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Aging of Hydraulic Engineering Structures and some Measures towards Prolonging their Term of Service and Averting Ecological Crises

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ABSTRACT. The obtained expressions enable to assess the level of vulnerability or the onset time of the condition of breakdown of facilities of various purposes, for different prognostic variables, at any time interval and value of impact . Assessment of vulnerability according to diverse prognostic variables will allow to select the parameter that is most "to blame" for the facility becoming vulnerable. This parameter should form the basis for developing measures towards relieving the facility from the vulnerable state. *© 2007 Bull. Georg. Natl. Acad. Sci.*

***Key words**: aging, dams, structures, ecological.*

The problem of how long a built and exploited structure and designs will serve has attracted attention in all ages and will be the subject of close scrutiny of specialists of various countries for a long time to come. The answer to this question is not simple but is especially important for facilities standing it out for a high hazard at breakdown, i.e. dams. This disaster may, along with enormous material and ecological damage, entail human casualties [1-4].

The aging of hydrotechnical facilities - as well as other technical systems - should be understood as a degradation process taking place with the increase of age; it is accompanied by an increase of vulnerability to all impacts and lowering of functional capacity. Assessing the resistance to wear by prescribed or acceptable characteristics, the aging of a facility, causing its degradation process, depends on the property of the material used in its construction, completing parts, on the type and individual properties of the facility, technology of its building - both the primary materials and the facility as a whole, the regime of exploitation, regular and extreme loads and environmental conditions.

The inability to withstand destruction has the same nature as dissipation of energy. That is to say, aging is equivalent to the increase of entropy, which serves, as is known, as the measure of the lack of regulation of any system. In closed systems, or in irreversible interactions, entropy always increases. Understanding the physical sense of entropy is rendered difficult by the fact that its value cannot be measured by any device. It is only calculated. In a broad sense entropy is the measure of the disorder of a facility by any characteristic and is calculated by the expression

$$H(E) = -\sum_{i}^{n} P(E_i) \log P(E_i), \qquad (1)$$

where $P(E_i)$ is the probability of state.

The degree of indeterminateness of a system depends on the number of possible states n and the a priori probabilities $P(E_i)$. For example, if $P(E_i)$ =0.95 and $P(E_2) = P(E_3) = 0.02$, then it may be asserted a priori with a high degree of validity that it is in the state n and the indeterminateness of such a system is small. If $P(E_2) = 1$, and the probability of all other states equals zero, then the system has no indeterminateness and

$P(E)=0$. When all a priori probabilities of a system are equal: $P(E_1)=P(E_2)=\cdots P(E_n)=1/n$ entropy of the system

$$H(E)=-\sum_{i}^{n}P(E_1)\log(P_i)=\log n,$$

has maximum value and it corresponds to the greatest indeterminateness.

In nature, all inanimate objects, as well as living organisms, and their parts suffer aging. Man - the king and part of nature, as asserted by biologists - departs from life without reaching an insignificant part of theoretical longevity. From the moment of being born, man is destined - slowly but inevitably - to approach non-existence [5]. Aging depends on multiple interconnected, mutually determined factors. In a word, aging is the result of a symbiosis of factors. At the aging of facilities, there takes place a deterioration of their physico-mechanical and other parameters set in designing and construction. Deterioration is a process of degradation of their inherent indices.

A dam, analyzed here in outline as an example, consists - as any supercomplex structure - of multiple parts and units created of various materials with diverse, interdependent properties. Therefore, in studying this problem it is advisable to apply the interdisciplinary approach, widely using modern achievements of reliability theory and longevity of facilities, theory of random processes, thermodynamics, etc. That is to say, it is necessary to resort to modern potentialities of systems analysis.

In studying the aging of facilities one involuntarily recalls the well-known dictum of the great Goethe "The art of aging is not great, great is the art of overcoming old age", i.e. it is important to increase the period of the "active life" of any facility and inanimate world. Along with this, some specific systems are characterized by a mechanism special to those facilities and factors determining them. The mechanism itself is determined by a continuous degradation process, an irreversible drift of the diagnostic variable of the system, characterizing its fitness for functioning. Although there are several dozens of theories on the aging of animate beings, in particular humans (with a fairly long history of study), so far there is no commonly accepted one.

Various models of aging are proposed in reliability theory [4,6]. In the simplest case, when the probability indices do not change, the intensity of failures is constant, corresponding to the case of exponential distribution. More often than not at aging failures occur with an increasing function of intensity (IFI). The aging models, proposed by Barlow and Proshan, are set forth in (10,11).

Thus, e.g. the estimation of the probability of failure-free work through quintiles has the form:

$$P(t)\begin{cases}\geq e^{-a\xi p} & at \quad t\leq \xi\ p\\ \leq e^{-a\xi p} & at \quad t\geq \xi\ p\end{cases} \tag{2}$$

where $\alpha=\ln(1-p)/\xi\ p$; $\alpha\xi$ is the P quintile of the IFI distribution, i.e. is the lower limit of the probability of failure-free work , $P(t)$ is determined by the expression

$$P(t)\begin{cases}e^{-t/T} & at \quad t\leq T\\ 0 & at \quad t>T\end{cases} \tag{3}$$

where T is the value of time $T=\int_0^\infty P(t)dt$.

In individual cases an analysis of the kinetic degradation of facilities is feasible or of the universal thermodynamic model of aging. The model takes into account the dependence of the mean velocity V change of the parameter under study - the criterion of usefulness from the temperature of their exploitation on the basis of the well-known Arrhenius equation:

$$V=A\exp\left(-\frac{E_\alpha}{KT}\right) \tag{4}$$

where A is the scale coefficient; E_α the nominal energy of activation of the process of aging of facilities; K is the constant coefficient of Bolzman. Application of the equation of Arrhenius to the case under consideration is not feasible.

Use of the cited dependences in predicting the longevity of such complex facilities as dams encounters unforeseen difficulties. Under such possibilities of study of the given problem, use of experimental data on the time of breakdown of facilities or analogous structures, considered at their long-term exploitation, seems to be the best technique of assessing longevity. Application of elegant, well-studied modern methods of mathematical statistics (the theory of cognizing the world through experience) that proved good in solving analogous tasks in other areas and the theory of random numbers appears to be fruitful.

To assess the possible forms of damage of materials it is necessary to determine the area of the existence of the process of aging, primarily the conditions of its emergence. For the process of aging to begin a definite level of resistance to loads, temperature changes and other indices determining the occurrence of the degradation process should be overcome.

The present status of science hardly warrants absolutizing the results of even most flawless analytical calculations, for in a number of cases they are made on the basis of tentative values of initial parameters. The extreme importance of obtaining the initial data in scientific studies is stressed specially by the recent Nobel Prize winner Robert Aumann (USA). He considers this task to be a major criterion of assessment for any scientific study, for the other results to a considerable extent depend on the quality of these data. In connection with the foregoing, close attention should be given to obtaining reliable initial data of studies.

To work out measures towards prolonging the term of service of a facility, along with the identification of the mechanism of aging and determination of the risk-factors, it is necessary to know the actual causes of the growing frequency of troubles and damage with age. On the basis of an analysis of troubles and the causes of their origin (rise), resisting the adaptation of the facility to new conditions, one can plan measures: both general for all structures and specific ones for individual facilities.

Precise analytical description of damage due to aging, and related prediction of the lowering of the reliability of individual parts, elements and the facility as a whole is a very difficult, if not unsolvable, problem. A purely empirical method is unacceptable for the facilities under discussion because of the flaws inherent in this method. Neither can the approach set forth in V.V. Bolotin's [1] basic work be used due to the uniqueness of the facility under analysis in each case and interrelated multifactorialness. Therefore, it is important to solve the main problem: select the strategy of exploitation or solve the question of discontinuing the further work of the facility.

For ecological safety, in the context of the abovesaid, it is important to "spoil" the mechanism of aging, thereby increasing the duration of the active life of facilities. The aging of dams is discussed in more detail in [6], where methods of predicting the reliability and longevity of aging dams are presented, based on modified formulae from the mathematical demography of Gompers and the Tiel formula [6].

The solution of analogous problems in physics and engineering (Brownian motion, various deformations and degradation phenomena) in predicting diverse extreme processes and floods [6] has given me ground to use the methods of Markov processes. For these processes, at each moment of time t of the probability of occurrence in the future, considered at this point of time, depend only on t and $x(t)$ (so-called "processes without memory"). An analysis of the potentialities of various techniques of reliability theory shows that methods of Markov processes appear to be most appropriate and effective for an approximative solution of the task set, as well as for other similar tasks.

Vulnerability is defined as the property of a facility to lose its capacity to perform the functions imposed on it as a result of degradation processes that accompany aging. As is known, the process of losing or deterioration of properties (degradation processes) can be described most fully with equations of diffusion processes - stochastic differential equations of Ito type [7, 8], having the form

$$dy(t) = m(t)\,dt + \sigma(t)\,dx(t), \tag{5}$$

where $y(t)$ is the prognostic variable, $m(t)$, $\sigma(t)$ respectively, the mean rate of change of the prognostic variable and standard deviation; $x(t)$ is the random component of a Gauss process.

As in solving analogous tasks, the principal stage of the process of the loss of properties, causing vulnerability, is to determine the time distribution prior to the attainment of the pre-set value of the parameter determining the process of the loss of the properties of the facility.

Obviously, the task may be solved, if the nominal density of the transition of the process (5) from one state to another is known. The nominal transitional density for a Markov process of diffusion type is described precisely by the equation of Fokker-Planck-Kolmogorov [3,5-7,9,11]. As the process of a facility losing its properties is due to the continuous impact on the system, it may be assumed that the change of the character of a random process is of monotone nature. Considering the process of change in time of the properties of a system monotonic with constant mean rate m of change of the prognostic variable I, and constant standard deviation σ, the equation (5) may be expressed in a different way, using [6], thus

$$dy = m\,dt + \sigma\,dx(t). \tag{6}$$

From the standpoint of reliability theory, the equation (6), describing the change of the prognostic variable m, leads to a diffusional distribution of the time of functioning without the onset of a vulnerable state of the facility due to the failure. The form of distribution is determined by the corresponding conditions of solving the Fokker-Planck-Kolmogorov equation

$$\frac{\partial P}{\partial t} + m\frac{\partial P}{\partial y} - \frac{\sigma^2}{2}\frac{\partial^2 P}{\partial y^2} = 0 \tag{7}$$

Dropping the calculations that are analogous to those used in assessing the hazard and set forth in [6], at a monotone process the function of the time distribution of the first attainment of the prescribed limit by the process (5) will be

$$F(t) = \Phi\left(\frac{t-\mu}{\alpha\mu\sqrt{t}}\right) \tag{8}$$

The probability of the functioning of the system under analysis without the onset of a prescribed state:

$$P(t)=\Phi\left(\frac{t-\mu}{\alpha\mu\sqrt{t}}\right); \text{ risk } r=1-P(t). \tag{9}$$

In the realization of a random process, described by non-monotonic curves, for $P(t)$ we shall have:

$$P(t)=\Phi\left(\frac{t-\mu}{\alpha\mu\sqrt{t}}\right)-\exp\left(\frac{2}{\alpha^2\mu}\right)\Phi\left(\frac{t+\mu}{\alpha\mu\sqrt{t}}\right) \tag{10}$$

where $\mu=\frac{I}{m}$; $\alpha=\frac{\sigma}{\sqrt{am}}$; $\Phi(Z)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{Z}e^{-x^2/2}$

$0.00\le Z\le 4.99$

Z is the statistical margin of resistance and it determines the probability of functioning of the system without breakdown; α is the threshold value of the prognostic variable. The functional capacity of the onset of the pre-set state of the system is characterized by an area of limiting states, going beyond the limits of which is qualified as a failure.

Omitting the calculations set forth in detail in solving analogous problems [3,10], the value of time t of the first attainment by the process of the loss of properties of the system of the sought threshold value I_r, described by the equation (6), i.e. the time of onset of a vulnerable state, will be

$$t=\mu\left[\frac{2+Z^2v^2\pm\sqrt{\left(4+Z^2\upsilon^2\right)Z^2v^2}}{2}\right], \tag{11}$$

Prediction of the time of onset of the vulnerable state is extremely important. As is known, the view is current that at major catastrophes the following dependence acts: the increase of the losses of time in the arithmetic progression leads to the growth of human casualties already in geometric progression.

Knowing that $\mu=\frac{I_r}{m}$, one can determine the threshold value I_r, corresponding to the time t and the probability of failure-free functioning $P(t)=\Phi(Z)$. At this value I_r the facility becomes vulnerable:

$$I_r=\frac{2tm}{\left(2+v^2Z^2\right)-\sqrt{v^2Z^2\left(4+v^2Z^2\right)}}\ . \tag{12}$$

From the equation (8) one can determine t_d, according to which the remaining longevity of the facility in question of prescribed reliability (risk): $P(t)=\Phi(Z)$; $r=1-P(t)$ may be predicted. For aged structures a "sparing" (eased) regime of exploitation and respective (corresponding) reliability $P(t)$ may be allowed.

$$t_d=\frac{I\left(2+Z^2v^2-\sqrt{v^2Z^2\left(4+v^2Z^2\right)}\right)}{2m}, \tag{13}$$

where t_d is the term of service with account of factors. In calculating longevity, e.g. for coast-protecting structures, the intensity of abrasion is the prognostic variable, at pipe corrosion - the rate of corrosion, in calculating oil pipelines, at river crossings - the depth of pipeline scour until the exposure of the pipes; in calculating the longevity of obsolescent structures the parameter reflects the lowering of resistance owing to aging, and so on.

The applied approach allows to solve problems of reducing negative impacts and various types of damage of permissible limits, i.e. allowing them to perform the functions imposed with tolerable disturbances at minimum expenditure of labour and finances during exploitation. The expectation of the mean rate of change of the prognostic variable, m is determined for individual intervals of observations for consecutive years of variational series.

The index of the facility that most fully characterizes the fitness for work of individual units, elements, completing parts, of the facility as a whole is chosen as the prognostic variable needed for functioning, as well as the threshold of its change.

Knowing the term of service t_d, the level of corresponding eased load and the reliability of the obsolescent facility may be determined by the expression (13). Thus, the cited expression permits selection of a permissible load, appropriate to the age of the facility and, consequently, a "sparing" regime of reasonable exploitation with a pre-set risk $r=1-P(t)$.

In the absence of data the use can be made of the information obtained from analogues, and at insufficiency of data, one may have recourse to the bootstrap method, Monte-Carlo techniques and expert assessment [6].

The obtained expressions (11) and (12) enable to assess the level of vulnerability or the time of onset of the condition of breakdown of facilities of various purposes, for different prognostic variables, at any time interval and value of impact. Assessment of vulnerability according to diverse prognostic variables will allow to select the parameter that is most "to blame" for the facility becoming vulnerable. This parameter should form the basis for developing measures towards relieving the facility from the vulnerable state.

ჰიდროლოგია

ჰიდროტექნიკური ნაგებობების დაძველება და მისი განგრძლივების ღონისძიებები

ც. მირცხულავა

აკადემიის წევრი, წყალთა მეურნეობის ინსტიტუტი, თბილისი

ნაშრომში აღწერილია ჰიდროტექნიკური ნაგებობების დაბერების მექანიზმი. მოცემულია მისი მიმდინარეობის პროგნოზირება თანამედროვე საიმედოობის თეორიის გამოყენებით, კერძოდ, იტო-ფოკერ-პლანკ-კოლმოგოროვის განტოლებების ერთობლივი ამოხსნის შედეგად დადგენილია ობიექტების ხანმედეგობა დატვირთვისა და გარემოს პირობების გათვალისწინებით.

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