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Lifetime of earth dams

Срок эксплуатации грунтовых плотин

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Abstract. The level of safety of small earth dams, operating without staff and measurement and control equipment, are considered in this study. Approach enabling the possibility to define the finite lifetime (Tf) of a small earth dam here presented. The proposed approach does not require any variables monitoring. It is based on the definition of Tf by assessing the water impact on the small earth dams by quantitative methods of system analysis. To assess the earth dam Tf, two approaches are offered, which based on the digraph method. They are the classification scale construction and the cluster method. On a quantitative base the Tf of small dam on urban area can be defined as the minimum between the two (75 year for the classification scale and 80 for the clustering), which is however well above the Russian regulations, which indicate a period of 50 years (design life). The estimated value allows defining robustness of earth dam and can be used as a criterion for safety management of earth dams, defining the needs to undertake actions to improve, during the life cycle, earth dam structural features.

Аннотация. Работа посвящена оценке безопасности низконапорных грунтовых плотин, эксплуатирующихся без персонала и контрольно-измерительной аппаратуры на объекте. В статье предложен метод по определению критического срока эксплуатации низконапорных грунтовых плотин, не требующий данных о фактическом состоянии объекта. Предложенный метод основан на количественной оценке различных видов воздействия воды, приводящих к разрушению грунтовой плотины. Для определения критического срока эксплуатации грунтовой плотины, значения полученные методом импульсного процесса, обрабатывались методом построения классификационных шкал и кластерного анализа. Минимальное из полученных значений принято за критический срок эксплуатации грунтовой плотины в пределах урболандшафта. Методом построения классификационных шкал выявлен критический срок эксплуатации грунтовой плотины, равный 75 лет, а методом кластерного анализа – 80 лет. Критическим сроком эксплуатации грунтовой плотины выбрано минимальное из двух полученных, поскольку в соответствии со СНиП 33-01-2003, нормативный срок службы грунтовых плотин IV класса – 50 лет. Полученное значение позволяет определить запас прочности грунтовой плотины и может служить критерием управления безопасностью грунтовых плотин, а именно определяет необходимость проведения мероприятий по увеличению жизненного цикла плотины при обязательном учете особенностей конкретных объектов.

Introduction

Earth dams make about 85 % of all planned and constructed dams all over the world and in most cases they are small dams, in accordance with International commission on large dams (ICOLD), with the height of less than 15 meters [1]. Earth dams are used as a protection against floods and mainly with

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drinkable and irrigation water systems supply, such dams now support approximately 30–40 % of the 271 million hectares of irrigated agriculture [2]. The wide use of earth dams as water retaining structures is now determined by the possibility to use local soils, by the emergence of powerful mechanisms and capability to build dams in difficult engineering-geological and seismic conditions. However, not all small dams are designed according to engineering criteria and moreover their maintenance and management criteria are not strictly regulated [3, 4].

The life cycle of any earth dam can be divided into intervals: 1) construction and initial filling; 2) normal operation; 3) a residual life [5]. The cycle construction and initial filling characterized by high failure rate, but at the end of this interval failure rate of the structures is stabilized. During normal operation of dam, failure occurs when excess impacts. The first two intervals are design life (lifetime).

When designing an earth dam, in the technical documentation a design life of dam is determined, before reaching of which dam maintains the normal operational characteristics or operating state. Upon reaching the design life an earth dam is not always taken out of service, because of its durability, which allows exploiting the dam for some time after the end of design life. It is time called residual life and during this time the dam is operational. But at some point the dam from the operating state becomes inoperable, that is a condition in which the object is able to partly perform the required function, that is there comes finite life time (or finite lifespan). At this time the restoration of a working condition is impossible or impractical, and further operation of the earth dam is unacceptable by reason of an emergency [6, 7].

According to the ICOLD, a large number of earth dams nowadays have been operated for more than 50 years, reaching their design life, with an increase in damage occurrences probabilities [8]. For example, today in the Russian Federation there are about 30 thousand dams and their condition of safety level distributed as follows: at normal safety level – 39.4 %, low – 43.4 %, unsatisfactory –12.5 % and the 4.7 % are hazardous. The number of hazardous dams, compared with the previous decade, increased by 2. But the safety conditions are similar worldwide: in China 96% of dam failures, between 1954–2003, involved small dams [9].

Earth dams safety management is directly connected with the possibility to control and monitor the current state and age of the construction, natural and geographical factors, operational planning. Monitoring techniques open the way to forecasting safety level and risk, which can be pursued either in a probabilistic or in a deterministic framework.

Probabilistic models, considering the safety level and risk as random variables and predicting occurrences probabilities, are rather robust methods but need long series of recorded data to perform statistical analysis [10]. Authors in [11] describe a number of different quantitative risk assessments analyses; in [12] consider evaluation of the probabilities of dam safety levels; in [13] prefer the model for service life of dam based on time-varying risk probability and in [14] present rational quantitative optimal approach for the reduction of risk from overtopping of earth-fill dams.

The problem of earth dams durability in the loss of abilities of earth dam to accomplish the assigned functions because of the aging process [15]. This problem is analyzed in a probabilistic approach in [16, 17]. The authors in [18] are proposed probabilistic method which is based on the calculation of two major indexes: a condition index and a condition control index. For stability analysis of dams authors in [19] present new probabilistic method, which is based on First Order Reliability Method and considers some variables as random.

On the other side, deterministic models basically consist of a comparison between monitored variables and the value given to these variables in the current regulations and then they are hindered by the lack of monitored data.

As a result, existing models only allow estimating dam safety risk or critical level of safety for small earth dams, defined as level at which maintenance occurs because of a decreasing dam stability and an excess of maximum allowable safety criteria values, indicating the shift from partially disabled to disabled conditions. In this connection the aim of this article is to present comprehensive approach enabling the possibility to define the finite lifetime (T_f) of a small earth dam. Obtained earth dams T_f value is criteria for monitoring and planning future actions for improving sustainability and ensure safe operation. The lack of statistical and experimental data causes difficulties in assessing dam finite lifetime. Therefore to overcome this problem system analysis method is used, as demonstrated in the following research.

Methods

The proposed approach differs from the probabilistic and deterministic models. It is based on the definition of T_f in the following sequence:

1. Building of directed graph (or just digraph).
2. Calculation of the digraph using the pulse process.
3. Construction of classification scale.
4. Construction of the dendrogram by the results of cluster method.

This approach does not require any variables monitoring, which is rather important for the small earth dams, where usually there are no measurement and control equipment and operating staff.

Digraph method

At construction of a settlement model (digraph) one of the primary procedures is to identify loadings and impacts acting on earth dam at different modes of operation and directly or indirectly leading to the destruction of earth dams, which are in this article divided into:

– climatic (flood, earthquake, karst etc.);

– technogenic (failure of spillway due to insufficient capacity and enginery, substandard work, material defect, staff error etc.);

– water impact (high pressure, filtration, suffusion, cavitation erosion, corrosion processes, wave pressure etc.).

The impacts are selected depending on the physico-geographical conditions of the area, the design features and operating conditions of earth dams. Between the selected impacts directly or indirectly leading to the destruction of earth dams, establishes a correlation and constructs the digraph. In this case an output parameter of a digraph is the damaging effect of impacts.

As rule, a digraph consists of a non-empty finite set of elements called vertices and a finite set of ordered pairs of distinct vertices called arcs [28]. A weighted digraph consists of a digraph and an assignment of a weight on each arc. The weight of the arc can be interpreted as the relative strength of the effect, and can be either positive or negative.

For a quantitative assessment of impacts on earth dams, it is possible to either use observed data or to assign weighting coefficient to each of the arcs. Instrumental measurement is a time consuming process, it requires special equipment and is not generally operated for small earth dam because of the large cost impact.

Due to the lack of data by the each type of impact on earth dams, weights are assigned to each arc. For definition of weight of digraph arcs and signs propose method of expert evaluations (by experts' interviews), further considering that the sum of absolute values of the weight coefficients is equal to unit. For example, authors in their work [16] used expert's judgment.

Pulse process

Modeling of changes in the values of the components included in the digraph (in our case different types of impacts) is made by steps *(S* = 1, 2–12*)* as a pulse process [29]. Each step consist of 10 years, so, in this specific study, the maximum age of an earth dam is made of up to 120 years. The pulse process can be explained as in the following: each vertex *i* refers to a value $V_{i(s)}$ at each step *S*. The succeeding value $V_{i(s+1)}$ introduced at vertex *i* at step *S+1*, and from information about whether other vertices *j* adjacent to *i* went up or down at the last step. If there is an arc from *j* to *i* and *j* goes up by a units at step *S*, then as a result *i* goes up at step *S+1* by an amount equal to steps the sign of arc *(j, i).* For any step *S* value components $V_{i(S)}$ at the vertices *i* is determined by the formula [29]:

$$V_{i(S)} = V_{i(S-1)} + \sum_{i,j=1}^{n} a_{ji} \cdot P_{j(S)} \tag{1}$$

$$P_{j(S)} = V_{j(S)} - V_{j(S-1)}, \tag{2}$$

where $V_{i(S-1)}$, $V_{j(S-1)}$ – the value of components in step *S–1* at vertices *i* and *j*;

i, j – number of vertices;

a_{ji} – weighting coefficient;

n – the number of components included in the calculation component.

Classification scale construction method

Construction of a classification scale is based on cumulative distribution function and is performed according for the formula [30]:

$$V_{c.s.} = \frac{1}{N+1} \cdot \left(\frac{V_{(s)} - a}{b - a} + s - 1\right), \qquad (3)$$

where $V_{c.s}$ is the value of damaging effect of impacts, transformed by the method for constructing classification scales;

$V_{(s)}$ – the value of damaging effect of impacts on the step s, calculated by the digraph method;

a – minimum value of $V_{(s)}$;

b – maximum value of $V_{(s)}$;

N – sample length.

The identifier c is calculated by the formula:

$$c = \frac{\sum_{i=1}^{N} V_{(s)}}{\sqrt{\frac{\sum_{i=1}^{N} V_{(s)} - \sum_{i=1}^{N} V_{(s)}^{2}}{N-1} \cdot N}} \qquad (4)$$

Cluster method (dendrogram)

The cluster analysis is an alternative quantitative method for the analysis of the system under investigation. The earth dam T_f will be estimated through the identification of clusters, that are, by definition, groups of elements featured by a high degree of similarity among themselves. Clusters allocation is identified by the construction of the dendrogram.

Inclusion in a particular cluster is defined on the basis of the minimum distance in the Euclidean space. The distance between two damaging effect of impacts corresponding to two different periods of maintenance can be defined as:

$$d_s = \left| \frac{V_{n(si)} - V_{n.av.}}{V_{n.d.}} - \frac{V_{n(si+1)} - V_{n.av.}}{V_{n.d.}} \right|, \qquad (5)$$

where d_s – distance in the Euclidean space;

$V_{n(s)}$ – value of damaging effect of impacts on steps i and i+1 derived from the digraph method;

$V_{n.av.}$– average value of damaging effect of impacts;

$V_{n.d.}$ – deviation of value of damaging effect of impacts.

In this article calculated T_f for the small earth dam, forming a pond on urban area, in accordance with the proposed methods and with the following initial conditions:

- there is no operating staff on dams, so technogenic impact – staff error, leading to the destruction of earth dams is excluded;
- failure of spillway due to insufficient capacity is not considered, because the ponds within the urban area, mostly undrained, and the dam is only the pressure front, which does not contain a spillway;
- natural impacts as earthquake and flood are not considered, as they relate to rare events [20]. For example, earthquakes have been the cause of only around 1.5 % of all dam failures and it is considered as less obvious [21, 22];

- urban area with small earth dams located outside of karst fields and is relatively stable;
- the main reasons of the earth dam destructions, according to the ICOLD are overflowing water through the crest and dam basis breakings, which in turn can be caused by a flood [23] and by different types of water impact, for example, high hydrostatic pressure levels, cavitation erosion, filtration, piping, etc. [8, 24–27]. In this regard, settlement model for small dam of urban area includes only different types of water impact. Water exerts intensive physicochemical and biological impacts on earth dams, which are divided into a number of subtypes, increasing variety forms of impact.

Results and Discussion

In accordance with the above initial conditions the digraph is obtained (Fig. 1).

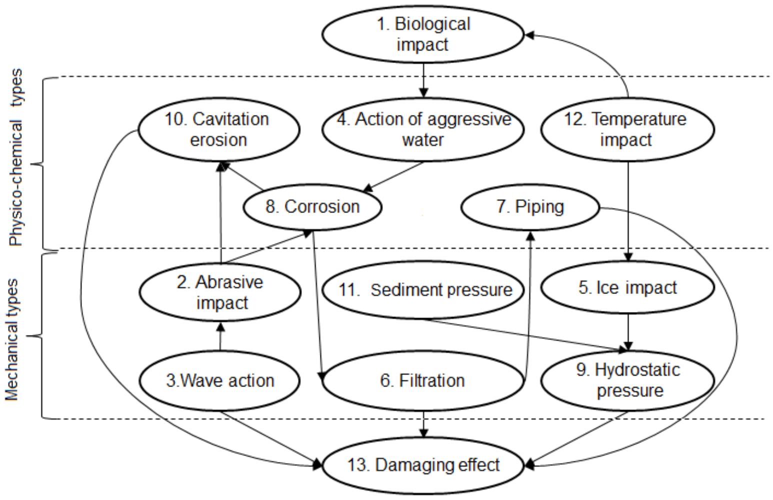

Figure 1. Directed graph, describing the correlation between the forms of water impact

The digraph in Figure 1 illustrates the correlation between different forms of water impact on small earth dams of urban area. It will be used in the following research for further quantitative assessments.

Output digraph parameter is the cumulative impact of all kinds of water impact on earth dam, leading to the destruction of the dam (the damaging effect of water).

To determine the weights of digraph arcs, a survey was conducted of 20 specialists from the following organizations: University of Salerno and Center of laboratory analysis and technical measurements, whose research activities directly or indirectly connected with earth dams. The final result is presented in the work. The expert evaluation assessment in terms of weight coefficients and signs for each arc is graphically represented in Figure 2.

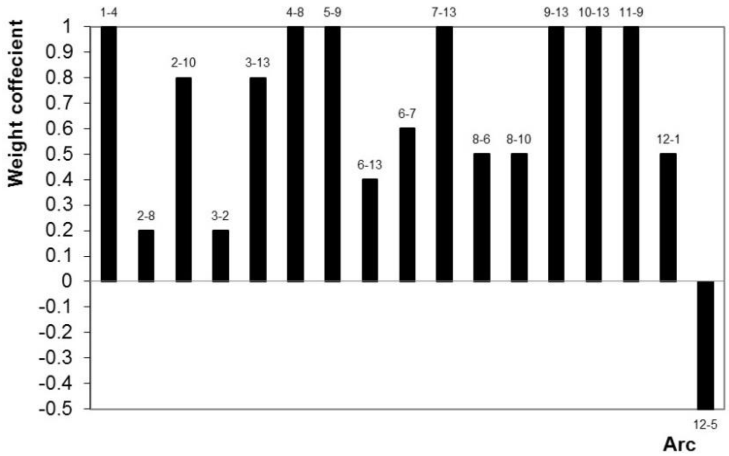

Figure 2. The weights and signs for arcs

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As an example, negative value of the weight coefficient appropriated to the arch 12–5 (temperature impact – ice impact) is explained by that at increase in temperature, there is a weakening of ice impact. In other cases coefficients are faced by a positive sign which, by rules, indicates that the increase of one type of water impact leads to the increase of values of a dependent component. For example, the increase of sediment pressure at an earth dam leads to increase in hydrostatic pressure.

As activating the components selected wave action (3), the pressure sediment (11) and temperature impact (12), that is, those components that are do not depend on the other.

On the basis of a digraph (Fig. 1) and formula 1, formulas for calculating the value of components V_i are received:

$V_{1(S)} = V_{1S-1} + a_{12-1} \cdot V_{12(S-1)}$;

$V_{2(S)} = V_{2(S-1)} + a_{3-2} \cdot V_{3(S-1)}$;

$V_{4(S)} = V_{4(S-1)} + a_{1-4} \cdot V_{1(S-1)}$;

$V_{5(S)} = V_{5(S-1)} + a_{12-5} \cdot V_{12(S-1)}$;

$V_{6(S)} = V_{6(S-1)} + a_{8-6} \cdot V_{8(S-1)}$;

$V_{7(S)} = V_{7(S-1)} + a_{6-7} \cdot V_{6(S-1)}$;

$V_{8(S)} = V_{8(S-1)} + a_{1-8} \cdot V_{1(S-1)} + a_{2-8} \cdot V_{2(S-1)} + a_{4-8} \cdot V_{4(S-1)}$;

$V_{9(S)} = V_{9(S-1)} + a_{5-9} \cdot V_{5(S-1)} + a_{11-9} \cdot V_{11(S-1)}$;

$V_{10(S)} = V_{10(S-1)} + a_{2-10} \cdot V_{2(S-1)} + a_{8-10} \cdot V_{8(S-1)}$;

$V_{13(S)} = V_{13(S-1)} + a_{3-13} \cdot V_{3(S-1)} + a_{6-13} \cdot V_{6(S-1)} + a_{7-13} \cdot V_{7(S-1)} + a_{9-13} \cdot V_{9(S-1)} + a_{10-13} \cdot V_{10(S-1)}$.

For example, here is the calculation of the values of components: piping (7), hydrostatic pressure (9), cavitation erosion (10) and damaging effect (13) at S = 1.

$V_{6(1)} = 0 + 0.5 \cdot 0 = 0$;

$V_{7(1)} = 0 + 0.6 \cdot 0 = 0$;

$V_{9(1)} = 0 + 1 \cdot 0 + 1 \cdot 1 = 1$;

$V_{10(1)} = 0 + 0.8 \cdot 0 + 0.5 \cdot 0 = 0$;

$V_{13(1)} = 0 + 0.8 \cdot 1 + 0.4 \cdot 0 + 1 \cdot 0 + 1 \cdot 0 + 1 \cdot 0 = 0.8$.

Similarly calculated values of all digraph components (fig. 1) on the steps S = 1, 2–12.

As a result of the modeling of the directed graph components values on the basis of the pulse process, the dependency of the damaging effect of water and earth dam maintenance time is shown in Figure 3.

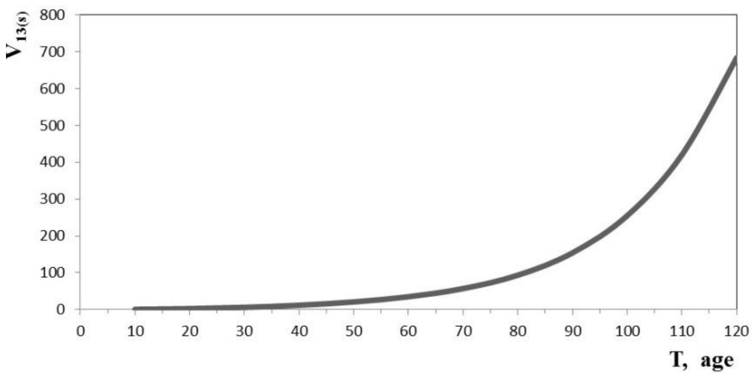

Figure 3. The dependency between the damaging effect of water and the maintenance time of earth dam (T)

As can be seen from Figure 3, it is not possible to determine accurately the finite lifetime T_f of earth dams, because the used modeling approach reproduces a monotonic non-linear increase of damaging effect of water for increasing earth dam maintenance time, without the possibility to identify a value for T_f, as a quantile of the curve.

The obtained values of V_{13} on the steps S = 1, 2–12 were substituted into formula 3. For example, here is the calculation of the damaging effect of water on the steps S = 1 and S = 2:

$$V_{13.c.s.(1)} = \frac{1}{12+1} \cdot \left(\frac{0.8-0.8}{683-0.8} + 1 - 1\right) = 0;$$

$$V_{13.c.s.(2)} = \frac{1}{12+1} \cdot \left(\frac{2.6-0.8}{683-0.8} + 2 - 1\right) = 0.076.$$

Similarly calculated values of the damaging effect of water on the steps S = 3–12.

For the presented report, by construction of a classification scale, the calculated value for c (c = 0.66) and the sample length (N = 12), lead to the number of classes of the maintenance period of earth dams equal to 2.

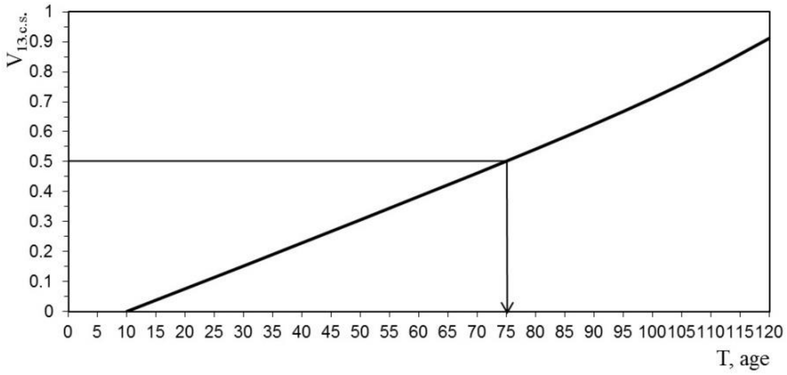

Figure 4. The dependence between the damaging effect of water and the maintenance time of earth dam (classification scales construction method)

Figure 4 illustrates the variation of $V_{13.c.s}$ versus T. Since a number of two classes have been calculated as optimal for the classification scale method, a correspondent estimation of about 75 years for the T_f is reported.

The obtained values of V_{13} on the steps S = 1, 2–12 also were substituted into formula 5. For example, here is the calculation of the minimum distance in the Euclidean space between values of damaging effect of water on the steps S = 1 и S = 2.

$$d_s = \left| \frac{0.8-146.6}{213.5} - \frac{2.6-146.6}{213.5} \right| = 0.01.$$

As a results of cluster method, a matrix containing the minimum distance for each damaging effect of water corresponding to a given maintenance period can be derived (Table 1).

Table 1. Euclidean distance matrix

$V_{n(s)}$	Step	1	2	3	4	5	6	7	8	9	10	11	12
0.80	1		0.01	0.02	0.05	0.10	0.16	0.27	0.44	0.73	1.20	2.03	3.23
2.60	2	0.01		0.02	0.04	0.09	0.15	0.26	0.43	0.72	1.24	2.03	3.23
6.06	3	0.02	0.02		0.03	0.07	0.14	0.24	0.41	0.70	1.23	2.01	3.21
11.90	4	0.05	0.04	0.03		0.04	0.11	0.21	0.39	0.67	1.20	1.98	3.18
20.90	5	0.10	0.09	0.07	0.04		0.07	0.17	0.34	0.63	1.16	1.94	3.14
34.90	6	0.16	0.15	0.14	0.11	0.07		0.11	0.28	0.56	1.09	1.87	3.07
57.10	7	0.27	0.26	0.24	0.21	0.17	0.11		0.17	0.46	0.99	1.77	2.97
93.40	8	0.44	0.43	0.41	0.39	0.34	0.28	0.17		0.29	0.81	1.60	2.80
154	9	0.73	0.72	0.70	0.67	0.63	0.56	0.46	0.29		0.53	1.31	2.51
265	10	1.25	1.24	1.23	1.20	1.16	1.09	0.99	0.81	0.53		0.78	1.98
430	11	2.03	2.03	2.01	1.98	1.94	1.87	1.77	1.60	1.31	0.78		1.20
683	12	3.23	3.23	3.21	3.18	3.14	3.07	2.97	2.80	2.51	2.01	1.20	

The minimum Euclidean distances in each pair in Table 1 are highlighted. Allocation of clusters is then obtained by successive comparisons of the estimated values of the minimum distances (Table 1): according to the hierarchical levels 0.25; 0.50; 0.75; 1.00; 1.25 etc. The results of the cluster analysis are presented in the form of the dendrogram (Fig. 5).

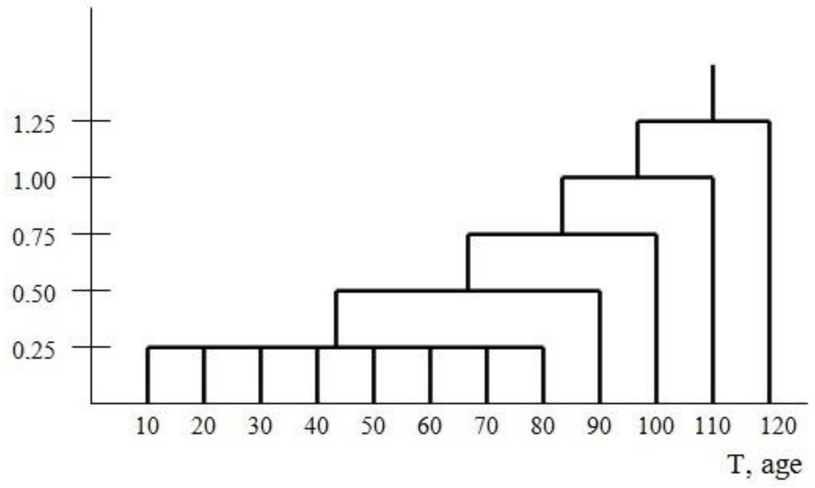

Figure 5. Dendrogram of cluster analysis of maintenance periods of earth dam

According to cluster approach, the dendrogram representation indicates that quantitatively the earth dam T_f is of about 80 years, similar to what found in the case of the classification scales construction approach.

On a quantitative base the T_f can be defined as the minimum between the two (75 year for the classification scale and 80 for the clustering), which is however well above the Russian regulations, which indicate a design life of 50 years.

The resulting value T_f (75 year), comparable with literature data. For example, authors in [31, 32], indicate that earth dams on the territory Moscow city, run for more than 65 years, are in poor condition and need of major repair.

Conclusions

1. Quantitative methods of system analysis (pulse process, method for constructing classification scales, method of cluster analysis) are applied in this report to assess the finite lifetime of small earth dams on urban area. All of the applied methods converged through a value of 75 years for the finite lifetime.

2. The estimated value allows defining robustness of earth dam and can be used as a criterion for safety management of earth dams, defining the needs to undertake actions to improve, during the life cycle, earth dams structural features. In case of excess of design life over T_f is recommended to conduct technical examination of a dam and to make decision on further maintenance. At approach of the real time of maintenance to T_f it is recommended to take additional measures for safety in order to increase stability of a dam to the influence of climatic and technogenic factors. One of such actions is the assessment of stability of a dam to biological, physicochemical and mechanical types of water impact.

3. Like any other method, the approach has its own limitations. Firstly it is the exclusion of natural impacts and other loadings from the settlement model, secondly, the use of expert method for the estimation of weights. On the other hand, considered settlement model can be extended to the excluded loadings and calculated in accordance with the proposed approach. In the settlement model can be used real data of water impact forms on earth dam.

4. Maintenance of earth dams constantly has to adapt for changing conditions during life cycle and must be under strict monitoring of both the operating organization and the state, to ensure public safety. The definition for T_f, and its quantitative assessment, would undoubtedly represent an important step ahead in practical management issues.

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