

RELIABILITY- AND RISK- BASED DESIGN OF COASTAL FLOOD DEFENCES

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In low-lying coastal regions coastal flood defence systems (CFDS) are important to protect the low-lying hinterland from sea flooding. The appropriate characterisation of failure mechanisms of CFDS, determination of failure probability and determination of failure consequences are key components in effective reliability analysis and flood risk assessment. Having a CFDS, three questions often rise: (i) what the actual safety of the hinter lands is? (ii) how safe is safe enough? and (iii) given a pre-defined level of protection what the “best design” of the system would be? This study focuses on the application of the probabilistic design method to develop reliability and risk based models in order to answer these above questions with an application to a CFDS in Vietnam.

INTRODUCTION

In the low-lying coastal countries such as the Netherlands, Japan, Vietnam, and Bangladesh, the coastal flood defence system (CFDS) is very important to protect the low-lying hinterland (polders) from sea flooding. This system contains typically water defence structures i.e sea dikes, dunes, estuarine river levees, dams, and water discharging structures such as sluices, pumping stations, etc.

Main interests for any coastal flood defence system typically are: What the actual safety of the protected hinterland/polders is? How safe is safe enough? If safe is not safe enough, to which level of safety the system needs to be improved or in other words, to which level of protection the “best choice” is (e.g 1/100, 1/250, 1/250 or 1/10000 per year)? And having a pre-defined level of protection, what would be the *best design* of the system?

The first question can be answered by implementing a reliability safety assessment of the considered system. This can be done by probabilistic reliability assessments of all system elements which consider all possible failure mechanisms of these elements, by comparing the total strength of the elements and the joint loads acting on it. The safety level of the whole system can be easily determined by combination of failure probabilities of these considered system elements. This will be called in this study as *probabilistic safety assessment*.

The second question is possible to solve by doing a risk analysis of the whole system. For various protection levels the cost of protection and the risk as consequences of system failure need to be quantified. In general the first term is

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increased when the level of protection is higher while the risk decrease. It is possible to search for the point which provides the minimum total of these two components. This leads to a concept of *risk-based optimization*. The result from this risk analysis will be used as an input condition for answering the next question.

In order to answer the last question, various geometry alternatives of the coastal flood defences can be generated given a pre-defined failure probability. Total cost of construction here includes initial investment cost and the maintenance-repair cost during the total service lifetime of the structures. The investment cost can be estimated based on given geometry while the later term can be expressed through the failure probability of the each consider alternative. The minimum point of total construction cost in space of failure probability is looked for. This algorithm and procedure are, in this study, named *reliability-based optimization*.

Important inputs for these previous models are load and strength boundaries. Loads are mainly defined by hydraulic loads (water levels, wave conditions). Both waves and water levels at the sea are random and can be best described by statistic distributions, which are physically relevant. The strength of structures can be determined based on design geometry and materials used. Other important issues are inventory and investigation of all possible failure mechanisms of the system and quantifying the consequences of the system failure.

Combining all these above study components leads to an overall probabilistic safety, reliability and risk based approach for CFDS, see Fig.1, which aims at answering these above questions.

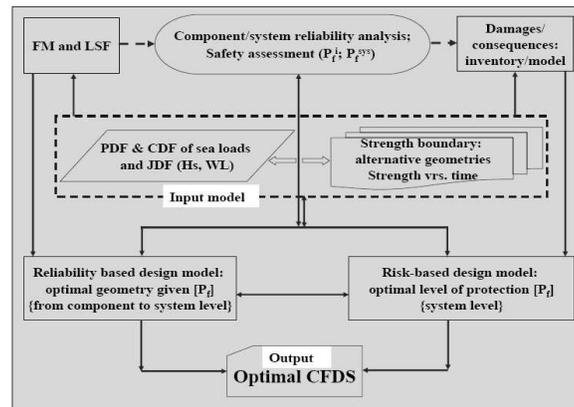


Figure 1. Overview of study approach

In this paper three main components of the overall study approach are discussed, further developed and applied to design of coastal flood defences.

These include probabilistic safety and reliability assessments, reliability based optimisation and risk analysis and risk based determination of optimal safety of the system. Study on probabilistic load boundary condition and uncertainty of the strength parameters will be treated separately in another paper.

Application of the study approach is done for a case of coastal flood defences in Vietnam, a developing country with limited initial investment, fast economic growth and cheap labour, and therefore, all the new design works should be under careful considerations in terms of reliability and optimization.

SEA FLOOD DEFENCES IN VIETNAM

Vietnam lies in a tropical monsoon climate region that has a long coastline along the South China Sea that regularly experiences substantial floods and typhoons. Typhoons arrive on average 4 to 6 times per year at the Vietnam coast. The deltaic coastal areas are protected by more than 2000 km of sea dikes, are threatened by storm surges and high tides from the sea and high water levels from the rivers. Thus, water defences are crucially important to protect the country from flooding.

The applied design safety levels of sea dikes are relatively low. This was also noticed in 1996 after the visit of Dutch expertise missions (DWW/RWS, 1996). Most designs of the sea dikes in Vietnam are based on sea loads with a return period 20 years. Besides this fact the Dutch mission marked that most Vietnamese dikes were in poor and disputable conditions (DWW/RWS, 1996). Consequently, the true probability of failure of the Vietnamese sea flood defense system exceeds by far the design frequency (Mai *et al.*, 2006, 2007). Although designed to fail once in 20 years the sea defense system might well fail almost every year. The experiences in the past years support this statement.

Since 1953, Vietnam was affected by numbers of flood disasters, each disaster responsible for the loss of hundreds of lives and considerable damage to infrastructure, crops, rice paddy, fishing boats and trawlers, houses, schools, hospitals, etc... The total material damage of the flood disasters over last 60 years exceeded \$US 7.5 billion. Additionally, floods and storms caused the loss of more than 20,000 lives (ADRC, 2006 & DDMFC, 2007).

Currently, the design guidelines for sea dikes, named 14TCN-130-2002, are used for all sea dike design in Vietnam. In this guidelines the design water level comprises of two components of i) sea water level of 5% exceedence frequency (1/20 year return period) of occurrence of tidal levels, and ii) storm surge heights cause by the design storm which corresponds to the wind speeds at the Beauford scale 9 to 10. The storm surge heights in dike design were fixed in the code by specific values. Arbitrary selection of 5% tidal level and artificial treating storm surge level and tidal level as two independent components does not reflect well the physic of total water level due to typhoon occurrence. In addition, selection of the design storms does not properly reflect statistical sense with no associating by any frequency of occurrence. Therefore, the safety level in the design

guidelines only explicitly refers to a 1/20 year return period of the tidal level; it does not statistically count for extreme events i.e. typhoons.

The improvement of this situation calls for the use of presently available knowledge on all levels. Vietnam has profound practical experience in the field of flood protection, however, the theoretical knowledge in the fields of dike design, reliability and safety approach, risk analysis, policy analysis, statistics in relation to boundary conditions and mathematical modeling is not up to date. Therefore, the transfer of this knowledge was strongly recommended (DWW/RWS, 1996; Vrijling *et al.*, 2000; Mai *et al.*, 2006).

DESCRIPTION OF CASE STUDY

Coastal flood defence system of Nam Dinh province in Vietnam is selected as a case for this study. Nam Dinh coastal zone is protected by 90 km of sea dikes. The dike system has been constructed on the basis of a sea load with 20 year return period. In September 2005 the typhoon Damrey in northern Vietnam caused approximately more than 8 km of sea dike breaches at different sections along coastline of Nam Dinh. The total direct loss of the effected region is over 500 Million USD (DMWG 2005).

In an attempt to rehabilitate the sea dike system in a long run, a huge sea dikes program has been established by the Ministry of Agriculture and Rural Development (MARD). The sea dike program is being implemented for 2005-2015 period and charged with two important tasks: (i) research on safety standards, boundary conditions and finding optimal solutions for sea defences along the whole country; (ii) designing and constructing new dikes at places where sea dikes have not been built or were breached, and reinforcing the existing dikes on the basis of findings of the first task.

Coastlines along Nam Dinh province were selected as pilot locations for implementation of the new sea dike design. However, design of the new dikes is still based on the existing safety standards (with a design frequency of 1/20 year), which is known as out of date. It is necessary to check if the safety of the new constructed dike system at the pilot locations provides enough safety given the present situation. Findings will be an important input contributing to the sea dike program, which aims at providing design guidelines for sea defences on a national scale.

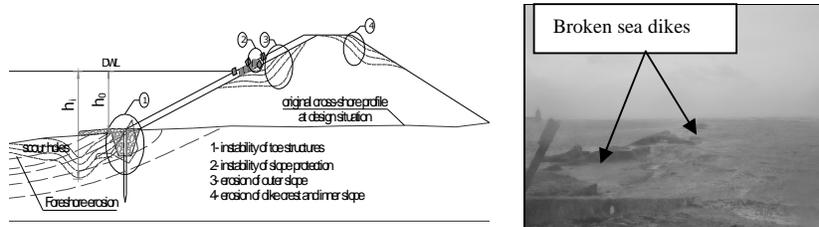


Figure 2. Sea dike breach in Nam Dinh province, Sep. 2005.

PROBABILISTIC DESIGN OF COASTAL FLOOD DEFENCES

Safety assessment and reliability analysis

Presently, there is an increasing interest to quantify the reliability of water defence system using probabilistic approach (see e.g. the concept, method and application in Bakker & Vrijling 1980; Oumeraci *et al.* 2001 and Voortman 2002). In this approach every mechanism is described by a mathematical expression by the so-called reliability *limit state function*, $Z = \text{Strength} - \text{Load}$. The failure condition is defined as the boundary between the area that associates with failure (negative values of Z) and non-failure (positive values of Z), $Z=0$. The probability of failure can be expressed by $P\{Z < 0\}$.

Quantification of the probability of system failure starts with the definition of reliability functions for all potential failure modes of all system elements. As from literatures, the general form of reliability function can be written by:

$$g(z, X) = R(z, X) - S(z, X) \quad (1)$$

where R is the resistance of the component, S is the load acting on the component, z is a vector of design variables describing among others the structural geometry of the component and X is a vector of load of random variables.

If the joint probability density function $f_{R,S}(R, S)$ of R and S is known, the probability of failure can be calculated by means of integration:

$$P_f = P\{Z < 0\} = \iint_{Z < 0} f_{R,S}(R, S) dR dS \quad (2)$$

The solution can be calculated with numerical methods (level III) or approximated by first order reliability methods and/or second order reliability methods (level II), see CUR 141 (1990).

The overall failure probability of a system component is then given by combination of failure probability of all considered failure modes:

$$P_{\text{failure}}^{\text{comp}} = P(Z_1 < 0; Z_2 < 0; \dots Z_i < 0; \dots Z_m < 0) \quad (3)$$

where $(Z_1 < 0; Z_2 < 0; \dots Z_i < 0; \dots Z_m < 0)$ denotes that at least *one* of m failure mechanisms occurs;

Consider that a dike system is a uniform cross-sectional system which comprises a number of independent sections. This can be described as a series system in probabilistic design. The maximum failure probability of this series system with n elements can be calculated (Vrijling *et al.* 2000):

$$P_{f, \text{system}} \leq 1 - (1 - P_{f, \text{section}})^n \quad (4)$$

On the above basis, if the geometry of CFDS is known and the joint probability distribution of load and strength variables is quantified, the

probability of failure of the system of flood defences can be found. This can be applied for technical management purpose to determination of safety levels of an existing system and to find out the weak points of the system.

On the other hand, for a pre-defined failure probability (e.g. given an acceptable level of probability of flooding for a certain location) vector of acceptable design geometrical alternatives can be given by Eq. 5a. In order to find the solution a cost optimization can be done by Eq. 5b.

$$\left\{ \begin{aligned} D &= \{z \mid P_f(z) \leq P_{f,max}\} \dots\dots\dots(a) \\ \text{Min.} & \{I(z \mid P_f(z) \leq P_{f,max}) + PV[R_T(z \mid P_f(z) \leq P_{f,max})]\} \dots\dots(b) \end{aligned} \right. \quad (5)$$

where $P_{f,max}$ denotes the maximum acceptable probability of system failure; I is the initial investment cost and R_T is the maintenance/repair cost during the total service lifetime of the structures, T . The investment cost can be estimated based on given geometry while the later term can be expressed through the failure probability of the each consider alternative. The reliability-based optimisation algorithms can be illustrated as in Fig. 3 (Mai *et al.* 2006, after Voortman 2002).

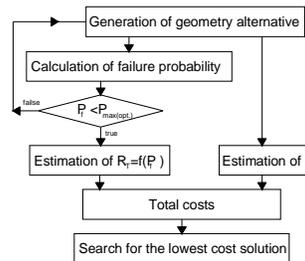


Figure 3. Reliability-based design of coastal defences

RISK ANALYSIS AND RISK BASED DESIGN

Risk can be defined as the probability of a disaster, e.g. a flood, related to the consequences (usually the multiplication of both variables), see CUR/TAW 1990. The idea of acceptable risk for different regions/ countries may be influenced by a single spectacular accident or incident like the 1953 flood disaster in the Netherlands; tsunami disaster 2004 in Asia; Katrina in New Orleans, USA 2005; Typhoon Damrey in Vietnam 2005; and large flood disaster in Bangladesh 2007. These unwanted events could be starting/ turning points of any new safety policy establishment for the countries.

From literature, the acceptance of risk in a public view should be studied from two different points of view in relation to the estimation of the consequences. The first point of view concerns the risk assessment by society on a national level related to the number of casualties due to a certain hazardous

event (Vrijling *et al.*, 1998). The societal risk can be modelled by the frequency of exceedance curve of the number of deaths, called the FN-curve. Secondly, acceptable level of risk can be formulated in terms of economic cost benefit. Basically, the total costs in a system are determined by the sum of the expenditure for a safer system and the expected value of the economic damage. The acceptable risk measure can be estimated by comparing the cost of protection to a characteristic value of the consequences of flooding (DMWG, 2005). The optimal level of economically acceptable risk relating to an optimal level of safety will correspond to the point of minimal total costs. The total potential economic damage that will be caused by a flood can be presented by an exceedance frequency curve for damage, the so-called FD-curve.

Societal risk

The basis of the calculation of societal risk is formed by the probability density function (pdf) of the yearly number of fatalities. From the pdf an FN curve can be derived, which shows the probability of exceedance as a function of the number of fatalities, on a double logarithmic scale (Jonkman, 2007).

$$1 - F_N(x) = P(N > x) = \int_x^{\infty} f_N(x) \cdot dx \quad (6)$$

Where: $f_n(x)$ the probability density function (pdf) of the number of fatalities per year; $F_N(x)$ probability distribution function of the number of fatalities per year, signifying the probability of fewer than x fatalities per year.

Vrijling *et al.* (1998) notes that the societal risk should be judged on a national level by limiting the total number of casualties in a given year. The total number of casualties is tested against the norm of $\beta_i * MF$ by the following form:

$$E(N_{di}) + k * \sigma(N_{di}) < \beta_i * MF \quad (7)$$

The multiplication factor MF is country-specific and based on: the value of the minimum death rate of the population, the ratio of the involuntary accident death rate (exclusive diseases) with the minimum death rate, the number of hazardous activities in a country (on average about 20 sectors) and the size of population. In Mai Van *et al.* (2008) the multiple factor was determined, $MF=550$, for the Vietnam situation. This value is reasonable while comparing to that of Netherlands ($MF_{NL}=100$), and of South Africa ($MF_{SA}=750$) by van Gelder *et al.* (2004). Therefore, the norm for Vietnam situation can be set at $\beta * 550$ and used for all successive calculations.

Economic approach in determination of acceptable risk

In this approach the total costs of a system (C_{tot}) are determined by the sum of the investments ($I_{\Delta H}$) for a safer system; the expected value of the maintenance

cost M and the expected economic damage D (van Dantzig, 1956). The total cost of the system with dike heightening ΔH is:

$$C_{tot}(H_0, \Delta H_{P_f}, P_f) = \left[I_{0, P_{f0}} + I_{\Delta H_{P_f}}(\Delta H_{P_f}) + PV(M + P_f * D) \right] \quad (8)$$

The optimal level of safety indicated by $P_{f,opt}$ corresponds to the point of minimal cost. The present value of the expected maintenance and damage costs are estimated by:

$$PV(M) = E(M) * \sum_{i=0}^{i=T} \frac{1}{(1+r)^i} \quad (9)$$

$$PV(P_f * D) = P_f * E(D) * \sum_{i=0}^{i=T} \frac{1}{(1+r)^i} \quad (10)$$

Where: P_f is probability of failure per year; $E(M)$ is yearly expected maintenance cost; $E(D)$ is expected damage in case of flood, this can be determined from FD-curve, an exceedance frequency of the economic damage; r is real effective rate of interest; T is planning period, in years.

APPLICATIONS

Safety assessment

By the probabilistic safety and reliability assessment models, the safety of the Nam Dinh sea dike system is determined. All possible failure mechanisms of the sea dike sections are taken into account. The safety assessment of the present dike system and of different scenarios of dike improvement has been made. By using level III method with Monte Carlo simulation the failure probability of possible failure modes and of the whole dike system is analysed. In addition contribution of failure modes to the total system failure probability can be determined by fault tree analysis. Analysis result is summarized in Fig. 4. More details on all calculations methods and extensive calculation steps, see Mai Van *et al.* 2006).

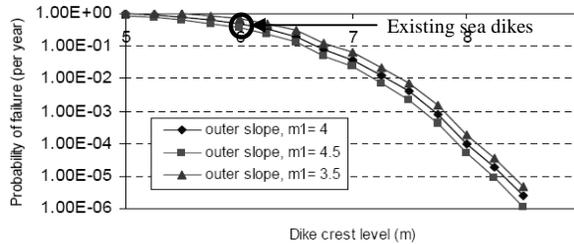


Figure 4. Reliability of the Nam Dinh sea dikes

Study found that the failure of the Nam Dinh sea dikes is mainly due to wave overtopping. The existing sea dike system has a total failure probability of 0.78 per year (1/1.3 per year) when taking into account the length effects, although the dike system was designed to withstand a one in 20 year sea load. From Fig.4, in order to come up with the current existing standard of 1/20 per year, the dikes should be heightened up to around 6.8m. Findings of this study are in good agreement with results of deterministic safety assessments and what have happened at the case study area during the last few decades (DWW/RWS 1996).

Reliability based optimisation

By applying the reliability-based model the design parameter can be determined. Maximum failure probability of the Nam Dinh sea dike system is 5% (1/20 year safety standard) as from the current safety standard (14TCN-130-2002). Taking into account the length affects the acceptable failure probability of a dike section approximates 0.0171. By implementing a fault tree analysis, based on the failure probability of the dike section the failure probability of every failure mode can be reallocated. Design values of the interested geometries for the dike section are obtained as in Tab. 1, column e.

Table 1. Failure probability vs. failure mode and the design values of interested parameters per mechanism				
Failure modes	Safety assessment		Reliability based design	
	P _f [year ⁻¹]	important	P _f [year ⁻¹]	design value
(a)	(b)	(c)	(d)	(e)
Overflowing	3.81E-03	12.80%	0,00022	
Excessive wave overtopping	1.30E-02	43.69%	0,00075	Z _{crest} =6.80
Instability of armour unit	6.25E-03	21.00%	0,00036	D _{n50} =0.61
Instability of outer slope	3.10E-05	0.10%	0,000002	m ₁ =3.25
instability of inner slope	5.70E-03	19.15%	0,000327	m ₂ =2.75
Instability of toe protect	1.10E-03	3.70%	0,000063	d _p =2.90m
Excessive toe erosion	1.89E-04	0.64%	0,000011	h _{scour} =1.34
Instab. of toe structure	1.00E-02	0.64%	0,000011	
Piping condition 1	6.57E-04	0.00%		
Piping condition 2	9.00E-12	0.00%		
Section failure probability	0.0492	0.0171		
System failure probability	0.78	0.05		

Determination of acceptable risk levels for flood in Vietnam

From the Department of Dike Management and Flood Control (DDMFC, 2007) of Vietnam yearly fatalities and economic loss data due to floods and storms are collected. The data set is available from 1970 up to 2007. In addition, from the Asian Disaster Reduction Centre (ADRC, 2006) the top 25

flood disasters of Vietnam in the 20th century are available, in which, there are twenty events that were due to floods and storms. These events are considered as historical events and included in analysis. The FN and FD curves due to flooding for the whole country, including historical events are presented in Fig. 5 and 6. Inspection of the FN data a lognormal frequency curve with $\mu=541$ and $\sigma=1169$ are found as the best-fit to the yearly fatality dataset.

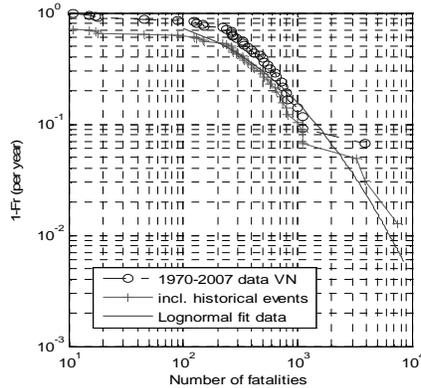


Figure 5. Flooding FN-curve in Vietnam

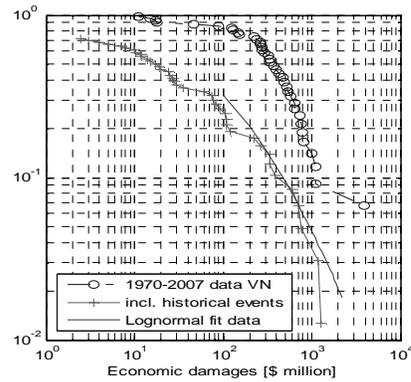


Figure 6. Flood FD-curve of Vietnam

In order to satisfy criteria by Eq. 7, different choices for k give different policy factors β approximately ranging from 3 to 7.5 (see Tab. 2). Comparing to the situation in the Netherlands, this factor is in range of 0.01 to 1.0 and associated with a safety standard of 1/10000 years, hence a different factors of 10 to 100 are found. Therefore, the safety standards for flood in Vietnam may be set at a design frequency of 1/100 per year or less.

k	Total risk	β
1	1710.7	3.1
2	2880.4	5.2
3	4050.1	7.4

Economic optimization of protection level for the Nam Dinh dike ring

The 55 year damage data (includes historical events) is best fitted to lognormal distribution with $E(D)= 181.3$ and $\sigma=309.5$ ($*10^6$ US\$). This means average flood damage of $181*10^6$ US\$ with an uncertainty of one to three times $\sigma=309.5*10^6$ US\$ is acceptable per year. This is comparable with the reported actual flood situation during the last 10 years with the annual flood damage is of around 1.5% of Vietnam GDP during the last 10 years, [sources:

<http://www.vnexpress.net/Vietnam/Xa-hoi/2007/10/3B9FB183/>, accessed on 25 April 2008]).

Based on design documents of existing Nam Dinh sea dikes by DDMFC/MARD 2005, taking into account the actual inflation rates of Vietnam the costs of dike heightening are presented in Fig. 7.

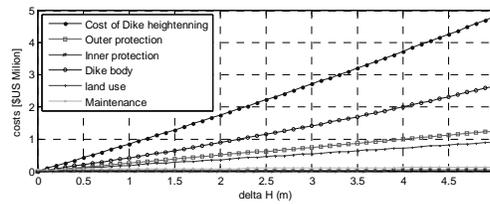


Figure 7. Expenditure as a function of dike heightening (per km)

Economic risk analysis for the case of Nam Dinh coastal flood defences, taking into account the actual economic growth rate of Vietnam and expected damage from the FD-curve (Fig. 6) gives results as in Fig. 8.

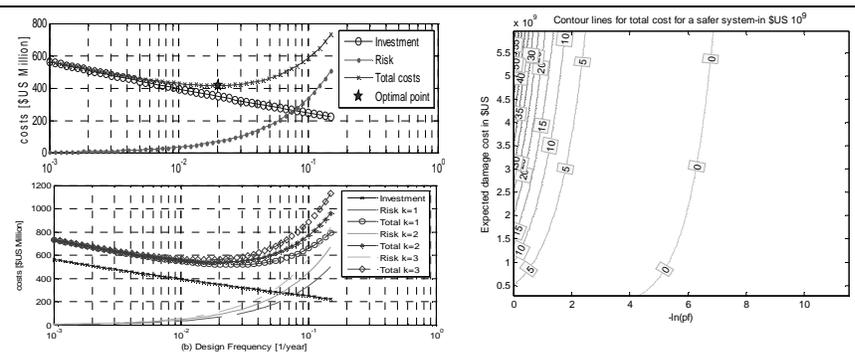


Figure 8. Economic risk-based safety levels (left) and sensitivity analysis (right)

It is clear that the optimal level of safety is around 1/70 years for different k values of 1 to 3. If factor k takes a value of 1.0 the design of the sea dike system should be based on a return period 50 years. A supplementary design for a return period 100 years might turn out to be an even better choice since double safety level is achieved with relatively small incremental investment. Selection of the design return periods of less than 30 years leads to very high risk as well as high expenses for maintenance and repair and is therefore a bad choice in this situation. Selection of 100 years return period is, therefore, recommended for the future planning of coastal protection in Nam Dinh. Without improvement the dike height remains at 5.5 m with an annual failure probability of 0.15 for single dike section and 0.78 for the whole system. This leads to an economic loss of

over \$US million 500, which is in the same order of magnitude to the total direct loss caused by the typhoon Damrey in 2005. Sensitivity analysis for a range of expected damages gives results as shown in Fig. 8 (right). Contour lines show the total costs of the system, line *zero* means the lowest total cost, and therefore, is the optimal set.

CONCLUSIONS

This study presents the methods of reliability- and risk- based approaches with an application to the field of coastal flood defences. It clearly shows that the proposed methods and models are powerful to answering the three given research questions in terms of safety assessments, optimal safety and optimal design.

Application of the methods for the case study of the sea defence system in Vietnam gives interesting results and allows the following remarks:

The existing sea defence system needs improvement in view of current safety standards and as well as according to acceptable risk philosophies, which counts for the recent development of Vietnam.

Application of the reliability-based design geometry of the dikes provided in this study fulfills the current safety standard of 1/20 year.

Flood risk analysis with the societal risk criteria results in the policy factor β for Vietnam are in the range of 3 to 7.5. The safety level for sea flood defences of the case study area should be set at 1/100 per year or less;

Economic risk analysis showed that the actual safety standards in design of coastal flood defences of the Vietnamese case study (1/20 years) are not safe enough in views of the current Vietnamese development with fast economic growth. An optimal choice of the acceptable safety level is suggested to set at 1/100 years. This is in good agreement with the upper bound of the societal acceptable risk.

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