Risk-based Procedure for Design and Verification of Dam Safety

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4th International Symposium on Flood Defence
May 6-8, 2008 in Toronto, Ontario, Canada
Overview

• Introduction (RIMAX and Objectives)

• Proposed Concept
  • Types of considered failure
  • Comprehensive procedure

• Study Areas

• Modules of RIBADD (M1 – M6)

• Conclusion
RIMAX

• Project is part of the program on
  “Risk Management of Extreme Flood Events (RIMAX)”

• Aim of RIMAX:
  • To develop and implement improved instruments of flood risk management
  • Extreme flood events in river basins with a return period of more than a 100 years and a highly destructive potential

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Objectives

- Development of a risk-based procedure for design of a dam and verification of dam safety
- Combining traditional with risk-based components
- Scientifically validated and practicable
- Application to several case studies
- Support further developments of design standards
- Integration into a Flood Risk Management
Failure Types (caused by flood loads) and corresponding probabilities of failure $P_F$

- Large spillway discharges $\rightarrow P_{F,A}$
- Overtopping without dam breaching $\rightarrow P_{F,B}$
- Overtopping with dam breaching $\rightarrow P_{F,C}$
- $P_{F,A} > P_{F,B} > P_{F,C}$

Failure type A: Spillway damages in Saxony (2002)

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RIBADD (Risk-Based Design of Dams)

- Estimation of Failure Probabilities (M1, M2)
- Potential Dam Breaching (M3)
- Flood Wave Modelling (M4)
- Damage analysis (M5) and Risk Assessment (M6)
Study area 1: Möhne Dam

- **arch-gravity dam**
- catchment area: 436 km²
- height: 40.3 m; crest length: 650 m
- capacity 134.5 hm³
Study area 2: Henne Dam

- rockfill dam
- catchment area: 98 km²
- height: 59 m; crest length: 376 m
- capacity 38.4 hm³
RIBADD (Risk-Based Design of Dams)

- Estimation of Failure Probabilities (M1, M2)
- Potential Dam Breaching (M3)
- Flood Wave Modelling (M4)
- Damage analysis (M5) and Risk Assessment (M6)
M1: Synthetic Flood Event

- Usage of a stochastic model
- Calibrated for two study areas
- Observed daily flows (46 years) were used
- Artificial series of reservoir inflow
M1: Synthetic Flood Event

- Reservoir inflows at the Möhne Dam

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M1: Synthetic Flood Event

- Reservoir inflows at the Möhne Dam
- Validation of Model Performance

Frequency distribution of monthly peaks

Frequency distribution of annual peaks

46 observed / 7360 generated values

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M2: Probability of hydro-meteorological failure

\[ P_F = P(h_0 + h_R + h_f > b) \]

\[ = \int \int f_{h_0}(h_0) \cdot d_{h_0} \cdot f_{h_R}(h_R) \cdot d_{h_R} \cdot f_{h_f}(h_F) \cdot d_{h_f} \]
M2: Probability of hydro-meteorological failure

\[ P_F = P(h_0 + h_R + h_f > b) \]

\[ = \iint f_{h_f}(h_0) \cdot d_{h_f} \cdot f_{h_R}(h_R) \cdot d_{h_R} \cdot f_{h_f}(h_f) \cdot d_{h_f} \]
M2: Probability of hydro-meteorological failure

\[ P_F = P(h_0 + h_R + h_f > b) \]

\[ = \int f_f(h_f) \cdot d_f \cdot f_r(h_R) \cdot d_r \cdot f_h(h_0) \cdot d_h \]

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M2: Probability of hydro-meteorological failure

Historical data of measured daily water levels
M2: Probability of hydro-meteorological failure

Empirical cumulative density functions for every month

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M2: Probability of hydro-meteorological failure

\[ P_F = P(h_0 + h_R + h_f > b) = \int \int \int f_{h_0}(h_0) \cdot d_{h_0} \cdot f_{h_R}(h_R) \cdot d_{h_R} \cdot f_{h_f}(h_f) \cdot d_{h_f} \]

**Freeboard**

**Module 2**

Introduction

Concept

Study areas

Conclusion

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M2: Probability of hydro-meteorological failure

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P_F = P(h_0 + h_R + h_f > b) = \int \int \int f_{h_0}(h_0) \cdot d_{h_0} \cdot f_{h_R}(h_R) \cdot d_{h_R} \cdot f_{h_f}(h_f) \cdot d_{h_f}
\]

Introduction

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Study areas

Module 2

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M2: Probability of hydro-meteorological failure

- Results of a scenario with different operating rules
M2: Probability of hydro-meteorological failure

- Results of a scenario with varying capacities of spillway
M3: Dam breach modelling

- Models vary in complexity and basis
- A simplified dam breach model was developed
- Estimating the discharge by combining stochastic, parametric and physical based models
- Outflow hydrograph by using MCS
M3: Dam breach modelling

- Breach formation
  - Probability density function for $B_{\text{MAX}}$
  - Parametric breach curves

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M3: Dam breach modelling

- Stochastic Outflow Hydrograph by using MCS
- $B_{\text{max},1} = 50$ m and $B_{\text{max},2} = 90$ m

![Stochastic Outflow Hydrograph](image)
M4: Flood Routing – hydrodynamic simulation

- Determination of flooded areas, maximum water depth and maximum velocities

**Used 2-D hydrodynamic model (MeadFlow)**

- Finite element method (FEM)
- St. Venant equations (complete or simplified)
- Steady and unsteady flow
- Automatic procedures for refinement of network
- Numerical stability
- Very short computation times
M4: Flood Routing – hydrodynamic simulation

- Determination of flooded areas, maximum water depth and maximum velocities

Location of the dam

Introduction

Concept

Study areas

Module 4

Conclusion

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M4: Flood Routing – hydrodynamic simulation

- Determination of flooded areas, maximum water depth and maximum velocities

Finite element mesh of the hydrodynamic model
M4: Flood Routing – hydrodynamic simulation

• Verification of the model’s applicability on the basis of the failure of the Möhne Dam during World War II
M4: Flood Routing – hydrodynamic simulation

- Application for reference scenarios and dam break waves
M5: Consequences

Overall consequences of dam failure

- Public safety consequences
- Economic consequences
- Environmental consequences

Landuse

Inundation characteristics

Damage function

Damage

Relative Damage [%]

Intensity

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M5: Consequences

- Other damage criteria (flow velocity times water depth)
- Inundation – Partial Damage – Total Damage

![Map showing different damage levels](image)

- Hydrostatic Damage
- Total Damage: Masonry, Concrete, Brick
- Partial Damage

- $v' \times h < 2 \text{ m}^3/\text{s}$
- $2 < v' \times h < 7 \text{ m}^3/\text{s}$
- $v' \times h > 7 \text{ m}^3/\text{s}$
M6: Risk Parameters

- Failure probabilities
- Product of failure probability and potential damage
- People at risk (PAR)
- Subjective risk in the field of socio-economics and ecology
- Presentation of Risk in maps and Risk level graphs
- Acceptance limits ("Acceptable Risk")
Conclusion - RIBADD

• With RIBADD a scientifically validated and practicable risk-based procedure for design and verification of dam safety was developed

• Cognitions from the application of RIBADD to several case studies will support further developments of design standards

• Safety evaluations of dams with respect to risk on a practicable and economically significant basis are possible through RIBADD

• RIBADD can be used as a part of an integrated flood risk management

• RIBADD provides tools for the selection of risk reduction measures like emergency plans
Thank you for your attention!