ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ
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VULNERABILITY OF THE OPERATION OF SMALL DAMS – STATE OF THE ART

B. Nikolov[1], D. Kisliakov[2]

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ABSTRACT

The dam is a complex natural-technical system that is under the influence of various and constantly changing factors. In order to be able to fulfil its intended purpose sufficiently reliably, this system must be constantly and competently monitored and maintained. These activities represent the so-called technical operation of the dam and its facilities. The water economy operation of the dam comprises the activities on the management of the dam reservoir for the fulfilment of the water economy goals set by its building.

This paper defines the basic concepts related to the technical and operational reliability of the dam and its vulnerability, respectively. The present state of knowledge on the main aspects of this vulnerability is presented. Based on the performed review, the idea is suggested for the use of this concept for small dams as part of their risk assessment.

1. Vulnerability Definition

The topic of vulnerability is a key concept throughout the industry. Each system possesses certain vulnerability of every chain ring in its structure and process flows, and the larger the system, the greater the damage will be if it fails. As time progresses, the vulnerability of the structural elements of the system also changes which makes addressing this topic always up-to-date and thus it represents a challenge for researchers in all fields.

[1] Bogdan Nikolov, Eng. PhD student, Dept. "Hydraulic, Irrigation and Drainage Engineering", UACEG, 1 Hr. Smirnenski Blvd., Sofia 1046, e-mail: b.nikolov.vd@abv.bg

[2] Dimitar Kisliakov, Prof. Dr. Eng., Dept. "Hydraulic, Irrigation and Drainage Engineering", UACEG, 1 Hr. Smirnenski Blvd., Sofia1046, e-mail: kiss_fhe@uacg.bg

There is no single definition of vulnerability. Vulnerability refers to the inability (of system or unit) to withstand the effects of a hostile environment. The vulnerability window is period of time during which security measures are reduced, compromised or lacking [1].

Understanding social and environmental vulnerability as a methodological approach involves analyzing the risks and assets of disadvantaged groups, such as the elderly. The vulnerability approach itself has high expectations e.g. for social policy [2, 3].

In military terminology and defence industry, vulnerability is a subset of survivability, the others being susceptibility and recoverability. Vulnerability is defined in various ways depending on the nation and armed forces concerned, but in general it refers to the near-instantaneous and direct effects of a weapon attack. In aviation, it is defined as the inability of an aircraft to withstand the damage caused by the man-made hostile environment [4]. In some definitions, recoverability (damage control, firefighting, restoration of capability) is included in vulnerability. Some military services develop their own concept of vulnerability [5].

Human vulnerability refers to a state of physical, emotional, and cognitive stability that is in danger of being disturbed or destroyed due to being susceptible to destabilizing influence. These three dimensions of vulnerability roughly coincide with the three main domains of human abilities as introduced in developmental psychology, namely physical, social, and intellectual abilities [6, 7].

The vulnerability of industrial systems is referred to as a degree of loss as a function of some external effect on the system and is measured by the level of damage / loss. In Civil Engineering, damage is most often discussed in relation to the occurrence of an undesirable event such as collapse of a facility or building that either happens or not. Failures are also measured in terms of the degree of the undesired result, identified as loss. In this case, the loss means the cost of repair, the impact on the safety of life and loss of functionality (money, casualties and disfunction time), or as degradation of environment, quality of life, historical value, etc.

The resulting definition of vulnerability of industrial systems also covers Hydraulic Engineering facilities and dams in particular and can be considered as a basis for presenting the vulnerability study of small dams further below.

Vulnerability is distinguished from risk. Risk refers to the deviation from one or more outcomes of one or more future events from their expected value. Technically, the value of these results can be positive or negative. Positive risk is seen as an opportunity, and in the common use of the word, risk focuses only on the potential harm (damage or loss of positive results) that may arise from a possible event, which may result from either undesired costs or the inability to acquire any profit.

In general, it can be summarized that vulnerability is a component of the risk.

Natural hazard studies help to develop an appropriate interpretation of the risk definition and the perception of vulnerability, some of them are cited below according to [8]:

- In [9]:

  Total risk = Impact of hazard × Elements at risk × Vulnerability of elements at risk.

- In [10]: Risk = Hazard × Vulnerability.

- "Risk is the probability of a loss, and this depends on three elements: hazard, vulnerability and exposure". If any of these three elements of the risk increases or decreases, then the risk being a product of them also increases or decreases, respectively [11].

- "Risk (i.e. 'total risk') means the expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular natural phenomenon… Total risk can be expressed symbolically as [12]:

$Risk_{(total)}$ = Hazard × Elements at Risk × Vulnerability.

This approach is not only elegant, it is also very practical. Given the complexity of urban communities and the degree to which the various elements of risk are interdependent, the 'total risk' approach is considered mandatory. Further, it also lends itself to quantitative, qualitative and composite analytical approaches".

- Risk = Probability × Consequences, although "this simple product is not sufficient in itself to fully describe the real risk, but... it provides an adequate basis for comparing risks or making resource decisions" [13].
- "Risk is the actual exposure of something of human value to a hazard and is often regarded as the combination of probability and loss" [14].
- Risk is "expected losses (of lives, persons injured, property damaged, and economic activity disrupted) due to a particular hazard for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability". Hazard is "a threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area". Vulnerability is "degree of loss (from 0% to 100%) resulting from a potentially damaging phenomenon" [15].

These references indicate that risk is fundamentally a combination (i.e. product) of hazard and vulnerability. Here, the stochastic nature of the hazard has to be emphasized. In order to mathematically combine hazard and vulnerability to quantify risk as mathematical expectation, quantitative descriptions of hazard and vulnerability are necessary.

The vulnerability of the system is distinguished from the fragility of the system; as already mentioned the vulnerability measures the level of losses, and the fragility measures the probability of occurrence of these losses, Fig. 1.

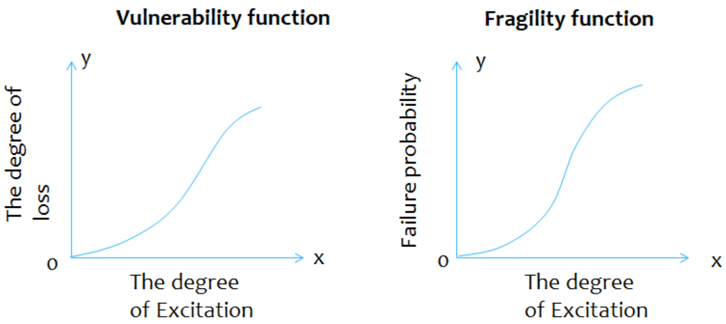

Figure 1. Graphical representation of vulnerability and fragility function

2. Methods to Derive Vulnerability Functions

This short review work does not provide guidance on how to derive vulnerability functions, but rather briefly discusses the three leading methods for extracting them, referring to the state of the art in this field.

The three general approaches to derive vulnerability function are empirical, analytical and expert opinion.

2.1. Empirical Derivation of the Vulnerability Function

Since deriving is entirely based on the observation of the actual results of the asset due to real impact, such as an earthquake for example, the obtained characteristics are reliable, and hence this is one of the most desirable derivation methods. This method records the observations without specifying the degree of damage, i.e. without sampling since damages are registered. From the observations records:

x_i = environmental excitation (ground motion, wind speed, etc.) at each property i;

y_i = loss (repair costs, rate of fatalities, duration of loss of function, etc.) at property i;

c_i = attributes of property i (structural material, lateral force resisting system, height, age, etc.) [16].

Observation records are grouped based on one trait or another, and regression analysis is performed for each group to formulate the vulnerability function.

The disadvantages of the empirical model for deriving the vulnerability function are:

- Observations tend to be few or missing at high levels of excitation, where high losses are most likely;
- Damage assessment – predominantly external only. An internal assessment of all damages is required;
- Credibility on the source of the information is a problem;
- Empirical observations do not describe the cause / mechanism of failure.

In Fig. 2, an example of an empirically calculated vulnerability function is shown. The example is of damage investigated on buildings made of wooden frames, the damage was caused by the 1994 Northridge earthquake [16].

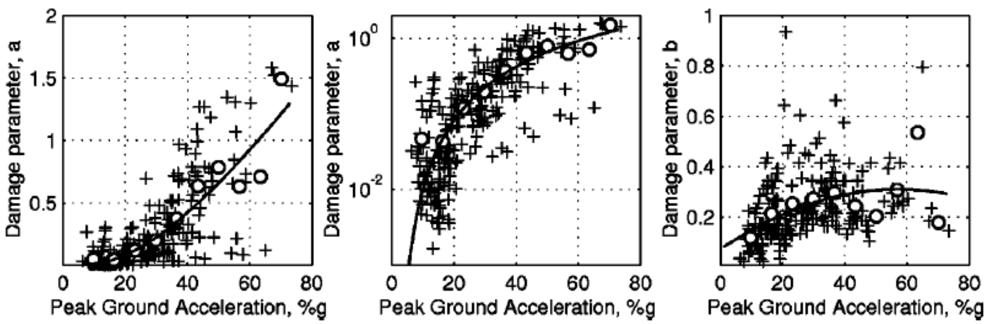

Figure 2. Regression analysis of damage to wood frame buildings in the 1994 Northridge earthquake [16]

2.2. Analytical Derivation of the Vulnerability Function

Almost all analytical methods use the four steps presented in Fig. 3. First, the asset at risk is defined, describing the location, the site conditions followed by a hazard analysis, calculating the probability of different levels of the external impact or their return period, respectively. Then, a structural analysis is performed to evaluate the forces and deformations of the facility and the corresponding possible damage state. Finally, relation between damage states and corresponding losses is used.

In fact, this is a graphic presentation of the risk analysis procedure where the vulnerability represents only the product of the last three steps (without hazard). Moreover, no iteration is needed but repetition of the computation for obtaining statistically representative sets of results for subsequent transition to probability distributions. The risk is evaluated actually by integration over both hazard and vulnerability ranges.

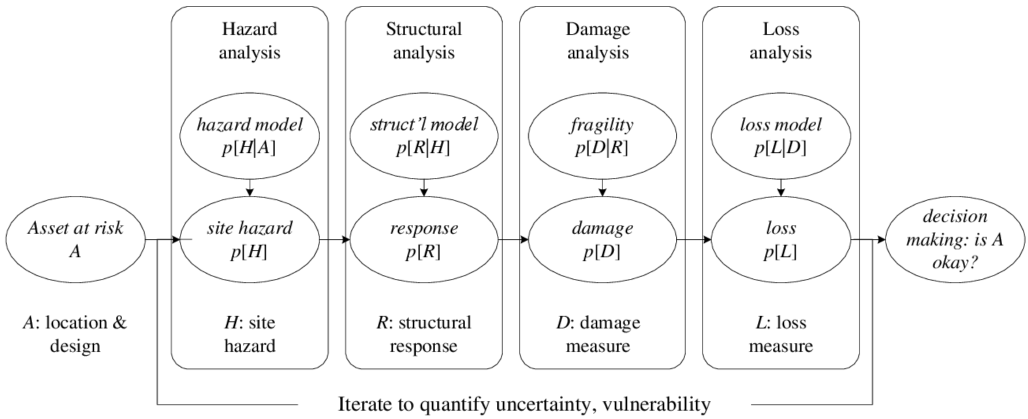

Figure 3. Analytical methods for estimating seismic vulnerability of a single asset [17]

Structural responses with the applicable impact are entered as fragility functions to evaluate the probable damage to each faulty component at each impact (excitation) level.

The probable damages are treated as loss assessment for each impact level by expressing quantitative features such as loss of life, money, etc.

The process is repeated many times until the uncertainty is dispelled by means of representative statistical assessment, and the external impact, such as the seismic impact for example, is linked to the quantitative loss.

The analytical method can be applied to develop vulnerability functions for multiple asset samples of the same class.

Of course, the analytical method has its advantages and disadvantages.

Advantages of the method are:

- The analytical method provides insight where the empirical method does not.
- It does not rely on the reliability of the source of information.
- It gives clear details explaining the causes of damage and consequences.

Disadvantages of the method are:

- The method is time-consuming.
- It lacks built-in validation.

Despite the abundance of data that the model incorporates, it is not based on real-world observations as in the empirical model. For this reason, it can be said that the overall vulnerability function in the analytical derivation method lacks the reliability of the empirical vulnerability function.

Fig. 4 shows a model developed for the processes and mechanisms of failure of dikes [18].

For complex boundary state functions and integrated modeling of the dependencies of the failure mechanisms in the analysis of the fault tree, a closed analytical derivation of the instability curve is not possible. Therefore, the fragility curve is numerically extracted by extracting discrete state nodes.

This analysis tree shows the relationships between the events that lead to the main event, namely the event of failure. All mechanisms are modeled as stationary processes, which gives a conservative upper bound on the probability of failure. Failure mechanisms are divided into three categories: hydraulic, geo-hydraulic and geostatic [18].

Hydraulic and geostatic events are individual events that lead directly to failure. In the hydraulic category, the mechanism for failure of the erosion stability of the slope of the dike is taken into account. A triggering event can be a crest overflow due to the waves caused by wind.

For events of geostatic failure, the stability of the slopes of the dike is analyzed by the segmental method of Krey [18] for the calculation of sliding surfaces. Separation into macro and micro-stability is carried out, too.

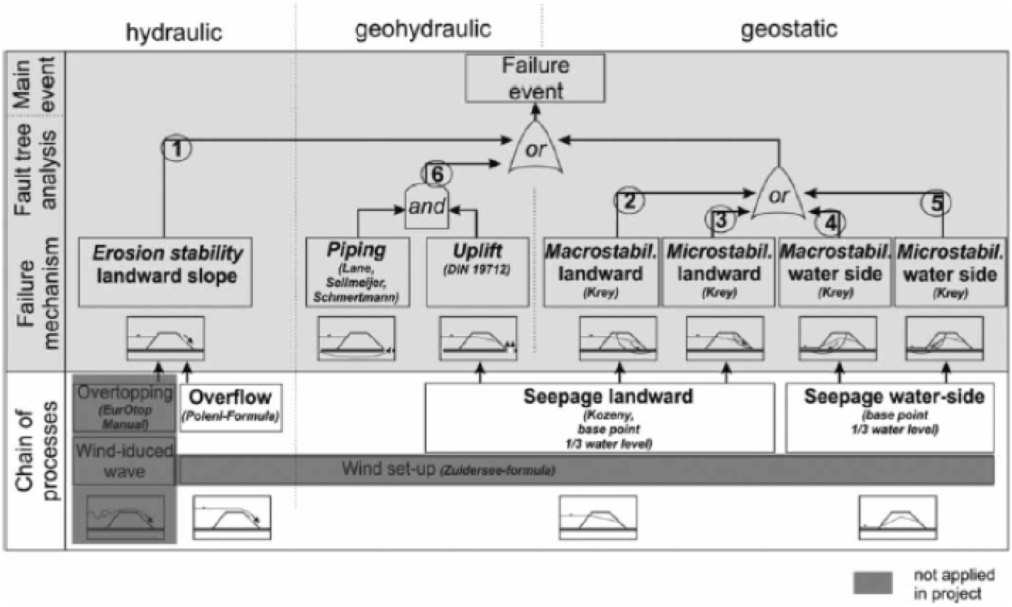

Figure 4. Fault tree analysis, failure mechanisms, process chains and the hierarchical order of failure mechanisms (numbers) of a dike implemented in PROMAIDES [18]

In the category of geo hydraulics, filtration scenarios under the dike base are included in combination with intersecting pipeline filtration.

Considering the analytical derivation of vulnerability curves, many other sources also can be referred to in presenting analytical approaches to the vulnerability of engineering systems and facilities. As an example, the Czarnecki's method and its later modifications can be mentioned here for the use of laboratory test data for the fragility of building components and applied construction cost-estimation principles to the estimation of repair costs.

2.3. Expert Opinion

When there is a lack of empirical data, or the analytical method is too resource consuming, one can draw on expert opinion.

Essentially, the process involves gathering several experts (in the order of 5 to 10) covering particular profiles together in a meeting and presenting to them as detailed as possible the case of interest. The expert team has then the task to evaluate the possible losses for different levels of external impact (such as earthquake, wind, flood, etc.) as well as in some cases to quantitatively assign values of probability of occurrence to the corresponding branches of the event tree into consideration. Of course, all experts should be quite well familiar with the investigated facility and the process of its operation.

Assumptions are treated as if they were actual observations, weighed in proportion to the judgment or experience of the experts, and combined to create vulnerability functions for the class of impact and facility or latter's component.

Formal methods to elicit expert opinion date at least back to the 1960s [16].

The advantages of this method are:

- Expert opinion is very efficient, capable of produce a new vulnerability function at the cost of a few person-hours.
- Possibility to evaluate the performance of an object that has not yet experienced a significant impact, and to evaluate the effects of object characteristics as a state of soft history.

The disadvantages of this method are as follows:

- Lack of credibility because the result cannot be objectively tested.
- Underestimation of uncertainty.
- Experts often have an exaggerated idea of their own potential.

3. Operation of Small Dams in Bulgaria and Their Vulnerability

The dam is a complex natural-technical system constantly under the influence of various and changing impacts. In order to be able to fulfil its intended purpose sufficiently reliably, this system must be permanently and professionally monitored and maintained. These activities represent the so-called technical operation of the dam and its facilities. The water economy operation of the dam consists in the management of the dam reservoir for the fulfilment of the water economy goals set by its building.

The number of small dams is significantly greater than that of large ones; this is a well known fact. Large dams represent about 10% of the total number of dams worldwide. They are technically well operated with sufficient resources for the necessary activities. This is related to the fact that large dams have great regional and national importance in many fields of the economic and social life.

There are much less resources for the technical operation and maintenance of small dams. Furthermore, small dams are in general designed and built for lower intensity levels of loads and impacts. Thus, the secondary risk of these systems in the case of possible failure increases. Furthermore, they have been built according to old design and construction methods, thus often not corresponding to meanwhile upgraded contemporary safety requirements. Along with the natural impacts such as hydrological and seismic hazard, other phenomena (human factor, lack of maintenance, non-functional equipment, etc.) also increase the probability of damage or failure of the system. Based on all these considerations, the consequences of such undesired event have to be evaluated and quantified in every particular case in order to assess the weaknesses of the system, i.e. its vulnerability. Hence, a unified approach to the evaluation of the operational vulnerability of small dams is strongly needed. On the one hand, such approach has to be general enough to allow its implementation at least to the vast majority of existing small dams. On the other hand, it should enable accounting for the individual system parameters in every particular case. It became clear from the shortly presented review above that there is no comprehensive definition of operational vulnerability which could be directly implemented to the field of small dams.

The problems with the operation of more than 5000 small dams in Bulgaria represent legal, administrative and technical issues, resulting mainly in the technical conditions of the dam and its appurtenant structures and its ability to fulfil the water economy tasks, respectively.

The shortly summarized problems in the operation of small dams in Bulgaria are:

- Unclear property – there are striking cases where the dam and its appurtenant structures is owned by an individual while the land beneath the lake is owned by other parties.
- Lack of qualified staff – the lack of qualified personnel is a serious problem which over time results in improper operation of the facilities.
- Lack of financial resources – currently, a central administrative mechanism is being introduced by the state for overcoming this problem.
- Lack of interest from water users – due to the destroyed agriculture in Bulgaria in the last 30 years, the absence of water users is a major problem because the dams are not used for their intended purpose [19].
- Lack of technical maintenance in the last decades – this has led to a deteriorated technical condition of a large number of small dams.

Figure 5. Damage of an eroded chute after spillway

Figure 6. Damage crest area after overflow [19]

Based on the above discussion, we would suggest herewith the following formulation of the operational vulnerability of small dams. In general, it is illustrated by Fig. 3 considering the remarks made here just above the figure. However, the computational procedure has to be carried out (no iteration!) for all main impacts which occur in the lifetime of the system over their intensity ranges. Some of them have stochastic nature, e.g. flood or earthquake. For obtaining probability distribution functions, a statistically representative number of simulations have to be performed. Furthermore, a set of typical damage / failure scenarios have to be formulated, and a damage-loss relation has to be introduced. After summing the contributions of all particular vulnerabilities by taking into account all conditional probabilities where available, the total vulnerability function for the small dam system can be obtained.

4. Conclusion

The presented work constitutes an attempt for introducing the vulnerability concept to the operation of small dams based on the review of some existing applications of it. This approach would allow for a separate and clearer assessment of hazard and vulnerability as two components of risk. In a subsequent research step, implementation of this idea for typical case studies is strongly needed.

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УЯЗВИМОСТ НА ЕКСПЛОАТАЦИЯТА НА МАЛКИ ЯЗОВИРИ – СЪСТОЯНИЕ НА ПРОБЛЕМА

Б. Николов[1], Д. Кисляков[2]

Ключови думи: *малки язовири, уязвимост, експлоатация*

РЕЗЮМЕ

Язовирът е сложна природно-техническа система, която е под действието на различни и постоянно променящи се фактори. За да може да изпълнява достатъчно надеждно своето предназначение, тази система трябва да бъде постоянно и компетентно наблюдавана и поддържана. Тези дейности представляват т.нар. техническа експлоатация на язовирната стена и съоръженията към нея. Водностопанската експлоатация на язовира обхваща дейностите по управлението на завирения обем за изпълнение на поставените с неговото изграждане водностопански цели.

В настоящата работа се дефинират основните понятия, свързани с техническата и експлоатационната надеждност на язовира, респективно с неговата уязвимост. Представя се съвременното състояние на знанието по основните аспекти на тази уязвимост. Въз основа на извършения преглед се предлага идеята за използването на концепцията за това понятие за малките язовири като част от изследването на техния риск.

[1] Богдан Николов, инж. докторант, кат. „Хидротехника и хидромелиорации”, УАСГ, бул. „Хр. Смирненски“ № 1, 1046 София, e-mail: b.nikolov.vd@abv.bg

[2] Димитър Кисляков, проф. д-р инж., кат. „Хидротехника и хидромелиорации”, УАСГ, бул. „Хр. Смирненски“ № 1, 1046 София, e-mail: kiss_fhe@uacg.bg