kyzylagash village of the Almaty region of the Republic of Kazakhstan) shows the effectiveness of the developed mathematical model of predicting the consequences of a dam break.

The tragic events in the spring of 2010 in the Almaty region and in 2014 in the Karaganda region with human casualties and destruction, as well as floods in other regions of Kazakhstan, served as a serious lesson to prevent similar situations in the future. It is necessary to develop recommendations on equipping hydraulic structures with modern control and measuring devices, equipment and means to improve the safety of operation.

The practical significance of the work is to develop a system that provides current and forecast information that contributes to the correctness of decision-making at the territorial or republican level.

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БӨГЕТ БҰЗЫЛЫСЫНЫҢ САЛДАРЫН БОЛЖАУДЫҢ МАТЕМАТИКАЛЫҚ МОДЕЛІ

Аннотация. Мақала бөгеттің бұзылуына жол бермеу және оның ықтимал салдарын болжаудың математикалық моделін жасауға арналған. Осылайша қолданыстағы әртүрлі әдістерді талдау негізінде гидродинамикалық апатты төтенше жағдай ретінде болжау әдістерін жасау үшін зерттеудің мақсаты мен негізгі міндеттері тұжырымдалды. Бұл жұмыста шешімнің қолданыстағы әдістеріне талдау және зерттеу мақсаттарына тұжырым жасалды. Мәселе талданып және оны шешу барысында туындауы ықтимал негізгі проблемалар анықталған. Мәселенің жалпы сипаттамасы және зерттеу мақсаттарының тұжырымдамасы келтірілген. Сипатталған әдістердің артықшылықтары мен кемшіліктері көрсетілген. Математикалық модельдеудің заманауи технологияларын және есептеу нәтижелерін географиялық ақпараттық жүйеде көрсетумен қатар бөгет бұзылысының математикалық моделін зерттеумен есептеу тәжірибесін қолдана отырып, кешенді талдаудың, табиғи және техногендік сипаттағы төтенше жағдай салдарын болжаудың белгілі әдістеріне салыстырмалы талдау жасалды.

Климаттық мәліметтерді таратуға арналған автономды микрокомпьютерлік жүйе жасалды, нақты уақыт режимінде серпінді толқын факторларын болжау мәселесінің жалпы сипаттамасы мен міндеті келтірілген. Жерсеріктік деректерді беру жүйесінің дербес электрмен жабдықтау жүйесіне келесі энергияны пайдалану үшін энергия өндіруге және жинақтауға кіретін жабдықтар кешені кіреді. Су деңгейі өлшеу жабдықтары әртүрлі болуы мүмкін. Жүйе қызметін қамтамасыз ету үшін өлшеу құралдары деректерді берудің ішкі жүйесімен және электрмен жабдықтау жүйесімен байланыстырылады. Көрсетілген жүйелерді біріктіру орналасуы күрделі өзен көліндегі су деңгейін бақылауға мүмкіндік береді. Су деңгейін өлшейтін жабдық түрлі кезеңдік сенсорлардан мәліметтерді алуы керек. Жиналған мәліметтер ситуациялық орталықтарға жіберіліп, арнайы қызметтер ықтимал су тасқыны мен су тасқынын болжау, су шығынын есептеу және басқа мақсаттар үшін пайдаланады.

Бөгеттердің сипаттамалары, микропроцессорлық технологияны қолдануға негізделген қазіргі заманғы басқару жүйелерінің мүмкіндіктері талданады.

Су қоймасының жағдайын бақылаудың математикалық моделі жасалды, оның негізінде мүдделі ұйымдарды (әкімдіктер) және жергілікті төтенше жағдай бөлімдерін жедел хабарлау үшін аппараттық-бағдарламалық кешен енгізілді. Талдау келесідей қорытынды жасауға мүмкіндік береді: мүмкін гидродинамикалық апат салдарын болжаудың ұтымды әдісі – аналитикалық модельдерге негізделген қолданыстағы модельдеу бағдарламалық құралын пайдалану.

Математикалық модельдеу мен есептеу экспериментінің заманауи технологияларын пайдалана отырып, табиғи техногендік сипаттағы төтенше жағдай салдарын кешенді талдау, модельдеу және болжаудың белгілі әдістеріне салыстырмалы талдау жүргізіліп, нәтижелерді геоақпараттық жүйеде көрсете отырып және бөгет бұзылысының математикалық моделіне зерттеу жүргізілді. Тасқынның салдарын болжаудың түрлі математикалық модельдері, әдістері мен алгоритмдері сипатталған.

Бөгет бұзылысының әсерін болжаудың математикалық моделі ұсынылған. Гидравликалық құрылымдардың көптеген параметрлерін ескере отырып, серпінді толқынның максималды деңгейін есептеу алгоритмі тұжырымдалған. Әзірленген алгоритмнің теорема түріндегі жинақтылығы дәлелденді. Бұл әдіс қолданыстағы формулалармен салыстырғанда үлкен практикалық бағытқа ие.

Java тілі бөгет бұзылысының әсерін болжауға арналған бағдарламалық-аппараттық кешенді (БАК) жүзеге асырды. Ол келесі модульдерден тұрады:

1) бөгет бағанасындағы су деңгейі, ылғалдылығы мен температурасы туралы ағымдағы ақпаратты алуға және жіберуге арналған модуль;

2) бөгеттің бұзылу қаупі туралы тұрақты және жедел ақпаратты өңдеуге арналған модуль (сервер);

3) бөгет бұзылысының әсерін болжауға арналған модуль.

Модельдік есепті шешудің негізінде әзірленген аппараттық-бағдарламалық кешеннің тиімділігі көрсетілген. Модельдік есептің практикалық негізі ретінде Қазақстан Республикасы Алматы облысының Қызылағаш ауылында болған апатты оқиға алынды.

Түйін сөздер: математикалық модельдеу, су басу, бөгет, бұзу, серпінді толқындар, су ресурстары, су деңгейі, гидротехникалық құрылым, аппараттық-бағдарламалық кешен.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ПРОГНОЗИРОВАНИЯ ПОСЛЕДСТВИЙ ПРОРЫВА ДАМБЫ

Аннотация. Статья посвящена разработке математической модели предупреждения прорыва плотины и прогнозированию возможных его последствий. Таким образом, на основании проведенного анализа различных существующих методов были сформулированы цель и основные задачи исследований, направленных на разработку методики прогнозирования гидродинамической аварии как чрезвычайной ситуации. В данном исследований проведен анализ существующих методов решений и формулировка задач исследования. Проанализирована задача и выявлены основные проблемы, которые могут возникнуть в ходе ее решения. Приведена общая характеристика проблемы и постановка задач исследования. Выделены достоинства и недостатки описанных методов. Выполнен сравнительный анализ известных методов для комплексного анализа, прогнозирования последствий чрезвычайных ситуаций природного и техногенного характера с применением современных технологий математического моделирования и вычислительного эксперимента с отображением результатов в географической информационной системе и исследование математической модели прорыва дамбы.

Разработана автономная микрокомпьютерная система передачи климатических данных, приведена общая характеристика и постановка задачи прогнозирования факторов прорывных волн в реальном масштабе времени. Автономная подсистема энергоснабжения для спутниковых систем передачи данных включает в себя комплекс оборудования, функции которого заключаются в выработке и накоплении энергии для последующего его использования в целях обеспечения электропитания оборудования передачи данных. Оборудование измерений уровня воды может быть различным. Для обеспечения функционирования системы измерительное оборудование будет сопрягаться с подсистемой передачи данных и подсистемой энергообеспечения. Сопряжение указанных систем позволит осуществлять мониторинг уровня воды в моренных озерах, расположение которых является крайне труднодоступным. Технические средства, измеряющие уровень воды, должны быть способны получать данные с датчиков с различной периодичностью. Накапливаемые данные будут передаваться в ситуационные центры и использоваться специальными службами для прогнозирования возможных паводков и наводнений, подсчета расхода воды и в прочих целях.

Проанализированы характеристики плотин, возможности современных систем контроля, основанных на применение микропроцессорной техники.

Разработана математическая модель мониторинга состояния водохранилища, на основе которой реализован аппаратно-программный комплекс оперативного оповещения заинтересованных организаций (акиматов) и местных подразделений ЧС. Проведённый анализ позволяет сделать следующие выводы: рациональным способом прогнозирования последствий возможных гидродинамических аварий является применение существующих имитационных программных инструментов на основе аналитических моделей.

Выполнен сравнительный анализ известных методов для комплексного анализа, моделирования и прогнозирования последствий ЧС природного техногенного характера с применением современных технологий математического моделирования и вычислительного эксперимента с отображением результатов в географической информационной системе и исследование математической модели прорыва дамбы. Описаны различные математические модели, методы и алгоритмы для прогнозирования последствий наводнений.

Предложена математическая модель прогнозирования последствий прорыва плотины. Сформулирован алгоритм вычисления максимального уровня волны прорыва, учитывающий множество параметров гидротехнических сооружений. Доказана сходимость разработанного алгоритма в виде теоремы. Данный метод имеет большую практическую направленность по сравнению с имеющимися формулами.

На языке Java реализован аппаратно-программный комплекс мониторинга и прогнозирования последствий прорыва плотины, состоящий из следующих модулей: 1) модуль получения и передачи текущей информации об уровне воды, влажности и температуры на гребне плотины; 2) модуль обработки постоянной и оперативной информации об угрозе прорыва плотины (сервер); 3) модуль прогнозирования последствий прорыва плотины.

На основе решения модельной задачи показана эффективность разработанной программы. Практической основой для модельной задача послужили события, произошедшие в с.Кызылагаш Алматинской области Республики Казахстан.

Ключевые слова: математическое моделирование, наводнение, плотина, проран, волны прорыва, водные ресурсы, уровень воды, гидротехническое сооружение, программно-аппаратный комплекс.

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