Several cases of backward erosion/liquefaction piping from Hungary

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BSTRACT: Some cases of backward erosion/liquefaction piping are dscribed. These distinguish between usual sand boils and the 'fast' piping, the - possibly dynamic liquefaction induced – breach. The latter happens in a matter of minutes, whereas in the former emergency response measures can be effective.

Keywords: liquefaction; grading curve, sand boil, fine sand, piping, failure path

1. *Introduction*

Experience to date (see e.g., [1 to 18]) shows that during major floods, hundreds of sand boils may develop, but only a small percentage may need significant response measures. Only a small fraction of these have caused breach disaster. We still not know these processes very precisely.

The backward erosion/liquefaction pipings may develop in fine-grained soil with no cohesion, which is poorly graded and extremely loose. It is called „liquefiable sand” or „liquid sand" in Hungary. The current name of it is fine silty sand according to soil classification; earlier, it was called as sand flour (Mo). It can be noted that this sand is simultaneously internally unstable on the basis of the grading entropy criterion and liquefiable on the basis of the well-known criteria [10, 18].

In thin layers of poorly graded sand, the increasing flood water level may lead to the usual sand boils, which can be mitigated by counter-pressure. The event tree can be seen in Fig. 3-35. Remedial measures, sandbags ringing the sand boil can be effective as emergency response measure on condition a protocol is followed to keep counter pressure. At the end of the flood, first, the sand material of the ringing sandbags are used to fill the pipe, some additional measures are made afterwards.

In case of thick layers of loose, poorly graded sand, the flood may lead to 'fast' piping, failure within seconds - minutes after the observation of a sand mud geyser, and a simultaneously appearing vortex funnel in the river which is moving towards the dyke. The reason of the breach is liquefaction. The pipe in the waterside is formed along with the least resistance under the minimum energy principle before the breach.

Szepessy, J.(1983) [11] gave first the interpretation of the fast piping events based on case studies 4 and 5 (happened in 1954, 1965, 1980), suggesting the hypotheses that liquefaction may take place. In these cases, the breach occurred within minutes/seconds after the appearance of a mud geyser and a simultaneously appearing vortex funnel moving towards the dyke in the river.

In this work, it is found that case study 3 (happened in 1926, Fig. 1) has a similar failure scenario and failure path (see Fig. 3-35) as in case studies 4 and 5, except that in the 1926 case study, there is an early stage of the flood with usual sand boils, too (which probably may occur if no plastic soil cover is present).

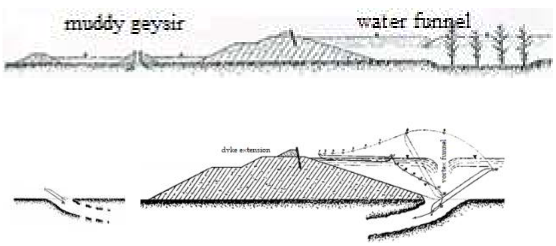

Figure 1. Illustration of the boat diving to the pipe in 1926, (a) condition some minutes before breach, (b) the path of the boat, which ended on the safed side at around the first sand-boil spot.

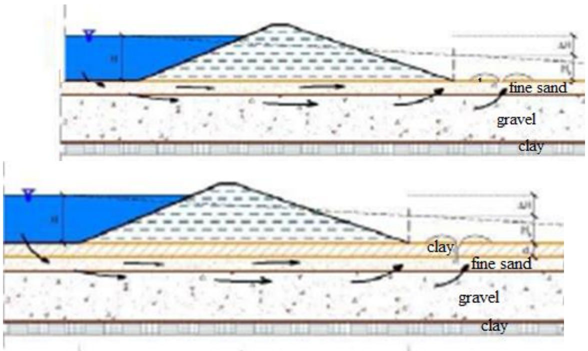

Figure 2. Layers leading to sandboils.

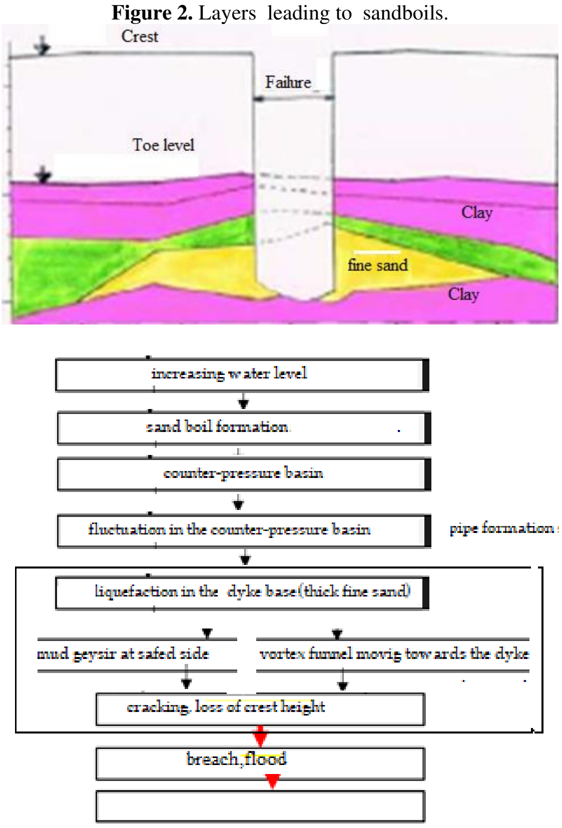

Figure 3. Layering leading to fast piping and possible fast piping scenario. It is a question if static liquefaction, dynamic liquefaction may occur or both.

The failure scenario was as follow. In the first days of the flood, small, usual sand boils occurred. Then the breach happened within minutes/seconds after the observation of the first mud geyser (at the place of the first sand boil) and simultaneously a moving vortex funnel towards the dyke in the river. The initial part with a normal sand boil may occur if no plastic cover soil layer is present.

The main influencing local factors are the "liquid sand" layer itself in the dyke base over the large permeability river bed foundation and the layer thickness. In the vicinity of old crossings of meanders, the sand layer can be thick, loose; in this case, fast piping breach may occur. If a plastic cover layer is present, then this layer may be torn off due to upward seepage, causing a dynamic effect. The pipe is assumingly forming with a combination of backward erosion and liquefaction.

2. *Case descriptions*

2.1 General

Hungary has the longest river dyke system in Europe along the two big rivers (Danube and Tisza) and their connecting parts (Figure 2-1). The main characteristics are as follows.

The Danube valley has a 0.5-6.0 m thick silty fine soil cover, which is prone to piping and liquefaction. The river bed is lying in granular soils. The dyke material is sand in the northern part and silt in the southern part. The most frequent flood damage is piping.

Dykes of the Duna river have the following leading dimensions. The height is about 6 to 8 m; the crest width is 4 m, the waterside slope is 3:1, the landside slope is 2:1. The dykes have been built of silt (IP=12-20%), sand or sandy gravel. The stratification under dykes comprises a sandy, silty cover overlying a highly permeable gravel bad.

The subsoil of the Tisza-Kőrös valley varies from the granular (northern part) to the highly plastic (southern part). The dyke material is granular soil in the north part and plastic soil in the south part. The surface is generally covered by plastic soil.

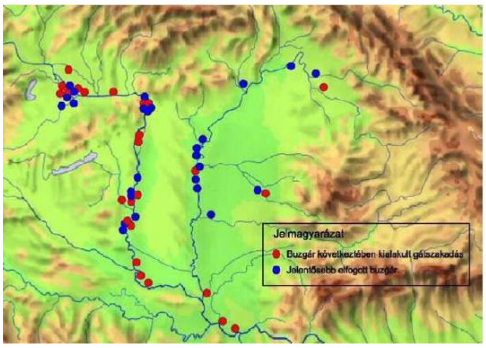

Figure 4. The big rivers and piping failures (red) and defended sand boils (blue) in Charpatian basin [6] , [10] Nagy, 2014.

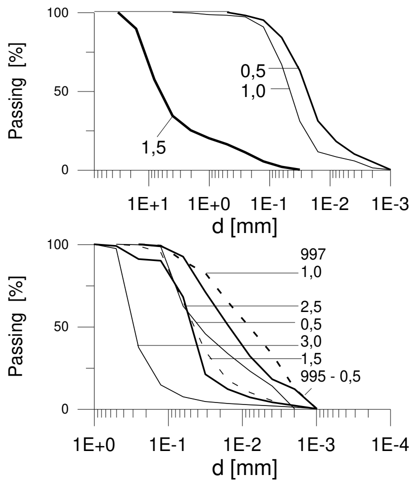

Figure 5. Grading curves for the (a) Dunakiliti soils and (b) the Dunafalva soils.(c) and (d) Layers leading to sandboils.

2.2 Sand boil case study 1

Dunafalva, Dunakiliti (layers and grading curves shown in Figs. 2 and 5, based on [2 to 9, 12 to 14])

Sand boils were observed at several locations along the Duna river in Szigetköz and Mohács areas in the flood period of 1965. Piping took place in the thin, poorly graded silty fine sand layers being situated above the sandy gravel bed. Strange softening of the surface soil layer within some meter distance from the downstream toe was also observed.

Protection (sand boil capture) was made mainly using sandbags to form counter-pressure pools. The measure at the sand boils was made by applying a proper counter-pressure pool water level with continuous observation. A high water level (back pressure) should be created on the saved side, as it can be used to stop the particles from moving out to be washed out. The size of the pool is not too large since the sand boil is the source of the water.

Soil layers below the dyke were explored at two piping sites: at Dunakiliti and Dunafalva Figure 3-27. The Danube valley has a thick silty cover. A 0.5 m thick silt layer and a 0.5 m thick Mo layer were found above the sandy gravel layer at Dunakiliti (Mo is a soil category between silt and sand in earlier soil classification systems). Mo, silt, Mo and sand layers were found with a thickness of 0.6, 0.9, 1.3, 0.2 m, respectively, above the sandy gravel bad at Dunafalva. The grading curves are shown below.

2.3 Sand boil case study 2

Tiszasas (extremely long flood period and sand boil defence, based on [10], [16])

During the flood in 2000, 4 sand boils had occurred along the flood control section [10] (Nagy, 2014).5, from which the section of 14+7[10] (Nagy, 2014) was the largest one Figure 3-28 to 3-30 2-2.

The sand boil of Tiszasas occurred on April 18 2020, in the section of 14+7[10] (Nagy, 2014) on the left side of Tisza. On April 16, it seemed to be a sand boil with 3-5cm diameter, which transferred little granules but clear water as well. In the next two days, there wasn't any protection in this area.

The sand boil almost with 25-30 cm diameter arose 4 m from the levee toe on the landside. The height of the groundwater mound was almost the same. The discharge brought a large amount of soil (in the context of flood protection "material") with little soil clots. The protection began immediately; soldiers of the nearby area were detailed to the site.

According to the workers, the outbreak of the sand boil was not indicated. The sand boil occurred, and at the same time, the waterside started to eddy almost 30m from the levee on the border of the forest zone.

Forty-three people, who were on the site, started to create a 5-row counter-pressure basin. The surface of the water was strongly bubbling, and it transferred granules. According to the protection group, the capturing of the sand boil till 12:30,it was 1,7 m high.

A secondary sand boil arose with a quite strong blow-up under the counter-pressure basin around 3:00 p.m. Consequently, the water level in the counter-pressure basin, which was already built up, lowered almost 0,5m in a few minutes. The power of the blow-up was very concerning. Construction of the counter-pressure basin of the first cassette was carried out by soldiers and civils; its walls were 3 rows wide and 8 sandbag row high. The basin of the first cassette fitted the previous semi-circumference shaping. Then, there was a need for building a new counter pressure basin (2nd cassette) in order to prevent another failure (Figure 3-28).

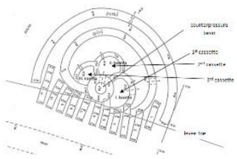

Figure 6. Tiszasas sand boil on May 1, left-hand side, a memorial of Tiszasas sand boil right-hand side

There was a strong water blow-up in the first cassette at [10] (Nagy, 2014): 00 p.m. and 3 rows were lifted up in order to provide the counter-pressure (meanwhile, the water level started to lower in the first counter-pressure basin). The walls of the I. cassette were lifted up with 3 rows. Due to the lifting, the blow-up stopped. However, the water started to foam heavily, and thick, brown foam occurred at the surface water from the first counter-pressure basin.

The 3rd cassette, fitting the 2nd cassette as well as to the counter-pressure basin, was built up in order to prevent another failure. Namely opaline coloured water blew up from the base of the basin. The height of the 1st cassette was lifted up to the level of the counter-pressure basin with the same leakage level in order to make an immediate locking up possible in case of a failure in the counter-pressure basin. The overtopping in the counter level stopped for a while, and afterwards, it started again (again throbbing!).

The overtopping stopped in the I. cassette between 8:00 and 8:30 a.m., the water level lowered ([10] (Nagy, 2014)cm) when the eroded soil, made by the secondary sand boil, occurred. At the same time, the water in the counter-pressure basin became blurred. The lifting of the basin level's height (with 4 rows) was carried out. In the I. cassette the water level was rising slowly, but it didn't top over. The height of the counter reservoir's water column was lifted at the same time with the cassettes' leakage level (with 1-2 rows), taking constant attention to the stability.

Two days later, the waterside of the levee collapsed because of a trailer tractor in the early morning. The soil was lifted by handwork from the collapsed area, which was 1,2 x 1,5 wide and 1,4 deep. The wall of the hole was widened like a bell shape by a defined failure surface. The walls were hard, but after hitting them, they had a rumbling sound effect. The refilling was made with the help of sandbags.

Based on the measurement of the eroded material, it could be stated that three cubic meter of soil left the levee. This soil is missing from somewhere! The collapse by the tractor in the morning made clear that regarding the stability of the levee, it is very dangerous if the soil is eroded in a larger quantity. Therefore, a mass balance is needed with the help of an approximate method. Most part of the eroded material could come from the collapse. In fact, it was satisficing to know the origin of the eroded soil.

In the afternoon, a trimming cassette (shape like a horseshoe) fitting the levee was constructed. The four sandbags wide trimming cassette embraces all cassettes 2m away from each other.

Divers arrived at the site, and they found the supposed opening hole of the sand boil quickly, which was approximately 3m far from the waterside crest edge. After filling the opening hole with more than 30 sandbags, they started foiling the waterside.

Thanks to the lowering water level of Tisza, the sand boil as well as the water of the cassettes subsided further during the night, in so much that a crater occurred in the sand boil. There was a bit of functioning sand boil in the crater, but the leaking water disappeared between the sandbags. The water level in the crater of the sand boil was 2,7 m lower than the water level Tisza river.

Soil investigation showed that basically, the embankment was constructed by fine-grained soil, but a layer of transitional soil was also discovered. The layers of the embankment and the upper part of the subsoil were relatively mixed. There was a clay layer from 5,9 m beneath the crest, which had absolutely nothing to do with the occurrence of the sand boil. The site investigation also showed that the problem is not the sand boil in the subsoil but the flood event in the mixed layers of the levee.

Based on the washout soil, which was more than two cubic meters, a sieve analysis was carried out. The uniformity coefficient of the silty sand was CU = 2,74, d80 = 0,11 mm. The opening of the sand boil could only took place at the beginning of September. The cut through the levee showed the stratification and the path of the sand boil, which was first deep at the bottom and then it went up the waterside. Figure 3-29. shows the investigation and suggested that the sand boil occurred in a thick silty sand layer, which was covered with arched clay.

Figure 7. Opening of the sand boil

The sand boil of Tiszasas proved that the big, as well as the medium-sized sand, boils always need to be constantly observed and measured. These measurements must be analysed. A decision can only be made based on the basis of the above-mentioned steps. The measurement possibilities are limited regarding the fact that the stability of the levee cannot be endangered. We have to recline upon the observation of the surface like the blurriness of the water of the counter-pressure basin, the temperature and amount of the leaking water, the amount of eroded soil from the counter pressure basin, as well as its temporal dispersion. The behaviour of the levee must be valued based on these factors. Probably the great sand boil of Tiszasas is the only one in the world which has a Memorial (Figure 3).

2.4 Piping breach case study 3

(ended in fast failure ~ 5 days after the first sand-boil, deep and large diameter pipe development, [1]).

In 1926 there was a very high and long flood, and on the Danube Drava crossing there was a very deep and fast piping failure.

5 days before breach: sand-boil in 12 m distance, counter pressure basin was made. 2 days before the breach, the water level in the counter-pressure basin is started to oscillate, indicating pipe formation; therefore defending material (boat to sink if needed, piles, sandbags, piles etc.) was carried over there. The boat was about 10 meters long and 2 meters wide and was put on standby. A water funnel or vortex about 30 meters on the upstream side appeared, which was constantly approaching the embankment. When it approached the dyke at 15-

20 meters, the boat suddenly began to tilt into the vortex, his nose up and made the path dived under water and reached the other side of the dyke Fig. 6.

Breach day: The breach happened as follows within some minutes. A mud geyser appeared at the spot of the first sand boil. Seeing this, the chief engineer immediately ran up to the embankment crest and glanced at a funnel about 30 m from there, which was constantly approaching the embankment (Fig. 6). He immediately set the boat perpendicular to the embankment and carried earth sacks in the tail of the boat to sink (Fig. 6). During this time, there were again 2-3 volcanic muddy water eruptions, and these were already stronger than the first.

When the vortex water funnel - constantly approaching the embankment - was 15-20 meters away from the crest, the boat suddenly began to tilt, his nose staring at the sky and made a path marked with numbers while diving under the water. The boat appeared on the other side of the levee. Subsequently, the crest began to crack, the embankment settled to a length of 8 to 10 meters, the water began to flow into the saved area, and the dam breach soon widened to 80 to 100m. The depth of the washout was 24 meters below the flood level .

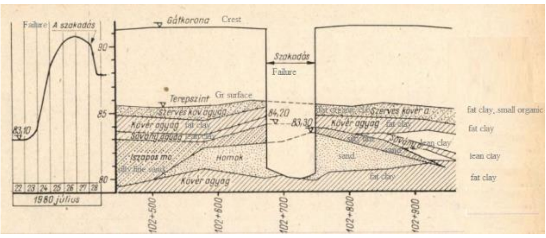

Figure 8. Kettős Körös river, Hosszúfok in 1980, fast piping failure, schematisation of subsurface at failure location.

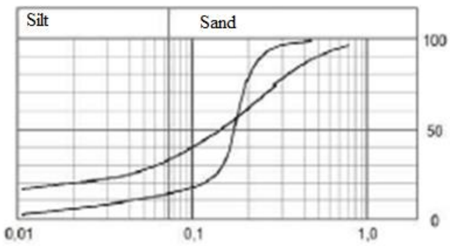

Figure 9. Kettős Körös river, Hosszúfok in 1980, fast piping failure, grading curves, indicating the very loose sand inclusion with 3<Cu and e~0,8 (Szepessy, J.(1983)).

2.5 Piping breach case study 4 (fast piping, 5 minutes after the first geysir – type sand-boil, Hosszúfok based on Szepessy and Fehér 1981 [17], Szepessy 1983 [11].

The river Kettős Körös, Hosszúfok in 1980. The dam guards, who were responsible for observing damages during this flood, they did not notice any signs of damage until early Morning on July 28, 1980 (Figures 3-32, 3-33).

At 6:35 a.m., the guards were about 100 m away from a very strong water geyser spurt has been observed. The water, they reported, was "black and thick muddy."

The dam burst took about 5 minutes. The width of the tear grew rapidly, reaching a final width of 78 m. This was the first dam failure where detailed soil mechanical exploration was made afterwards

The evaluation: the piping mechanism is possibly liquefaction of the extremely loose and thick sand lens at the thickest dimension of the layer. The cause was assumed dynamic effect caused liquefaction. The possible dynamic effect was the tearing off the clay cover layer at the first geyser spot and the sudden displacement of the dyke body due to the increased horizontal load.

2.5 **Piping breach case study 5**

(fast piping, breach few minutes after the first geyser type sand-boil, Ásványráró, Csicsó, based on [10 to 11]).

The first observed event is a 0.5 m diameter geyser that suddenly appeared at 5 m from the landside toe, throwing off the cover layer. Within 2 seconds, the pipe reached the riverside since a vortexfunnel developed at the river approaching the dyke and then the dike collapsed. In this case, the poorly graded silty sand layer was extremely loose and thick (July 15, 1954, at Ásványráró). A similar case occurred in 1965 in Csicsó, but there is no precise description. Some Information indicated that in these environments, several smaller sand-boils appeared beforehand, which were not mitigated by counter-pressure basins properly in the lack of workers. This comment is not changing the fact that the fast piping occurred starting from a water geyser suddenly appeared, not from a usual smaller sand-boil and the failure was extremely fast.

3. *Sand boil treatment protocol*

- A guard has to stay at the sand-boil to watch it all the time.
- The outflow water volume, temperature and composition are measured, more than one counter pressure basin is built if needed for the new „children" sand-boils.
- No crashed stone is used in Hungary, although it could help.
- The change in the outflow indicates the pipe; it is varying periodically.
- Protection (sand boil capture) mainly sandbags counter-pressure pool design. The defence of the sand boil is with continuously increasing water level, continuous observation. A high water level should be created on the saved side, as it can be used to stop the particles from moving out to be

washed out. The size of the pool is not too large since the sand boil is the source of the water.

- After the flood, the sand of the sandbags is used to fill the sand boil and cover the soil surface. Then additional measures may follow.
- The more general defence protocol is based on reducing the hydraulic gradient by counter pressure, by increasing the leakage path length and draining the leaking water (see Fig. 3-36).

Figure 10. Danube, Margitta Island piping, counter-pressure and diaphragm walls at the waterside, the cause was the vicinity of an old meander, Horváth 2001

4. *Evaluation of piping case studies*

The sand-boil formation is related to poorly graded fine sand. The piping may start by backwards erosion, which may be accompanied by liquefaction, depending on geometry and soil density.

Slow piping may occur in the case of a thin layer of poorly graded fine sand (see site geometry and event tree for slow piping in Figure 3-33). The sand boil is started by individual grain movements on a micro level due to upwards seepage forces Figure 3-27, 3-33. The initiation of a sand boil is the mobilisation of the grains in the surface layer due to upwards seepage (see Garai, 2016).

Fast piping may occur in the case of thick layer of extremely loose and poorly graded fine sand, generally in the vicinity of some old river bend crossings. The breach may happen within seconds/minutes of observation of the first muddy geyser on the land side and simultaneously appearing vortex funnel in the river. The vortex is moving towards the dyke and causes a breach.

In the thick layers of loose poorly graded and, the flood may lead to 'fast' piping, which is a failure within minutes after the observation of a water geyser on the safe side and simultaneously a vortex funnel in the river water, which is moving towards the dyke. The pipe may be forming due to the liquefaction of the sand in the whole fine sand layer. The path is likely formed under minimum energy principle before the breach.

The liquefaction may be caused by the following effects: high pore water pressure in the dyke base, the tear off the plastic cover layer, spreading the dyke with the sudden change from static to sliding friction (i.e., sudden shear strain increment of the dyke base) due to the increased load, cracking of the dyke, gradual saturation of the dyke material.

Concerning the earlier soil classification; the sand flour (Mo) category was useful. This fine sand has too small grains in terms of gravity and too large in terms of surface forces. This sand is simultaneously internally unstable and liquefiable on the basis of the well-known criteria [10, 18].

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