This paper reviews the main factors that caused piping in five earth dams built in Cuba in the late 1980's. As a common geological feature we can mention that the dams were built in alluvial basins consisting of bedded granular particles. These soils are characterised by a high permeability. In the situation where the continuity of the layers under the dam foundation is extended downstream, the likelihood of occurrence of piping is very high.

PIPING PHENOMENON IN EARTH DAMS: CASE HISTORIES

R. VÁZQUEZ BALLONA[1] – M. ALVAREZ GRIMA[2]

In the five historical cases analysed, piping took place in the dam foundations and not in the embankments. The principal reason is that dam embankments are made from selected materials which are subjected to rigorous compaction and control tests whereas dam foundations are dictated by Mother Nature.

It was noticed that the position of the dam axis contributed considerably to the occurrence and acceleration of the piping process. In some cases piping might have been avoided by making a better selection of the dam axis location.

The distribution of continuous and permeable layers beneath the dam foundations which connected the reservoir with areas downstream was a common feature as well. In most of the projects the selection of dam axis was based not only on geological and geotechnical considerations, but also on economical aspects such as the transportation distance of suitable borrow materials for the construction of the embankments.

Piping occurred in sandy gravels. It is worth mentioning, however, that piping can also take place in dispersive soils. These soils are characterised by a dissolved sodium content of the pore water which is higher than in ordinary soils. Dispersive soils usually have a high exchangeable sodium content. They rapidly erode, forming tunnels by a process in which the clay particles go into suspension in slow moving water (colloidal erosion) damaging earth dams. This type of piping is often called chemical piping.

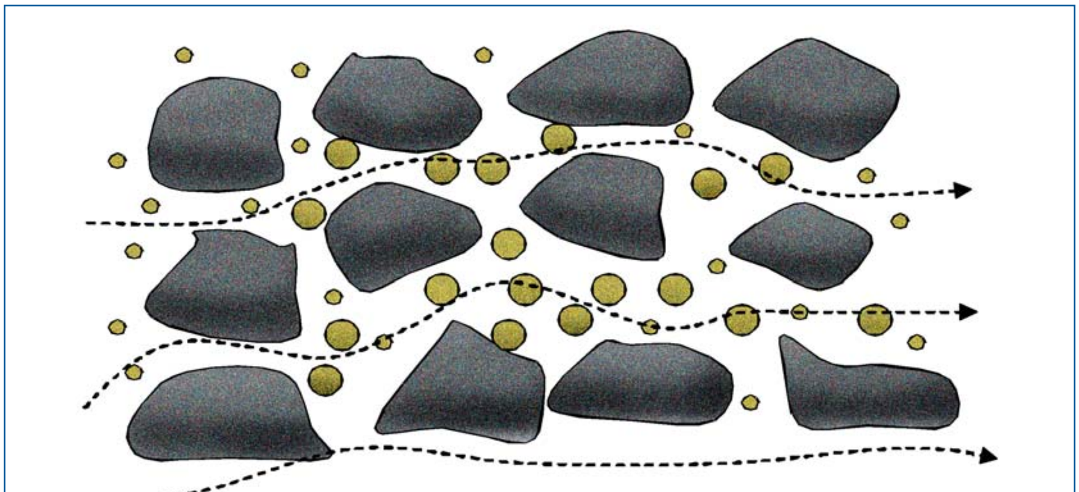

FIGURE 1
PIPING PHENOMENON: TRANSPORT OF FINE SOIL (FINE SAND) AMONGST COARSE PARTICLES (GRAVEL).

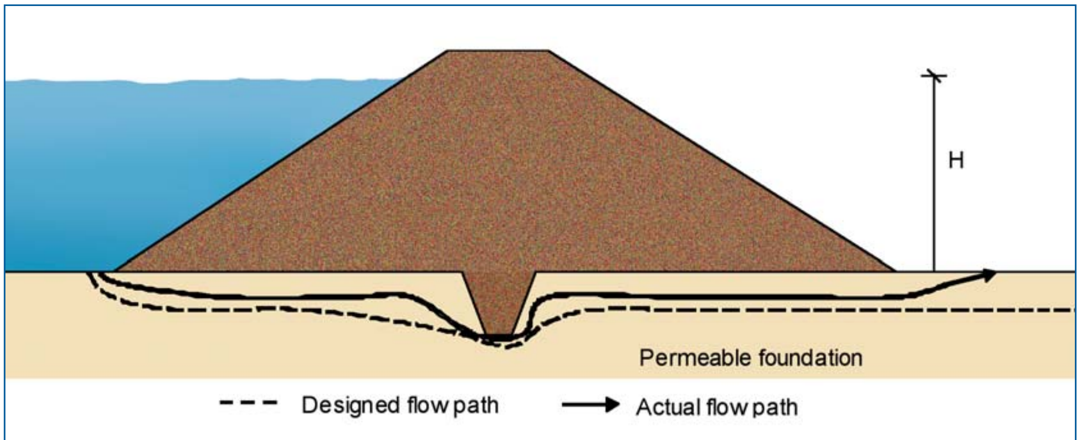

FIGURE 2
SCHEMATIC REPRESENTATION OF SEEPAGE UNDER DAM FOUNDATION CAUSING PIPING.

PIPING MECHANICS AND IDENTIFICATION

Piping occurs when water seeps through the soil and tends to transport the soil particles with it. This generally occurs when the pore sizes are larger than the soil particles *(Figure 1)*. This phenomenon occurs in sites composed of soils characterised by a high permeability. As a consequence, a change of water flow rate occurs and the piping process commences, giving rise to an outcrop of water seepage. As a result of this, the finest soil particles are washed away with the water flow. The diameter and the depth of the resulting hole will enlarge in time, bringing into existence the piping through which the reservoir and lower dam slope toe are connected *(Figure 2)*.

Piping can occur along a spillway and other conduits through the embankment. Sinkholes that develop on the embankment are signs that piping has commenced. A whirlpool in the reservoir surface may soon follow and then likely a rapid and complete failure of the dam. Emergency procedures, including downstream evacuation, must be rapidly implemented if this condition is observed.

The failure can be shown as a sudden raising of the foundation at the apron of the embankment. This undermining is generally caused by a gradual increase of piping, and it can lead to the appearance of ruptures such as longitudinal and transversal cracks on the embankment *(Figures 3 and 4)*. The most dangerous ruptures are transversal cracks, in as much as if they appear on the same level with the banked-up water level, a new outlet of reservoir water starts to form, and it could lead to a complete catastrophic failure.

Seepage can cause slope failure by creating an increase in water pressure or by saturating the slope. The pressure of seepage within an embankment is difficult to determine without proper instrumentation. A slope which becomes saturated and develops slides may be showing signs of excessive seepage pressure.

ENGINEERING GEOLOGICAL PROPERTIES OF INVESTIGATED PIPED SOILS

Properties of the piped soils in the five dams were analysed. In all cases the soil consisted mainly of non-cohesive granular particles: fine and medium sand (Figure 5). They had a vertical permeability of K=0.5-10 m/day. The horizontal permeability varied between 5-50 m/day. In fact, this is characteristic for Cuban alluvial terraces where the dams were built.

By analysing the geological site conditions of the dams, it was observed that the affected dike stretch was founded on permeable alluvial deposits consisting of heterogeneous soil with continuous horizontal stratification. This caused a natural path beneath the dike between upstream and down-stream. Seepage took place as a result of the existing hydraulic gradient (i). Table 1 lists the values of the actual critical gradient of the five dams analysed.

$i=\Delta H/L$

ΔH = difference between reservoir and downstream water levels

L = water running length from reservoir to water outlet lower dam

It can be seen in *Table 1* that the piped soils have a critical hydraulic gradient smaller than 0.15, with an average value of about 0.10. *Table 2* lists the smallest values found in the literature at that time, these values were used in the design of the dams as an admissible gradient to prevent piping.

FIGURE 3
LONGITUDINAL VIEW OF DAM AXIS

FIGURE 4
TRANSVERSAL CRACK CREATED ON DAM AXIS.

TABLE 1 CRITICAL HYDRAULIC GRADIENT

EARTH DAM	HYDRAULIC LOAD *(DH), [m]*	WATER RUNNING *LENGTH (L), [m]*	CRITICAL GRADIENT *(I)*
CASE A	3.2	45	0.07
CASE B	6.0	60	0.10
CASE C	15.0	115	0.13
CASE D	20.0	150	0.13
CASE E	18.0	300	0.06

TABLE 2 ADMISSIBLE HYDRAULIC GRADIENT USED IN THE DESIGN

TYPE OF SOIL	ADMISSIBLE GRADIENT
CLAY	1.20
SANDY CLAY	0.65
GRAVELLY SAND	0.45
MEDIUM SAND	0.38
FINE SAND	0.29

OBSERVATIONS AND ANALYSIS

The engineering properties analysed in the piped soils were: grain size distribution, hydraulic conductivity, admissible hydraulic gradient, critical gradient, and geological and engineering/geotechnical conditions of the sites.

The analysis of the results revealed that the piped soils had more than 50% of granular particles and the transported particles consisted mainly of fine and medium sand (Figure 5). Moreover, we could

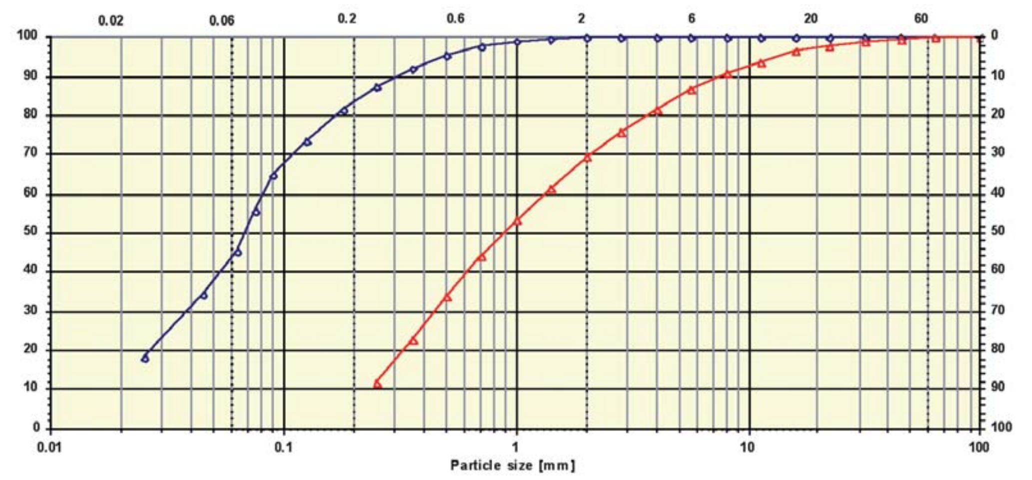

FIGURE 5
GRAIN SIZE DISTRIBUTION RANGE OF PIPED SOILS.

TABLE 3 MAIN FACTORS THAT CAUSED PIPING

CASE A	SANDY LAYER CUT BY STEEL PILE, BUT LAYING ON FISSURED LIMESTONE.
CASE B	THE IMPERVIOUS CUT-OFF DID NOT CUT UP THE SANDY LAYER AT AFFECTED ZONE.
CASE C	REINFORCED CONCRETE STRUCTURE PLACED (WATER IN-TAKE) ON GRANULAR LAYERS, WITH IMPERVIOUS APRON AND DRAINAGE STRUCTURE, BUT DESIGN CRITICAL GRADIENT 0.25 COMPARED TO 0.13 (THE ACTUAL GRADIENT MEASURED).
CASE D	GROUT CURTAIN MADE FROM CEMENT IN GRANULAR FOUNDATION, BUT RESERVOIR WAS FILLED BEFORE GROUT CURTAIN WAS FINISHED, SEEPAGE WAS CONCENTRATED IN AFFECTED STRETCHES.
CASE E	DEEP IMPERVIOUS LAYER WAS NOT CUT UP WITH STEEL PILES USED. HOWEVER, IN THE ZONE WHERE BENTONITE MIX WAS APPLIED, THERE WAS NO PROBLEM.

verify that for the piped soils with a low value of hydraulic load (ΔH=3-6 m) and a low hydraulic gradient (i=0.06-0.13) piping can occur; provided that granular layers are laying underneath the dam foundation. The presence of fine particles (0.2-2.0 mm) in large amounts can also be an indicator for the possible occurrence of piping based on the grain size distribution of the piped soils.

We could observe that for these soils the assumed design values for admissible gradient were generally ranging between 0.20 and 0.40 and they were based on experience and scarce data available from literature at that time (Table 2).

Despite of the fact that the designers took into consideration some preventive measures to reduce seepage underneath the dams, in practice these measures were not effective at all. Some of them were incomplete or inefficient, resulting in locally high seepage through the foundation. The use of sheet piles did not avoid high seepage, as it was thought.
Also permeable layers beneath the foundations were not cut up totally. In case B piping took place at low water level in the reservoir (about 5 m below the normal water level). Also we could observe clearly the tunnels created by the piping mechanism. The diameter of the tunnels observed varied between 15 cm and 35 cm. Also the presence of flow of fine sand was observed.
Besides the above mentioned aspects, it can be said that some geological and geotechnical conditions contributed to the occurrence of the piping phenomenon too: dam location (axis) in meander zones and location of concrete structures on permeable sandy layers laying parallel to the underground water flow. Also preventive measures were not totally completed before the filling of the reservoir. *Table 3* summarises the main factors that caused soil piping.

CONSIDERATIONS ABOUT SOME MEASURES TAKEN AGAINST PIPING

The main considerations are as follows:

- Drainage structure with an inverted filter acts as pore water pressure dissipater. However, it does not avoid seepage, which is considered high in permeable foundations. This measure might be feasible when the dam foundation is less granular and when the soil permeability is not too high.

- An apron or a partial cut-off (or a combination of both) lowers the hydraulic gradient since the water running path is enlarged. It was found that in practice this measure was not totally effective.

- Grout curtains made from cement and bentonite are effective when the soil porosity allows it, but requires finishing 3 to 4 profiles before the reservoir is filled up, avoiding in this way seepage concentration at the middle stretches. This measure requires time and control measures while it is executed.

- Soil-cement walls built by means of a trench or sheet piling together with pouring of blended bentonite-cement is considered a safe measure when permeable layers are cut.

CONCLUDING REMARKS

- In the five analysed dams we could corroborate that the admissible gradient reported in the literature at that time was not safe.

- Piping took place in permeable foundations consisting of fine and medium sand having a high permeability. ■

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[1] **R. Vázquez Ballona** *is Senior Advisor, National Enterprise for Applied Research, Havana City, Cuba*
[2] **M. Alvarez Grima** *is Project Manager, MTI Holland, Kinderdijk, The Netherlands*