学位論文要旨

降雨と地盤特性の不確実性に対する堤防の安全性評価に関する研究

—確率過程論と信頼性解析の河川工学への導入—

Study on Safety Evaluation of Levee for Uncertainty of Rainfall and Soil Properties
-Introduction of the Theory of Stochastic Process and Reliability Analysis to River Engineering

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Background and Aim

Due to the global climate change, the scale and frequency of natural disasters are more difficult to predict and measure. Extreme rainfall often brings an astonishing amount of water and causes very serious damage. According to the report of natural catastrophes 2014 "Analyses, assessments, positions 2015 issue", most of the loss events are caused by the meteorological events and hydrological events are the most natural events during 1980 to 2014. Here the natural disaster events can be subdivided into the following four types, geophysical events, meteorological, hydrological and climatological events. From this statistic result, we can observe that in addition to geophysical events, other events induced by weather or climate change are growing year by year. In particular, in East Asia, there are serval typhoons hit every year. Therefore, how to predict, prevent and reduce the loss from natural disasters is a very important issue.

However, most of the past studies on the analysis of natural disasters are based on the deterministic theory, it means that the analyses are only two results, safe or failure. It's not enough to illustrate the real environment because there are a lot of uncertainty factors that would affect the occurrence of disasters. Moreover, all these natural disasters would affect the human activities like economic, transportation, social development and so on. Therefore, the most important is how to evaluate the hazard of disasters by considering the uncertainty of the disasters. Until now, the prevention and reduction of a natural disaster are mostly based on the deterministic evaluation/design model however it exists some problems. First is the result of dichotomy, safe or failure, no transition from safe to failure. Second is the uncertainty of parameters that are usually decided by observation or laboratory experiment. It's not enough to explain the realistic environment. Final is without considering the risk tolerance, or just by the safety coefficient like the freeboard of the levee. Therefore, in the thesis, the aim is by the introduction of the theory of stochastic process and reliability analysis, the probability concept can be applied in the river engineering.

In the past studies, the evaluation of natural disasters usually analyzed by deterministic theory. Therefore, the result of the analysis dichotomy, safe or failure. However, it is difficult to explain the reality of real environment. Generally, the uncertainty would have two possible types, one is the limitation of observation or experiment and the other is an error of data. The uncertainties come from three possible sources. First is intrinsic quality of social, economic or natural phenomena. Second is limitation of the knowledge. Final is from decision making. For the evaluation of reliability design, there is two operations, one is the calculation of failure probability, and the other is decision making. For the failure probability, it's the purely mechanical problem with considering the basic mechanical properties. Therefore, the necessary work is the investigation and statistic of parameters. For the decision making, the best option should be select among all the solutions. This study is mainly analyzes of natural disasters and therefore the content of this chapter will discuss the uncertainty of the basic mechanical properties.

Scope and Contents

In the thesis, there are main six chapters. The following will explain the contents of each chapter.

Chapter 1 is the introduction of the thesis. First is the background information including of the levee of Japan and the disaster types of levee. According to the statistical data of MILT (Ministry of Land, Infrastructure, Transport and Tourism) in March, 2015, the total levee length of the government-administered rivers is 8,784.2 km. The basic structure of levee is including of design high-water level (H.W.L.), freeboard, crown and the slope of the levee. The height of levee is design high-water level plus the freeboard, that is according to the "Government Ordinance for Structural Standard for River Administration Facilities." In general, the common failure types of levee can be subdivided into three types, overflow/overtopping, erosion and infiltration failure.

Second is the explanation of uncertainty, occurs when a collection of values associated with respective uncertain "states of nature" occur with strictly non-negative probabilities for a least different possible values.

Final is the research aim, the category and thesis scope. The status of the reality levee is very complex. It can be divided to two respects, one is the conditions of the levee, and the other is the effective of water level from the terrain of the river. The soil material is inhomogeneous from the soil characteristics, construction and others. The effective of water level is from the terrain of the river and it will affect the design of the levee. Therefore, before solve all these complex problems, in the thesis, I will propose a new method to evaluate the reliability analysis of levee safety by simplification the above problems.

Chapter 2 is the hydrology model based on the stochastic process theory. There are a lot of probability methods to calculate the water level of flood and herein the authors would use the method, which based on the relation between the runoff heights of stochastic differential equation and the mathematic equation of Fokker-Planck to obtain the uncertainty of rainfall and runoff.

First is the basic equation of a generalized rainfall-runoff model by mathematics. The equation applied to the single slope plays a very important role in the thesis.

Second is the definition of the uncertainty of hydrology. Uncertainty in rainfall observation and estimation also can be categorized into natural inherent variability (aleatory) and knowledge uncertainty (epistemic). The data of rainfall is got from the several methods like rainfall gauge in the ground or weather radar. With different method, it exists the following uncertainty. Aleatory uncertainty of rainfall consists of physical uncertainty with temporal and spatial. On the other hand, the uncertainties in hydrology model stem mainly from the three important sources, observational uncertainty, model uncertainty, and parameter uncertainty.

Third is the stochastic process theory including of its development to be the basis for the stochastic process of the hydrological model. It is subdivided to the two parts: the developments of the stochastic different equation theory and the probability density function.

Final is according to the above sections, herein the uncertainty of water level will base on the relation between the runoff heights of stochastic differential equation and the mathematic equation of Fokker-Planck to obtain the uncertainty of rainfall and runoff.

Chapter 3 is the stability analysis of levee. The types of levee failure can be classified to infiltration failure, erosion failure and overflow/overtopping failure because of the increasing water level during rainfall. In the chapter, the infiltration failure will be discussed by the slope stability method.

In general, the analysis method of slope stability categorized into circle slide method and infinite slope method. The safety factor of slope is defined as the ratio of the shear strength divided by the shear stress required for equilibrium slope. In japan, the method most commonly used is the Ordinary method of slices (Fellenius, 1927), and second is Bishop's Modified Method (Bishop, 1955). However, the pore water pressure in Fellenius method are treated as acting perpendicular to the sliding surface. When the slip surface gradient becomes large, the pore water pressure will be excessively calculated. In order to solve the such problem, the Modified Fellenius method has be suggested. Furthermore, failure of soil slopes, both natural and man-made, during or shortly after rainfall is a commonly occurring phenomena. It means that water is the most important factor in most of the slope stability analysis. Pore water in soil can strongly influence the physical interaction among soil grains. Changes in pore water pressure can directly affect the effective stresses, which in turn, affect both the shear strength and consolidation behavior of soil. Therefore, analysis of pore fluid seepage plays an important role in the solution of many geotechnical problems, especially those concerning the stability analysis of slopes and man-made structures. Thus the know-how about the infiltration is very important for the stability analysis of levee. There are a lot of methods that can calculate the seepage face and can be can be categorized into experiments method, analytical method, numerical method, semi-theoretical method and so on. The following will introduce the Casagrande's method (1932, 1937) and Uchida method, then propose a new method for the solution of seepage face.

Second is the uncertainty of soil parameters. Soils are geological materials formed by weathering, erosion and sedimentation processes and so on. They have been subjected to various stresses, pore fluids, and physical and chemical changes. Thus, it is hard to decide by experiments with some specific boring sites. In other words, the uncertainty of soil parameters comes both from the spatial variability and from errors in testing. Final is the infiltration failure probability of levee. For the infiltration failure evaluation of the levee, the thesis uses the circular slip method of slope stability to calculate the safety factor of the levee slope.

According to the above section, the modified Fellenius method is be used. In the equation, the main parameters of the equation are soil cohesion, soil friction angle, the weight of the soil block, the pore water pressure and the geometry conditions of the circular slip. Among these parameters, the geometry conditions are according to the slip surface to decide, the pore water pressure and the weight are change with the water level change, and the soil cohesion and the friction angle are usually decided by the lab test or in situ test. Traditionally, the cohesion and the friction angle are the unique value. Herein in order to consider the uncertainty of soil parameters, the variation/ deviation of the parameters will be conduct to evaluate the failure probability of the levee slope. In the thesis, the failure probability is calculated by the equation. $P_f(h) = \frac{n_h}{N_h}$.

Chapter 4 is the reliability analysis. Reliability is probabilities or statistics in mathematics. Therefore, the performance of phenomenon or decision must display by probability. For example, the expression of "absolute safe or failure" is impossible and relatively "99% safe" or "99% failure" is used. In other words, in reliability analysis or design, never failure of construction does not exist.

In this chapter, the failure probability of levee and its reliability analysis will explain as followings. Traditionally in civil engineering assessments of the risk of failure are made on the basis of allowable factors of safety, learned from previous experiences for the considered system in its anticipated environment. Conventionally, the designer forms the ratio of what are assumed to be the nominal values of external force S and resistance force R. In general, the demand function is the resultant of many uncertain components of the system under consideration. The external force function will depend on the variability of material parameters, test errors, construction procedures and so on.

In the thesis, the failure of levee can be classified two types, one is overflow and the other is infiltration failure calculated by circular slide method. The overflow failure probability is calculated by the distribution of water level. The infiltration failure is combined the probability of slip with considering the uncertainty of soil parameters in the certain water level h. The safety design is based on the failure probability of the external force. Here according to the design value of H.W.L. the failure probability may be estimated from 0 to ∞ that s is external force, f_s is the PDF of external force, r is resistance force, f_R is the PDF of resistance force and the failure condition is $R \leq s$. Finally, the summation of failure probability from the water level 0 ~ H is $\overline{P_f}(H)$ and σ_S is assumed and transferred to h_S. In numerical methods, $P_f(H)$ is equal $\overline{P_f}(H)$.

$$\overline{P_f}(H) = \int_0^{\mathrm{H}} dh_S \int_{-\infty}^{\infty} f_s(h_S, \sigma_S; h) \cdot f_R(h_R, \sigma_R; h) dh = \int_{-\infty}^{\infty} f_R(h_R, \sigma_R; h)[1 - F_S(H, \sigma_S; h)] dh$$

Probability theory is a branch of algebra with its own axioms and notation. The first notation is the expression for the probability of $f1$, where $f1$ is the first failure type, and the probability can be written as $P_{f1} = P[f1]$. In other words, the safety probability is $1 - P_{f1}$. If the failure types are dependent and more than three types, the associated probability will be shown as:

$$P_f = \sum_{i=1}^{m} P[f_i] - \sum_{\alpha<i\leq m}^{m} P[f_i \cap f_j] + \sum_{\alpha<i<j<k\leq m}^{m} P[f_i \cap f_j \cap f_k] - \cdots P[f_1 \cap f \cap \ldots \cap f_m]$$

In the thesis, there are main failure types considered, overflow and infiltration failure. Therefore, the detail probability calculated is including the following types: the only overflow failure, P_{fo}; the only infiltration failure, P_{f1}; when one of the two failures occurs, P_{f2}; when both overflow and infiltration failure occur, P_{f3}.

Chapter 5 is the scenario test. The chapter assumes some scenario conditions to simulate the failure probability of levee. The assumptions are the followings: the wetting plane is assumed that the same to the water level, the worst situation of infiltration inner levee; the infiltration directly from rainfall is ignored; the failure types are assumed two, one is overflow and the other is slide of levee by using circular slide method; the underlying material under levee is assumed impermeable layer; when the safety smaller than 1.0 is failure; the times of calculation is 10,000 times.

The calculation conditions of rainfall-runoff model is assumed. The geometry of levee is: the height of levee is7.5 m, H.W.L. is 6.5 m (freeboard is 1.0 m) and the grade is 1:2~1:5. The conditions of soil parameters are different according to the soil materials. Finally, the four results can be got: the only overflow failure, P_{fo}; the only infiltration failure, P_{f1}; when one of the two failures occurs, P_{f2}; when both overflow and infiltration failure occur, P_{f3}. Furthermore, the effective of the freeboard is also calculated. The freeboard is calculated from 0 to 1.0 m. it shows the effective of freeboard height to reduce the overflow and slip failure. The rainfall condition is the same with above section, and the average water level of calculation is in H.W.L, 6.5 m. For example, when the freeboard is 0.5 m height (the height of levee is 7.0 m), compared with overflow probability the H.W.L, the probability reduces from about 0.45 to about 0.008 and the slip failure probability reduces from about 0.07 to about 0.03.

Chapter 6 is the conclusion. Until now, the flood control management and safety of levee are usually evaluated by determinist. That's because many design aspects, the choice of nominal values/parameters are easier to decide. The reasons are: the main source of uncertainty is not explicitly considered.; compared to other scientific area, each case has its own unique characteristic with unrepeatable, therefore the database is difficult to establish. However, few data mean the analysis of uncertainty incomplete; compared to other scientific area, the civil engineering is more conservatism because that the civil engineering is very nearly the life of people.

In the thesis, the main concept is considering the uncertainty of external force- water level and resistance force- stability of levee to evaluate the reliability of levee. The followings are the conclusions in the thesis. In chapter 2, the definition of uncertainty from rainfall and soil are clear defined. In chapter 3, the failure analysis has been proposed by the stochastic process theory. It considered the uncertainty of rainfall and through the Ito process and Fokker Planck equation to obtain the rainfall-runoff model in stochastic process. Moreover, the new practical solution of seepage face inner levee is also suggested in this chapter. In chapter 4, the reliability analysis is conducted into the failure probability of levee with considering both of external force, water level, and resistance force, stability of levee, to evaluate the risk of levee. In chapter 5, the 4 scenario tests have been applied by the method of chapter 2 to chapter 4. It shows the very different result in different conditions of soil parameters. By the results of reliability analysis, the construction and reinforcement of risk tolerance can be added for consideration in the future. On the other hand, the early warning of flood can be more clearly made based on the results of reliability analysis.