River flow 2008-Altinakar, Kokpinar, Aydin, Cokgor & Kirkgoz (eds)
 ISBN 978-605-60136-1-4

Flood wave propagation and flooding of underground facilities

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ABSTRACT
After malfunction of flood protection measures a flood wave may occur. If underground facilities are arranged in the propagation zone, these might be flooded and people are at highly risk. Hence, it is necessary to get as much information about flood wave characteristics as possible and to analyze resulting hazards in underground facilities. With these information effective flood protection strategies can be developed. Therefore, a physical model is build up in the Hydraulic Laboratory at the University of Wuppertal's Hydraulic Engineering Section.

Keywords: flood, malfunction, underground facilities, flood wave propagation, simulation

1 INTRODUCTION

Flood protection measures can be separated into three parts: (1) technical flood protection, (2) flood area management and (3) prevention measures. Additionally operational flood protection measures during flood events have to be mentioned (DKKV, 2003). Especially the prevention measures include detailed analysis of hydraulic phenomena. Therefore also unpredictable scenarios, like malfunction of technical flood protection measures, are focused. Currently investigation aim on analyzing hydraulic processes of flood wave propagation after malfunction of river dikes or walls. But there are no detailed descriptions of flooding processes of underground facilities. Hence, a physical model is build up to simulate wave propagation on a plate and following flooding of an underground volume to detect main flow characteristics.

2 PHYSICAL MODEL

The physical model (see Fig. 1 and 2) is scaled 1:20 to 1:13. A flume with an integrated breach is arranged. This breach can be opened with a weight-system. Six openings with different geometrical boundary conditions can be found on the propagation plate.

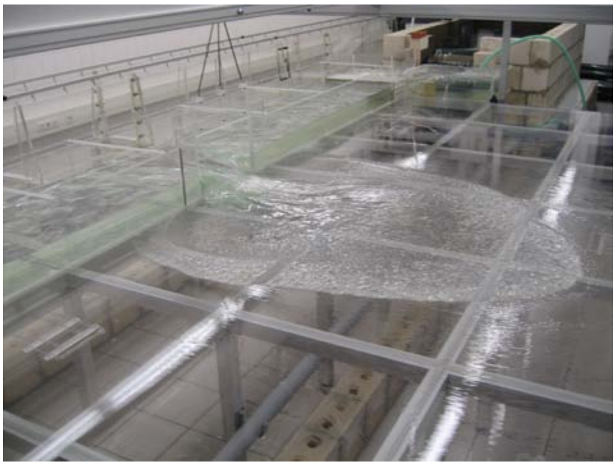

Figure 1. Sample flood wave in physical model

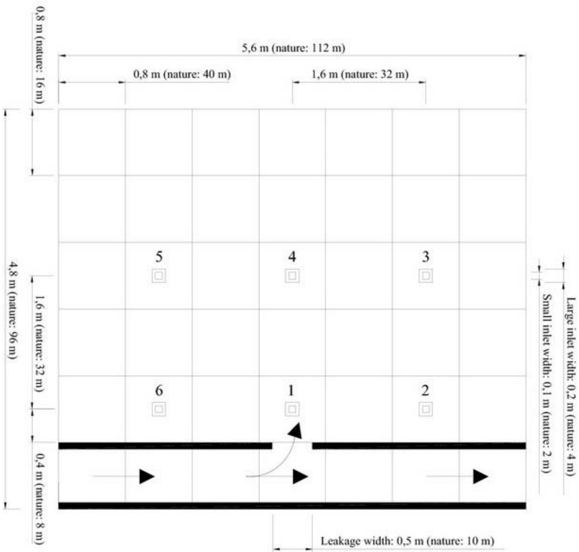

Figure 2. Technical plot of physical model

3 RESULTS

3.1 *Wave propagation*

The wave propagation is non-symmetric because of the flow velocity in the flume. The wave is recorded by ultrasonic sensors at nearly 1,000 measuring points on the plate. The data allows calculation of water depths, velocities, and time dependent wave propagation. Two main conditions are considered: (1) steady-state wave and (2) transient propagation (see Fig. 3 and 4). The wave propagation demonstrates the boundary condition for the flooding processes of the underground control volume. Hence, it has to be analyzed in detail – especially in matters of scaling effects.

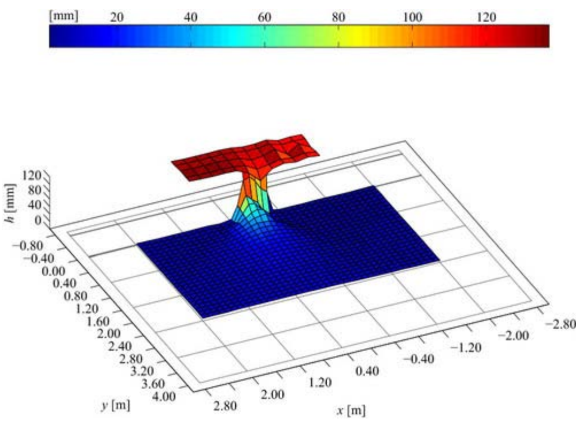

Figure 3. Steady-state wave

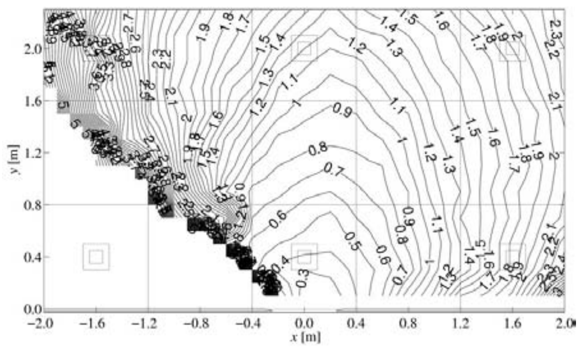

Figure 4. Transient propagation

3.2 *Scaling effects*

Briechle (2006) develop an analytic model for wave propagation on the breach axis with a physical model scaled 1:1 to 1:2. The own results are compared with this model with good consistence.

Outside the breach-axis scaling effects can be assumed because of low water depths and flow velocities. A detailed analysis is carried out to quantify the influence of the small model scale. Reynolds- and Weber-numbers are calculated on the propagation plate. Critical values are detected (see Fig. 5). The analyses show that there is no influence of surface tension, but of viscosity. Thus, an inverse method, calculating absolute roughness values (k), is developed to quantify the viscosity influence. Details can be found in Oertel (2007). Fig. 6 shows the results of calculated absolute roughness. Especially on the left side, large k values, scaling effects occur.

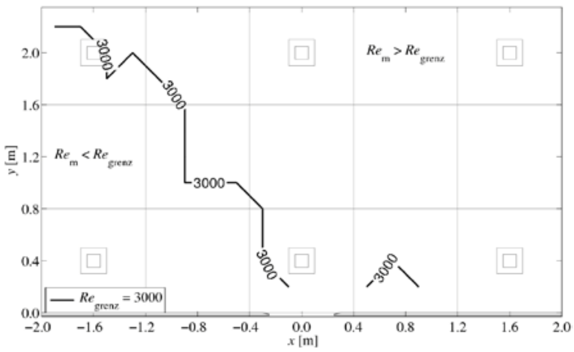

Figure 5. Critical Reynolds-numbers

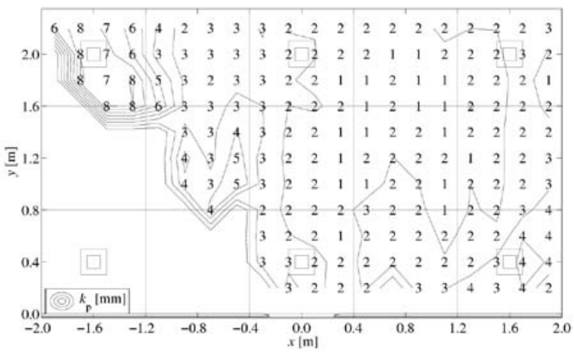

Figure 6. Inverse calculated absolute roughness k

3.3 *Flooding processes of underground facilities*

3.3.1 *Flood-types*

Three varying flood-types of underground facilities are identified:

1. Direct, active flooding (dynamic)
2. Sidewise, active flooding (dynamic)
3. Indirect, passive flooding (static)

To 1.) The first flood-type describes a direct inflow into the underground facility. Main flow components are radial to the opening. Fast increasing water levels in the underground volume characterize this flood-type. → Main variables: radial water depth and flow velocity at entrance to underground facility; geometrical boundary conditions.

To 2.) Flood-type 2 is comparable to sidewise overfall over a weir. Some investigations dealing with breach discharge can be used to identify the discharge into the underground building. → Main variables: tangential water depth and flow velocity at entrance to underground facility; geometrical boundary conditions.

To 3.) The third flood-type occurs during static floods. With minimum energy head at the entrance the underground volume will be flooded. → Main variables: water depth at entrance to underground facility; geometrical boundary conditions.

3.3.2 *Hazards in underground facilities*

The two main hazards in underground facilities are the strength of the inflowing water and the rising water level inside the underground building. The first one occurs especially at the entrance area where resistance forces of people can be exceeded. RESCDAM (2000) analyze the possibility of withstanding flowing water in a large flume. So called product numbers or fall numbers are given by combination of flow velocity v and water depth h:

$$SN = v\,h \quad [\mathrm{m^2/s}] \qquad (1)$$

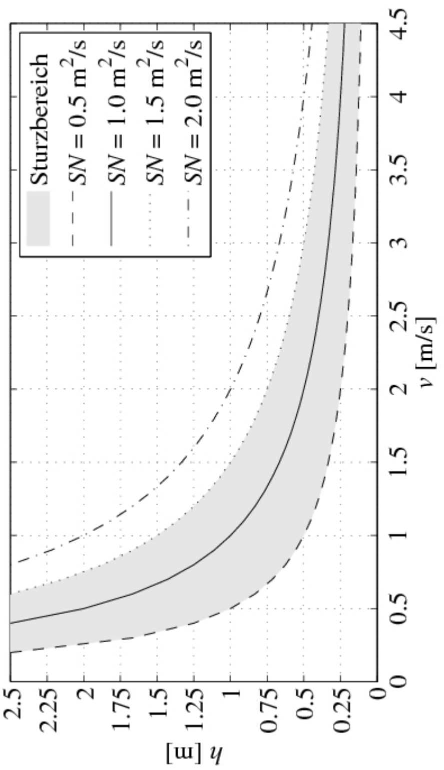

Figure 7. Fall number

People can withstand fall numbers between SN = 0.64 and 1.26 $\mathrm{m^2/s}$ (RESCDAM, 2000). The second hazard can be found inside the underground building, where rising water levels up to a critical water depth of h_{krit} = 1.5 m increase the risk of drowning. Thus, the risk inside the underground building depends on the critical fill time t_{krit} in connection with inflow Q_{fill} and floor space A_{p}:

$$t_{\mathrm{krit}} = h_{\mathrm{krit}}\,A_{\mathrm{p}}\,Q_{\mathrm{fill}}^{-1} \quad [\mathrm{s}] \qquad (2)$$

3.3.3 *Results for flood-type 1*

The presented results of wave propagation are used to define the risk of underground facilities for flood-type 1. Fall numbers SN and critical fill times can be calculated after transforming the measurements into nature scale (Froude-model, see Fig. 8 and 9). Especially in the near filed (Oe1) large fall numbers can be identified. Critical fill times of less than one minute are resulting. Additionally impulse forces are estimated to get information about the possibility to open arranged doors in emergency exits. This also have an important influence on the existing risk, but will not be discussed in detail in this paper (see Oertel, 2008).

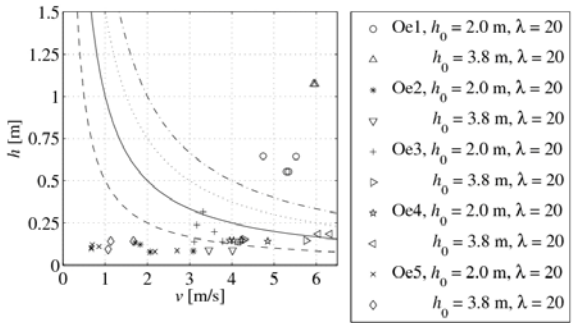

Figure 8. Fall numbers for flood-type 1

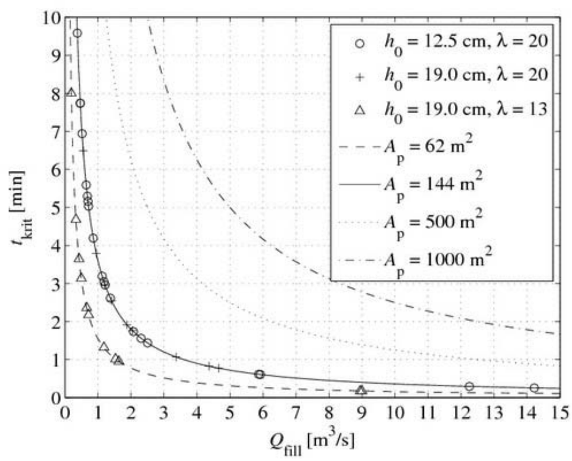

Figure 9. Critical fill times for flood-type 1

3.3.4 *Results for flood-type 2*

As mentioned, flood-type 2 can be compared with sidewise breach discharge investigation. German directive give a simple solution to calculate the sidewise discharge over a weir by using an overfall coefficient. Disse et al. (2003) observe this problem more detailed and give an equation to calculate the discharge through a breach. This equation is used to assign the sidewise inflow into the underground facility by flood-type 2:

$$Q_{\mathrm{fill}} = 2/3\ \sigma_{\mathrm{st}}\ 0.577\ \mu^*\ (2g)^{-0.5}\ b_{\mathrm{Oe}}\ h_{\mathrm{s}}^{1.5} \qquad (3)$$

Where:

$\mu^* = 0.1146 \ln(\xi) + 0.6895$

$\xi = 0.4\ (\mathrm{Fr})^{0.5}\ (\beta)^2$

$\beta = (1.18 - (\mathrm{Fr})^{0.5})\ b_{\mathrm{s}}\ b_{\mathrm{Oe}}^{-1}$

$\mathrm{Fr} = v_{\mathrm{s}}\ ((g\ h_s)^{0.5})^{-1}$

Q_{fill} Inflow into underground facility
σ_{st} coefficient for sidewise overfall
μ^* standardized overfall coefficient
g gravity
h_{s} water depth in street canyon
b_{Oe} opening width
v_{s} velocity in street canyon

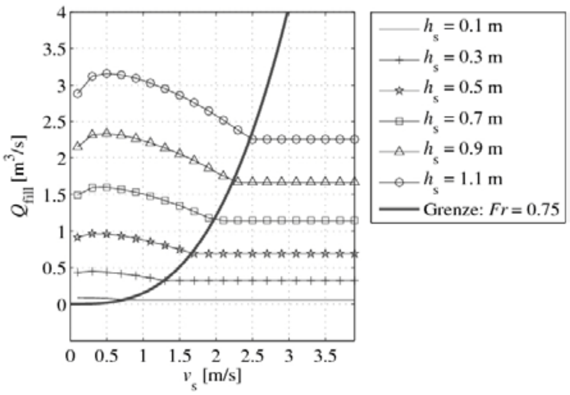

Figure 10. Example results for sidewise overfall

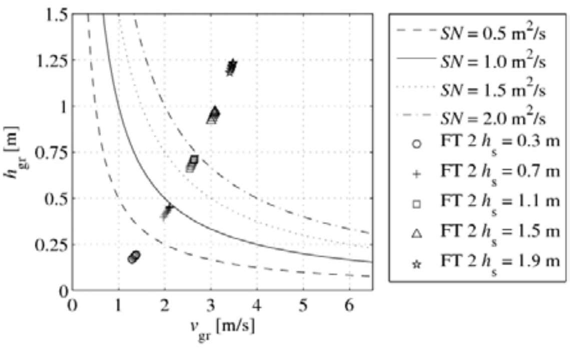

Figure 11. Example results for flood-type 2

The maximum sidewise overfall occurs for small velocities v_{s} in the street canyon (see Fig. 10). The recommend use for Fr > 0.75 is demonstrated as well. The results are compared with numerical simulations using FLOW-3D. Validation runs are done with flood-type 1 to approve the possible usage. The good conformity allows the usage of FLOW-3D for calculating discharges for flood-type 2. To approve the possible usage of Eqn. [3] 32 numerical model runs with varying boundary conditions are done. The results show a good conformity between numerical simulation and analytic solution. The resulting fall numbers *SN* point out, that there's no important influence of the velocity v_{s} in the street canyon (Fig. 11). The numerical simulations show that it is possible to use the analytical approach by Disse et al. (2003) to calculate inflows into the underground facility in matters of flood-type 2. Hence, fall numbers can be calculated at entrance area and critical fill times can be estimated.

3.3.5 *Results for flood-type 3*

Inflows to the underground facility for flood-type 3 depend on the static water level h_{l} in a defined distance the opening. The minimum energy rate at the overfall area leads to decreased water levels $h_{\mathrm{gr}} = 2/3h_{\mathrm{l}}$ with appearing flow velocities v_{gr}. Resulting fall numbers *SN* are given in Fig. 12.

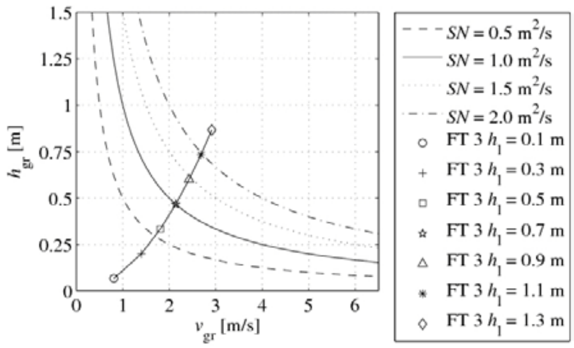

Figure 12. Example results for flood-type 2

3.3.6 *Hazard-classes*

All calculated results are translated into hazard-classes with standards of Switzerland government (see Fig. 13) and combined in tables for varying geometrical and hydraulic boundary conditions. A risk tool named RoFUF (Risk of Flooding Underground Facilities) is developed to calculate the hazard/risk based on these tables (www.rofuf.de, for free non-commercial use, Fig. 14). It gives hazard classes for underground facilities by varying boundary conditions for the itemized three flood-types. Mentionable is that the color green is only used when NO RISK occurs. Some hazard maps using this color for small risks, which is implicitly declined in this paper. The color green can be interpreted in a wrong way (green = no risk) by non-professionals in flood vulnerable areas. This has to be avoided, especially in flood hazard and risk maps for public use.

Table 1. Example results for flood-type 2

h_I	h_{gr} [m]	v_{gr} [m/s]	H_{min} [m]	SN [m²/s]	Q_{fill} [m³/s] (b_{Oe} = 2 m)	Q_{fill} [m³/s] (b_{Oe} = 4 m)	t_{krit} [min] (b_{Oe} = 2 m, A_p = 144 m²)	t_{krit} [min] (b_{Oe} = 4 m, A_p = 144 m²)
0,1	0,07	0,81	0,10	0,05	0,11	0,22	33,4	16,7
0,3	0,20	1,40	0,30	0,28	0,56	1,12	6,4	3,2
0,5	0,33	1,81	0,50	0,60	1,21	2,41	3,0	1,5
0,7	0,47	2,14	0,70	1,00	2,00	3,99	1,8	0,9
0,9	0,60	2,43	0,90	1,46	2,91	5,82	1,2	0,6
1,1	0,73	2,68	1,10	1,97	3,93	7,87	0,9	0,5
1,3	0,87	2,92	1,30	2,53	5,05	10,11	0,7	0,4

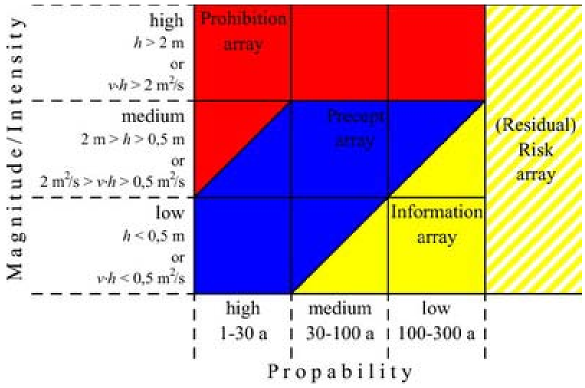

Figure 13. Hazard-classes, Switzerland government

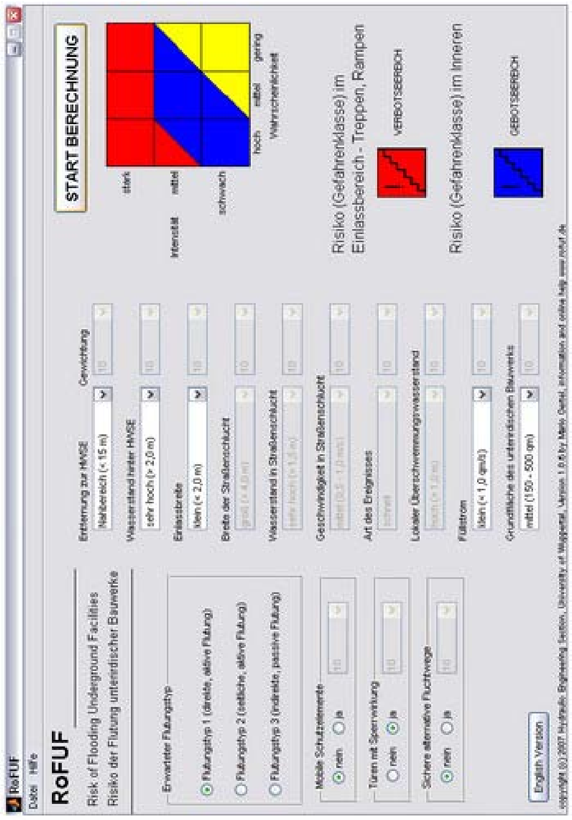

Figure 14. RoFUF GUI

4 CONCLUSION

It could be shown that there is a partially high risk at entrance to or inside underground facilities during flood events. Flow velocities and water depth are assigned. This allows a classification of underground buildings with varying geometrical and hydraulic boundary conditions into defined hazard or risk classes. Especially in the near field of flood protection measures, as well at areas where high water depths at the entrance can be estimated, a high risk results. Hence, comprehension of underground facilities in hazard or risk maps is recommended. The flooding processes can be classified into three different flood-types. For each, important hydraulic boundary conditions give the foundation to determine resulting hazard classes. All results are implemented into RoFUF, a decision support system as risk tool.

5 REFERENCES

Briechle, S. (2006) Flood Wave Propagation on a Plate after Malfunction of Flood Protections Measures. Original title: *Die flächenhafte Ausbreitung der Flutwelle nach Versagen von Hochwasserschutz-einrichtungen an Fließgewässern*, PhD Thesis, RWTH Aachen, Germany.

Disse, M.; Kamrath, P.; Wilhelmi, J. and Köngeter, J. (2003) Simulation of Floodwave and Propagation in matters of Dike Breaking. Original title: *Simulation des Hochwasserwellenablaufes und der Ausbreitung von Überflutungsflächen unter Berücksichtigung von Deichbrüchen*, WasserWirtschaft 5/2003, DWA, Hennef, Germany.

DKKV (2003) Lessons Learned. German Committee for Disaster Prevention (DKKV), Bonn, Germany.

Oertel, M. (2007) Scaling Effects on Flood Wave Propagation by Physical Modeling. Original title: *Maßstabseffekte bei der physikalischen Modellierung flächenhafter Flutwellenausbreitungen*, Meeting of jung Scientists (JuWi) 2007, Kassel, Germany.

Oertel, M. (2008) Analyzing Flooding Processes of Underground Facilities in Urban River Areas after Malfunction of Flood Protection Measures. Original title: *Analye der Flutung unterirdischer Bauwerke in flussnahen urbanen Regionen nach Versagen von Hochwasserschutz-einrichtungen*, Dissertation, University of Wuppertal.

RESCDAM (2000) The Use of Physical Models in Dam-Break Flood Analysis. Final Report of Helsinki University of Technology, Finnland.

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