JOURNAL OF THE KOREAN SOCIETY OF AGRICULTURAL ENGINEERS MAR. 2003, pp. 35-44

한국농공학회지
제45권 제2호

Lifetime Reliability Analysis of Irrigation System

관개조직의 수명기간 신뢰성 해석

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Abstract

A system reliability method is proposed to decide reliable serviceability of agricultural irrigation system. Even though reliability method is applied to real engineering situations involving actual life environments and maintaining costs, a number of issues arise as a modeling and analysis level. This article use concepts that can be described the probability of failure with time variant and series-parallel system reliability analysis model. A proposed method use survivor function that can simulate a time-variant performance function for a lifetime before it is required essential maintenance or replacement to define a target probability of failure in agricultural irrigation canal. In the further study, it is required a relationship between a state of probability of failure and current serviceability to make the optimum repair strategy to maintain appropriate serviceability of an irrigation system.

Keywords : System reliability, Time variant performance function, Life time, Probability

I. Introduction

Agricultural structures are spatially scattered over rural area. It is necessary for assessment of the structural performance to evaluate a reliability of overall lifetime as well as to consider environmental load conditions. However, since it is not possible for all manager and supervisor to reuse an available initial design record and construction files of the agricultural facilities,[9] which makes difficulties evaluate serviceability of the agricultural irrigation systems in a deteriorating process and the variance of the capacity that can preserve an acceptable degree of the serviceability. Those are usually main-tained with visual inspection without sufficient information of actual condition states, because it

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can't reflect exact deficiency or physical deterioration of components of reservoir or irrigation canal system. Aging irrigation systems subjected to corrosion or deterioration means that existing systems often fail to satisfy requirements as specified for new systems. It must be a strong financial incentive that existing irrigation system should be conserved and their remaining service life extended for constant productivity in the field.[9)]

In general, performance of an irrigation system is conducted to either: 1) confirm an existing requirement (if decreasing water requirements is not suspected), or 2) sustain a storage capacity of reservoir and canal whether those are decreased by corrosion or sinking obstacles. Analytical or predictive approaches to determining performance of irrigation system are well documented, however, since it is not desirable that existing system may not behaved in idealized or conceptual manner, such an approach may result in retaining or replacement of the components that are in fact 'satisfactory'.[7)]

The reliability concepts may be used to verify or assess analytical or predictive system models. A reliability system model can measure directly risk and consequence of failure in service conditions.[6)] In this study, components are used to identify potential deficiency resulted in failure and malfunctioning of the system. Even if a component maintains a proper reliability without severe damage for a lifetime, the balancing performance should be checked over a lifetime. But it is hard to be provided by the basic inspections without system evaluation models, because there is no method to estimate effect of the failure or malfunction of any components.[9)] It is required that techniques and analytic methods about degradation model should be introduced for the agricultural facilities. As a result, it reduces uncertainty associated with the performance of irrigation system and reveals target elements to increase its reliability state. Their approach and results exactly demonstrate an acceptable reliability of degraded system to owners or supervisor and they can evaluate structural grade and probable serviceability of structures with cumulative damages for a lifetime.[14)]

In this article, considers a practical implementation of such a probabilistic approach, in this case by using reliability-based method, FOSM, to propose target reliability index[6)] of an irrigation system consisted of two basic components. Hence, the present paper proposes to implement the maintenance plan for agricultural facilities over a lifetime using time variant reliability theory. And it is expected this study contribute manager or supervisor of agricultural facilities to maintain the histories of performance. And then, this result will be adapted to Korea for the decreasing rehabilitation and repair cost of facilities. It is considered for an irrigation system with a short-term, however, cost-benefit analysis is not considered herein.

Ⅱ. Approach Methods

1. Components of the Irrigation System

An irrigation system consists of water resources and delivery parts. Reservoirs and pump stations can be used for water resources of the irrigation system. However, when reliability theories are applied to solving uncertainties, sometimes, it is not convenient approach to gather and to analyze all of random variables. In this study, first, reservoir component only is investigated, because it is difficult to acquire the operation and maintenance history of pump station. Consider random variables of irrigation system to represent serviceability condition with relationship between resistance variables and load variables.

- Reservoir component: hydrological performance, storage capacity, physical state
- Canal component: capacity of main canal, lateral canal, and tributary canals

2. Probability Function of Components

In general, the type of failure mode in serviceability of agricultural reservoirs can be summarized; one of components is disabled for service, partly failed, or trivial defected. As reported by ICOLD (1983), there are several causes that resulted in dam failure such as overtopping, sliding, piping and leakage, foundation failure, etc. Agricultural reservoir consists of embankment, spillway and canal, intake tower or inclined conduit, tunnel, and appurtenant. It is necessary for the probability assessment of reservoir to define a failure probability function of each component, but it is very difficult to find the function of each component, because it can be achieved through structural analysis such as slope stability and seepage analysis.[9),10)] In this study, it is assumed that if components are statically independent, structure is a series system with each component and failure probability function of a structure can be proportionally described by the failure probability of one of the components. To define overall performance function of agricultural reservoir analyses precise safety assessment reports of agricultural reservoirs are performed by KARICO (Korea Agricultural and Rural Infrastructure Corporation).

A. Failure probability of hydrological performance of reservoir

Causes frequently leading failures of dam are represented in the report of ICOLD (1983). Those are foundation deficiency, overtopping, piping, seepage, etc. It can be summarized by the annual conditional probability; over flow, 34%; seepage and internal flow, 43%; slope stability, 16%; others, 7% and occurrence ratio of failure with main causes in earth fill dam as shown in Fig. 1 with aging effects. About 96% of agricultural reservoirs in South Korea are over 15 years and about 85% of agricultural reservoirs are constructed before 1970's. Therefore, it is necessary for this proportion of agricultural reservoirs to be maintained because most of them are exposed without appropriate maintenances on time.[9)]

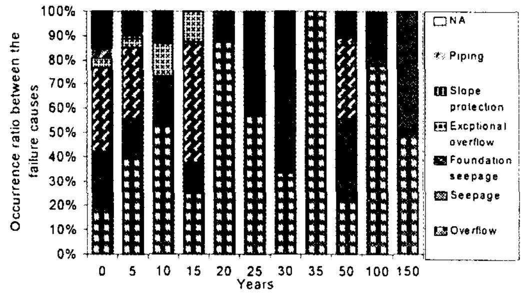


Fig. 1 Occurrence ratio between failure causes of earth fill dam (ICOLD, 1983)

So far, since design of dam dealt with mostly hydrological capacity, design flood for a dam is chosen by the anticipated consequences of failure due to hydrological events. In general, a reconnaissance-level appraisal of the major social and economic consequences of failure may be adequate for selection. Where the decision is less obvious, a more through and detailed evaluation of failure consequences may be required.[2),3)] To reduce the effort required safety design flood with deterministic procedure, flood of a watershed must be formulated by adjustable probability distribution. In this mode, limit state equation consists of demand and capacity of spillway. Adequate capacity of a spillway has to carry the expected peak inflow made from an extreme flood of watershed. For a spillway with side canal, the discharge is given by USBR[5)] (1977) Eq. (1). The peak flow of an extreme flood have to carry over the spillway as soon as the flow arrived the spillway, because storage of agricultural dam assumed that full water level should be kept up. The inflow rate Q is the peak flow upstream to the reservoir.

$$M = nCLH^{3/2} - fQ \quad \cdots\cdots (1)$$

where C is the discharge coefficient that is influenced by a number of factor such as depth of approach canal, upstream face slope, etc.; L is the effective length of the crest; H is the total head on the crest, including the velocity of approach head; n is the correction for imperfection in the empirical formula; Q is peak runoff of watershed; f is the attenuation factor to account for the volume effect of the reservoir, M is a marginal safety of a spillway.[1)]

Each variable has to be assigned as an appropriate probability function through an adjustable statistical analysis.[1)]

B. Probability function of reservoir based on severity conditions

Most reservoirs are all deteriorated eventually for a lifetime. States of deterioration are mainly consisted of dam body deterioration, concrete defects, and facility erosion that are cause by employed time and condition of management. The deteriorating appearance of each structural part was investigated by analyzing the PSAAR (Precise Safety Assessment Annual Reports)[9)] data from 1996 to 2000. It is assumed that performance of a reservoir can be taken in to account by the statistical properties of physical defects on the parts of reservoir. This properties are useful in practice for determining the distribution of the reliability of a reservoir at given age. The probability of severity which is a state condition of physical defects is defined by statistical analysis of physical state of reservoir.[9)] And the system model constructed with series system because if one of components fail then dam will be failed to perform the objectives.

Condition of severity 3 is defined as one of components is fully deteriorated, severity 2 means that one of components partly deteriorated, and severity 1 means that one of components has trivial defects. The failure probability of serviceability in physical condition means that the reservoir fails to supply the required yield. The cumulative reliability function is shown Fig. 2. This function of Eq. (2) is investigated as Weibull distribution with two parameters by best-fitness method.[14] We have interests in the low probability zone of $F(t)$, since it is assumed that reservoirs usually are maintained before reaching severe condition. In this paper, $S(t)$ which is reliability function of performance or survivor function of system can be represented by the Eq. (3) as a complemental function of $F(t)$.

$$F(t) = 1 - e^{(-(\lambda t)^{x})} \quad \cdots\cdots (2)$$

$$S(t) = 1 - F(t) \quad \cdots\cdots (3)$$

where, $F(t)$ is cumulative probability function of severity 3 in age t, λ and x are scale factor and shape factor of Weibull distribution, respectively.

It is assumed that the severity of condition state of reservoir is independent on the other random variables such as storage capacity, hydrological performance. In the Fig. 2, though system function for reservoir have scale factor $\lambda(=.007)$ and shape factor $x(=2.60)$ in the condition of severity 3, scale factor and shape factor of embankment are higher than those of reservoir system. Scale factor $\lambda(=.0057)$ and shape factor $x(=3.45)$ of embankment are also

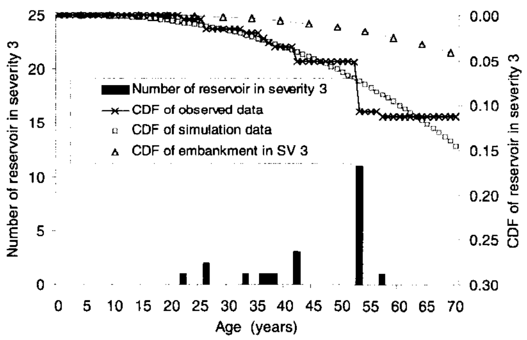


Fig. 2 Cumulative probability of reservoir and embankment in severity 3

parameters of Weibull distribution.

C. Probability function of irrigation canal

Most of canal produced by reinforced concrete have open canal type. Thus, it can be assumed that each branch of canal is able to use a survivor function to describe a degradation of structure over lifetime.[14] Information on parameters of canal capacity can be updated prior condition by inspection. In this approach, it is assumed that capacity of each canal components can be measured at control points of canal and capacity of the canal will be decreased gradually until transported sediments of the irrigation canal are removed and defected parts of canal are repaired. In general, sediment removal are treated as annual maintenance, therefore capacity of concrete canal will be influenced by deterioration of concrete. As time passed, failure probability in providing water to paddy field may increase, and there is a strong financial incentive that existing structures be conserved and their remaining service life extended. Parameters taking into account conventional essential maintenance pattern are achieved by numerical method. In general, agricultural canal should be replaced between 15 and 20 years because their lifetime depends on the performance of carrying water to field with low leakage rate. For overall performance of an irrigation canal, individual parameter related to canal capacity assumed that they vary with age. The probabilistic capacity degradation model considering leakage, serviceability, and physical deterioration should be analyzed by inspection data, however, it is difficult to investigate those data. Since in the present context the main emphasis is on the usage of probabilistic model for determining system performance, in the following analysis, their performance function is temporary used two parameters Weibull distribution also.

Ⅲ. Reliability Analysis for Performance of A Irrigation System

Compose limit state equations for each component of an irrigation system, and make out failure path (i.e. cut-set). In each failure path, if it has a failure of upper level component in the irrigation canal, directly descended canal must be failed because water can't be delivered to lower level. It can be considered by correlation matrix with hierarchy of canals. However, in this study, it is not included because it is difficult to acquire hierarchical data of canals. Reliability analysis of irrigation system performed is to define target reliability index. In this study, it is calculated by using hydrological performance of reservoir, and it is applied to decide the serviceability level of irrigation system for a lifetime.

1. Define A Target Reliability of Irrigation System

Probability of failure in functioning of irrigation canal can be evaluated by serviceability, because an irrigation system can't provide requirement water to paddy field any more, it is assumed that system is failed. For the small paddy field, it is analyzed system reliability of safe and stable delivery system in order to supply a maximum water requirement during the rice planting season. Capacity of canal is always decided by which maximum requirement of paddy field should be provided for one or two days. Table 1. shows a result of irrigation canal design to deliver requirement of water at the paddy fields. Sum of two branches is 19.1 km and this irrigation system has covered 903 ha of an example paddy field.

In the Fig. 3, irrigation schematic diagram for example is shown. There are two main lines and each main line is designed to transfer required water from water resource to lateral canals. Since time to the field is only influenced according to condition of canals and area of paddy

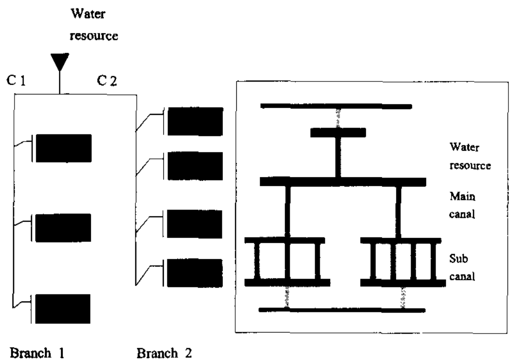


Fig. 3 Hierarchical model and function model of target irrigation system

Table 1 Design example of an irrigation canal system

(Unit: m^3/s)

Branch type	Main 1	Line 1-1	Line 1-2	Line 1-3	Main 2	Line 2-1	Line 2-2	Line 2-3	Line 2-4
Capacity	2.500	0.600	0.1089	0.2539	1.250	0.280	0.1883	0.1461	0.1235
Demand	2.174	0.343	0.0720	0.1410	0.708	0.072	0.0500	0.0410	0.0370

field, for constructing target reliability of an irrigation system, it is assumed that failure probability of water resource system can be evaluated by one of Eq. (1), or Eq. (2).

As an example, each parameter of Eq. (1) and type of distribution are shown in Table 2. All of the parameters that represent these random variables are taken from the existing literature,[1] and dispersion of the assumed distribution, uncertainties are assumed with engineering point of view.

Table 2 Statistical data of variables of the spillway performance function*

Variables	Parameter 1	Parameter 2	Type
N	1.0	0.200	Normal
C	2.85	0.270	Normal
L	64.0	1.700	Normal
H	1.00	0.220	Normal
F	0.70	0.098	Normal
Q	21.0	0.028	Type I Large

* Type and parameters are all assumed.

Target reliability calculated by system reliability analysis model, RELSYS[6] are shown in Table 3. From this results performed by reliability theory (First order reliability method), it shows how to define a serviceability condition of an agricultural irrigation system by using the probability of failure. For example, if dimension and requirements of canals do not change, we can suppose that probability of failure for an irrigation system is not changeable.

Geometric and material properties will be deteriorated during a lifetime. It was assumed that a deterioration process of structural parts could be modeled by survivor function like a Weibull function. Usually, after the agricultural infrastructures are built, there may be no damage in a few years. Therefore the mathematical degradation of channel performance is applied to simulate reduced capacity caused by changed discharge coefficient and leakage came from

Table 3 Reliability index of components and reduction systems

Components	L.S.E.	Probability of failure (β)	Reduction process 〈Probability of failure and reliability index (β)〉				
Main canal 1	1	0.163 (0.98)	*Assemble 11* (*Series*)	0.163 (0.983)	*reduced system 13*	1.33E-3 (4.20) Parallel	*reduced system 15*
Main canal 2	2	0.000082(3.77)	*Assemble 12* (*Series*)	8.16E-3 (3.77)	*reduced system 14*		
Sub 1-1	3	0.00011(3.7)	1.1E-9 (6.68) (*Parallel*)	*Reduced system 11*			
Sub 1-2	4	0.00022(2.85)					
Sub 1-3	5	0.00005(3.89)					
Sub 2-1	6	0.0(7.2)	0.00 (10) (*Parallel*)	*Reduced system 12*			
Sub 2-2	7	0.0(7.1)					
Sub 2-3	8	0.0(6.9)					
Sub 2-4	9	0.0(6.7)					
Resource	10	0.0126(2.24)	*Assemble 15*	0.0126 (2.24)		***Final system***	

* L.S.E is number of limit state equation

several damages from the time they started to use. They are plotted based on Weibull distribution of failure probability with time variant when the target probability of failure is between 10^{-2} and 10^{-3}. In the Fig. 4, it is shown the result of parametric study for the survivor function using the Weibull distribution. It is assumed that each component is independent and corrosion rate of concrete structure, λ is varied from 0.005/year to 0.02/year. Even though the corrosion rate or deterioration rate is necessary to verify by statistic analysis, however, parameters of Weibull distribution for canal are chosen by an engineering point of wiew. If the proper function was made by further study, it can be used to know when maintenance action must be applied on a system during the service life as well as how to optimize maintenance option for a long term.

In order to construct model simulating damage states of irrigation structures survivor function, $S(t)$ is applied with the parameters, $\lambda=0.017$ and $k=2.0$. It is used to describe when the system reliability would be degraded with high gradient. The parameters of canal component are described in Eq. (4).

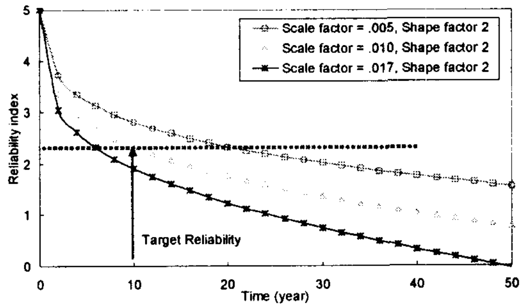
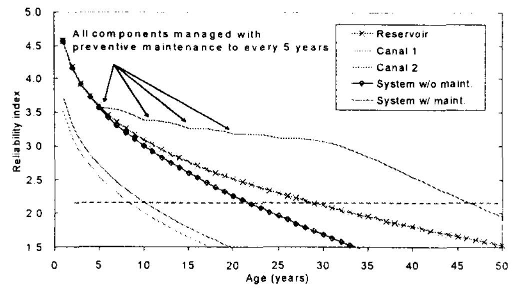


Fig. 4 Survivor functions for structural parts of an irrigation canal

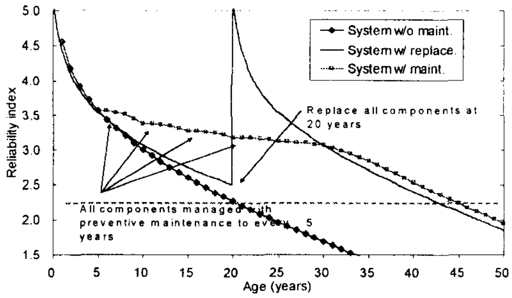
$$S(t)=e^{(-(.017\cdot t)^{2.0})} \quad (4)$$

2. Evaluation of maintenance option for a irrigation system

Reliability index curves of Fig. 5 are as result that is applied with survivor function of reservoir. In order to quantify, for the first time, it is assumed that initial reliability index is higher than 5.0, the beginning performance of system is reduced with high gradient because cumulative deterioration process appears justly in nonlinear reliability index curve at that time. For the one of the survivor functions that has the parameters, and compare reliability indxe of system with reliability index of components in Fig. 5 a). In Fig. 5 b) according to preservation maintenance pattern shows change of performance function that change. Preventive maintenance is recognized for the cost-effective maintenance strategy to be successful, it means that maintenance should be on the timing of the activity and the quality of the work performed better than resulted in from early reconstruction of structures deferred maintenance.[12] Even though preventive maintenance is applied to a system with optimum interval, activities do not significantly improve the capacity of system but extend the useful life and improve the level of service. Because preventive maintenance strategy intended to arrest light deterioration, retard progressive failures, and reduce the need for replacement maintenance and several services activities. And since it is cyclic or periodic action in nature, it is very important thing to define what is the preventive replacement rate or optimal interval for next maintenance based on the cost for each policy.[12]



a) Performance function of each component and preventive maintained system



b) Comparison of performance function of preventive maintained system and replaced system

Fig. 5 Time variant reliability index with various survivor functions

Ⅳ. Conclusions

In this paper, we have proposed a system reliability method to decide appropriate rehabilitation strategy for agricultural irrigation system. Even though reliability method is applied to real engineering situations involving actual life environments and maintaining costs, a number of issues arises which further study and discussion. This article is used two concepts which can be described the probability of failure with time variant and series-parallel system reliability analysis model. One study at the University of Colorado can evaluate the reliability of system using the RELSYS. The result of the analysis is used to assume the target probability of failure for an agricultural irrigation system, between 10^{-1} and 10^{-2}. The other is used to make a system performance function that can simulate reliability index with survivor function of a reservoir, $S(t) = e^{(-(.007 \cdot t)^{2.6})}$ and $S(t) = e^{(-(.017 \cdot t)^{2.0})}$ for a survivor function of main canals. In the further study, to make an optimum maintenance strategy maintain appropriate serviceability of an irrigation system, a relationship between a state of probability of failure and current serviceability shoud be revealed based on the experimental and statistical researches.

Acknowledgements

The financial support of Korea Science and Engineering Foundation (KOSEF) is gratefully acknowledged. The opinions and conclusions presented in this paper are those of writers and do not necessarily reflect the view of the sponsoring organization. The writers would like to thank Dan M. Frangopol and Yang S.I. for discussion and assistance in completing the analysis described herein.

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