Case Study on Failure Mechanism of Flood Embankments Due to Rapid Sand Boiling on Alluvial Flood Plains and the Identification of Vulnerable Levee Sections

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CASE STUDY
ON FAILURE MECHANISM OF FLOOD EMBANKMENTS DUE TO RAPID SAND BOILING ON ALLUVIAL FLOOD PLAINS AND THE IDENTIFICATION OF VULNERABLE LEVEE SECTIONS

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ABSTRACT

Hungary is situated in the deepest part of the Carpathian basin. The majority of the country is alluvial plain. Rivers crossing these plains filled the basin with their sediments and meandered on the deposited sediment during the geological ages. Thus the continuous levee systems developed in the second half of the 19th century, replacing the earlier, rather local defenses, intersected at a number of locations the unforgotten and invisible ancient riverbeds. Experience showed that as the height of the levees was raised to follow the rising tendency of the flood crests, the number of failures due to foundation stability loss started increasing. Fighting against piping (sand boiling) became a major issue. Professionals observed that in many cases there was no time to interfere against rapidly developing sandboilings which led to the collapse of the levee section. A research program discovered the reasons and conditions of these phenomena and gave solutions and tools to recognize the problematic sections in advance.

Key words: flood defense, hydraulic failure of levees, rapid sand boiling/piping

GEOLOGICAL HISTORY

The mighty ranges of the Alps and the Carpathians had emerged in the Middle-Miocene epoch laying bare the early Tertiary, mostly Oligocene and Eocene marine sediments. The blocks in the central parts of the basin started submerging at different rates. Transgression has created the Pannonian Sea, which has covered the largest area during the Pliocene epoch. Sediments eroded from the mountains, which rose like islands from the sea, have started filling the marine depression. The surface features leading eventually to the evolution of the present river network have taken thus shape some 20 million years ago. (*Fig. 1*.)

The Pannonian inland sea which had covered the closed basin of the Carpathian range in the Pliocene communicated to the East with the lake filling the Transylvanian Basin, while to the SE – very likely – with the Pontian Basin (the present Black Sea). The seawater in the closed lakes was gradually replaced with freshwater and continued silting up.

In the early Pleistocene epoch (*Fig. 2.*), or some 1-1.5 million years ago, the Pannonian sea has already receded and minor lakes were only reminders of the former sea in the Transylvanian Basin. No traces of a river network have evolved at that time here. (The German-Austrian headwater section of the Danube has already started developing.) The water masses rushing down the mountains have deposited vast alluvial fans.

A pattern resembling more the present one has evolved by the Middle Pleistocene (4-500,000 years ago), with huge depressions attracting the streams arriving from the N and NE mountains.

The actual river network started taking shape some 200,000 years ago, by which time the frequently shifting streams discharging into the lowlands have built an intricate pattern of alluvial fans, oxbows and lakes. Even the ancient Danube was deflected to this area. In the dry periods of the successive climate changes windblown formations contributed to the surface topography. The alluvial fans of the Ancient-Maros and Ancient Körös rivers, further the increasingly more pronounced fault lines in the West have shifted the main stem of the river network gradually towards the present pattern.

High sediment yields in the wake of successive glaciation periods, coupled with high-rate mountain elevation and accompanied by depression at the perimeter of the lowlands, further the deep trench developed along the present course of the Middle-Tisza, have attracted the streams and deflected also the Danube to its present bed in the Late Pleistocene epoch some 100,000 years ago (*Fig. 3*).

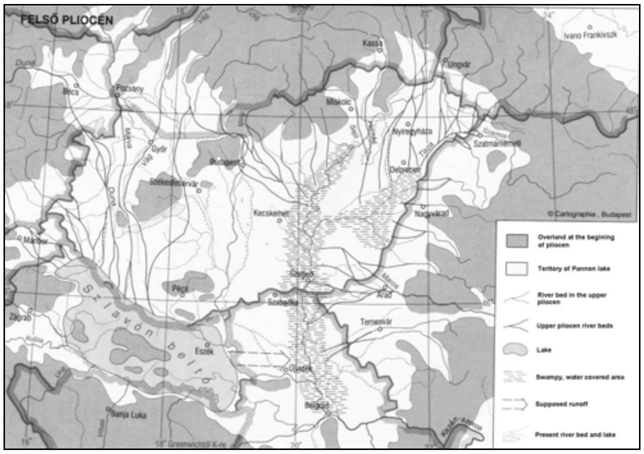

Fig.1. The Carpathian basin at Upper-pliocene

These processes have persisted throughout the merely 10 000 years of the Holocene epoch to these days. The meanders have kept shifting, overdeveloping and severing; the rivers change their course owing to crustal movements. Some of the more recent bed changes are illustrated in *Fig. 4.*

Table 1. Geological history of the Carpathian basin

Geol. age	Time span	Impact in the Carpathian basin
Early Holo-cene	100,000 yrs	Evolution of the recent network of the fluvial system
Late Pleis-tocene	200,000 yrs	Evolution of the upper fluvial valleys
Mid Pleis-tocene	300-400,000 yrs	Local depressions and erections in the Carpathian basin
Early Pleis-tocene	1,5 million yrs	Completion of the sedimentation of the Pannonean Sea
Mid Plio-cene	10 million yrs	Evolution of the Pannonean Sea
Miocene	15 million yrs	Evolution of the ranges of the Carpathians and that of the Alps

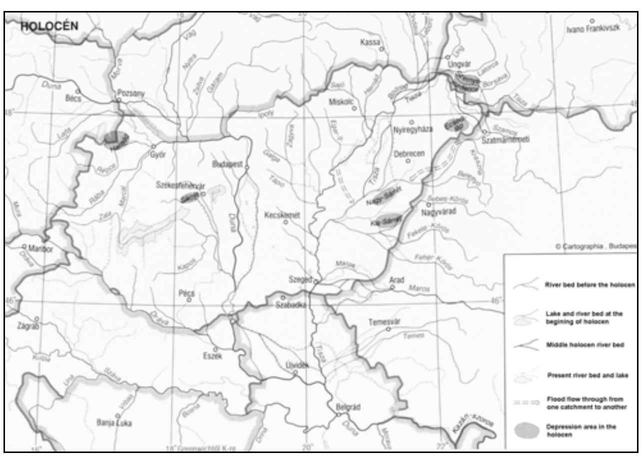

Fig.4. The Carpathian basin at Holocene.

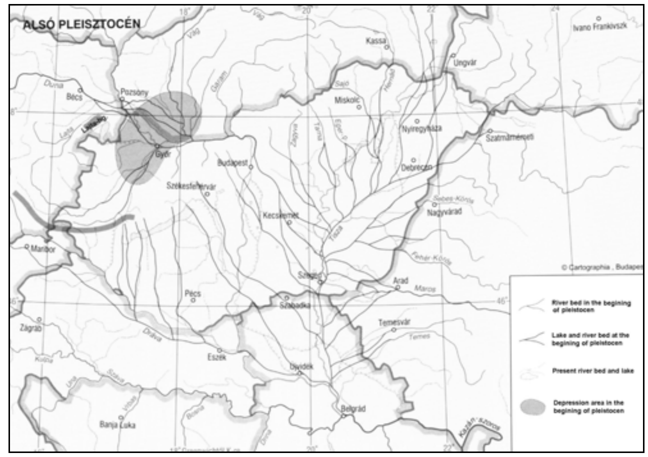

Fig.2. The Carpathian basin at Lower-pliocene

The hydrographic pattern keeps still changing, in that the land-scape is transformed by shifting meanders while the streams have also been modified by human measures over the last 3-500 years. The key events over geological history have been compiled in Table 1.

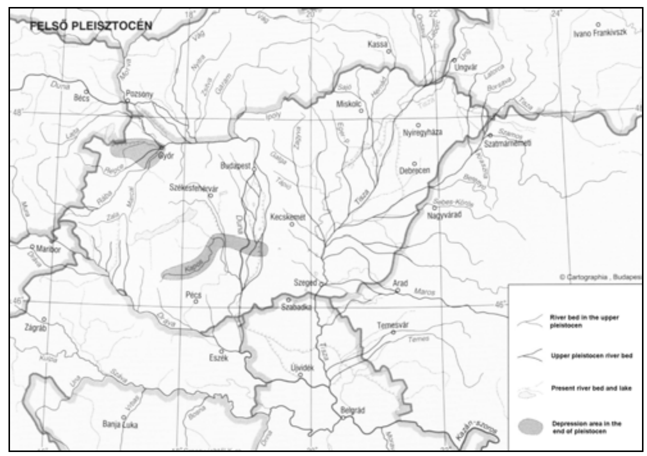

Fig.3. The Carpathian basin at Upper-pleistocene

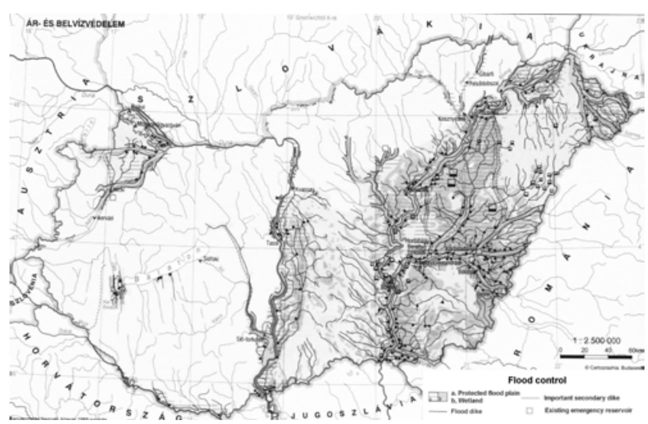

Fig5. Levees and floodplains in Hungary

Due to the human interference in natural floodplain reduction as well as to extreme precipitations, flood peaks raised continuously thus the levees were raised and reinforced consequently and the cross section of the levees are recently similar to the structure of onion. [8]

As a consequence of the continuous heightening of the levees the failure types and mechanisms during flooding has been changed: while in the earlier period of the history of flood protection the main cause of levee breaches was overtopping which was followed by the complete erosion of the dike body itself, the heightened profile increased the load to the foundation soil.

Decades of observations have proved that the failures of otherwise properly built levees were caused in a great part by loss of the foundation soil stability along alluvial river dikes: sandboilings and concentrated piping became the most dangerous phenomenon to the safety of the levees despite the increased base of the dikes.

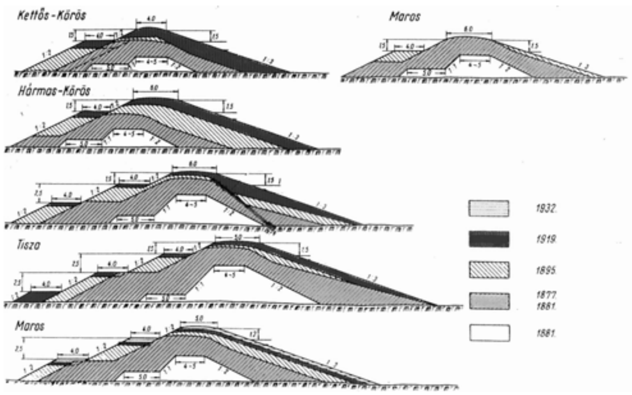

Fig. 6. Cross sections due to successive levee strengthening in Hungary

FAILURE OF LEVEES AS A CONSEQUENCE OF THE INCREASED HEAD ON THE FOUNDATION SOIL

Conventional piping/sandboiling phenomenon

Figure 7. shows structure and the process of the conventional piping/sand boil phenomenon [3]. The levee is built upon a relatively thin impermeable covering layer, underneath of which a layer of fine sand can be found, and the undermost layer is a relatively thick aquifer consists either of coarse sand, graveled sand, or sandy gravel. In the covering layer, on the protected side of the dike a channel arises for certain reasons, like a decayed root or a hole of a fieldmouse, etc. The water coming out concentrated has a relatively high velocity exceeding the critical gradient of the fine sand. There is an erosion process starting, transporting the fine sand and building a crater from it on the surface around the hole. As the sand is being washed out from under the covering layer, the length of the channel is growing towards the riverside. This results in the continuous increasing of the initial ΔH/L ratio. The channel growing under the dike reduces the stability of the covering layer and the dike itself: a sliding of the slope or a subsidence of the levee may occur, causing levee breach.

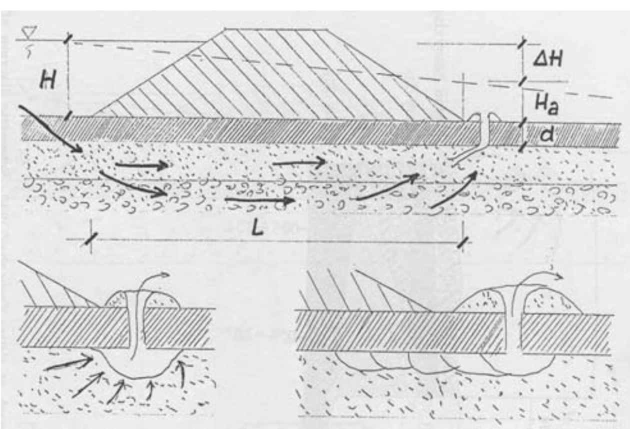

Fig. 7. Schematic diagram of a conventional or "slow" piping

It is very important that in this process the amount of water that transports the fine sand originates from seepage process. On the other hand the critical gradient of the fine sand is i = 0,8 – 1,0. But the value of ΔH/L along our levees is round 1/8-1/12. So the initial gradient of a piping phenomenon must be considered as Ha/d, its value may reach or exceed the critical gradient so the process of erosion may start. Simultaneously the surface of the channel is growing, but the amount of water coming from seepage as well as the velocity will not increase considerably. These are the reasons why this phenomenon may be called as „slow" piping, and fighting against is rather possible, usually there is left time enough after their observation for the countermeasures like it is shown in *Fig. 8.*

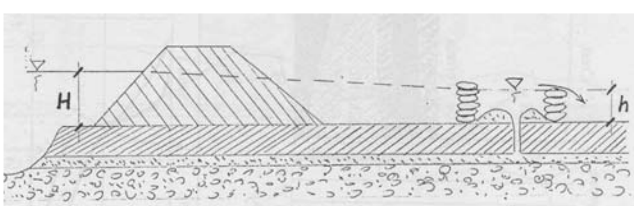

Fig. 8. Schematic diagram of the countermeasure during flood fighting against piping

Photo 1-2. The Tiszasas piping

Rapid piping phenomenon

There were some levee breaches in the past decades in Hungary and is some of our neighboring countries caused by hydraulic failure of the foundation soil of the dike, where and when there was no chance to fight against them because of the very rapid process that occurred.

One of the last ruptures like that occurred at the right bank of Kettős-Körös (Double-Körös) river in 1980 [2]. The flood wave hydrograph, the longitudinal profile of the section, including the soil stratification as well as the particle distribution curve can be seen in *Fig. 9.* The guards who were to check the conditions along the levee section periodically did not observe any harmful phenomenon during this flood until the early morning of July 28, 1980. At 6.35 am., about 100 m away from the approaching guards a sudden and very strong eruption of water was observed. The water was reported „black and densely muddy". The dike broke through in some five minutes. The width of the rupture increased rapidly, at 7.00 am. it reached 10 m, the final width was as much as 78 m.

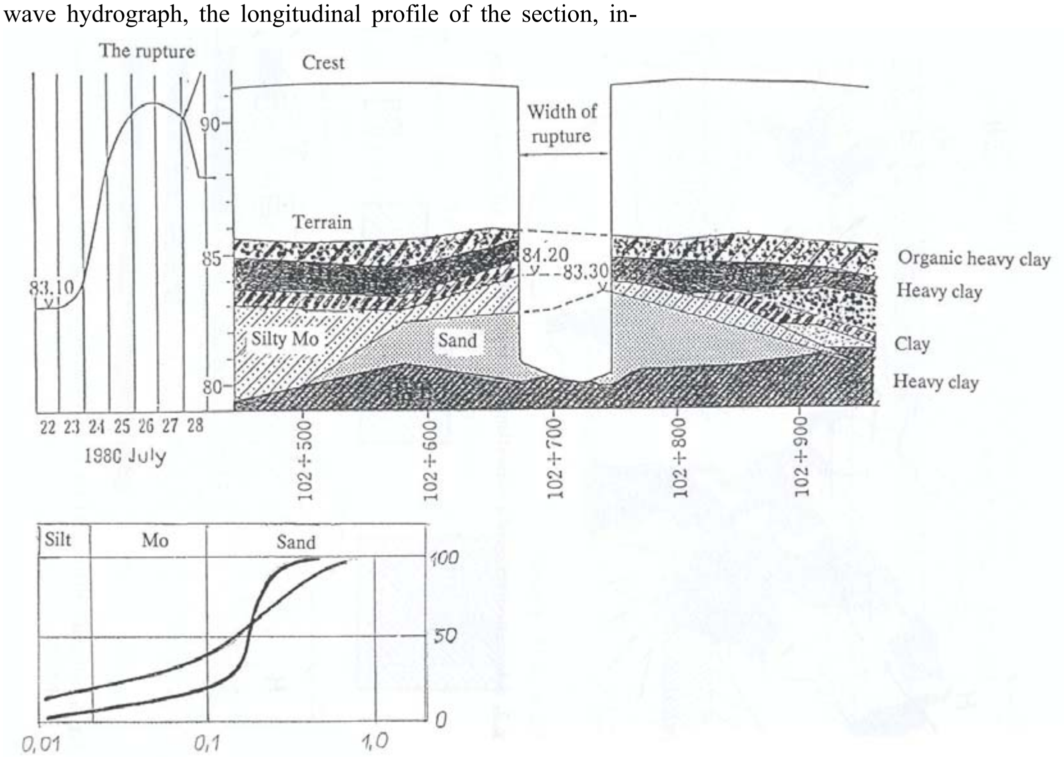

Fig. 9. The levee breach at Kettős-Körös River right bank, 1980. Schematic diagram of the hydrograph, that of the longitudinal profile and the particle distribution curve

The investigations [4] that were carried out have proved that a „rapid” piping phenomenon occurred. *Figure 9.* illustrates that there was a lens formed layer of a badly graduated (uniformity coefficient is mostly less than 3) loose (e = 079!) sand layer in the subsoil. This layer was in communication with the river bed itself. The increasing hydraulic pressure broke suddenly and intensively the relatively thick clay layers, because they were still stiff: the torrential flood wave did not enable the clay to get saturated, which could have turned it into elastic state. So, the saturated and pressed, badly graduated and loose sand layer lost its support and the channel of this sand layer got liquefied in its whole length. This initiated a very quick rupture of the levee. The process and the rapid change of piezometric pressure are shown in *Fig. 10. a, b, and c.*

Similar levee breaches where observed in Hungary at Szigetköz along the Danube in 1954, in the vicinity of it, but at the left bank of the Danube in Czechoslovakia as well as in Yugoslavia, also along the Danube in 1965.

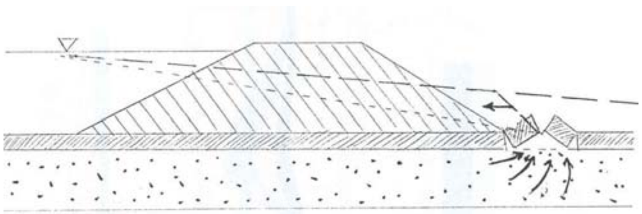

Fig. 10. a. Schematic diagram of the start of a rapid piping

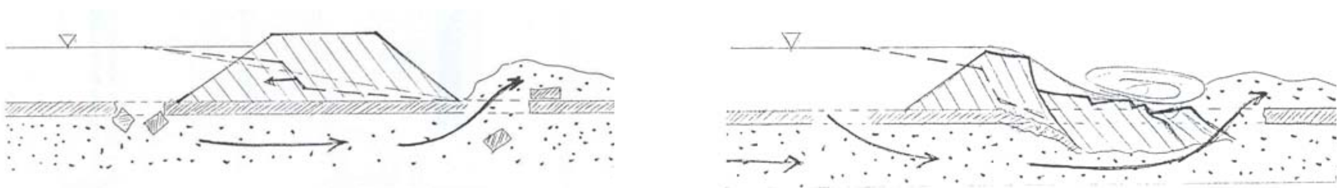

Fig. 10. b., c. Schematic diagram of the development of a rapid piping

MEASURES TAKEN IN ORDER TO IDENTIFY THE SECTIONS PRONE TO HYDRAULIC FAILURE ALONG THE LEVEES

The above mentioned dangerous phenomena, including conventional or „slow” piping are expected to develop in special stratification conditions, usually in the three-layered stratification that was shown in Fig. 7. Such conditions are due first of all to the differing stratification of the subsoil within a shorter section from that of the neighboring sections.

Further investigations [5] have proved that these anomalies in the stratification are expected, and all the mentioned hydraulic failures along the dikes occurred in those points, where the track of the levee has intersected ancient river bed that had disconnected and silted up several hundred or possibly several thousand years ago. The ancient river beds are easily identifiable in black and white aerial photographs.

An interpretation of ancient river bed system along the Körös river as well as the scheme of stratification at the concave bank of a silted river bend can be seen in *Fig. 11.*

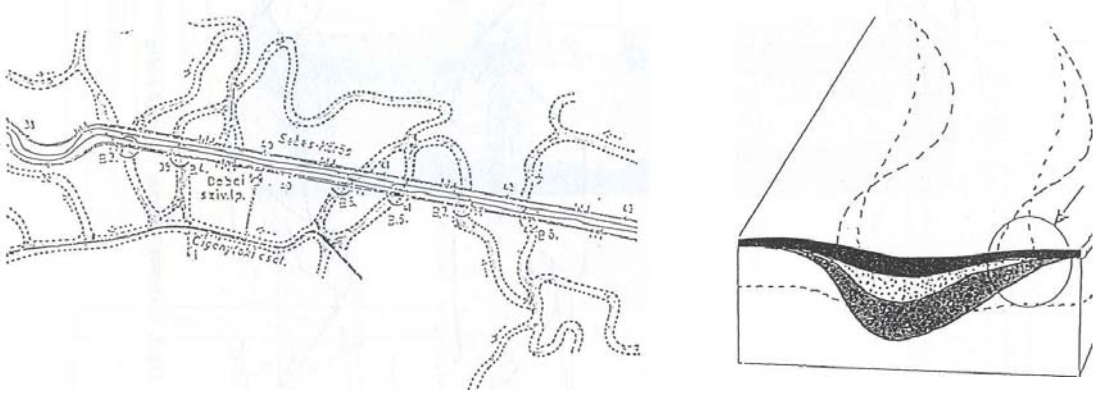

Fig. 11. Ancient river bed system and characteristic cross section of river bed

With a help of an interpretation of the ancient river bed we are able to identify the intersections of them with the levees, as well as to evaluate the weak points of the levee at these intersections from morphological point of view in order to prioritize further investigations and interventions.

The particular characteristics that must be considered are:

- the distance of intersection from the mean bed;
- the shape of the mean bed in the vicinity of the intersection (straight, convex or concave bank, inflexion);
- the shape of the ancient bed in the intersection.

This morphological classification [6] completed with the exploration of continuous stratification of subsoil by the means of horizontal geoelectric probing can be a proper method for identifying and determining the characteristic and individual sections.

METHODS OF REINFORCEMENT OF THE STABILITY OF THE SUBSOIL OF LEVEES

Since the major cause of damage to the levees at the intersections with ancient river bed is liquefaction of sand layers, construction of counterweight structures as well as decreasing the head to the foundation soil by the means of ground improvement or of lowering the groundwater table during floods were among the countermeasures considered. Of course, further basic requirements were: restoration of the original function of the levees, applicability to all the levees, feasible and sustainable solution, including not only the execution, but the maintenance of the construction as well.

Combination of the following countermeasures can be suggested as can be seen in *Fig. 12.:*

- application of insulation facing or layer on the wet side;
- construction of counterweight berm or basin on the protected side;
- installation of sheet pile walls;
- installation of drains and/or wells on the protected side;

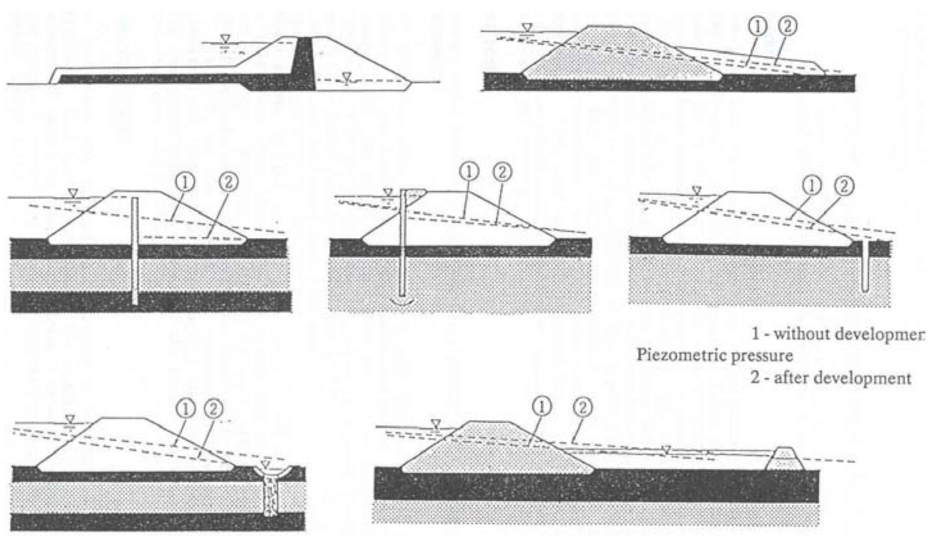

Fig. 12. Improvement of the stability of the foundation soil

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