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ABSTRACT

The flood risks in the Red River delta in Vietnam, in particular for the Bac Hung Hai polder are determined. The risk analysis includes aspects such as hydraulics, hydrology, morphology, geotechnics as well as socio-economic evaluations of the dike system and is based on the formula: risk = failure probability x damage. Failure mechanisms as overflow, geotechnical slope stability and piping have been taken into account, resulting in failure probabilities for each dike kilometre. Also the consequences of a dike breach which respect to inundation are shown.

INTRODUCTION

Floods occur almost every year in the Red River delta in Vietnam causing large scale inundations leading to serious damages and loss of human lives. The most serious recorded flood in modern times occurred in 1971 when more than 500 people were killed, approximately 2,71 million people and 250,000 ha of land were affected. The estimated damage was approximately US$ 1 billion.

A water level at Hanoi of 14.80 m would have been attained if the dikes had not failed. Some 648 dike segments over a length of 74 km were distorted; at 307 places the crests were overtopped or nearly so and inundation depths up to 3.5 m were reported.

Obviously, improvement of the flood protection system is required. As part of the 2nd Red River Basin Sector Project, Part A for Water Resources Management a Flooding Risk Assessment (FRA) has been carried out. The FRA activity has the following objectives:

1. ranking of flood protection projects for the rehabilitation of dikes and irrigation structures;
2. demonstrating the FRA methodology to the Department of Dyke Management and Flood Control of MARD (Ministry of Agriculture and Rural Development).

The project has been carried out in Vietnam by WL | Delft Hydraulics and SWECO Groner under an ADB loan and includes aspects such as hydraulics, hydrology, morphology, geotechnics as well as socio-economic evaluations of the dike system [1].

THE RED RIVER BASIN

General

The Red River Basin in Vietnam is shown in Figure 1. It has a catchment area of 169,000 km^2, of which 86,000 km^2 is situated within the Vietnamese borders, 81,240 km^2 in China and 1,100 km^2 in Laos. From about 50 km upstream of Hanoi near Viet Tri the Red River flows in south-easterly direction to reach the Gulf of Tonkin over a distance of 214 km. The basin downstream of Viet Tri until the Gulf of Tonkin forms the Red River delta. The Red River delta measures 12,700 km^2.

In the delta the Red River is linked with the Thai Binh River through the Duong River and more downstream by Luoc River.

Figure 1. Vietnam with the Red River delta

Hydrology

The average annual rainfall varies from 1,500 to locally 4,800 mm, where the highest values are recorded near the Vietnamese-Chinese border. A clear seasonal pattern is apparent in the rainfall with the highest values in June-September.

About 5 typhoons on average cross annually the north and middle part of Vietnam. From June till September typhoon tracks cross the Red River. Particularly in August and September the occurrence rate is high with an average of 1.0-1.7 typhoons/month each year. Typhoons bring heavy rains with high wind speeds. Maximum wind speeds are up to 40 m/s.

The average inflow to the Red River delta amounts roughly 3,800 m3/s. The runoff from Da River is since 1988 controlled by the operation of Hoa Binh reservoir. The lower Red River basin is affected by tide.
Characteristics of largest floods on the Red River in the last century are presented in Table 1 It gives the peak discharge Q_{max} (m^3/s), date of occurrence and 8-day flood volume at Son Tay.

TABLE 1
Characteristics of the 5 largest floods in the Red River at Son Tay

Year	H_{max} Hanoi (m)	Son Tay		
		day-month	**Q_{max} (m^3/s)**	**8-day flood volume (10^6 m^3)**
1945	13.90	20-08	33,500	18,800
1968	12.23	15-08	24,000	12,960
1969	13.22	18-08	28,300	16,500
1971	14.80	21-08	38,000	19,600
1996		21-08	19,800	11,250

It is observed that the largest floods have all occurred between 15 and 21 August. In Figure 2 return periods of instantaneous natural flood peaks at Son Tay with and without the influence of the Hoa Binh reservoir are presented.

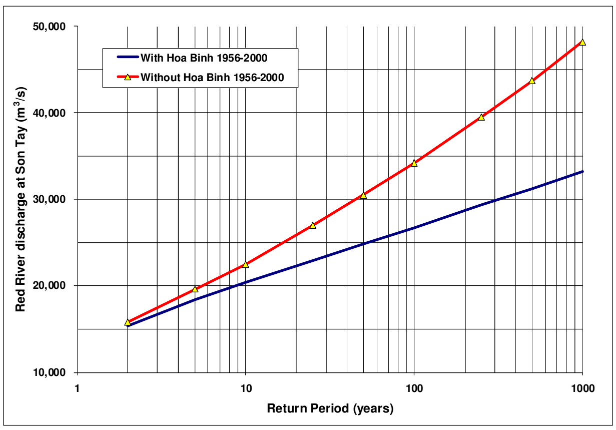

Figure 2. Frequency distribution of flood peaks (daily average discharges) with and without effect of Hoa Binh reservoir, period 1956-2000

Dikes and structures

In general, a flood control system consists of the physical control infrastructures, a flood forecasting system as well as an institutional or management infrastructure. The physical flood control infrastructure in the Red River delta contains the following elements:

- River and sea dikes, inclusive sluices and pumping stations;
- Reservoirs: Thac Ba, and Hoa Binh;
- Flood diversions;
- Retention areas.

At present, the river dike system in the delta consists of 2,417 km of dikes of which 1,667 km is in the Red River system and 750 km in the Thai Binh River system. River dikes attain heights up to 10 m.
More than 952 revetments and groins are built to protect the dikes. Furthemore, 2985 sluices are present for present and irrigation purposes.

The dike system in the Red River delta has a long history. There is archaeological evidence that already in the 3rd century BC dikes were constructed in the delta. However, significant dike building has likely commenced in the 10th century after Vietnam regained independence, further accelerated by the transfer of the capital to Hanoi in 1010 AD. In the last century several times in the aftermath of a serious flood (1915, 1924, 1926, 1945) the dikes strengthening and heightening programs were amended. In 1960 the design flood level for Hanoi amounted RL 13.0 m, with the crest level at RL 14.0 m. In 1971, however, flood levels reached RL 14.15 at Hanoi but would have reached RL 14.80 had not the dike on the left bank upstream of Hanoi breached. Thereafter, the 1971 flood conditions have been taken as the design criterion for the Red River dike system.

FRA METHODOLOGY

Approach

In this section the FRA calculation method based on failure probabilities of the various failure mechanisms will be described. The method is based on the philosophy that the safety of a polder depends on the weakest spot in the dike ring around the polder. The safety is historically derived from the probability that an area might be flooded, because the water defense around that area (the dike ring) fails at one or more locations.
A dike ring is considered, i.e. an area surrounded by a water defense system, Figure 3. This protection system may fail because the design water level exceeds the crest levels of the dikes and hydraulic structures, but it may fail well before the design water level is exceeded by structural incapacities or operational flaws.

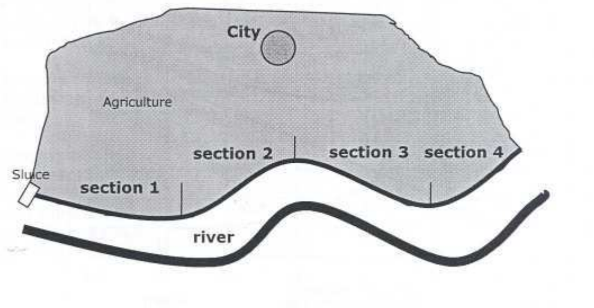

Figure 3. Example of a dike ring

For flood management in addition to flooding probability also the consequences of flooding have to be assessed. When the probability of flooding of a certain area is high but if the damages are small then from a flood management point of view there is little to gain with measures which reduce the probability as the risk is low. Therefore, to estimate the safety of the flood protection system and to determine in what sequence rehabilitation works can best be carried out to improve safety at minimum cost a flooding risk assessment should be carried out. Flooding risk is defined as:

$$\textit{flooding risk} = \textit{probability of flooding} * \textit{damage due to flooding} \quad (1)$$

So a flooding risk assessment has two elements:

- estimation of the probability of failure of the dike, when the river is in flood; this may be due e.g. to poor design, lack of maintenance or improper operation of hydraulic structures, and
- estimation of the losses due to flooding, tangible and intangible.

The FRA methodology will be used to rank flood protection projects in the Red River delta. To demonstrate the FRA methodology it has been applied to the Bac Hung Hai polder, hust south-east of Vietnam's capital Hanoi. This activity resulted in a quantitative assessment of priorities regarding dike sections, presented as Average Annual Damage (AAD) values for the different sections. The AAD values are essentially a translation of both potential damage and flooding probability into a single figure for expected annual costs due to flooding. The AAD values are part of a cost-benefit analysis to assess economic viability of flood projection investments.

Probabilistic computations use the reliability function and the probability density functions of the variables in the reliability function as the base for the determination of failure probabilities. The reliability function Z is the difference between the strength (R = resistance) and the load (S = Solicitation) of a particular failure mode: Z = R - S. Wherever Z < 0 the load exceeds the strength and the system will fail.

Many failure mechanisms might be considered, for instance, failure due to: overflow of water over the crest of the dike, overtopping due to waves, piping, macro-instability of the outer slope during the flood, macro-instability of the outer slope after a rapid fall of the flood levels, macro-instability of the inner slope during the flood, structural strength of hydraulic structures, not closing the gates of the structure before a flood.

In principle, a reliability function for each mechanism should be defined. Hereafter, the reliability functions for the following failure mechanisms are presented:

1. overflow, including wave overtopping and settlement
2. piping, including soil rupture and sand transport, and
3. macro-instability, including instability of the inner and outer slope of the dike.

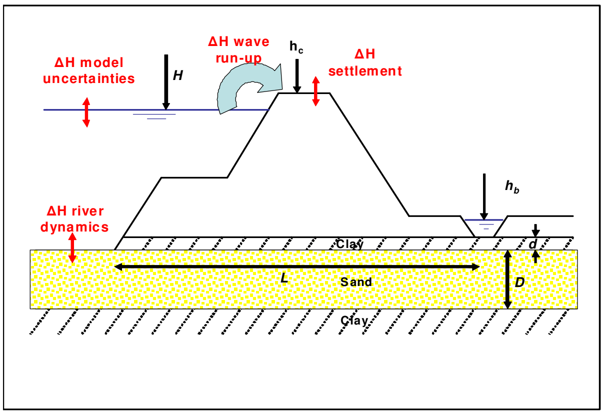

Figure 4. Reliability function for mechanisms overflow, overtopping and piping

Failure mechanism overflow

The reliability function applied for the failure mechanism overflow has the following form, with reference to Figure 4:

$$Z = (h_{crest\ level} - \Delta H_{settlement}) - (H_{flood} - \Delta H_{river\ dynamics} - \Delta H_{runup} - \Delta H_{model\ uncertainty}) \quad (2)$$

with: $\Delta H_{riverd\ ynamics} = \Delta H_{fluctuations} + \Delta H_{trend}$

where: $h_{crest\ level}$ = crest level of the dike (m), $\Delta H_{settlement}$ = uncertainty in the crest level due to settlement of the dike (m), H_{flood} = flood water level (m), $\Delta H_{river\ dynamics}$ = water level trend and uncertainty due to river dynamics (m), $\Delta H_{fluctuations}$ = uncertainty in the bed level variations due to dunes, bed ripples (m),

ΔH_{trend} = assessing the trend in bed level changes, i.e. morphology and encroachment (m), ΔH_{runup} = wave run-up (m), $\Delta H_{model\ uncertainty}$ = uncertainty in water level due to model imperfections (m).

Failure mechanism piping

The reliability function for piping consists of two sub-mechanisms, soil rupture and transport of sand, (see also Figure 4):

1. sub-mechanism soil rupture:

$$Z_1 = \rho_c g d - \rho_w g\,(H - h_b) \qquad (3)$$

2. sub-mechanism transport of sand:

$$Z_2 = \left(\frac{L}{c_1} + \frac{d}{c_2}\right) - \left(H - h_b - d\right) \qquad (4)$$

where: h_b = water level at the inner or field side of the dike (m), d = thickness of the clay layer (m), ρ_c = density of wet clay (kg/m^3), ρ_w = density of water (kg/m^3), g = gravity acceleration (m/s^2), L = seepage path length (m), c_1, c_2 = constants, depending on the soil type (m).

Both conditions must be satisfied for piping: soil rupture, i.e. the clay layer under the dike must be ruptured (in case of the presence of a clay layer) and there must be continuous transport of sand. So, Z_1 as well as Z_2 must be negative at the same time at the same location. The piping probability then reads:

$$P\{piping\} = P\{Z_1 < 0\}\ P\{Z_2 < 0 \mid Z_1 < 0\} \qquad (5)$$

Above equations also apply for piping at hydraulic structures. In that case there is no clay layer, e.g. d = 0 m.

Failure mechanism macro-instability

For the computation of the failure probability due to macro-instability either the river side or the field side slope of the dike has been considered. The actual macro-stability can be computed for both sides using the Bishop method (see Figure 5 for a definition sketch) for different conditions. In the Bishop method the actual safety factor is computed from:

$$F_{actual} = f_0 \frac{\sum \frac{\left[c + \left(p - u\right) tg\varphi\right] \Delta x}{n_\alpha}}{\sum \Delta W \cdot tg\alpha + Q} \qquad (6)$$

where: F_{actual} = actual factor of safety (-), f_0 = correction factor (-), c = cohesion (N/m^2), p = overburden pressure (N/m^2), u = pore pressure (N/m^2), φ = friction angle (degrees), Δx = width of segment (m), n_α = factor of iteration (-), ΔW = weight of segment (kg), α = angle of slide circle to horizontal (degrees), Q = external horizontal load (N).

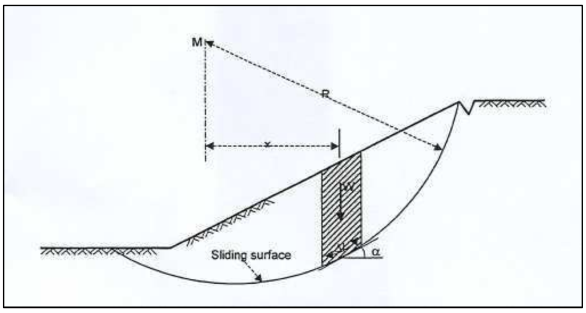

Figure 5. Reliability function for mechanism macro-stability

Combined failure probability

Reliability functions can be solved by different methods, like Monte Carlo simulations or by linearization of the limit state function. The actual failure probability for a dike section then reads:

$$P_{f,actual} = P_{f,overflow} \cup P_{f,piping} \cup P_{f,sliding} \cup P_{f,termites} \cup etc \qquad (7)$$

The probability of failure of a dike ring is to be derived by combining the failure probabilities for the various dike sections, where the lower and upper bound follows from complete correlation and full independence between the sections.

Flood damages

The following damage types are distinguished:

1. Direct damages,
2. Indirect losses,
3. Intangible effects, and
4. Macro-economic effects.

The damage types are elaborated below.

a) Direct damages

Direct damages occur at the time of the actual disaster. The main items include:

- The total or partial destruction of physical infrastructure:
- The destruction of crops ready for harvest
- Farm equipment and stock.

b) Indirect losses

Indirect losses refer to the flows of goods and services that will not be produced or rendered over a time span that begins after the disaster and may extend throughout the rehabilitation and reconstruction periods.
Some examples of indirect losses that can be measured in monetary terms:

- Higher operational costs: due to the destruction of physical infrastructure and inventories or losses to production and income (e.g., losses in sales of perishable goods; unexpected costs incurred in the replacement of lost records in the health care system);
- Diminished service provision: due to the total or partial paralysis of activities (e.g., damages due to the loss of a full school term);
- Added cost of alternative means of production: or provision of essential services (e.g., greater costs arising out of the use of longer or low standard roads (detours) and the construction of emergency roads;
- Cost of budgetary reorientation or reassignment;
- Income reduction: due to the non-provision or partial provision of services by public utilities (power; drinking water); reduction in personal income owing to loss of employment or being forced to work part-time;
- Costs during the emergency stage;
- Cost of situations arising from a disaster: (e.g., health campaigns to prevent epidemics);
- "Forward" or "backward" linkage effects (e.g., the destruction of a factory reduces the economic activities of suppliers who have no alternative markets or of clients who have no other suppliers);
- Costs or benefits of external factors: (e.g., any disaster repercussion or side effect whose costs (or benefits) are absorbed by third parties who are not direct victims (or beneficiaries) of the disaster).

c) Intangible Effects

Disasters may produce indirect effects, some of them major effects, that may be difficult to identify and impossible to quantify. These effects lead to "intangible" damage (or benefits) such as: human suffering, insecurity, a sense of pride or antipathy at the way in which authorities have faced the disaster's consequences, solidarity, altruistic participation, the impact on national security and many other similar factors that have an effect on well-being and the quality of life.

d) Macro-economic effects

If the disaster is large enough, it may affect prices and employment nationally and internationally. Macro-economic effects reflect the manner in which the disaster modifies the performance of the main economic variables of the country. The magnitude of the disaster is important for defining the time-frame for which macroeconomic effects are to be estimated. Experience shows that a "reasonable" time is normally the remainder of the year in which the disaster occurs plus another one or two additional years.

FAILURE PROBABILITIES

Bac Hung Hai polder

First, the failure probabilities of each kilometer along the river dikes have been determined. Results will be discussed of the left Red River dike protecting the Bac Hung Hai polder. Also the consequences of a dike breach which respect to inundation will be shown.

Secondly, it will be shown in this paper how local scour at the toe of a dike due to river flow velocities in combination with an incorrect bank protection results in slip circle instability. The interaction of disciplines as hydraulics, morphology, geotechnics and statistics resulted in failure probabilities for particular dike sections.

The Bac Hung Hai irrigation and drainage system is located south-east of Hanoi in the lower area of the Red River Delta and surrounded by Duong River in the north, Red River in the west, Thai Binh River in the east and Luoc River in the south (Figure 6).

The dikes protect 2.8 million people (year 2003) most of them living in small villages. The polder itself is about 225,000 ha of which most is agricultural land situated within Ha Noi, Bac Ninh, Hung Yen, Hai Duong provinces, including Hai Duong and Hung Yen cities. The land use in the polder is mostly rice production. In the western part along the river some annual crops are grown. Residential land also consumes a considerable amount of space.

The National Highway no 5 and the National Railway both connecting Ha Noi via Hai Duong with the port city of Hai Phong cross Bac Hung Hai polder. This major transportation axis is part of the "Industrial Corridor" along which many (international) factories and businesses are located.

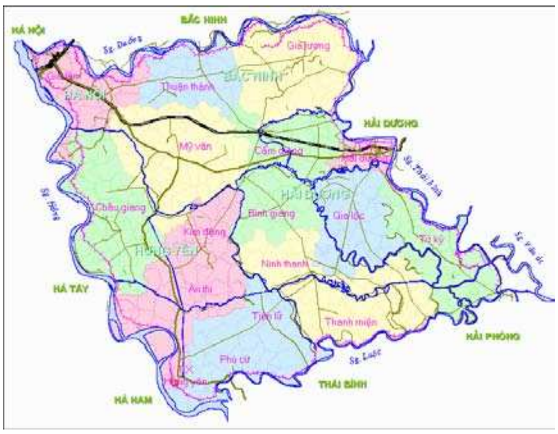

Figure 6. Map of Bac Hung Hai polder with important infrastructure

The elevation of the polder ranges between 10 and 0 meters, with the highest parts in the north-west and the lowest parts in the south-east.

The irrigation and drainage of Bac Hung Hai polder is regulated mainly by three main gates; one intake and two outlets. The main water inlet is the Xuan Quan Inlet located along the Red River left dyke at km 77.200. The total width is 19 m divided over 4 gates (each 3.5 m width x 4 m high) and 1 lock (5.0 m width x 8.5 m high). The inlet is designed for a discharge of 75 m^3/s. The main drainage sluices are located in the south-east of the polder.

In addition, the polder is connected with the surrounding rivers with many small inlet conduits and numerous pumping stations. The small inlet conduits have openings of about 1.0 m x 1.5 m. These conduits are built in the dike body at levels much lower than the dike crest level. Therefore, overflow is no failure mechanism. The conduits were built in the end of 1950s and in 1960s. Most of the conduits are in a good condition, although some conduits show cracks in the concrete.

Hydraulic boundary conditions

In the FRA extreme situations are studied for which appropriate observations do not exist, and the data are available only on a very limited number of stations in the project area. From these restraints it has been concluded that the complexity of the Red River Basin hydraulic behavior for this project cannot be assessed adequately from simple empirical relations.

Therefore, for quantitative predictions of the water levels and discharges during flood conditions state-of-the-art hydraulic modeling tools have been used that account for the dynamics and variations in geometry in the system, and that have been calibrated on the limited observations.

For the Red River delta a calibrated 1D model is already available. In Figure 7 results of computations are presented, in particular water level relation curves for the Red River at km 92, at Hanoi and at Son Tay for a certain discharge.

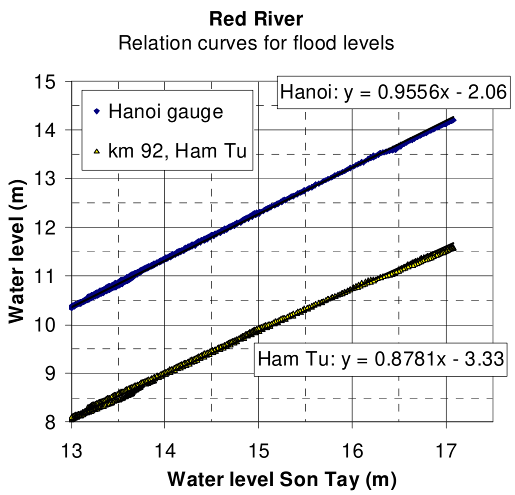

Figure 7. Relation curves for flood levels for the Red River computed from 1D hydraulic model simulations

Recurrence intervals for piping

Recurrence intervals (or failure probabilities) of dike sections were computed with a so-called “crude Monte Carlo” method. In this approach the random nature and uncertainties of the physical variables involved, are taken into account. Other variables are described in a deterministic way. Random variables are assumed to be normally distributed, except some variables, such as for instance the water level in the river (H) which is expressed as a relation with recurrence interval by a table of values and settlement of the dike body. Figure 8 shows the water levels in the Red River and in ditches at the inland side of the dike.

The average value d = 4.62 m of the thickness of the clay layer is determined on the basis of the available geotechnical data. For some locations a less thick clay layer is observed, for instance between km 90 and 100 only 3.3 m. The resulting recurrence intervals are presented in Figure 9.

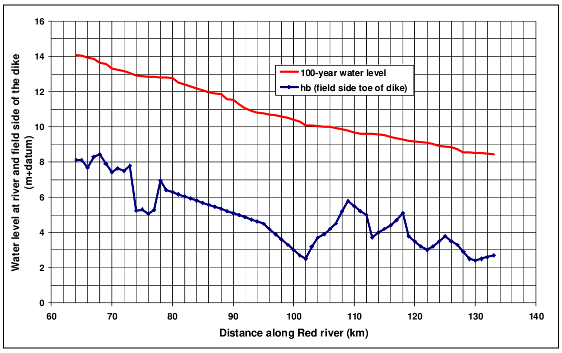

Figure 8. Water level in Red River ($H = H(T_{100})$) and water level at the inland side of the dike (h_b).

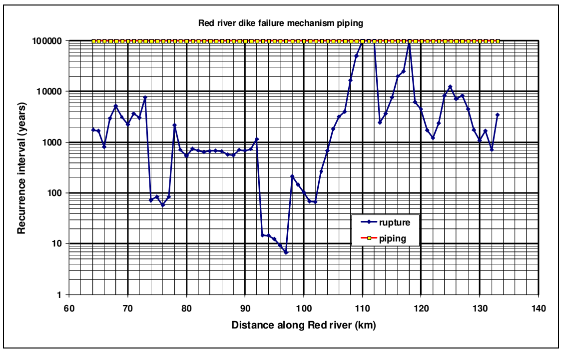

Figure 9. Recurrence intervals for the failure mechanism ‘piping’ along Red River

It is observed that soil rupture or sand boils can be expected during major floods. However, the reliability function for the sub-mechanism sand transport does nowhere lead to negative values. Hence, based on the failure probability analyses, it is concluded that dike failure due to piping is unlikely for the dikes along Bac Hung Hai polder.

Recurrence intervals for macro-instability

The slip circle computations have been carried out for different flood levels, but as the design flood level is related to the 100 year flood, the actual safety level computed for the 100 year flood has been selected. Besides, the differences between the safety levels for the different flood levels are small. The selected actual safety levels take into account the occurrence of a small flood some days/weeks before the extreme flood, which will result in a saturated dike body and water in the cracks.

The failure probability due to macro-instability for that dike is shown in Figure 10. It is observed that between km 90 and km 115 due to insufficient stability of the field side slope of the dike problems may be expected.

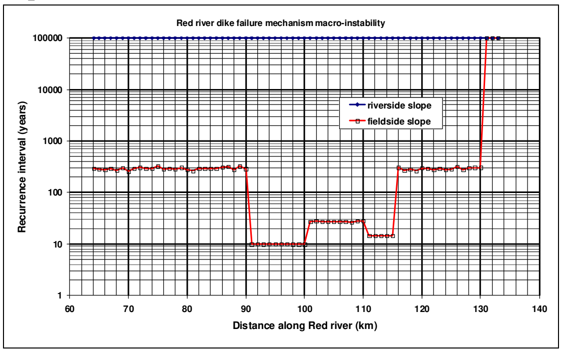

Figure 10. Recurrence intervals for mechanism macro-instability along Red River

Combined recurrence intervals

The probability of failure (or recurrence interval) of a dike ring is to be derived by combining the failure probabilities for each river kilometre, where the lower and upper bound follows from complete correlation and full independence between the sections.

Figure 11 shows that the combined recurrence intervals more or less equals the minimum value of the recurrence intervals due to the overflow or the macro-instability mechanisms. Basically, the dominant mechanism everywhere is overflow, except at the Red River reach km 90 to km 115, where the instability of the field side slope of the dike determines the overall failure probability.

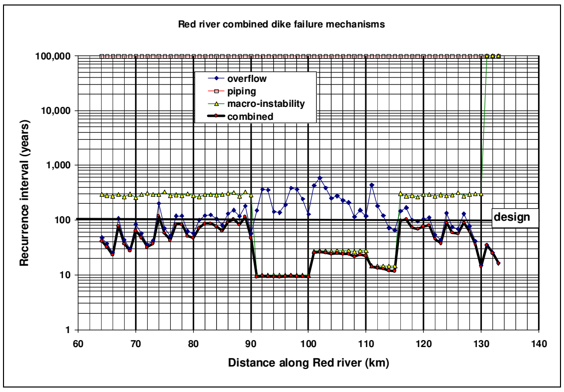

Figure 11. Combined recurrence intervals along the left Red River

Ultimately, the weakest locations can be determined on the basis of the combined failure probabilities. For the Bac Hung Hai polder they are shown in Figure 12.

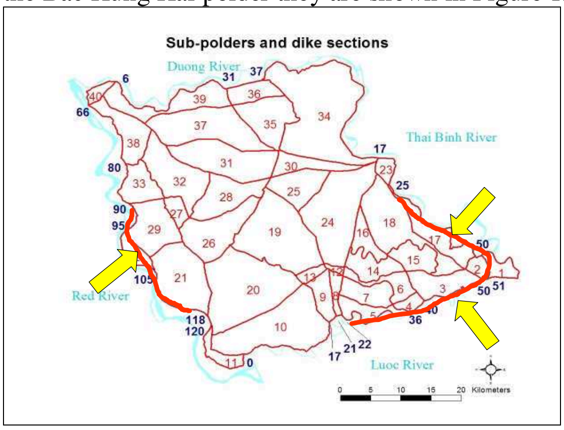

Figure 12. Overview of location of the weakest sections in the Bac Hung Hai polder dikes

Example of the consequences of a weak section

The combined recurrence interval or failure probability as computed above for each dike kilometre, includes the uncertainties in the river dynamics, in particular the trend in the vertical movement of the bed level. It is observed that the bed levels and water levels of the Red River downstream of Son Tay (down till the sea) are lowering with a rate of 1 to 2 cm/year in the long term. They seem to have changed even more in the period 1996 – 2000. It is most likely that the ongoing trend will persist, leading to an approximate degradation (of cross-section averaged bed levels) of about 1 meter in 2050 compared to the present situation.

In addition, river dynamics also refers to the horizontal movement of the river and this may form a major threat to the stability of the dikes. Hence, channel fixation by revetments at various locations has been carried out to maintain or improve safety. At the toe of the revetments in outer bends, however, bend scour due to the high flow velocities occur if the revetment has not been designed properly. In sequence, the following phenomena may occur:

- General scour of the bed level due to the bed lowering trend;
- Scour of the river bed in the outer bend;
- Erosion below the revetment resulting in a steepening of the under water slope (sometimes even steeper than 1 vertical to 2 horizontal);
- Loss of stability of dike material along a slip circle;
- Visible sliding (Figure 13).

Figure 13. Example of a sliding due to toe scour in an outer bend

Slip circle computations have been made using the available, very limited data regarding river bend scour and soil characteristics. Ground investigations and laboratory tests have not been carried out. The stability analysis was a common α-φ-analysis and even for moderate values for cohesion and friction angles, it resulted at some locations in values of the safety factor F in the range of 1 to 1.5, where 1.35 is the minimum requirement in Vietnam.

Figure 14 shows the damage to houses as a consequence of a sliding after a flood.

Figure 14. Damage to a house due to a sliding

DAMAGE ASSESSMENT

The flood-damage assessment for Bac Hung Hai is carried out by combining and aggregating spatial varying information using GIS-tools, hence spatially varying inundation depths and impacts are required. For that reason the inundation simulations are carried out using a two-dimensional (depth-averaged 2D) model that simulates the spreading of the inflow and filling of the polders dynamically and spatially.

In the simulations it has been assumed that dike failure occurs during the moment of maximum water level. This is the situation with highest pressure on the dikes, but also generates the highest inflow discharges (causing the highest damage).

On basis of a more detailed inspection of the topography 5 breach locations were selected that were expected to represent sufficiently the inundation process in each zone for breaches anywhere in large reaches of the adjacent dike-sections.

The inundations are representative for a 1/100 year median sized flood (maximum daily average discharge Son Tay = 26,700 m3/s). The moment of failure is assumed to be on August 21. Dike failures in the north-west along the Red River result in flooding of almost the entire Bac Hung Hai polder (Figure 15), whereas dike failures in the north-eastern result in partly flooding,

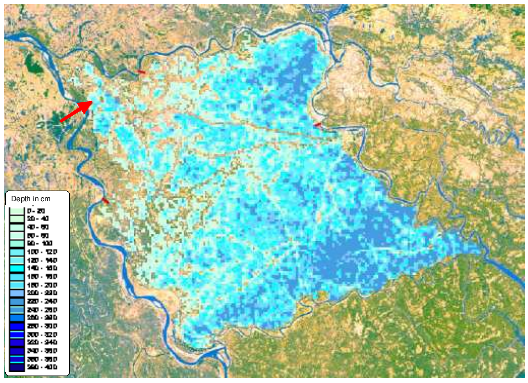

Figure 15. Computed inundation due to a breach in the most north-west part of the Bac Hung Hai polder

As an example, water levels as function of time for Hung Yen are shown in Figure 16. As can be seen in this figure, the water level reaches values up to 3 m. This is close to the inundation depth of 3.5 m observed at some locations during the 1971 flood, as reported by Ministry of Agriculture and Rural Development [2]. It is also observed from this figure that there will be severe flooding till several weeks after the breach, creating large damages, affecting people for a very long time and will have considerable environmental impact.

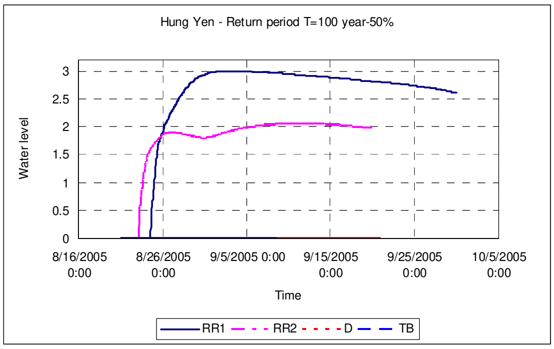

Figure 16. Water levels at Hung Yen as result of dike breaches at different rivers

Flooding risk is defined as the product of the probability of flooding and the damage of flooding. To assess the damage of flooding first the physical damage has to be determined and subsequently economic valuation of this damage should be carried out. The physical damage is determined by calculating areas of different types of land use that are inundated while valuation of the damage is done using an economic model. For ranking purposes a cost-benefit analysis of dike improvements is carried out. The ranking is further carried out using a composite index that includes an index for affected population, affected poor and volume inundated.

The final step in the economic valuation of flood damage is a cost-benefit analysis. The cost-benefit analysis is used as input for the priority ranking of the different dike sections. Additional information required for the cost-benefit analysis is the improvement costs of dike sections.

The outcomes of the damage assessment shows the largest damage if dike section 40 fails, followed by dike section 38 (Figure 12). Failure of these sections, located in the north-west region of the Bac Hung Hai polder, cause the whole polder to flood.

The calculated damages are based on the volume of water that entered the polder from two dike breach scenarios at 5 locations: due to a 25-year flood and a 100-year flood. From Figure 17 it is observed that a distinct relationship between flood volume and damage exists.

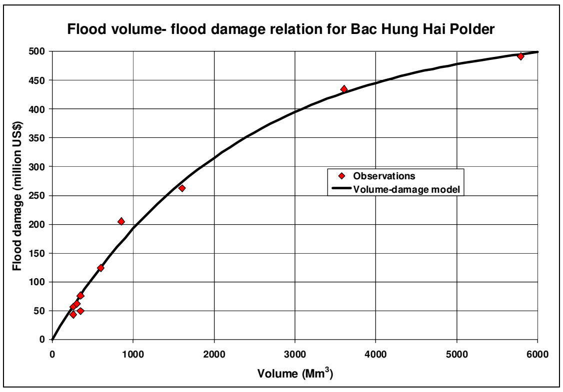

Figure 17. Relationship between flood volume and damage

Conclusions

Based on the Flooding Risk Assessment for the Bac Hung Hai polder in the Red River delta south-east of Hanoi the following conclusions can be drawn:

- The dike failure mechanisms overflow (including wave overtopping), piping and macro-instability have been considered. The analyses indicate that only overflow and macro-instability play a role for the dikes along Bac Hung Hai polder.
- Simulations based on the 1/25 and 1/100 year flood scenarios indicate that breaches particularly in the Red River dike will create inundation depth of up to about 3 m. Similar depths were observed during the inundations caused by the dike failure of 1971 flood event. The simulations also indicate that the flooding will continue for some months.
- Consequently, such dike failures will create enormous damages, affecting a large number of people and will have severe environmental impacts. The combination of the high flooding probability and the large damage costs in case of flooding make the average annual damage value large. Since the costs for dike repair and improvement are comparatively small, dike improvement projects will have a large benefit-cost ratio.

It can be concluded that a full FRA is a strong tool for ranking projects, e.g. weak spots along the dikes that require improvements. Obviously, there is a strong need for accurate predictions of water levels, river bed levels and detailed knowledge of geotechnical characteristics of the dikes.

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