Q. J. eng. Geol. London, 1980 Vol. 13 pp. 53–61 Printed in Northern Ireland

Development of piping erosion conditions in the Benson area, Arizona, U.S.A.

Y. M. Masannat

Civil Engineering Department, Faculty of Engineering and Technology,
University of Jordan, Amman, Jordan

Summary

Piping is a subsurface form of erosion which involves the removal of subsurface soils in pipe-like erosional channels to a free or escape exit. Although it develops in different types of soils and under a wide range of physico-chemical conditions, piping materials are commonly highly erodible. The present study in the Benson area, Arizona shows that piping commonly develops in alluvial deposits in the vicinity of arroyo-cuts and deeply incised gullies actively trenching in the flood plain deposits. It shows also that soils susceptible to piping usually comprise silts and silty sands with a low clay content, and that they are generally of low dry density, high void ratio, and have collapsing properties.

It was found that overgrazing the area of study in the past and misuse of the land, combined with the climatic conditions of long dry summers with intermittent short rain storms, have contributed to the initiation and development of piping erosion. Gully erosion and badland topography are quite extensive in the area of study due mainly to the collapse of the pipes at an advanced stage of their development.

Introduction

Piping is a type of subsurface erosion which acts under a set of physico chemical conditions that differ in many aspects from those under which other forms of erosion act. This type of erosion is responsible for the failure of many structures, especially dams, and also the configuration of many landforms in nature. The apparent intricacy of its action is due mainly to the complexity of the physico chemical conditions and geotechnical characteristics of the earth materials under which the phenomenon proceeds with its destructive action. The term 'piping' is customarily used to denote the process of erosion of the earth materials underlying man made structures by the removal of soil particles in pipe like erosional channels to a free or discharge exit.

Types and mechanisms of piping erosion

As water flows into a soil from a point of a higher total head to a point of a lower total head, as from the upstream side to the downstream side of a full-reservoir dam, it experiences a gradual dissipation in head. This dissipation is accompanied by an erosive seepage force which may tend to remove the soil particles in the direction of flow. If the seepage force acts upwards it decreases the effective weight of the soil particles and thus the stability of the soil. If the seepage force becomes equal to, or greater than, the effective weight of the soil, the soil loses its strength and an erosional channel may develop along which piping erosion of the soil particles can take place. This type of erosion is called 'piping due to heave' (Terzaghi & Peck 1948, 1967). The upward hydraulic gradient needed to cause piping in an unloaded cohesionless soil is called the critical gradient. It equals the ratio of the submerged unit weight of the soil to the unit weight of water. However, Terzaghi & Peck (1967) noticed that most piping failures of dams occur at hydraulic heads much smaller than those needed to initiate piping due to heave. They explained these failures by the occurrence of another type of piping called 'piping by subsurface erosion'. Piping by subsurface erosion starts at the discharge point of water seeping through the non-homogeneous foundation materials of a dam from the upstream side to the downstream side. It proceeds progressively backwards in an upstream direction towards the reservoir along zones of high permeability and low resistance to scour erosion. This process continues until the erosional seepage channel approaches the base of the reservoir where dam failure occurs by piping.

Parker & Jenne (1967) classified piping into three different types according to their mode of origin, namely:

(a) Desiccation-stress crack type of piping which might result from the subsidence of soils of collapsing structures upon loading and wetting, or from localized subsidence due to saturation of surficial sediments forming sinks or stress cracks.
(b) The entraintment type of piping which results mainly from the creation of hydraulic gradients large enough to induce the process of channelized subsurface erosion of the earth materials underlying the hydraulic structures, a process which eventually leads to the collapse of the overlying structures. This kind of piping can develop in nature by the occurrence of a landslide large enough to block the flow of a stream in a valley.
(c) The variable permeability-subsidence type of piping. This results from the development of hydraulic gradients that cause the flow of water through soil strata with a seepage velocity large

0481-2085/80/0100-0053$02.00

enough to remove the dispersed soil particles at the face of a gully, from the side of an embankment, or from a steep side slope.

Occurrences and soil conditions

Occurrences of piping erosion in many different parts of the world show that certain soils are more susceptible to piping erosion, and that certain physicochemical and geomorphological conditions are more conducive to piping erosion than others.

The importance of soil properties in piping erosion has been confirmed by many field and laboratory experiments. Fletcher & Carroll (1948) studied some properties of soils associated with piping in southern Arizona and found that piping soils are very high in exchangeable sodium, and uniformly high in calcium carbonate. Sherard *et al.* (1963) emphasized the importance of soil properties, especially plasticity index, in the resistance of soil to piping erosion in earth dam embankments. Zaslavsky & Kassif (1963) discussed the mechanism of piping in cohesive soils and concluded that the factor of safety against piping in cohesive soils is inversely proportional to the mean size of the soil particles. Ranganatham & Zacharias (1968) found that the shrinkage index correlates better with the piping resistance of clays than the plasticity index. Benites (1968) studied the geotechnical properties of the soils affected by piping near the Benson Area, Arizona, and confirmed the collapsing properties of these soils.

Parker & Jenne (1967) emphasized the importance of soil mineralogy in the development of piping erosion. They mentioned that one of the requirements for the development of desiccation-stress crack piping is that the strata must be montmorillonitic. They indicated that the higher the sodium to calcium plus magnesium ratio, the greater will be the swelling and ultimately the cracking potential of the montmorillonitic soils.

Many researchers emphasized the importance of soil structure and dispersibility characteristics in the development of piping erosion. Aitchison *et al.* (1963) have indicated that post-construction deflocculation has contributed to the failure of many earth dams by piping. Aitchison & Wood (1965) presented figures which define the boundary conditions between the flocculated and deflocculated states for illites and montmorillonites and showed their validity in case histories of sound and failed dams. Sherard *et al.* (1976*a*) developed a new laboratory test (pinhole test) through which the dispersibility of a soil can be identified with accuracy. Sherard *et al.* (1976*b*) considered the amount of dissolved sodium relative to other salts in the pore water as the main factor in determining the dispersibility of clay. They also confirmed that very few soils with total dissolved salts of less than 1.0 m. eq/litre are dispersive, and that the Atterberg limits for a given clay provide no indication as to whether it may be dispersive or not. Francq & Post (1977) indicated that the dispersiveness of a clay is more a result of the sodium that adheres to the clay particles than to the sodium dissolved in the pore water.

The views of Sherard *et al.* (1976*b*) support those of Taylor (1959) who considered that the presence of large amounts of monovalent ions (more than 15–20%), especially sodium ions, were a dangerous signal. He noted the possibility that such soils might deflocculate, especially when flooded with salt free water. He recorded that certain soils with a high sodium content remained in a fluocculated condition due to the presence of high occluded salt, but would deflocculate upon leaching. Parker (1963) confirmed this point by showing that the higher salinity of the roofs and walls of the pipes that he studied, as compared with their floors, would partially depress the dispersive effects indicated by the soluble sodium percentages.

Other factors like the geomorphological, hydrological, and soil profile characteristics as well as the biological activities were also reported sometimes as factors contributing to piping erosion in certain areas. Gibbs (1945) studied the tunnel gully erosion on the Wither Hills, Marlborough, New Zealand, and related it to soil properties, excessive runoff, and denudation following overgrazing by sheep and rabbits. Fletcher & Harris (1952) and Fletcher *et al.* (1954) discussed the conditions of piping erosion and emphasized the importance of the entire soil profile. Brown (1962) emphasized the importance of soil properties and overgrazing in the initiation of piping. Parker (1963) showed the importance of piping as a geomorphological agent in the landform development of the dry lands. Jones (1968) studied the development of extensive pipe systems near Benson in the San Pedro Valley, Arizona. He concluded that the long-term control of pipe development depends on aggradation in the channel of San Pedro River.

Area of study

Piping constitutes one of the common types of soil erosion in the arid and semi-arid lands, especially in the southwest of the United States. The area of study occupies a segment of the San Pedro Valley, Cochise County, Arizona, United States. It is about 2.5 km wide, 8 km long, and extends along the southside of the Southern Pacific Railroad to the east of Benson as shown in Fig. 1. Piping in this area is not only an engineering or agricultural problem but an economic and social problem as well. It has serious and harmful implications on the agricultural production of the cultivated lands as well as on the urban development. More than 50% of the agricultural lands in the area are affected by piping.

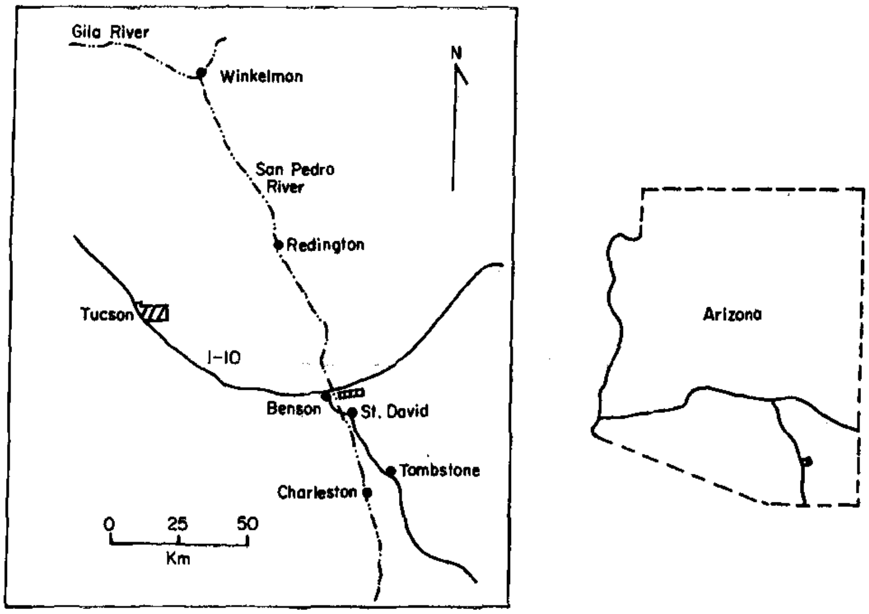

FIG. 1. Location map of the area of study.

The intensity, pattern, and distribution of the piping systems developed in the area are mainly governed by the following factors: (1) the properties of piping soils, (2) the local physical, geological, and hydrological characteristics of the area of study, and (3) the biological factors.

Properties of piping soils

Physical properties

Many soil samples were gathered from the area and their physical properties were determined. It was found that these soils are generally characterized by low dry densities, high void ratios and by low liquid limits. These results as well as the results of other researchers (Benites 1968 and Jones 1968) who studied the properties of piping soils in neighbouring areas are shown in Table 1.

Dispersion properties

A simple dispersion test suggested by Benites (1968) was used to examine the susceptibility of the soil structure to collapse upon saturation. This test is carried out by dropping a 2.5 g soil sample block into a

TABLE 1. *Summary of the physical properties of the tested soil samples*

Investigator	Soil property	No. of samples	Max value	Min value	Range	Mean	Standard deviation
Masannat	ρd	10	1.583	1.006	0.577	1.264	0.186
Benites	ρd	11	1.666	1.410	0.256	1.538	0.083
Jones	ρd	22	1.520	1.150	0.370	1.315	0.106
Masannat	L_L	10	33.3	20.6	12.7	28.36	4.56
Benites	L_L	11	56.5	34.0	22.5	43.90	8.12
Jones	L_L	9	48.0	20.0	28.0	36.60	8.44
Masannat	e	10	1.388	0.667	0.721	1.075	0.284

ρd = Dry density; values of dry density and their maximum, minimum, range, mean, and standard deviation are in Mgm^{-3}
L_L = Liquid limit
e = void ratio = vol. voids/vol. solids Range = Max value–Min value

cup containing 125 ml of distilled water and recording the time needed for the complete collapse. Dispersion tests were run on many soil samples from which the following conclusions are drawn:

(a) The soil samples have generally a non-stable water structure. The dispersion time ranges from 10 to 25 s for most of the soil samples.
(b) The time of dispersion for a given soil sample decreases with the increase in its initial water content.
(c) The time of dispersion is generally greater for soil with a higher clay content.

The saturation of an unsaturated soil sample (upon submergence in water) eliminates the state of tension in the pore water, as well as the softening of the clayey material that is weakly binding the silt and sand particles of the soil together. This usually results, in the absence of water stable cementing materials, in the collapse of soil structure.

Collapsing properties

Denisov (1951) suggested the use of an inundation consolidation test to assess the collapse of soil sample, both upon the application of a given load and upon wetting. The following coefficients were suggested:

$$R_P = \frac{e_0 - e_p}{1 + e_0}$$

$$R_W = \frac{e_p - e_w}{1 + e_p}$$

$$R_T = \frac{e_0 - e_w}{1 + e_0}$$

TABLE 2. *Void ratios and coefficients of subsidence of the tested soil samples*

Sample No	Pressure KN m^{-2}	e_0	e_p	e_w	R_p	R_w	R_T
1	12.5	1.107	1.064	1.005	0.020	0.029	0.049
2	25.0	1.061	1.008	0.881	0.026	0.063	0.087
3	50.0	1.388	1.200	1.043	0.088	0.074	0.162
4	100.0	1.560	1.108	0.730	0.210	0.179	0.385

Where e_0 = initial void ratio, e_p = void ratio in consolidometer under pressure 'P', e_w = void ratio in consolidometer under pressure 'P' after wetting, R_p = coefficient of subsidence due to loading, R_w = coefficient of subsidence due to wetting and R_T = coefficient of total subsidence.

Inundation consolidation tests were carried out on four undisturbed samples collected from different locations in the area under different consolidation stresses. The relatively high values of the subsidence coefficients, as shown in Table 2, clearly indicate that these soils are essentially collapsing types, with the collapsing parameters increasing both with the increase in consolidation stress and initial voids ratio.

Grading properties

The grain size distribution curves of five soil samples, typical of the soils affected by piping in the area, are shown in Fig. 2. The grading properties of these soils, expressed in terms of the coefficient of uniformity (*Cu*) and the coefficient of curvature (*Cc*), are

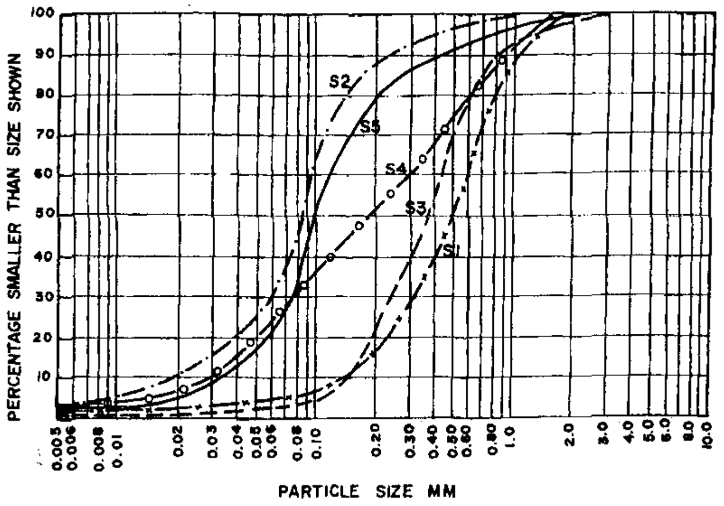

FIG. 2. Grain size distribution curves of the tested soil samples.

TABLE 3. *Grading properties of the tested soil samples*

Sample No.	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	Uniformity coefficient	Coefficient of curvature
s_1	0.14	0.31	0.60	4.29	1.14
s_2	0.019	0.06	0.096	5.05	1.97
s_3	0.15	0.24	0.43	2.87	0.89
s_4	0.03	0.076	0.30	10	0.64
s_5	0.033	0.076	0.12	3.64	1.46

TABLE 4. *Cation exchange properties of the tested soil samples (m.eq/100 g)*

Sample No	Exchangeable Na	Exchangeable Ca	Exchangeable Mg	C.E.C	Exch. Na (%)
1	1.4	12.8	1.1	15.3	9.15
2	0.7	8.4	1.9	11.0	6.36
3	1.1	10.2	7.8	19.1	5.75
4	0.2	15.0	4.1	19.3	1.04

shown in Table 3. These coefficients are defined as follows:

$$Cu = D_{60}/D_{10}; \quad Cc = (D_{30})^2/D_{60} \cdot D_{10}$$

Where: 10% of the particles are smaller than the size denoted by D_{10}. The sizes D_{30} and D_{60} are defined in a similar way. It is clear that no sample meets the gradation requirements of the Unified Soil Classification System where a well graded sandy soil should have both $Cu > 6$ and Cc between 1 and 3. The properties indicate that these soils are generally poorly graded, silty sands with a low percentage of clay.

Chemical properties

Four samples were collected from the area of study for chemical analysis. The results indicate that the exchangeable sodium percentages in the piping soils are low as indicated in Table 4. The cation exchange capacity values are also relatively low. These values, together with the low liquid limit values of Table 1 imply that the percentage of montmorillonitic clay in the soils, if present, is low. These results support the remarks made by Jones (1968) who noticed that the pipe systems in the San Pedro Valley are developed in soils which are still highly flocculated, and also the conclusions of Fletcher *et al.* (1954), that, while sodium may contribute to the severity of piping erosion, it is by no means necessary for the occurrence of piping.

Characteristics of the area of study

The climate in the area of study is semi-arid with the summer being very hot and the winter moderately cold. The mean annual precipitation is about 280 mm with most of the rainfall in July, August, and September. The most common vegetation in the area is mesquite, shrub, and saltbrush.

The area is bounded by the Whetstone Mountains to the southwest, the Rincon Mountains to the northwest, and the Dragoon Mountains to the east. Figure 3 shows a diagrammatic cross-section of the San Pedro

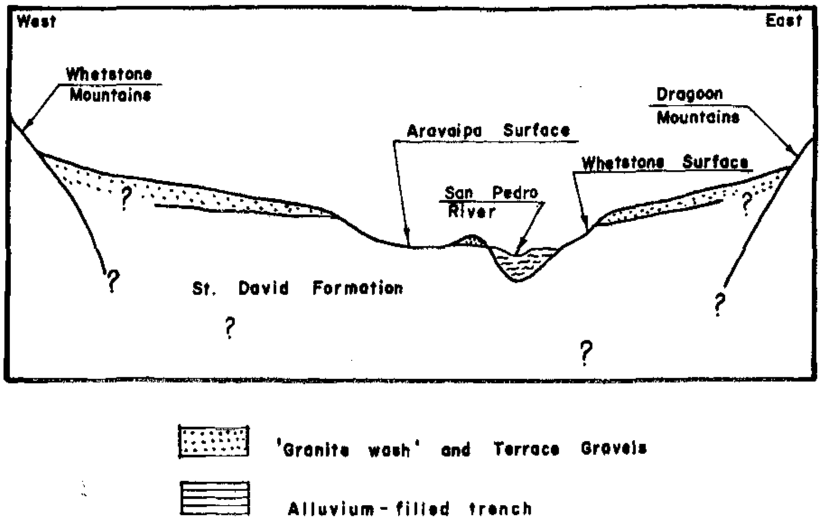

FIG. 3. Diagrammatic cross-section of the San Pedro Valley near Benson, Arizona (Jones 1968).

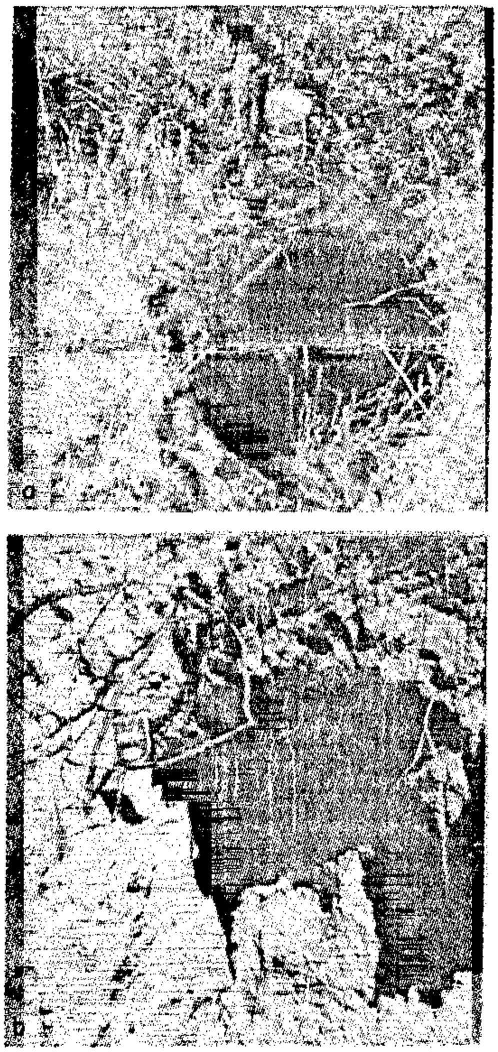

FIG. 5. A pipe developed in a 3 m-high arroyo bank, Benson area, Arizona. (a) Pipe inlet about 0.6 m in diameter, and 4.5 m away from the arroyo bank (b) the outlet of the same pipe.

well developed tunnel-like erosional channels on Anacapa Island, off the Southern California coast where no pocket or ground squirrels (gophers) are present. However, rodent holes undoubtedly constitute potential inlets and paths for the percolation of water through the soil profile, thereby increasing the probability of piping erosion.

Some authors consider vegetation as a factor contributing in certain aspects to piping since the plant roots support the roofs of pipes and thus aid in the continuation of the piping process. Also, holes left by decayed roots will assist deep infiltration (Jones 1968), and deep-rooted vegetation may cause deep soil cracking which will be the loci of subsequent piping (Carroll 1949).

The overall effect of the denudation of the vegetative cover however, will be the accentuation of both surface and subsurface soil erosion. Overgrazing the area of San Pedro Valley in the past is probably one of the major causes of piping erosion and arroyo-cutting in this area. It has been noticed that piping erosion is a common phenomenon that is not restricted to areas of high or low vegetation density. However, areas with advanced stages of piping and gully erosion are characterized by their low vegetation density. This is mainly due to the draining of the subsurface moisture by the erosional pipes to a low level where plants can no longer survive. It has also been noticed that while a dense permanent vegetative cover does contribute to the stability of soil structure, it does not necessarily prevent the process of piping erosion. It has been noticed in some locations that piping developed and channel banks collapsed leaving the roots of plants hanging in the air. These roots sometimes contribute to the stability of the bridges above the pipes after the collapse of their roofs.

Conclusions

It is clear that a certain combination of environmental conditions and the gross properties of soil is needed to initiate and promote piping erosion in a given area.

Piping initiation requires a threshold erosion force that can overcome the erosion-resistance of the soil. The main erosion force is the seepage force of flowing water which increases by the following factors:

(a) Lowering the local base level of the erosional channels in which the pipes outflow.
(b) The development of relatively steep potential paths for the concentration and seepage of water into the soil through the desiccation cracks and other types of fissures, as well as through the potential paths developed by burrowing animals and decayed plant roots.
(c) The increase in the rate of surface runoff by the decrease in the permeability of the top soil surface as a result of compaction by raindrop impact, and by the denudation of the vegetative cover.
(d) The stratification of the soil which leads to the concentration of water flow within the highly erodible and permeable horizons in the soil profile.

The resistance to soil erosion generally decreases due to the following factors:

(a) The conditions prevailing in the environment of deposition which result in the deposition of a soil with a high void ratio, low liquid limit, and an unstable structure with collapsing properties.

RANGANATHAM, B. V. & ZACHARIAS, G. 1968. Interaction of density, soil type, and time on piping resistance of cohesive soils. *Proc. 3rd Budapest Conf. Soil Mech. Fnd, Engng.* 237–46.

SHERARD, J. L., DUNNINGAN, L. P. DECKER, R. S. & STEELE, E. F. 1976a. Pinhole test for identifying dispersive soils. ASCE, *J. Geotech. Engng. Div., Am. Soc. Civ. Engrs.*, 69–85.

——, —— & —— 1976b. Indentification and nature of dispersive soils. *J. Geotech. Engng. Div., Am. Soc. Civ. Engrs.*, **102**, 287-301.

——, WOODWARD, R. J., GIZIENSKI, S. F. & CLEVENGER, W. A. 1963. *Earth and Earth-Rock Dams.* John Wiley and sons, New York.

TAYLOR, A. W. 1959. Physico-chemical properties of soils: ion exchange phenomena. *J. Soil Mech. Fdn Div., Am., Soc. Civ. Engrs.*, **85**, 19–29.

TERZAGHI, K. & PECK, R. B. 1948. *Soil mechanics in engineering practice.* John Wiley and Sons, New York.

—— & —— 1967. *Soil mechanics in engineering practice.* Second Edition, John Wiley and Sons, New York.

ZASLAVSKY, D. & KASSIF, G. 1965. Theoretical formulation of piping mechanism in cohesive soils, *Géotechnique* **15**, 305–16.