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Ouémé Bridge, hydraulic study: flooding risk and stability assessment using MIKE 21

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Abstract

With the objective to evaluate if rehabilitation of the road crossing the Ouémé River in Benin will lead to an increased risk of failure for the Ouémé Bridge due to higher extreme water levels and/or discharges at the bridge the MIKE 21 HD model was used to simulate the extreme flow conditions in the Ouémé River basin before and after the planned road rehabilitation. The stability of the bridge was subsequently analysed. The main findings in the project were the following: *1)* It was confirmed that large stretches of the existing road frequently are being flooded, whereas no parts of the rehabilitated road are being flooded; *2)* The water level at the bridge does not increase after rehabilitation of the road; *3)* The water discharge at the bridge is significantly increased for return periods above app. 1 year; and *4)* The increased discharge does not affect the stability of the bridge directly but could in a longer term affect the river banks or bed and thereby indirectly the stability of the bridge.

1 Introduction

1.1 Background

The Ouémé Bridge is located on RNIE 4 approximately 50 km east of Bohicon in the Republic of Benin, where it crosses the 200 m wide basin of the Ouémé River. See Figure 1 below. The bridge comprises 8 spans of 26 m each. Each bridge deck section is carried by two simple supported prestressed concrete I-beams resting on pile supported piers.

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See photographs in Figure 2 below. The bridge was constructed in 1974 - 1976. The clearance of the bridge is in level 19.6 m.

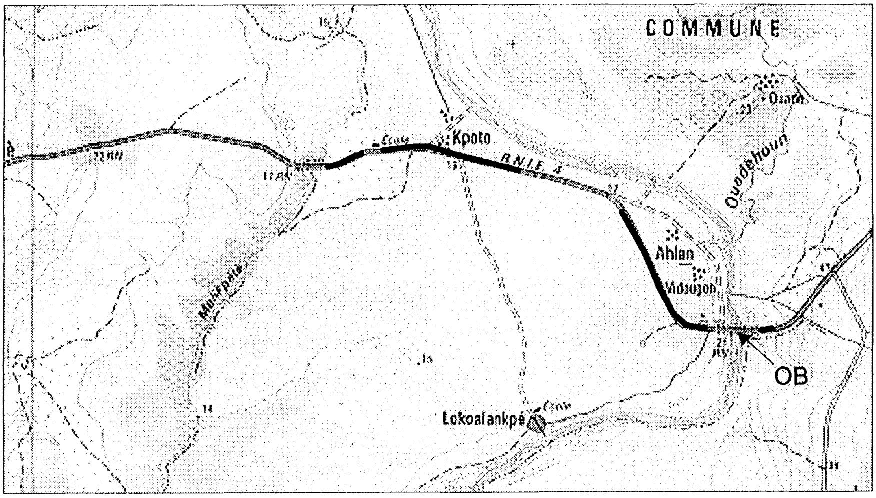

Figure 1: Existing road and Ouéme Bridge (OB) crossing the River Ouémé Valley. The marked stretches frequently being flooded, i.e. for water levels above app. 17.5 m.

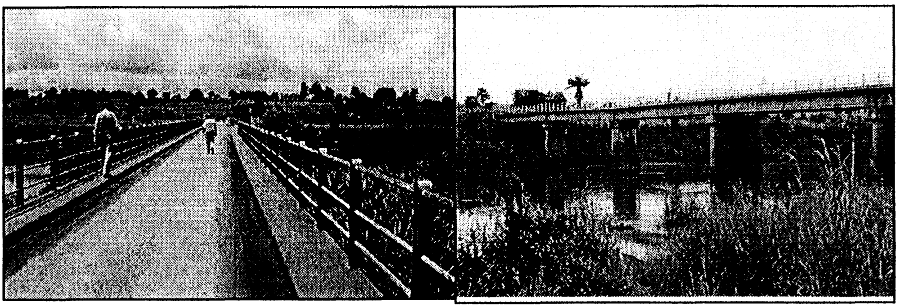

Figure 2: Photographs taken from the site of the Ouémé Bridge.

The daily mean discharge and daily maximum water levels at the bridge have been recorded since 1985,[3] and the yearly extremes varies generally between 17 and 18 m. The highest water level reported is 18.5 m which was observed in 1963, corresponding to a clearance only 0.1 m larger than the bridge's minimum design clearance of 1.0 m.

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With adjacent ground levels as low as 16.0 m, large areas outside the river banks are frequently being flooded when the water level exceeds 16.0 m. As the lowest level of the access road is less than 17 m the road is overspilled at the time of extreme floods, hence, providing an effective safety valve against reaching flood levels or discharges that could be critical to the bridge. See also Figure 1 above.

A road rehabilitation project for the RNIE 4 is currently being appraised by DANIDA. As part of this project the road levels on each side of the bridge are intended to be raised from the current levels to more than 19.0 m, without changing the road alignment or the bridge. The present study forms part of this appraisal.

1.2 Objective of Study

The objective of the present hydraulic study was to evaluate if an implementation of the proposed road rehabilitation projects would lead to an increased risk of failure for the Ouémé Bridge due to higher extreme water levels or discharges at the bridge.

This objective was met through:
1. Hydraulic investigations on basis of the proposed road rehabilitation project leading to assessment of the changes in the extreme water level and discharge statistics.
2. Stability analysis for calculated new extreme levels and discharges.
3. Assessment of the possible needs for additional measures.

2 Hydraulic Investigation

2.1 Measured Discharges and Water Levels

The Direction de l'Hydraulique du Benin has since the construction of the bridge on a regular basis measured water levels, discharges and flow velocities at the bridge,[2,3]. From the available records monthly extreme values of measured daily-mean discharge and daily-maximum water level were compiled and plotted. Cf. plots in Figure 3 below.

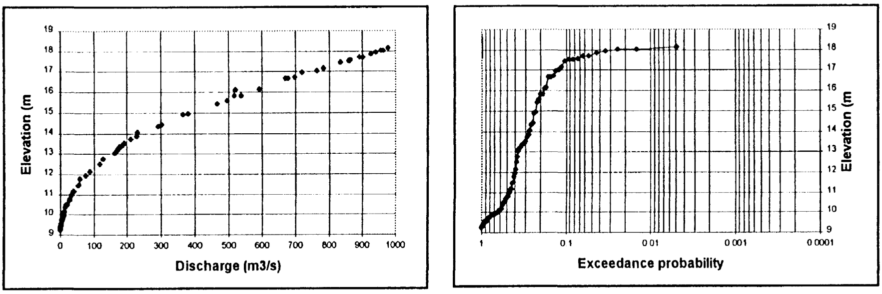

Figure 3: Monthly extreme daily-maximum water level at Ouémé Bridge vs. daily-mean discharge (left) and vs. exceedance probability (right).

Based on Figure 3 the most likely 1 year, 50 years and 100 years events of monthly extreme daily-maximum water levels and corresponding daily-mean discharges were estimated. These values are listed in Table 1.

Table 1: Estimated monthly extreme values for daily-maximum water level and daily-mean discharge with 3 return periods: 1 year, 50 years and 100 years

Return period	**Exceedance Probability**	**Max. Water level m**	**Max. Discharge m^3/s**
1 year	$8.3 \cdot 10^{-2}$	17.5	855
50 years	$1.7 \cdot 10^{-3}$	18.65	1060
100 years	$8.3 \cdot 10^{-4}$	18.8	1100

It is noted that the clearance of 1 m below the supporting beams, i.e. water level of 18.6 m, is likely to be reached only once every 50 year.

2.2 MIKE 21 Simulations

The MIKE 21 simulations were performed using the MIKE 21 HD module which is the basis module in the MIKE 21 package developed by Danish Hydraulic Institute (DHI) for modelling of 2D free surface flows. The module simulates the water level variations and flows in response to a variety of forcing functions in lakes, estuaries and coastal areas. It simulates the unsteady flow in one layer (vertically homogenous) fluids. The water levels and flows are resolved on a rectangular grid covering the area of interest when provided with the bathymetry, bed resistance coefficients, wind field, hydrographic boundary conditions, etc. The

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system solves the full time-dependent non-linear equations of continuity and conservation of momentum. The solution is obtained using an implicit ADI finite difference scheme of second-order accuracy. Further details on the HD module are given in DHI,[5].

2.2.1 Simulation Approach

The approach for the simulations was as follows:

1. Setting up the hydraulic model for the existing topography and for a situation where the road has been rehabilitated as proposed.
2. Preparing a test matrix covering the extreme range of water levels and discharges, i.e. return periods from app. 1 year to 100 years.
3. Calibrating the model towards the observed discharges and corresponding water levels.
4. Running the model for the existing road and the proposed road.
5. Comparing and evaluating the results from the simulations.

2.2.2 Setting Up the Model

Due to the lack of high quality data in Benin, especially on the topography, many assumptions have been made in order to establish a reliable model of the Ouémé River Valley.

The topography for the model was established on basis of a 1:50.000 chart series IGN,[4] SETEC,[1] and levelling performed by RAMBOLL during visits to the site.

21x14 km of the valley were modelled and to ensure sufficient resolution where the flow passes the Ouémé Bridge a 20 x 20 m grid was selected. This led to a 1050x700 element model for each of the situations: existing and rehabilitated road.

In order to determine accurately the discharge at the bridge, it was important to include the effects of the culverts allowing water to pass under the road. This was included in the simulations by placing pairs of sources and sinks on each side of the road. The strength of the sinks and sources were selected as the calculated maximum discharge capacity of each culvert. Larger structures, such as the Ouémé Bridge, were modelled by including in the model their correct total width and depth, and by including also the pier resistance from the piles supporting the bridge.

During extreme events the areas surrounding the river are flooded. These areas largely consist of agricultural land, mainly banana fields. It was therefore decided to vary the bottom friction in the model in a way that the river bed appeared much smoother than the surrounding land. Manning numbers of 32 and 20 $m^{1/3}/s$, respectively, were used in the models.

2.2.3 Test Matrix and Calibration

To cover the extreme events in Table 1 corresponding values of water levels and discharges for the existing situation were defined based on the relationships in Figure 3. These reference values are listed in Table 2.

Table 2: Reference values for the MIKE 21 simulations. Corresponding discharges and water levels at Ouémé Bridge, existing road model.

Water level	m	16.5	17	17.5	18	18.5	19
Discharge	m^3/s	680	770	860	940	1010	1110

The calibration of the model was performed by running the model with various upstream inflows and initial water levels until agreement with the simulated stable discharges and water levels at the bridge and the reference values in Table 2 was achieved.

2.2.4 Production Simulations, Main Results

After a number of preliminary runs the actual test matrix in Table 3 was established. Both models were subsequently runned with these values.

Table 3: Test matrix for MIKE 21 simulations. Existing and rehabilitated road models.

Upstream inflow	m^3/s	690	780	880	1120	1540	2440
Initial water level	m	16.5	17	17.5	18	18.5	19

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Examples of the calculated water levels, depths and fluxes for the Ouémé River Valley before and after the proposed road rehabilitation, are shown in Figures 4 and 5 below.

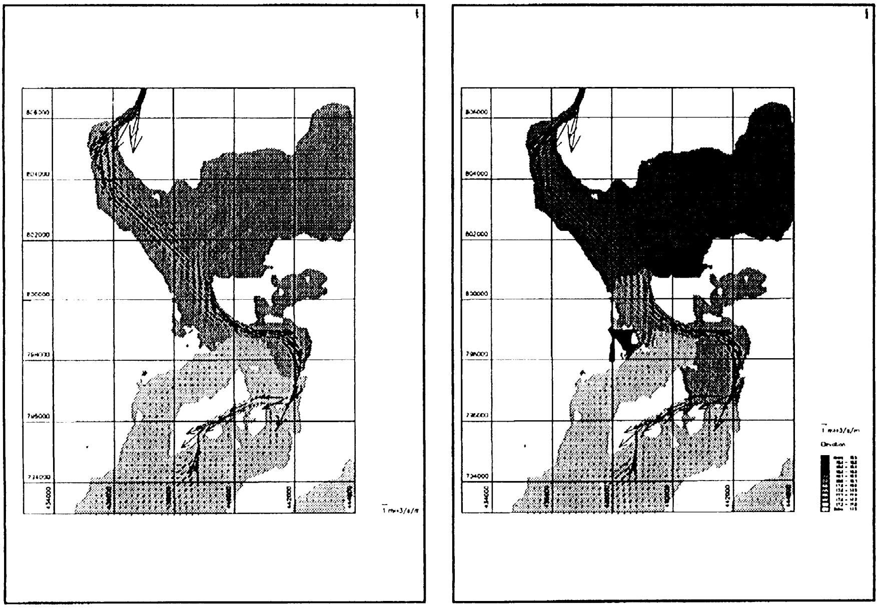

Figure 4: Water levels and fluxes in the Ouémé River Valley. Left: Existing road. Right: Proposed road.

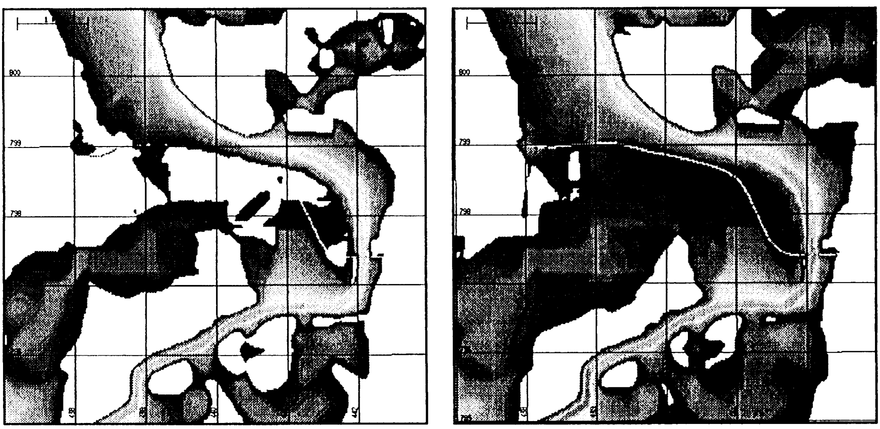

Figure 5: Water depths in the vicinity of Ouémé Bridge. Left: Existing road, 1 year event, water level 17.5m, discharge 855 m^3/s. Right: Proposed road, 100 years event, water level 18.85m, discharge 2350 m^3/s.

The simulations verify, as seen in Figure 5 above, that large portions of the existing road are being flooded even for water levels as low as 17.5 m, corresponding to a 1 year event, whereas the proposed road rehabilitation prevents the road from being flooded even for water levels of 18.8 m, corresponding to a 100 years event.

2.3 Calculated Discharges and Water Levels

Based on the MIKE 21 simulations the ratios between the monthly extreme daily-mean discharge and daily maximum water level vs. the corresponding exceedance probabilities were calculated. Values are plotted in Figure 6 below. In Table 4 corresponding values for the 1 year, 50 years and 100 years events have been extracted.

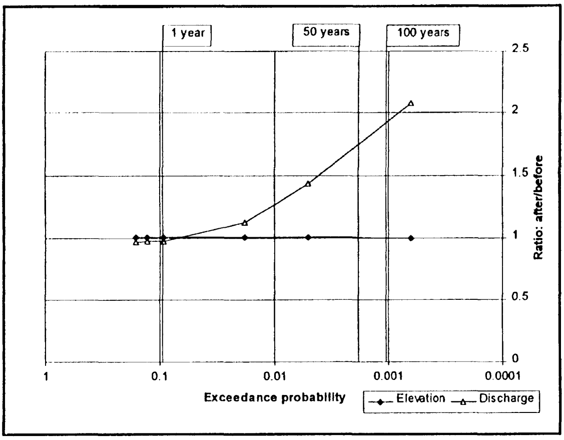

Figure 6: Ouémé Bridge monthly extreme water levels and discharges. Exceedance probability versus ratio between situation after and before rehabilitation of the road crossing the Ouémé River basin.

Table 4: Monthly extreme values for daily-maximum water level and daily-mean discharge before and after road rehabilitation for 3 return periods: 1 year, 50 years and 100 years.

Return Period years	Exceedance Probability	Before road rehabilitation		After road rehabilitation	
		Level m	Discharge m^3/s	Level m	Discharge m^3/s
1	$8.3 \cdot 10^{-2}$	17.5	855	17.5	820
50	$1.7 \cdot 10^{-3}$	18.65	1060	18.65	1950
100	$8.3 \cdot 10^{-4}$	18.8	1100	18.8	2150

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It is observed that the water level at the bridge generally is not affected by the rehabilitation of the road whereas the corresponding discharges for exceedance probability levels above 1 year are increased significantly because nearly all water in the river after rehabilitation of the road must pass the Ouémé Bridge.

3 Conclusions

3.1 Hydraulic Conclusions

The MIKE 21 simulations of the extreme flow in the Ouémé River before and after realisation of a proposed road rehabilitation project led to the following principal results:

1. In the existing situation, large parts of the road crossing the Ouémé River Valley are being flooded more frequently than once a year.
2. By rehabilitating the road, no parts of the road will be flooded - not even during a 100 years event.
3. The water levels at the bridge are virtually not affected by the rehabilitation of the road.
4. The water discharges at the bridge are increased significantly for events with return period larger than app. 1 year. For the 100 years event the discharge is increased by nearly 100%.

3.2 Bridge Stability

As the hydraulic study showed that the water level newer will reach the superstructure of the bridge only forces on the supporting piles have been considered in the assessment of the stability of the bridge. Depth integrated velocities at the position of the Ouémé Bridge were extracted from the MIKE 21 simulations and used to calculate drag forces on the piles after rehabilitation of the road.

The stability calculations concluded that extreme water levels with corresponding velocities (on the assumption that stowage of driftwood or similar in front of the columns will not occur) do not affect the stability of the bridge.

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3.3 Erosion Risk

At the bridge an upper sand layer covers a thick layer of plastic clay. The velocities measured at the bridge indicate that considerable movement of the sand takes place during extreme flow conditions. The simulations showed that these velocities, after rehabilitation of the road, will be significantly increased for events with return periods larger than 1 year.

The increase cannot be quantified on the basis of the present study, but is likely to be between 50 and 100% for the 50-100 years events. Hence, local scour around the piers cannot be estimated accurately and scouring of the entire sandy layer cannot be ruled out for the velocities in question. The bearing capacity of the upper sand layer should therefore generally not be considered.

To prevent erosion it could be necessary to carry out protective measures on the river bank due to the increase in discharge for extreme events. To identify the need for such measures it has been recommended that the river bed and river banks are monitored during and after each rainy season.

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