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OPTIMAL RISK-BASED DESIGN OF CHAO PHRAYA RIVER FLOOD CONTROL SYSTEM FOR BANGKOK

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ABSTRACT: Risk-based design is a design approach developed for quantifying the probability of failure and the expected annual damage cost of a structural system subject to variations of load such as the river flood level and of resistance such as the strength of flood protection dikes. The approach considers the joint probability density function of the load and the resistance in the computation of the probability of failure and the expected annual damage cost. In this study, an optimal risk-based design procedure of a flood control system is developed. The design approach is a computational framework using four relevant techniques, namely flood flow simulation analysis, coincident flood frequency analysis, load-resistance analysis and optimization of risk-based design. It is applied to determine the optimal capacity of the flood control system for Bangkok based on a maximum net benefit.

INTRODUCTION

As described by the Asian Institute of Technology (AIT) and the Thai-Austrian Consortium (TAC) (1986), the proposed flood control scheme is consisted of a diversion dam at Pak Kret, a flood diversion channel from the diversion dam to the sea, embankments along the east and west perimeters of Bangkok, a sea barrier with a pumping station at the river mouth. The schematic diagram of the current situation of the flood protection scheme around Bangkok and the proposed flood protection scheme is shown in Fig. 1. In the above-mentioned study, the exceedence probability distribution of flood levels was applied to determine the probability of failure of the flood control system given a fixed dike level. However, the approach cannot quantify the probability of flood protection failure when both flood level and dike crest level vary.

A risk-based design approach is developed in this study for quantifying the probability of flood protection failure considering the joint probability density function of the flood level (or load) and the dike crest level (or resistance). Moreover, the expected annual damage cost can be estimated by analyzing the joint probability density function of load and resistance together with a consequence function of load and resistance. The solution will be the optimal capacity of the flood control system with a maximum net benefit for an optimal design return period of flood protection failure. The optimal risk-based design procedure is consisted of four consecutive steps as followed: 1) flood flow simulation analysis, 2) coincident flood frequency analysis, 3) load-resistance analysis and 4) optimization of risk-based design.

Large floodings in Bangkok and its suburban areas with a duration of two to three weeks are mostly due to flow overtopping of existing river dikes of the Chao Phraya river. The dike

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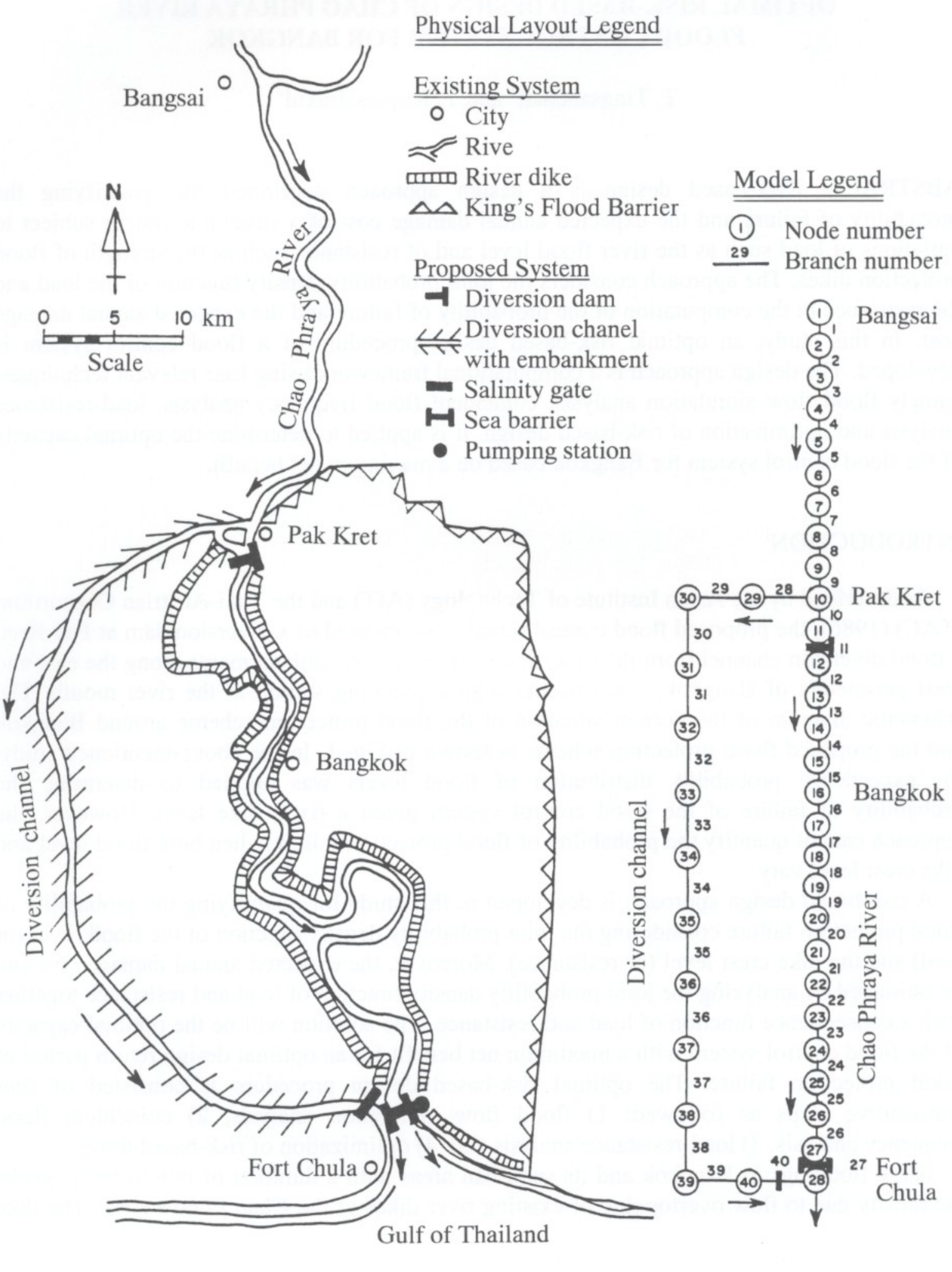


Fig. 1 Chao Phraya River, existing and proposed flood control system for Bangkok and mathematical model configuration

crest level may change locally with time due to either the natural actions such as land subsidence or due to human actions such as dike destruction. Other flooding causes are due to dike leakage and dike gate leakage. Therefore, the probability of flooding and the expected annual damage cost of flooding at Bangkok should be evaluated by the risk-based design approach.

This paper presents the original work on the development and applications of an optimal risk-based design of a flood control system to determine the optimal capacity of a proposed flood control system for Bangkok based on a maximum net benefit with a return period of flood protection failure not less than a specified minimum design return period.

DESIGN APPROACH

The procedure of the optimal risk-based design of a flood control system is consisted of four steps as follows :

1) Flood Flow Simulation Analysis: This is done by using a finite difference model for flood routing in river networks. The detail can be referred to Tingsanchali and Kitpaisalsakul (1999). The flood flow simulation model is applied to determine the relationship of the computed river flood level at Bangkok and the specified flood level boundary conditions at the upstream end (Bangsai) and at the downstream end (Fort Chula) for various alternatives of the flood control system.

2) Coincident Flood Frequency Analysis: As described by Tingsanchali and Kitpaisalsakul (1999), the dominant and non-dominant boundary stations are found to be at Bangsai and Fort Chula respectively. Therefore, the exceedence probability distribution of annual maximum flood levels at Bangsai and the average duration distribution of daily maximum tidal levels at Fort Chula covering a 3-month flood season period from October to December are developed. From the developed relationship of river flood levels in (1) and from the exceedence probability distribution at Bangsai and the average duration distribution at Fort Chula, the exceedence probability distribution of annual maximum flood levels at Bangkok can be developed. The effect of sea level rise is not considered in the analysis due to lack of previous data analysis.

3) Load-Resistance Analysis: From the results in (2), the probability density function of flooding load or annual maximum flood levels at Bangkok is determined. The probability density functions of the flooding resistances namely the river dike crest level, the dike strength and the full closure of dike gate can be constructed from field data. The consequence function of the flooding load and resistance is constructed from the flood level-damage curve at Bangkok. From the probability density functions of the flooding load and resistance and the consequence function, the risk of flooding and the expected annual damage cost of flooding for various alternatives of the flood control system can be determined.

4) Optimization of Risk-Based Design: From the results in (3), the relationships between the return period of flood protection failure, the project cost, the net benefit and capacity alternatives of the flood control system can be established. Based on the maximum net benefit for a design return period of flood protection failure for Bangkok, the optimal capacity of flood control system can be determined ultimately.

THEORETICAL CONSIDERATIONS

Load-Resistance Analysis for Flooding

The analysis uses a probabilistic approach to quantify risk of failure and expected annual damage cost of a system subject to variations of both load and resistance. The risk of failure will be considered through the joint probability density function of load and resistance (Ang and Tang 1975). Likewise, the expected annual damage cost of failure will be evaluated by analyzing the joint probability density function of load and resistance together with their consequence function relating to damage cost of failure (Plate and Duckstein 1987).

Reliability and Risk

The reliability (α) of the system is the probability that the resistance (R) exceeds or equals the the load (L). On the other hand, the risk (α') is the probability of the load exceeding the resistance. The summation of the reliability and the risk is equal to one. The risk of the system can be expressed as follows:

$$\alpha' = \int_0^{\infty} \int_0^{r=l} p_{L,R}(l,r)drdl \tag{1}$$

If the load and resistance are independent, Eq.(1) can be written as follows:

$$\alpha' = \int_0^{\infty} p_L(l)\left[\int_0^{r=l} p_R(r)dr\right]dl = \int_0^{\infty} p_L(l)P_R(l)dl \tag{2}$$

where $p_L(l)$ = probability density function of load evaluated at $L = l$, $p_{L,R}(l, r)$ = joint probability density function of load and resistance, $P_R(l)$ = cumulative probability density function of resistance evaluated at $R = l$. It is noted that the risk is equivalent to the integration of the joint probability density function of load and resistance over the area where the load exceeds the resistance.

Expected Annual Damage Cost

The estimation of the expected annual damage cost considers the joint probability density function of load and resistance. In addition, it requires a consequence function which quantifies the damage cost corresponding to each joint probability density function of load and resistance. The expected annual damage cost is defined as the integral over the whole (l, r) plane as

$$E(D) = \int_0^{\infty} \int_0^{\infty} K(l,r)p_{L,R}(l,r)dldr \tag{3}$$

where $E(D)$ = expected annual damage cost, $K(l, r)$ = consequence or damage function which depends on load and resistance.

The flood damage cost depends on flood level and can be represented by a flood level and damage cost relationship called the consequence function $K(l)$. Flood damages occur when the flood level exceeds the dike crest level or $l > r$. Therefore, Eq.(3) is expressed as follows:

$$E(D) = \int_0^{\infty} K(l)\left(\int_0^{r=l} p_{L,R}(l,r)dr\right)dl = \int_0^{\infty} K(l)p_L(l)P_R(l)dl \tag{4}$$

where $K(l)$ = consequence function of load. Note that Eq.(4) is derived analogously to Eq.(2). This indicates that the estimation of the expected annual damage cost is correlated with the risk computation. Hence, the method is called risk-based design.

Optimization of Risk-Based Design

The implementation of the structures leads to a project cost. On the other hand, it beneficially leads to a reduction in the expected annual damage cost, which can be considered alternatively in term of a project benefit. In the design, the decision parameters, X's, are the basewidth of the diversion channel and the pumping rate at the sea barrier. In the optimization, the objective function is to maximize the net benefit by searching for the optimal design parameters from the relationship between the design parameters and the corresponding net benefit while the constraint is that the optimal return period, T, of flood protection failure is not less than the minimum design value, T_d. The project cost, benefit and return period of flood protection failure are functions of the design parameters. The objective function is expressed as follows:

$$\text{Max } \{Z = B - C\} \tag{5}$$

subject to the following constraints:

$$T \geq T_d \tag{6}$$

$$B = f_1(X_1, X_2) \tag{7}$$

$$C = f_2(X_1, X_2) \tag{8}$$

$$T = f_3(X_1, X_2) \tag{9}$$

where Z = net benefit, B = benefit, C = cost, X = design parameter, T = expected design return period of failure, T_d = minimum design return period of failure.

COMPUTATIONAL PROCEDURE

The alternatives of the flood control system are the diversion channel basewidth ranging from 0 to 80 m and the pumping rate at the sea barrier ranging from 0 to 2,000 m^3/s. The flooding relationships and the probability distributions of the river flood level at Bangkok for various capacities of the proposed flood control system are used. The computation of the flooding risk, the expected annual damage cost and the determination of the optimal capacity of the flood control system are described as follows (Kitpaisalsakul 1996):

Computation of Flooding Risk and Expected Annual Damage Cost

Three causes of flooding due to failure of the existing river dikes are: (1) flood overtopping the river dike, (2) dike leakage and (3) dike gate leakage. The resistance of dike to flooding are the dike crest level, the dike strength and the full closure of dike gate while the load is the river flood level.

The ranges of load and resistance for the three dike failure causes are specified individually considering their consequences in reality. During dike overtopping, the effect of dike leakage and leakage of dike gate is considered to be relatively small and negligible. The ranges of load

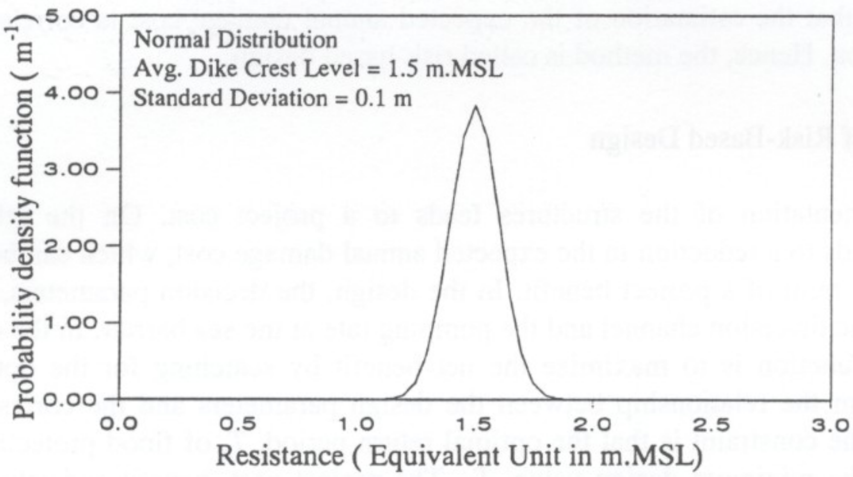


Fig. 2 Probability density function of resistance against flooding due to dike overtopping (river dike crest level) at Bankok

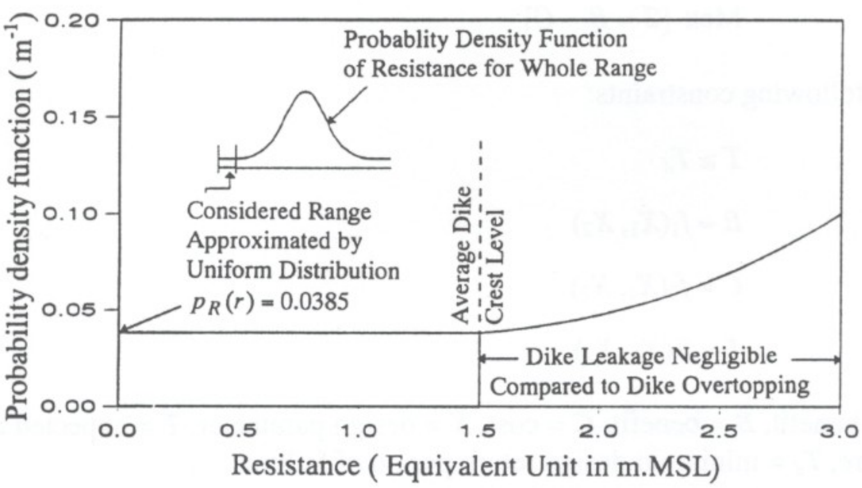


Fig. 3 Probability density function of resistance against flooding due to dike leakage (dike strength) at Bankok

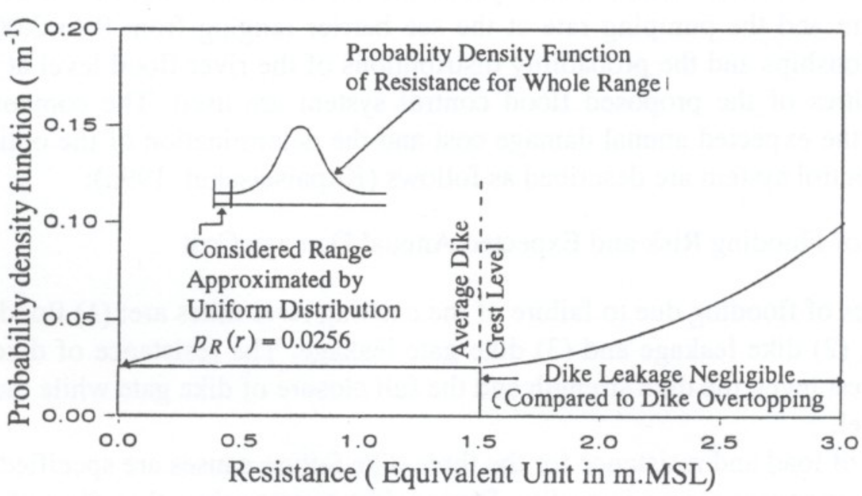


Fig. 4 Probability density function of resistance against flooding due to dike gate leakage (full gate closure) at Bankok

and resistance of flooding due to the dike leakage and the gate leakage are therefore considered from 0.0 m MSL (the lowest elevation of Bangkok flood plain) to 1.5 m MSL (the average dike crest level).

(a) Probability density function of flooding resistance :The probability density function of dike crest level in Fig. 2 is considered to have a normal distribution (Plate and Duckstein 1987) with a mean equal to the average dike crest level (1.5 m MSL). The standard deviation is assumed equal to 10% of the dike height of 1.0 m. The probable causes of this dike level variation can be due to various factors such as geological variations or human causes, etc. The whole range of the probability density function of river dike resistance against flow overtopping which is the main cause of dike failure is used in the analysis.

For the probability density function of dike leakage resistance, it is not commonly available. In this study it is determined by trial and error calibration based on the assumed risk of flooding of 0.03 equivalent to an occurrence of once in 33 years (or in the other words 1.5 times in the project life of 50 years). The risk of flooding due to dike leakage depends on the joint probability density functions of the resistance of dike leakage and of the flood level. As the effect of dike leakage is less significance than flow overtopping, only the tail portion of the probability density function of dike leakage resistance is considered as shown in Fig. 3. By trial and error calibration based on the assumed risk of dike leakage resistance of 0.03, a constant tail-end value of the probability density function is found to be 0.0385 m^{-1}. Similarly, for the probability density function of gate leakage the same procedure is applied but with an assumed risk of flooding of 0.02 equivalent of an occurrence of once in the project life (50 years). By trial and error calibration, the value of the probability density function at the tail is approximately equal to 0.0256 m^{-1} as shown in Fig. 4.

(b) Probability density function of flooding load : The probability density function of load is derived from the exceedence probability distribution of annual maximum flood level obtained from the coincident flood frequency analysis. The probability density function of the flood level varies with the capacity of the flood control system. The marginal probability density function of the river flood level (load) as shown in Figs. 5 and 6 is determined from the actual data which has a shape near to a normal distribution but slightly skewed toward higher flood levels.

(c) Consequence function of flooding : In general, the consequence function or the damage cost function is a relationship between the flood damage cost, the flood level and the flood duration. However, only past records of flood damage versus flood depth is available, therefore the effect of flood duration on flood damage is not considered in this study.

Determination of Optimal Capacity of Flood Control System

The project life of the proposed flood control system is considered to be 50 years from 1998 to 2047 in the benefit-cost evaluation. Both cost and benefit are estimated at the present value of the year 1997. In the design optimization, the minimum design return period T_d is taken as 100 years. The data used in this step are as follows:

(a) Project benefit: The project benefit is computed from the reduction of the cumulated expected annual damage costs throughout the project life for each flood control alternative.

(b) Project cost : The project cost is the implementation cost of the flood control system. It consists of costs of construction, operation and maintenance including project planning, design, tender preparation and administration.

(c) Return period of flood protection failure: The expected return period of flood protection failure is determined from the sum of all risks of flooding due to the three causes of dike failure.

RESULTS AND DISCUSSIONS

Risk of Flooding

The risk of flooding without flood control system is determined from the integration of the joint probability density function of load and resistance over the region where load exceeds the resistance as shown in the upper diagrams of Figs. 5 to 7. Without the flood control system, the risks of flooding due to flow overtopping the existing dike, dike leakage and gate leakage are 0.41, 0.03 and 0.02 respectively as shown in the upper diagrams of Figs. 5 to 7. The total risk is equal to 0.46. The return period of flood protection failure is about 2 years. Compared to the case that the dike crest level is constant at the average value of 1.5 m.MSL, the risk is equivalent to the probability of river flood exceeding 1.5 m.MSL which is found to be 0.40. The difference in the risk of flooding is due to the variation of the river dike resistance.

With the proposed flood control system, the joint probability density functions changes significantly from the case without flood control system. The flood control system changes considerably the probability density function of the river flood level. Accordingly, the risk of flooding for each dike failure cause is reduced significantly. For an example with a 40 m basewidth diversion channel without pumping at the sea barrier, the risk of flood overtopping the dike as shown in the upper diagram of Fig. 8 decreases significantly compared to the case without flood control system (Fig. 5).

Expected Annual Damage Cost of Flooding

The expected annual damage cost is determined from the integration of the product of the joint probability density function of load and resistance and the consequence function over the region where the load exceeds the resistance as shown in the lower diagrams of Figs. 5 to 7. When there is no flood control system, the expected annual damage costs for the three dike failure causes are analyzed as shown in the lower diagrams of Figs. 5 to 7. With the flood control system, the product of the joint probability density functions and the consequence function changes considerably from the case without flood control system. Likewise, the expected annual damage cost decreases significantly. For example with a 40 m basewidth diversion channel without pumping at the sea barrier, the expected annual damage costs due to flood overtopping the dike as shown in the lower diagram of Fig. 8 decreases significantly compared to the case without flood control system (Fig. 5).

Optimal Capacity of Flood Control System

The project benefit is the reduction of the expected annual damage cost for 50 years due to each flood control system. The net benefit is the difference between the project benefit and the project cost. The relationship between the capacity of flood control system and the net benefit (Fig. 9) has been developed for the range of pumping from 0 to 2,000 m^3/s and the diversion channel basewidth from 0 to 80 m. In the same figure, the return period of flood protection failure is also calculated for various capacities of diversion channel and pump capacity. It is found that the net benefit is maximum when the flood control system has a 40 m basewidth diversion channel without pumping at the sea barrier. The corresponding optimal return period of flood protection failure is equal to 270 years which is larger than the minimum design return period of 100 years.

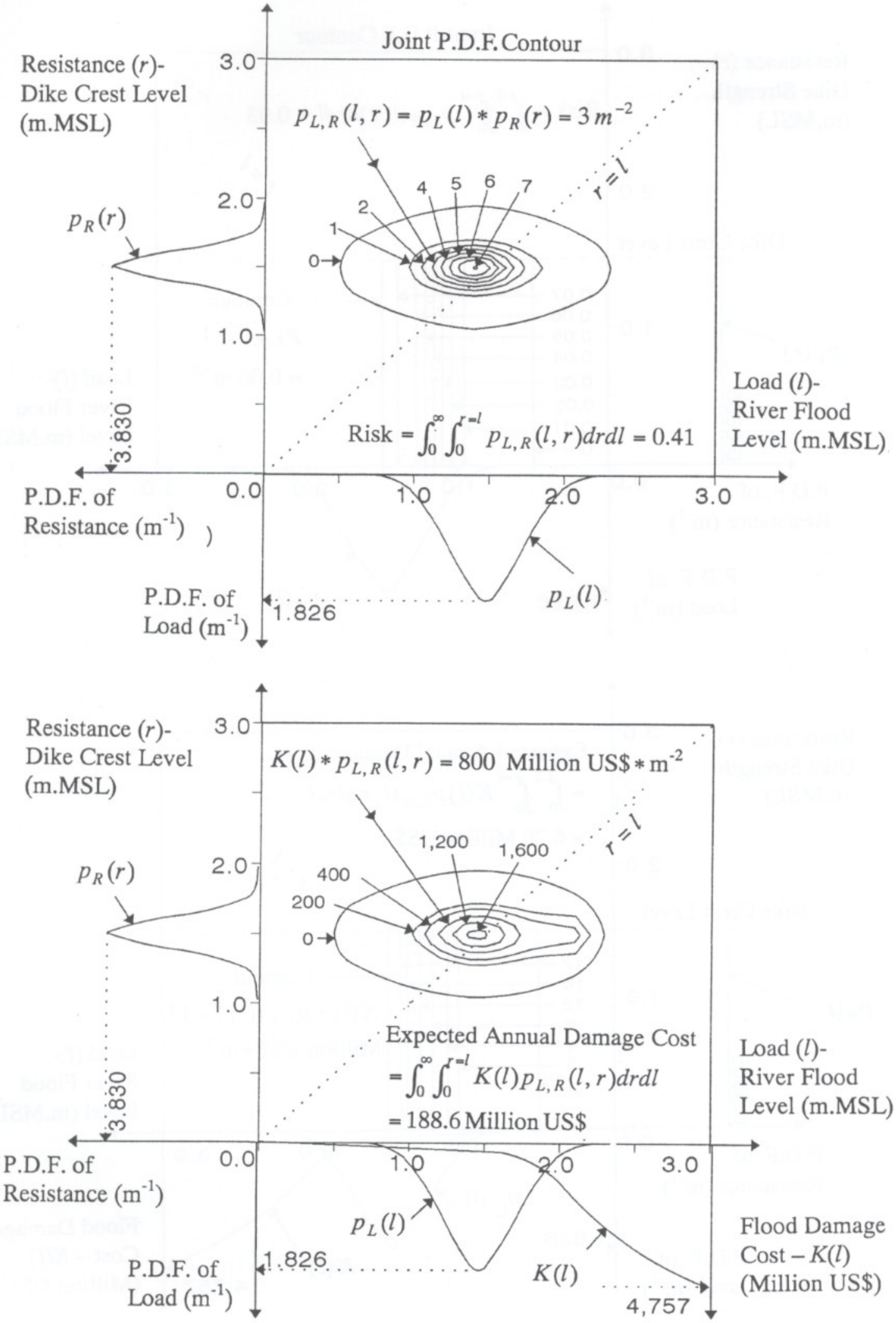
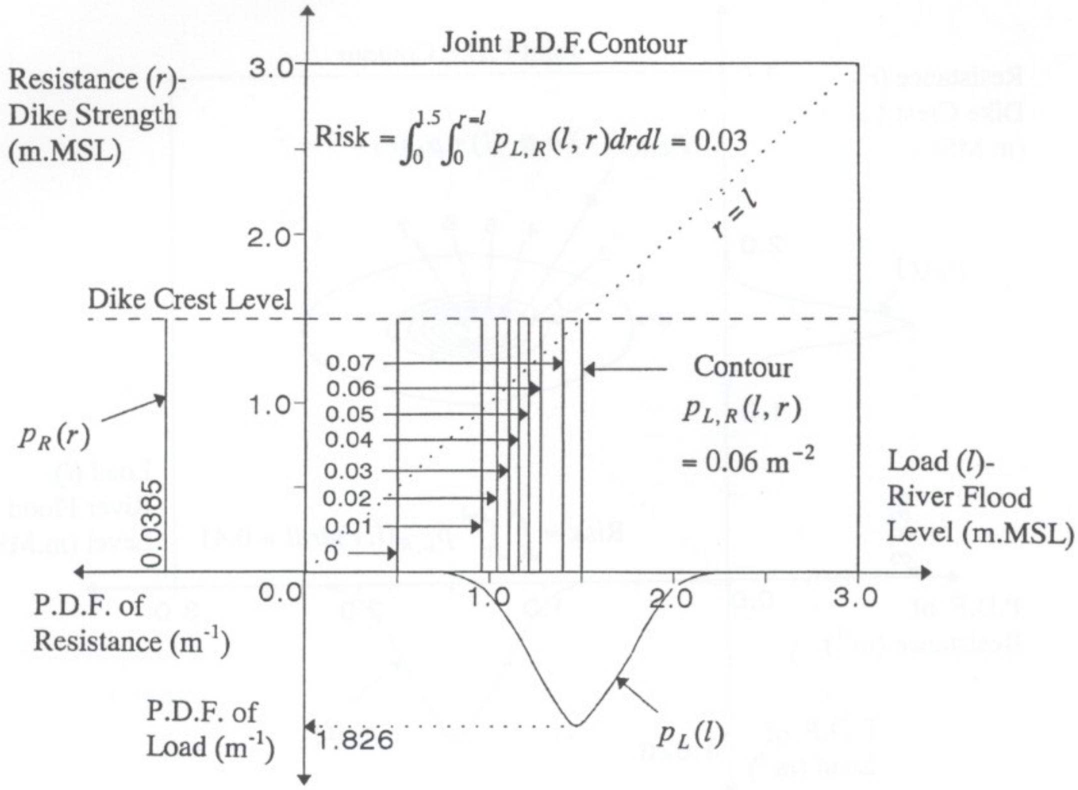


Fig. 5 Risk and expected annual damage cost of flooding due to dike overtopping at Bangkok without flood control system



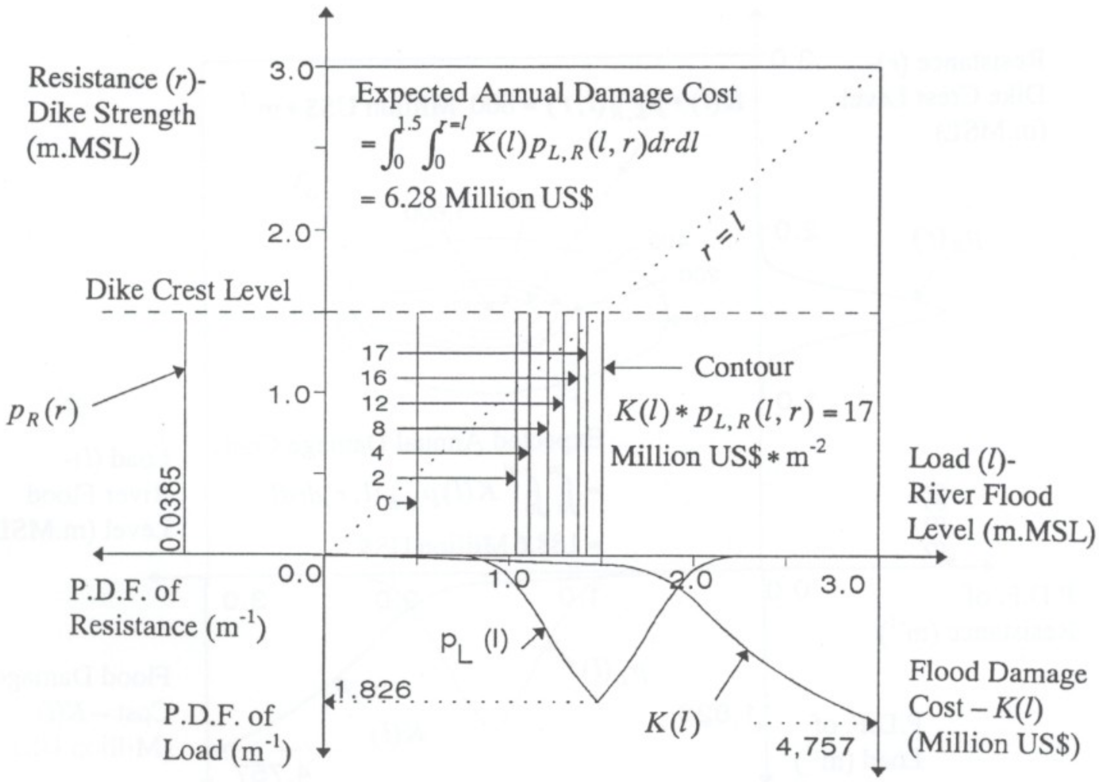


Fig. 6 Risk and expected annual damage cost of flooding due to dike leakage at Bangkok without flood control system

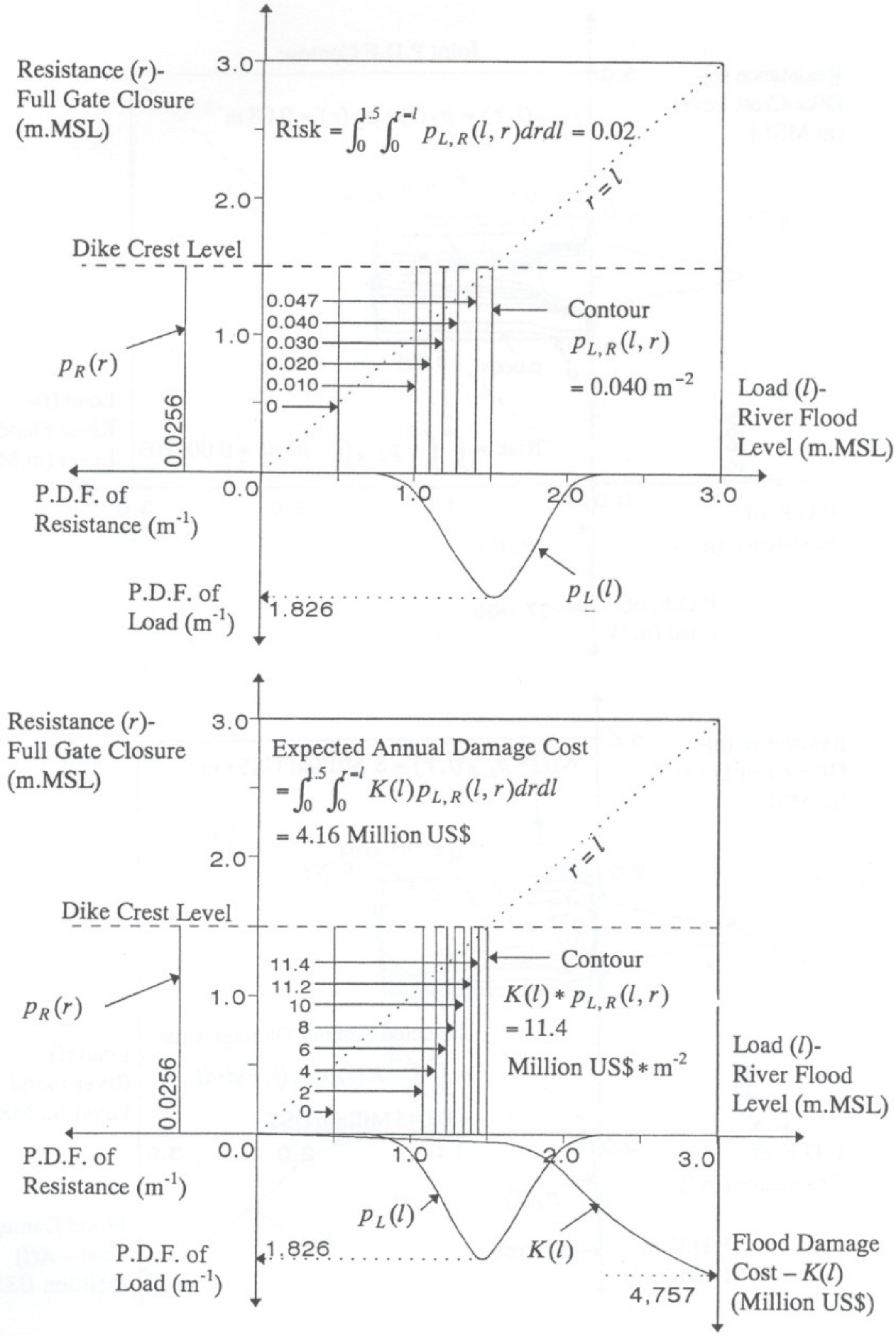


Fig. 7 Risk and expected annual damage cost of flooding due to dike gate leakage at Bangkok without flood control system

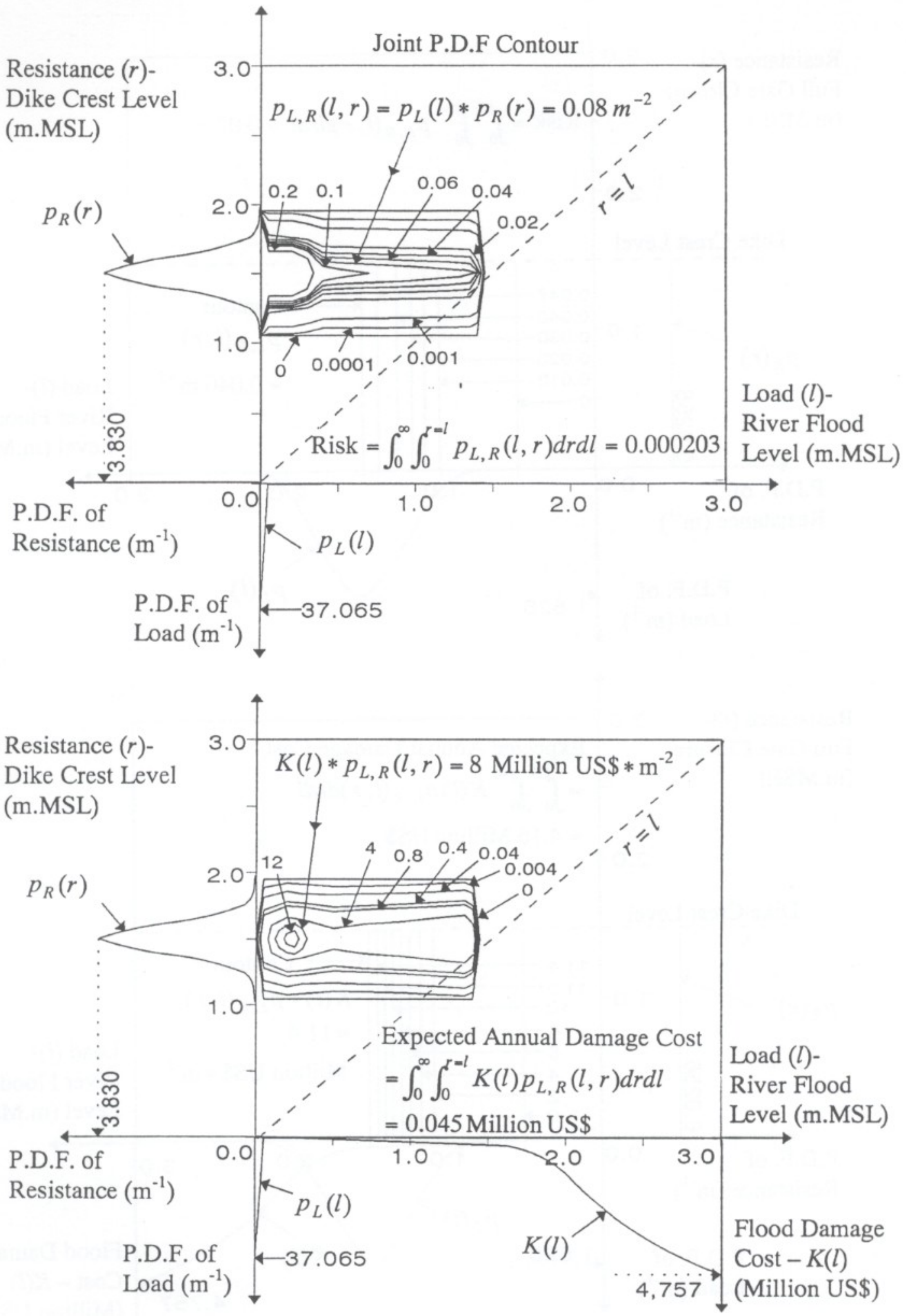


Fig. 8 Risk and expected annual damage cost of flooding due to dike overtopping at Bangkok without flood control system having 40 m base width diversion channel and no pump

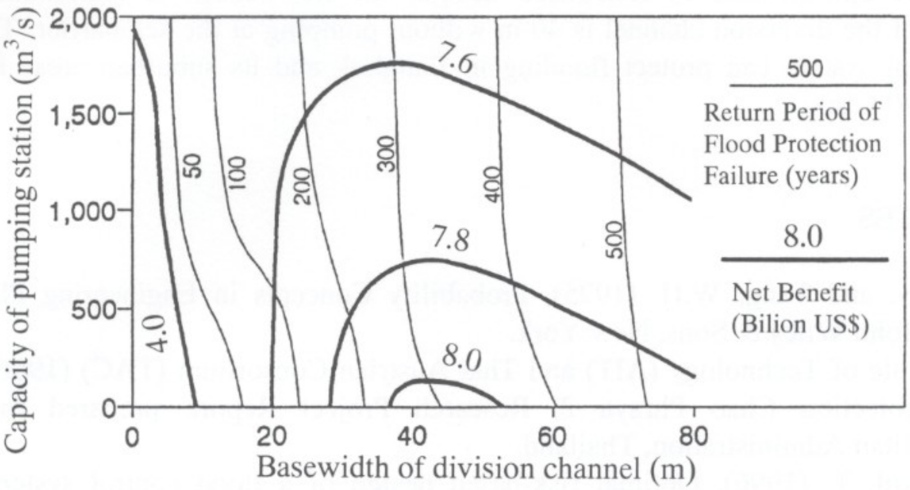


Fig. 9 Capacity of flood control system, net benefit and return period of flood protection failure at Bangkok

CONCLUSIONS

In this study, an optimal risk-based design of a flood control system is developed. The design approach is a computational framework using four techniques, namely flood flow simulation analysis, coincident flood frequency analysis, load-resistance analysis and optimal risk-based design. The design approach is applied to determine the optimal capacity of the proposed flood control system for Bangkok based on a maximum net benefit for a design return period of flood protection failure. The project benefit is contributed from the reduction of the cumulated expected annual damage costs of flooding throughout a 50 year project life.

The major interest of this approach is the application of optimal risk-based design using the load-resistance analysis in quantifying the risk and the expected annual damage cost of flooding considering the variations of both the flood load such as the river flood level and the flood resistance such as the river dike strength. The resistance of the river dikes is considered depending on the combined natural and man-made effects.

Floodings in Bangkok and its suburban areas is due to failure of the existing river dikes to prevent overtopping of flood water from the Chao Phraya river into the protected area. Three causes of failure of the existing river dikes are considered. They are dike overtopping, dike leakage and dike gate leakage. The corresponding resistance to flooding are the dike crest level, dike strength and full dike gate closure while the load is the river flood level. The study is carried out to investigate the effect of the flood control system in lowering the river flood level and, in turn, reducing the the risk and expected annual damage cost of flooding. The capacity of the flood control system are considered to vary with the diversion channel basewidth from 0 to 80 m and the pumping capacity at the sea barrier from 0 to 2,000 m^3/s.

From the flooding load-resistance analysis, it is found that, for each dike failure cause, the joint probability density function for the case with the flood control system changes significantly from the case without flood control system. Accordingly, the risk of flooding for each cause of failure is reduced significantly, thus increasing the return period of flood protection failure. Likewise, the corresponding expected annual damage cost is reduced significantly.

From the optimization of risk-based design, the net benefit is maximum when the basewidth of the diversion channel is 40 m without pumping at the sea barrier. This optimal flood control system can protect flooding in Bangkok and its suburban areas for a return period of 270 years.

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