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Lessons Learned from the Disaster at Lippe Canal Bridge

Markus Herten
German Federal Waterways Engineering and Research Institute, Germany

Eva Dornecker
German Federal Waterways Engineering and Research Institute, Germany

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Markus Herten
German Federal Waterways Engineering and
Research Institute, Karlsruhe
Foundation Engineering Section
(Bundesanstalt für Wasserbau, BAW)

Eva Dornecker
German Federal Waterways Engineering and
Research Institute, Karlsruhe
Foundation Engineering Section
(Bundesanstalt für Wasserbau, BAW)

ABSTRACT

In October 2005, during construction works at the new Lippe canal bridge, massive water leakage from the Dortmund-Ems-Canal occurred below a wing wall at the northern abutment of the old, still operated canal bridge. Water passed through a leak of the clay-lined canal, flowing underneath a pile-supported wing wall into a minor excavation pit. This excavation pit was supposed to be protected by a surcharge filter. Since failure of the lining should be considered for all construction phases, it cannot be regarded as the cause of the disaster. Consequently, the paper focuses on the verification against hydraulic heave and erosion for the excavation pit. It is demonstrated that Terzaghi’s statements on this topic remain valid and should not fall into oblivion.

1 INTRODUCTION

The Lippe canal bridge is a navigable aqueduct carrying the Dortmund-Ems-Canal (DEK) over the River Lippe. It was planned to replace the old Lippe canal bridge by a new set of parallel twin span bridges, each serving north- or southbound ship traffic. On October 11th 2005, during construction works at the new Lippe Canal Bridge, massive water leakage from the DEK occurred below a wing wall at the northern abutment of the old, still fully operational canal bridge. By closing the safety gates Datteln and Schlieker, the canal stretch that was emptied could be limited to 8 km (cf. Fig. 1). As the water could flow freely into the Lippe and as the involved engineers acted with care, personal injuries were avoided. However, the damage removal alone cost more than $ 20 million and the canal had to be closed for several weeks. In the following, the project and the accident are described briefly. Moreover, this paper presents some conclusions made from the investigation on the verification against hydraulic heave and erosion for the excavation pit, which was performed by BAW after the accident.

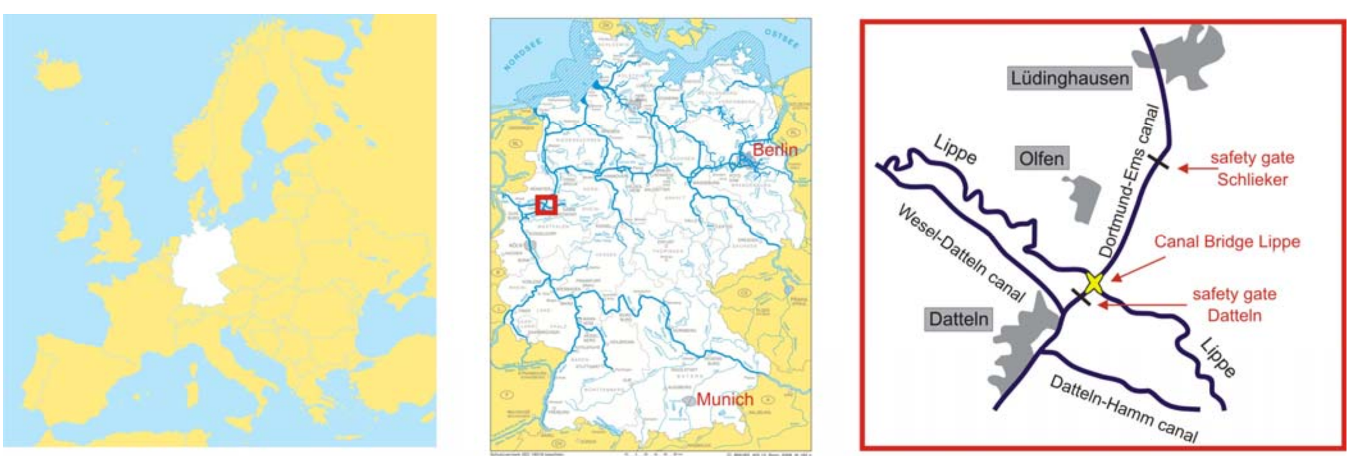

Fig. 1: Site plan

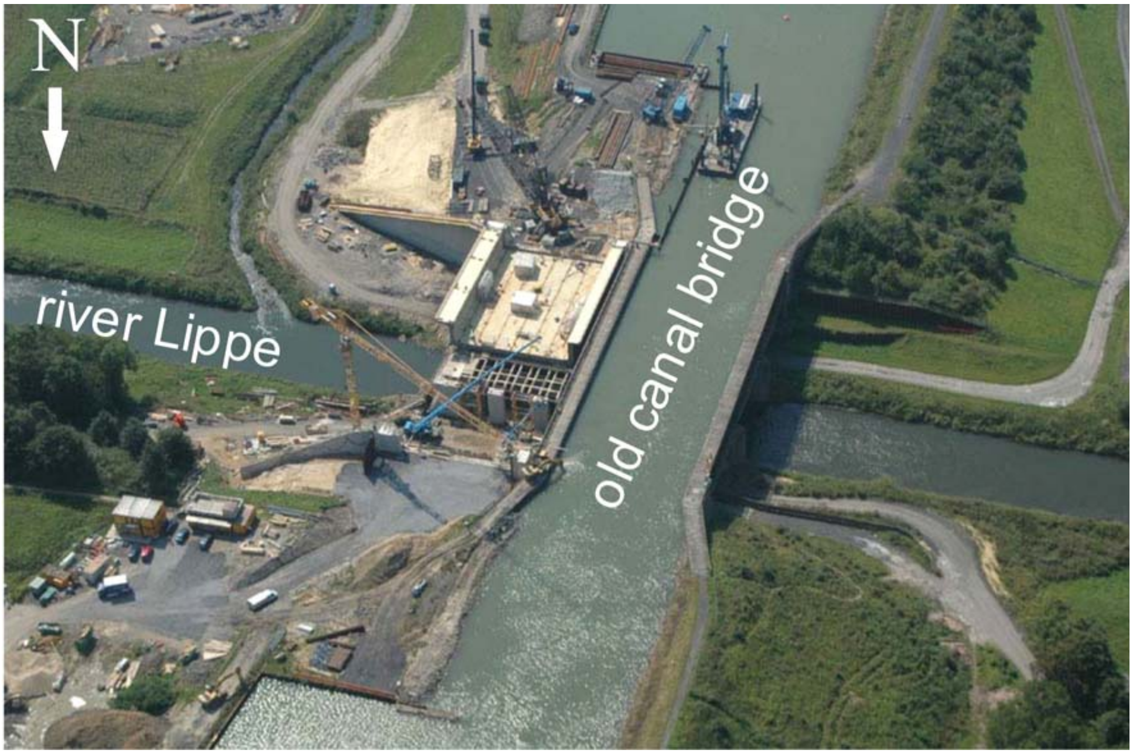

Fig. 2: Aerial photograph of the construction works (August 18th, 2005)

2 PROJECT DESCRIPTION

The DEK is being expanded to meet the requirements of larger motor cargo vessels. This measure requires the renewal of the canal bridges spanning the Ems and Lippe Rivers. Construction works at the Lippe canal bridge started in spring 2004. The construction of the Ems canal bridge is planned to start soon. The aerial photograph of the Lippe canal bridge (Fig. 2) shows that the construction area is situated in an above-ground canal stretch of the DEK. The embankment crest is at approx. 15 m above the natural terrain. The regular water level of the Lippe River is about 16 m below the regular water level in the canal. The DEK embankments are made of silty sands. The building ground consists of sandy marl.During construction works continuous ship traffic is maintained. This is why a new steel trough was installed directly adjacent to the existing trough made of concrete. It was not until the new trough was put into operation that the old canal bridge was supposed to be sealed off and demolished. The old aqueduct is supposed to be replaced by another new trough at the same location. At the time of the accident, the construction works on the new trough at the north side had almost as much progressed as the works on the south side in August 2005, as shown in Fig. 2.

The northern abutments of the old and the new canal bridge were constructed on a spread footing at 37.00 m above sea level (asl) on sandy marl. On the south side it is the same construction, but the sandy marl is found two meters deeper in elevation.

The old and new wing walls are founded on piles which reach into the sandy marl layer. The lower edge of the old northeastern wing wall is located at a much greater height (43.50 m asl) than the footing of the abutments.

3 DISASTER

On the day of the accident large steel parts were delivered by ship and unloaded by a truck mounted telescope crane. Shortly before noon, a worker observed leakage between the northern abutments of the old and the new canal bridge. Members of the construction supervision were immediately informed. They found a water whirl in the canal in front of the wing wall of the old northern abutment (Fig. 3). The leakage increased substantially within a short time period. The water from the canal flew first into a small construction pit (Fig. 4), passing under a wing wall footed on piles (Fig. 5). This construction pit was supposed to be protected by a surcharge drain. Then the water flew through the two abutments into the Lippe River (Fig. 6).

Disaster alarm was triggered and the safety gates Datteln and Schlieker were closed after all the ships had left the canal stretch (cf. Fig. 1). A downspout was moreover opened to empty the canal stretch. Several attempts to close the leak with soil material on the canal side failed (Fig. 7). Due to the high flow velocities, the embankment next to the wing wall eroded totally (Fig. 8). An 8 km long canal stretch was emptied completely. The water from the canal flew around the old and the new wing walls into the Lippe River.

Fig. 3: Water whirl in front of the wing wall of the northern abutment

Fig. 4: View of the construction pit between the two abutments

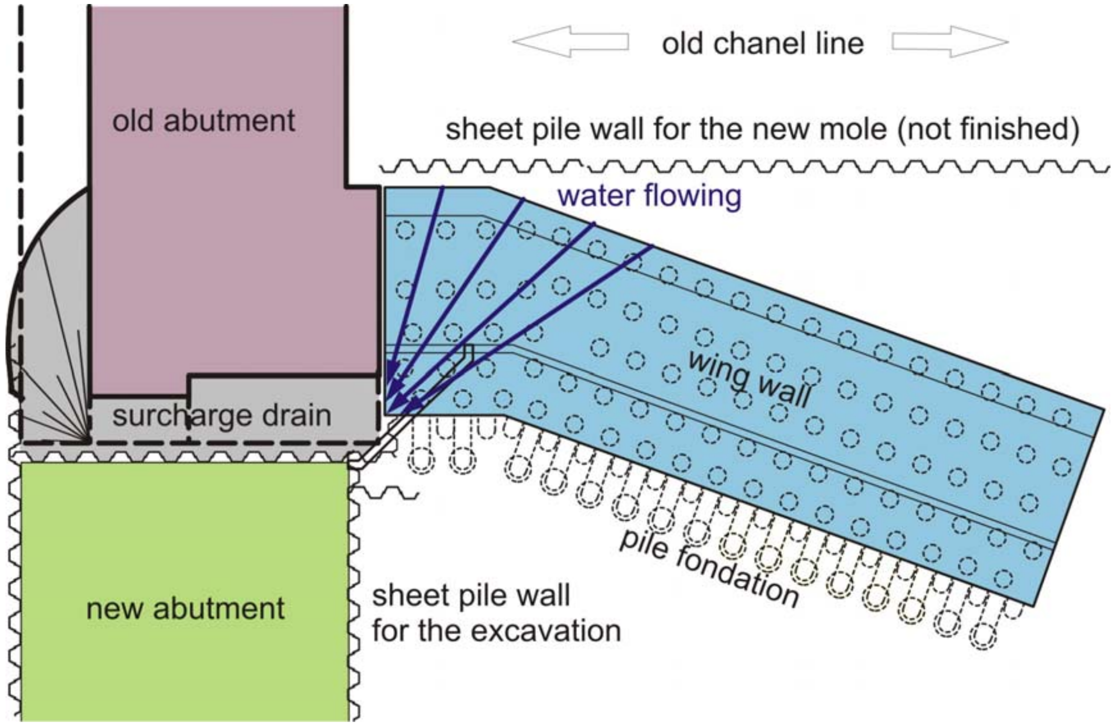

Fig. 5: Cross section of the footing at level 45 m asl; water flowing towards the surcharge drain

Fig. 6: Violent water flow through the two abutments into the Lippe River

Fig. 7: Attempt to close the leak by dumping soil material into the canal

Fig. 8: Aerial photograph of the failed embankment next to the concerned wing wall

4 HYDRAULIC HEAVE

The European Standard EN 1997-1 (2004) distinguishes between four types of ground failure, including failure due to pore-water pressure or pore-water seepage:

- uplift,
- heave,
- internal erosion, and
- piping.

When pore-water pressure under a structure or a low permeability ground layerbecomes larger than the mean overburden pressure failure by uplift occurs. Failure by heave occurs when upwards seepage forces act against the weight of the soil, reduce the vertical effective stress to zero. Soil particles are then lifted away by the vertical water flow and failure occurs (boiling). Transport of soil particles within a soil stratum is defined as internal erosion. Piping is restricted to the occurrence of a pipe-shaped discharge tunnel, whereas according to Terzaghi (1947) piping includes heave as well. The factor of safety G_s is determined by the ratio of the submerged weight W' of the body of soil and the total excess hydrostatic pressure U_e at the bottom of a column (Fig. 10b).

$$G_s = \frac{W'}{U_e} \tag{1}$$

U_e is equivalent to the seepage force mentioned in EN 1997-1. The European Standard allows including pore water pressure and total stress into the calculation, while the German national annex does not. As the European Standard uses a partial factor of safety, the equations differ from Terzaghi's formula. However, this does not matter in the following discussion.

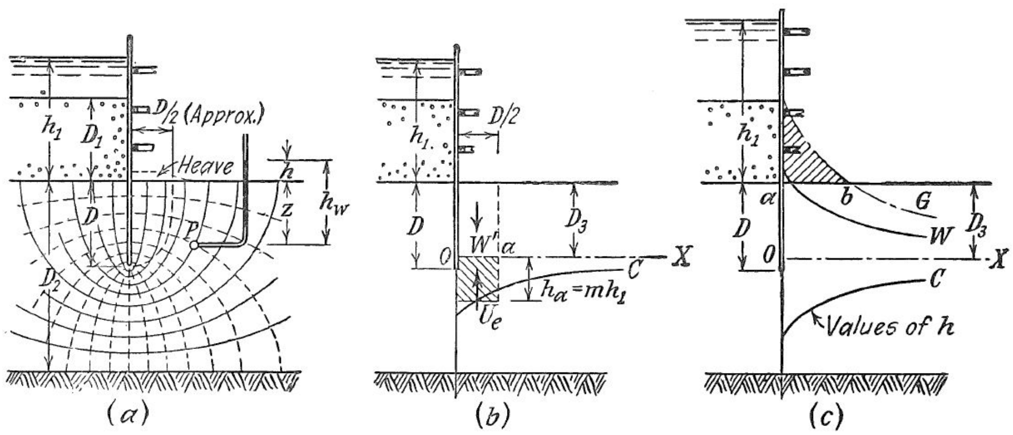

Fig. 9: Graphical determination of safety (from: Terzaghi K.(1947), Fig. 79)

Terzaghi further mentions in regard to failure by heave: "With sufficient accuracy we can assume that the body of sand which is lifted by the water has the shape of a prism with a width D/2 and a horizontal base at some depth D_3 below the surface. […] For the simple row of sheet piles represented in Figure 79b an investigation has shown that the critical section passes almost exactly through the lower edge of the sheet piles, or $D_3 = D$." In Germany, this is defined as the failure body after Terzaghi. Instead of using a potential net, another way of simplification is used in Germany for such a case; the potential at this wall base is calculated based on the formula by Brinch Hansen (1953), which is also mentioned in EAU (2004). According to this approach, instead of a prism with a width D/2, only a flow channel needs to be examined. The result for the simple row of sheet piles represented in Figure 9b would be on the safe side.

If the lining of the DEK canal is intact, only the groundwater interact with the Lippe River below the embankments and no failure due to water can occur. However, if the canal lining is leaking, a substantial amount of canal water may flow into the ground, leading to rising groundwater levels. At German waterways, the failure of a lining is always to be considered at least as an accidental design situation according to the Code of Practice "Stability of Embankments at German Inland Waterways (MSD)" (BAW, 2011). In the following, reasons for a failed clay lining will not be examined. Instead, the paper focuses on the verification of stability, and especially on the verification against hydraulic heave in this particular case. Furthermore, assumptions (e.g. on the ground) are simplified for better understanding.

Fig. 10 depicts a cross section of the northeast wing wall between the two abutments. As already mentioned, the wing wall is founded on piles, which reach into the marl layer. If the clay lining fails, canal water can flow through the non-cohesive soil around the wing wall towards the pit bottom (Fig. 5 and 10). According to BAW (2011), potential degradation below the pile head slab is not to be considered in case of structures founded on piles. This means that a hydraulically effective gap is to be expected between the pile head slab and the subsoil. Using a simplified approach, as potential degradation is to be neglected; the thickness of the construction can be reduced correspondingly. The wing wall, which can be up to 8 m wide, may be regarded as a sheet-pile wall (cf. structural scheme Fig. 10).

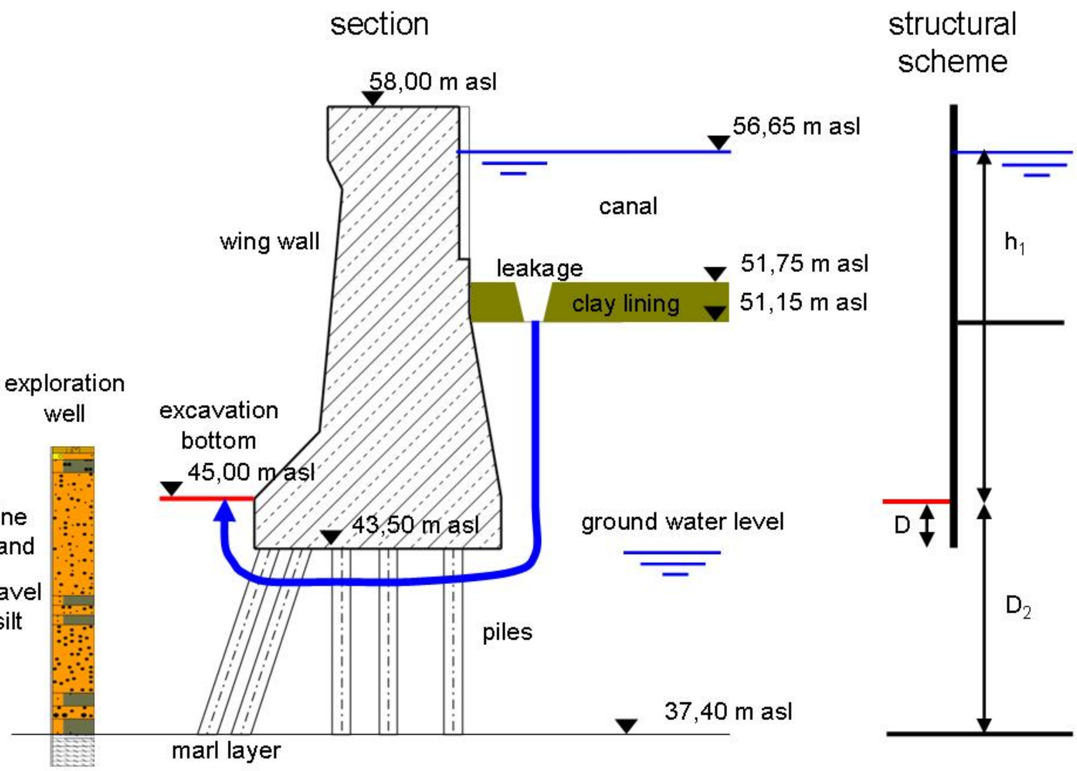

Fig. 10: Cross section of the northeast wing wall and structural scheme

The columns examined are described in Figure 11. The water level on the landward side corresponds to the red line. Assuming that the ground is homogeneous and no surcharge drain is installed, the safety against hydraulic heave would be much smaller than unity in regard to the permitted excavation bottom (Fig. 11a). For sufficient safety, the surface should be much higher (Fig. 11b). However, this was not possible due to the construction progress. Instead, a deeper pit was dug and a surcharge drain applied (Fig. 11c). The surface had to be on the level shown in Figure 11a. The safety was verified with the failure body according to Terzaghi, including the weight on the drain (Fig. 11c). But with a surcharge drain at the bottom of the sheet pile, the calculated safety would be infinite since the excess hydrostatic pressure U_e is zero (Fig. 11d).

A more realistic result is obtained if, as described in Terzaghi (1947), the balance is considered not only at the wall base but also at other depths $D_3 \neq D$ (Fig. 9c). Terzaghi writes: "The investigation can be repeated for different horizontal sections through the sand, which are located at different depths D_3 below the bottom of the pit. The critical head is determined by the condition h_p = minimum, and the horizontal section to which this minimum refers is the critical section. It represents the lower boundary of the mass of sand subject to lifting in the initial state of the piping phenomenon." However, this was not considered when planning the excavation pit at the canal bridge Lippe and hence a false safety was calculated.

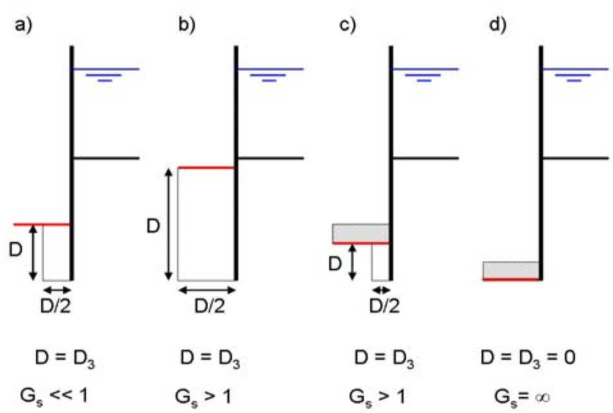

Fig. 11: Different columns reaching down to the lower edge of the sheet pile

Numerical analyses conducted by BAW show that even if Terzaghi's statements are considered, the necessary thickness of the surcharge drain d_f becomes less if the leftover soil at the sheet pile bottom is removed. In the diagram (cf. Fig.12), Δh equates h_1 and t equates D according to Terzaghi. If $t/\Delta h$ equates zero, the upper line in the diagram drops after reaching a peak. As this is surprising, BAW ordered experimental tests to be executed at the Bundeswehr University Munich to verify the theoretical results (Schober et. al. 2011). As shown by the lower line in the diagram, the same effect occurred in the test. The two lines are not identical since the calculation was performed only for the maximum thickness of the surcharge drain d_f without uniform distribution. Thus Terzaghi's statements were confirmed.

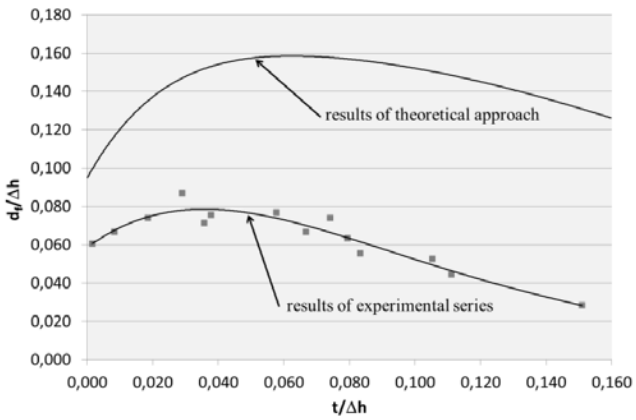

Fig. 12: Results of experimental series as a function of $d_F/\Delta h$ and $t/\Delta h$ in: Schober et. al. (2011), Fig. 12

5 PIPING

It must be considered that the risk of failure by piping increases enormously if the excavation ends near the bottom of the sheet pile. Therefore the surcharge drain must built with care. This was also described by Terzaghi & Peck (1948): "The emergence of water from the ground at the boundary between a coarse and a fine soil may cause scour of the finer material, provided the velocity of the discharging water is great enough. Scour usually begins with the formation of small springs at different points along the boundary, from which channels are eroded in a backward direction toward the area where the water enters the soil. Hence, the process is known as backward erosion. It is one of the most dangerous menaces to dams, and it has been responsible for some of the most catastrophic dam failures […]".

This means that even before excessively high flow forces can cause hydraulic heave, as described above, the construction is at risk to fail when water flows in, even if only low flow forces are present.

6 CONCLUDING REMARKS

The disaster at the Lippe canal bridge shows that failure of a bottom lining is no theoretical load case at all, especially if construction works are performed. But the failure of the lining only triggered the disaster. It cannot be regarded as its cause because at German waterways, failure of the lining needs to be considered for all construction phases.

Because a legally binding agreement on the distribution of the financial losses between owner and contractor has not been reached yet, no further information concerning the relevant cause of the disaster at Lippe canal bridge can be given at this point.

However, erosion and hydraulic heave can be avoided by considering Terzaghi's recommendations. Although he published his works in the first half of the last century, they should not fall into oblivion.

REFERENCES

BAW (2011): *"Code of Practice "Stability of Embankments at German Inland Waterways (MSD)""*, German Federal Waterways Engineering and Research Institute, Karlsruhe

Brinch Hansen (1953): *"Earth Pressure Caculation"*, The Danish Technical Press, The Institution of the Danish Civil Engineers, Copenhagen

EAU (2004): *"Recommendations of the Committee for Waterfront Structures Harbours and Waterways"*, 8th Edition, translation of the 10th German edition, Ernst & Sohn, 2006

EN 1997-1 (2004): *"Eurocode 7: Geotechnical Design – Part 1: General Rules"*, European Standard

Schober, P. et. al. (2011): *"Hydraulic Heave Safety at Excavations with Surcharge Filters"*, Proceedings of the 3rd International Symposium on Geotechnical Safety and Risk, Munich, Germany

Terzaghi, K. (1947): *"Theoretical soil mechanics"*, Section C: Effect of seepage on the conditions for equilibrium in ideal sand, pp. 235-264, John Wiley & Sons, New York

Terzaghi, K. & Peck, R. (1948): *"Soil mechanics in engineering practice"*, John Wiley & Sons, New York