

Experiences of using UAVs for monitoring levee breaches

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Abstract. During floods technical protection facilities are subjected to high loads and might fail as several examples have shown in the past. During the major 2002 and 2013 floods in the catchment area of the Elbe River (Germany), some breaching levees caused large inundations in the hinterland. In such situations the emergency forces need comprehensive and reliable real-time information about the situation, especially the breach enlargement and discharge, the spatial and temporal development of the inundation and the damages. After an impressive progress meanwhile unmanned aerial vehicles (UAV) also called remotely piloted aircraft systems (RPAS) are highly capable to collect and transmit precise information from not accessible areas to the task force very quickly. Using the example of the Breitenhagen levee failure near the Saale-Elbe junction in Germany in June 2013 the processing steps will be explained that are needed to come from the visual UAV-flight information to a hydronumeric model. Modelling of the breach was implemented using photogrammetric ranging methods, such as structure from motion and dense image matching. These methods utilize conventional digital multiple view images or videos recorded by either a moving aerial platform or terrestrial photography and allow the construction of 3D point clouds, digital surface models and orthophotos. At Breitenhagen, a UAV recorded the beginning of the levee failure. Due to the dynamic character of the breach and the moving areal platform, 4 different surface models show valid data with extrapolated breach widths of 9 to 40 meters. By means of these calculations the flow rate through the breach has been determined. In addition the procedure has been tested in a physical model, whose results will be presented too.

1. Background/Introduction

During a flood event, levee failures can lead to the inundation of large areas and therefore threaten the lives as well as the property of many people in the hinterland. In order to calculate the size of the inundated zone as well as water depths that are to be expected there, hydraulic models are powerful tools, if the required data is available. Usually, the analysis of a flooding combines hydraulic models with digital surface information (elevation models) and the measures of the dike breach at its maximum extent, as it is measured after the incident.

So far, there are no terrestrial surveying or monitoring methods implemented in the emergency management measures, which would allow for a real time information supply of the breach geometry and extent over time [1]. Remote sensing techniques and satellite based data are essential tools for Disaster Risk Management especially in terms of early warning systems and providing the background



of geospatial data [2] as well as covering large areas. But due to the processing requirements, limited temporal resolution (due to revisit capability), high costs [3] as well as copyright restrictions, these systems appear to be less suitable for monitoring purposes of highly dynamic and small levee failures rather than the flooding itself.

The technical progress of unmanned aerial vehicles (UAV) or unmanned aerial systems (UAS) and a decline in acquisition costs has led to a widespread use of these platforms, in private as well as commercial sectors. Although these systems differ in some technical details, most of the commercial off-the-shelf systems are capable of producing digital high resolution aerial images virtually at no cost and without the need of extensive preparation [4].

A wide range of publications and projects demonstrated the usefulness of UAV for common mapping purposes [4] as well as rapid mapping during or shortly after catastrophic events like post-earthquake disaster surveying [5], or mapping of floodplain inundation [6].

The primary outcome of these surveys may be simple videos, single geotagged or orthorectified images or orthomosaics, depending either on the precision of the on-board GNSS and IMU systems or on the presence of reliable ground control points (GCP). Either way, ground resolution can easily be brought to a few centimetres if needed. The temporal resolution is depending on flight time as well as numbers of batteries. Therefore, the observation of a highly dynamic process like a levee failure appears to be most suitable for UAVs.

2. The Breitenhagen levee failure 2013

In 2013, prolonged and intensive rainfall caused extreme floodings all over Central Europe, concentrating in the Elbe and Danube drainage basins. Water levels recorded at the Elbe and Saale exceeded the 100-year flood (HQ100) and 200-year flood (HQ200) levels and showed the maximum values since records began. As a consequence, a number of levee failures occurred. One incident near the city of Breitenhagen was recorded using a UAV, instructed on behalf of the State Service for Flood Protection and Water Management (LHW) in Saxony-Anhalt.

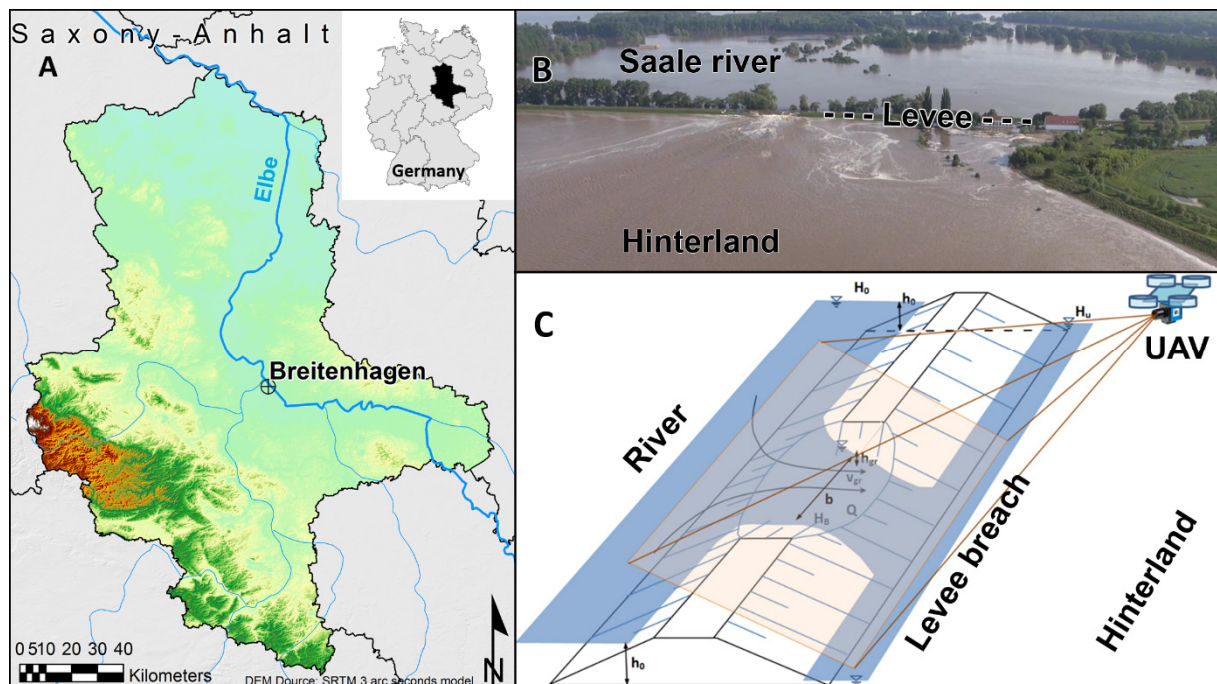


Figure 1. (A) Location of Breitenhagen (B) Picture taken from the UAV at the end of the recorded sequence (C) Scheme of the UAV survey showing the main flight pattern

The levee failure began at about 7:20 a.m. on 9th June 2016. Shortly after the beginning of the failure, the UAV took off and recorded five videos of 1:28 to 10:35 minutes length, only separated by battery replacement breaks of unknown lengths. The image resolution was 1280*720 pixel and 50 frames per second were recorded. The breach widened to about 40 m in 40 minutes and reached its maximum extend of 140 meters after nine hours. An area of 85 km² were inundated, leading to the partly evacuation of seven villages.

3. Methods

3.1. SFM modelling

Over the recent years, the increased availability of high resolution aerial footage has led to a more widespread use of photogrammetric techniques and algorithms, some of them are subsumed under the terms structure from motion or dense image matching. These software based analyses allow for a semi-automated production of 3d surface models and digital elevation models [7].

In order to process the data from Breitenhagen, the video sequences had to be converted into images using only 1 frame per second due to the slow movement of the UAV. Suitable sequences that focussed primarily the failure were arranged and analysed using the software Agisoft Photoscan.

Due to the limited resolution, four digital surface models with the maximum precision settings were created. As the number of suitable images were low for two models, additional information was added from other models. The dynamic parts, especially flowing water areas, were masked and only static areas mainly eastwards of the failure were put into the models.

The overall lack of surface information and ground control points caused some the most time consuming parts of the analysis. No geopositioning information was recorded during the flights, therefore georeferencing had to be applied indirectly by calculating an unrectified image of the surrounding area, which included locatable objects like power poles. The location of static objects could then be determined as national coordinates using a GIS. Digital surface models as well as orthoimages were combined to derive height profile lines along the levee failure. Additionally, the flow path of water within the breach was mapped to derive information about the water extent.

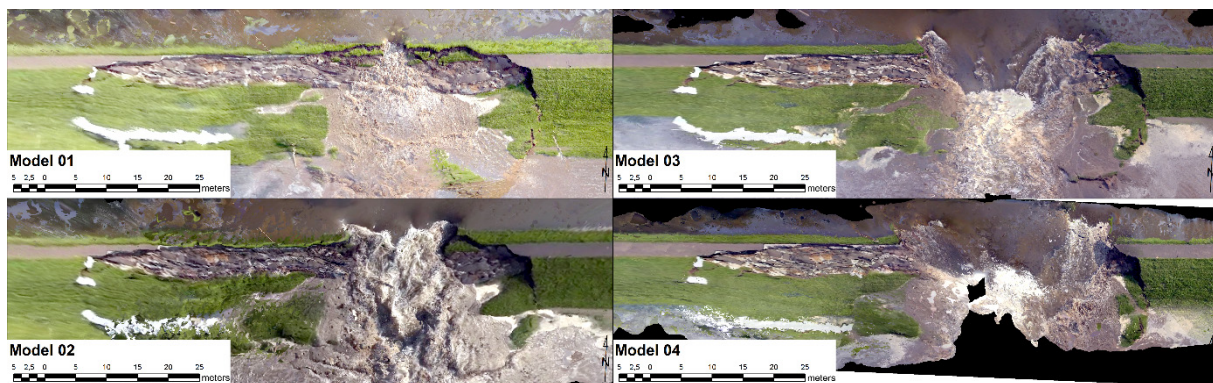


Figure 2. Orthoimages from the breach at 10, 15 21 and 27 minutes after the start of the failure

3.2. Hydrological modelling

Flow velocity and discharge are important characteristic values for the analysis of levee failures and the functional flood defence measures in the hinterland during the ongoing levee break. With these values the breach discharge, the progressive inundation of the hinterland and the inundation depth can be estimated when the terrain morphology in the hinterland and its release capacity (sluice, opening, pumping) are known. Further the size of the breach which is changing during the event as well as the flow situation upstream and downstream (river, lake, sea) should be known.

The calculation during the event will become difficult when direct measurements of the water levels, velocities and terrain points in the near of the breach are not possible. In this case it can be tried to get

the ground elevation data from aerial images by means of photogrammetry to become able to run a hydro-numerical computation. Missing terrain data of the rapidly changing breach region below the water surface complicate the real time analysis. Therefore some additional assumptions have to be made as follows:

- negligence of the approaching flow velocity far upstream of the breach in the river floodplain and downstream in the farer distance of the hinterland,
- negligence of the change of flow direction (lateral weir effect),
- assumption of a broad crested spillway or a Venturi flume with the critical depth and velocity respectively in the breach,
- retarded or submerged flow when the downstream water level exceeds about $\frac{3}{4}$ of the upstream water depth,
- no change of subcritical or supercritical flow when the downstream energy head is greater than the minimum energy head in the most constricted opening,
- any remaining levee (if existing) acts as a overtopped threshold,
- the breach geometry might be approximated by a trapezium,
- the often found very steep breach flanks justify the assumption of a rectangle, which will simplify the calculation,
- scour holes cannot be identified during the flood and can therefore only be assumed approximately.

The discharge can be calculated by multiplying the mean flow velocity with the flow area $Q = v \cdot A$ (s. a. figure 1C and [8]). Assuming the critical depth due to $Fr = v/\sqrt{g \cdot h_{gr}} = 1$ yields for an (almost) rectangular breach $Q = \sqrt{g} \cdot b \cdot h_{gr}^{3/2}$

With the minimum energy head $h_{E \min} = 1,5 \cdot h_{gr} = h_{gr} + \frac{v_{gr}^2}{2g}$ the discharge with negligible approaching velocity can be estimated only from the water level difference between the upstream approach (HO) and the breach (HB)

$$\Delta h = H_O - H_B = \frac{h_{gr}}{2} + \zeta \cdot \frac{v_{gr}^2}{2g} = \frac{h_{gr}}{2} + \zeta \cdot \frac{h_{gr}}{2} = (1 + \zeta) \cdot \frac{h_{gr}}{2} \quad (1)$$

$$\text{with } h_{gr} = \frac{2 \cdot \Delta h}{(1 + \zeta)} \quad (2)$$

$$\text{and hence } Q = \left(\frac{1}{1 + \zeta}\right)^{\frac{3}{2}} \cdot \sqrt{g} \cdot b \cdot (2 \cdot \Delta h)^{\frac{3}{2}} = C \cdot \sqrt{g} \cdot b \cdot (2 \cdot \Delta h)^{\frac{3}{2}} \quad (3)$$

where $C < 1$ is a loss coefficient due to friction and spot losses which can also be expressed as seen above by the entrance loss coefficient ζ which takes values between $\zeta = 0,5$ (sharp edged breach entrance) and $\zeta \geq 0$ (well rounded breach entrance). The breach bottom, being unknown during the discharge and breach progression has the elevation

$$H_S = H_B - h_{gr} = H_B - \frac{2 \cdot \Delta h}{(1 + \zeta)} \quad (4)$$

When considering a trapezoid gap (index T) with the overflow width b and the flank slopes $1 : m_1$ and $1 : m_2$ as broad crested spillway the following equations can be applied:

$$Q_{gr} = v_{grT} \cdot A_{grT} = v_{gr} \cdot \left(b \cdot h_{grT} + \frac{1}{2}(m_1 + m_2) \cdot h_{grT}^2\right) \quad (5)$$

$$\text{with } v_{grT} = \sqrt{g \cdot h_{grT} \cdot \frac{1 + \frac{h_{grT}}{b'}}{1 + \frac{2 \cdot h_{grT}}{b'}}} \quad \text{and } b' = \frac{2 \cdot b}{m_1 + m_2} \quad (6)$$

In the case of backwater without changes between subcritical and supercritical flow, besides the upstream water level also the downstream water level and the losses in between are needed as input data. Then the discharge can be calculated by means of the principle of energy conservation (Bernoulli equation). Depending on the operating stress a quick hydro-numerical calculation can also be carried out. But in this case the flow cross sections must be known or estimated in a pre-design stage.

4. Results

With the above equations the discharge (figure 3A) and the breach parameters were estimated (figure 3B). As there are uncertainties expected among the input data their spread was taken into account by uniformly distributed random variables in a Monte-Carlo-Calculation. The resulting confidence belts for 90 and 33 per cent respectively as well as the median are shown in figure 3A. The hydro-numerical 1-D-Calculation for the model 3 ($x + 21$ min) yielded similar results which represent one moment in the progressive levee breach process [9].

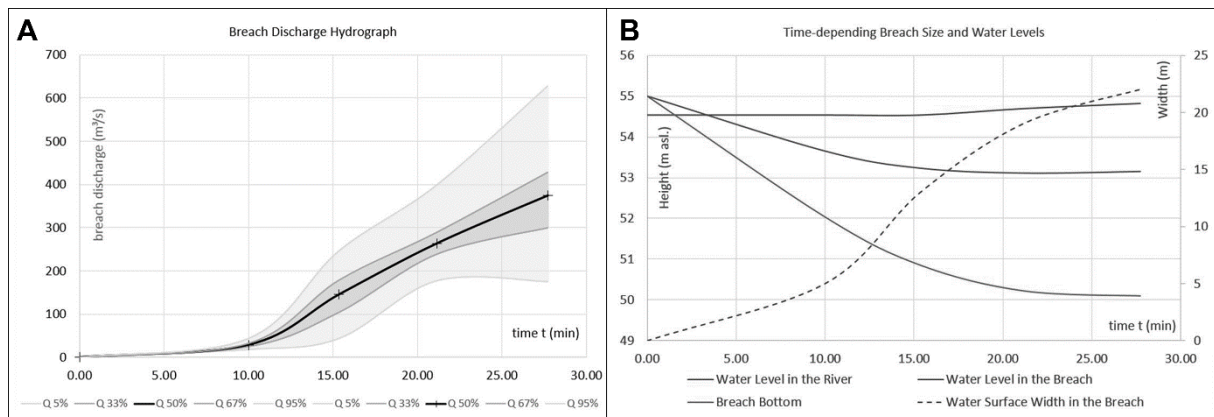


Figure 3 (A) Calculated breach discharge over time (B) Breach geometry over time

Models 02 to 04 show a distinct linear rise in breach discharge, after a steeper initial incline from model 01 to 02 (figure 3A). The temporal progression is one of the main sources of uncertainties, as the original video files were corrupted. Therefore, some assumptions about the gaps in between the video files had to be made. Due to personal expertise, the time for battery replacement breaks was set to 2 minutes (including landing and take-off).

5. Conclusions/Outlook

The results demonstrate that the implementation of UAV in emergency management measures is certainly an opportunity to use new data for emergency forces and clearly belong to the emerging technologies for monitoring levees. Real time or near real time information about the breach size and discharge would help to improve emergency management issues like evacuation lanes, etc.

Certainly, the goal of future works should be to incorporate new data sources and data management systems into emergency response strategies in order to quickly provide new information for decision support. But besides workflow improvement, these new issues also raise questions about the reliability of the spatial information in terms of precise location, fast processing and overall data quality. The most valuable information for disaster management response units is the precise location and geometry of disturbances and defective spots. Therefore, accurate georeferencing of orthoimages and 3d-models is the most crucial task as it is the most time consuming step in the processing workflow.

Some guidelines for future UAV pilots intending to survey levee failures could help to improve as well as simplify the processing workflow:

- orthogonal images are to be preferred over free camera angles
- pictures taken from an UAV usually have some coordinate information and other metadata tags stored in exchangeable image file format (Exif) and should be used instead of videos
- due to data copying issues, the correct time of the data acquisition was lost, an additional (handwritten) protocol would have been helpful
- camera objectives with a fixed focal length are preferable as the majority of SFM-programs are only capable of taking one focal length into account

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