Structural Failure of Western Highways Caused by Piping

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•PIPING, a type of subsurface erosion, is an extremely destructive erosive process which attacks certain structures of man and landforms of nature (1, 2). The objective of this report is to detail the current and potential damage of piping to the highways in the West as well as to point out some ways in which this damage may be minimized. A further report is in preparation presenting physicochemical-mineralogical analyses and the detailed mechanisms of piping and of subsidence in the western drylands.

Much has been written on the details of erosion, including the formation of gullies and arroyos, yet the geologic literature contains only sparse note of piping. Local attention has been given to this phenomenon by soil scientists (3-7), but no comprehensive treatment of the subject is currently available. Recently, however, Australian and New Zealand scientists became concerned about the frequent failure of small earth dams. It was determined that 8 percent of the dams constructed failed as a result of piping (8). The studies led to an extensive examination of the piping process as a major cause of dam failure and resulted in a Colloquium on Failure of Small Earth Dams in Melbourne, Australia, November 16-19, 1964.

Piping occurs with the greatest frequency in the world's drylands (arid and semiarid regions) and, in these regions, it occurs most commonly in valley alluvium which has been or is being trenched by gullies. Piping also occurs in the loess areas of the Mississippi Valley, where rainfall may exceed 50 in. per year (9), in New Zealand, where rainfall is about 28 in. per year (6), and in Africa, where the rainfall is about 30 in. per year (10). In the United States, piping has been observed at numerous sites. However, this report deals principally with piping in the western drylands, particularly in Colorado, New Mexico, Arizona, Utah, and Nevada.

Piping is basically the development of subsurface drainage systems in earth materials to a depth no greater than the nearby base level of drainage. It results in a surface expression much like miniature solution depressions in limestone or dolomite terrains. Three different types of piping have been recognized, depending on their mode of origin: (a) desiccation-stress crack, (b) entrainment, and (c) variable permeability subsidence.

An associated diagenetic phenomenon which causes fracturing of alluvium is that of subsidence or "collapsing structure"; the latter term being used by South African investigators (11-13). In essence, this subsidence results from the breakdown of secondary aggregates, which occurs as a result of saturating previously unwetted low-density earth materials. In the drylands, alluvium, colluvium, and loess are particularly susceptible to subsidence when wetted. Subsidence of this type may result in a volume decrease of as much as 13 percent (14) and a lowering of the ground surface by 10 to 15 ft (15), forming sinks (14) or voids beneath the land surface which provide routes for the movement of subsurface water and the development of pipes. Thus, subsidence may be a causative factor in the development of either the desiccation-stress crack or the variable permeability-subsidence types of piping.

The dominant type of piping currently damaging highway structures in the western drylands originates from desiccation cracks. Runoff enters a drainable desiccation crack at the land surface. As the runoff moves downward it erodes and enlarges the

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crack walls. Where the hydraulic gradient is sufficient, fine-grained sediment is transported in suspension along the crack to appear at an incipient pipe outlet in a gully wall, an arroyo side slope, or embankment. This type of pipe may also occur as a result of localized subsidence, due to saturation of surficial sediments, forming sinks or stress cracks; or, rarely, an animal burrow or rotted-root tube. These pipes have visible inlets and outlets except in those instances where the rainfall saturates the ground thereby causing slumping and temporary closure of pipe ends.

The entrainment type of piping occurs chiefly during the dewatering of building foundations, or during the rise of impounded water behind levees and dams (16). These pipes and their associated boils are induced where newly created large hydraulic heads cause channelized subsurface flow, with entrainment of water-saturated earth materials, to a discharge point in an excavation or to the down-gradient side of a dam or levee. The entrainment form of piping rarely produces open subsurface pipes; however, it may transport enough earth material to cause the collapse of the overlying surface with sudden destruction of the superjacent structure (1, 17).

The variable permeability-subsidence type of piping, which produces open pipes, results where a sufficient hydraulic head exists to move water through a stratum with sufficient velocity to transport dispersed clay or even silt and sand at the face of a gully, side of an embankment, or a steep side slope. Visible outlets develop, for example, at a gully wall and grow headward away from the wall.

Where piping is extensively developed, a characteristic and easily recognized topography termed pseudokarst (1) is generally present (Figs. 1, 2). The landform appearance is that of a miniature limestone or dolomite terrain marked by solution features such as sinkholes, natural bridges, caves, blind valleys, and haystack-shaped hills. The term "karst" is applied to this landscape; hence, for the piped landscape the term "pseudokarst" is applied. Although both the desiccation-stress crack and the variable permeability-consolidation types of piping simulate solution erosion in limestone or dolomite, at present there is no evidence that solution plays any important role in the piping process in sedimentary materials.

Figure 1. Aztec Wash showing pseudokarst developed in trenched and piped alluvium. Two culverts which discharge near north base of roadway fill are visible. Concentration of drainage runoff at edge of roadbed accelerates piping and gullying and contributes directly to undermining of highway. Tableland in background would provide excellent roadway in lieu of present location (see Figs. 13, 18, and 19).

PIPING PROCESSES

No single factor determines whether the desiccation-crack type of piping will occur at a given site in the western drylands; rather, it is the interaction of several physicochemical-mineralogical factors which determines whether a given sedimentary material will or will not pipe. However, four minimum requirements exist: (a) enough water must be available to fill drainable cracks; (b) the strata must be montmorillonitic; (c) the strata must desiccate thoroughly, if only seasonally; and (d) there must be an outlet for drainage. Furthermore, the higher the sodium to calcium-plus-magnesium ratio, the less the stability of crumb aggregation, the less the vegetative cover, and the less the slope, then the greater is the probability of desiccation-stress crack piping, and the greater its intensity where it does occur. Where uneven and differential subsidence occurs, the only minimum requirement may be that of a sufficient hydraulic gradient.

Although a sufficient hydraulic gradient must exist, a gradient which is adequate to facilitate piping in one stratum may not be adequate for another. Gullies, in alluvium, only 1½ ft deep have been observed with pipe outlets in their walls. Whether pipes outlet somewhere in the gully wall or at the base of the gully wall appears to depend upon the depth to which the desiccation-stress cracks occur, or the presence of permeable layers interstratified with less permeable layers above the gully floor.

Montmorillonite, mixed-layer illite-montmorillonite, and illite are the clay minerals which are nearly ubiquitous in the piping earth materials examined to date (1, 2). Recently obtained cation exchange capacity data indicate that the montmorillonite content of piping materials ranges from 20 to 50 percent on a dry-weight basis. Pure montmorillonite is capable of volume changes of up to 1600 percent in going from the air-dry state to maximum moisture sorption (18). Thus, surficial sediments containing 20 to 50 percent montmorillonite can be expected to crack widely and deeply upon thorough desiccation, such as occurs in the western drylands. In humid areas, similar materials would: (a) seldom have the opportunity for thorough desiccation, (b) have been wetted to depth so that further subsidence as a result of saturation would not be

Figure 2. Pseudokarst developed in dense, consolidated shaly bedrock of triassic Chinle formation; in this area it is largely derived from volcanic ash falls, weathered to red, green, and white bentonitic shales. Undrained, plugged sinkholes are partially filled with water from recent rainstorm.

expected to occur, (c) not be largely sodium saturated unless adjacent to salt water, and (d) commonly be kaolinitic (or illitic) rather than montmorillonitic. Thus, in humid climates similar materials would not be expected to pipe. However, in subhumid regions which have extended, hot, dry summers, weather conditions may cause cracking to occur. It is believed that desiccation caused by summer droughts largely explains the incidence of piping in areas which have 20 to 50 in. per year average rainfall.

Soluble and exchangeable sodium affect the susceptibility of a stratum to piping in a number of ways. The alluvial mineral grains are principally stabilized into crumbs by clay coatings and by the cementing action of iron and manganese oxides, silica, and calcite. These crumbs, which form the bulk of alluvial materials susceptible to piping, are stable under existing dryland weather and overburden conditions. As long as they remain dry, or at least unsaturated, they bear heavy loads but rapidly lose this ability upon saturation. The higher the sodium to calcium-plus-magnesium ratio, the greater will be the montmorillonite volume change during swelling. The greater the amount of swelling, the more thoroughly the cements and clay coating will be fractured. The greater the sodium to calcium-plus-magnesium ratio, at a fixed total soluble salt content, the more readily the montmorillonite will disperse and flush out in percolating waters. This removal of clay in percolating water may be referred to as colloidal erosion.

Dispersed montmorillonite clay particles may wash away in suspension, even through thin cracks in consolidated shale bedrock, or between larger sand-sized particles in unconsolidated sedimentary beds. Where fractures are enlarged sufficiently for turbulent flow to occur, erosion becomes greater through corrasion and the rate of localized erosion is thus greatly increased. A by-product of the clay dispersion, as a result of high soluble sodium content, is a decreased permeability of the ground surface which increases the amount of runoff available to enlarge pipes. Vegetative growth is also decreased by high soluble sodium contents.

Vegetative denudation, whether by overgrazing, recurrent burning, or climatic change, promotes piping (19, 20). This is a result of a decrease in surface permeability due to: (a) decreasing contents of organic matter; (b) increased breakdown of crumb structure at soil surface due to raindrop impact on unprotected surface; (c) the raising of surface and subsurface temperature which, in turn, results in greater desiccation; and (d) greater runoff due to loss of the obstruction provided by vegetative cover.

Some additional observations may be noted concerning the significance of desiccation-stress cracks to piping. Extensive piping occurs in alluvium derived from the cretaceous Pierre shale along US 85-87 south of Colorado Springs, Colo. However, piping has not been observed in irrigated fields in this area. More significantly, piping does not even occur in the highway right-of-way adjacent to the irrigated fields due, we believe, to subsurface movement of moisture from the irrigated fields. Town Dump Wash, near Bayfield, Colo., meanders on alluvial fill between two low hills of paleocene Animas shale. The piping intensity in the alluvium is distinctly less, alternatively on the one and then the other side of the Wash, depending on the nearness of the Wash to the Animas bedrock. It is presumed that subsurface moisture moves from the Animas shale into the alluvium and that the amount of moisture is adequate to support a good grass cover only in a reasonably narrow strip of alluvium adjacent to the shale. The density of the vegetative cover tends to be inversely related to piping intensity.

In a piped area, the frequency of pipe inlets commonly increases toward the arroyo banks. This results from an increased contribution of the gravity stress factor to the desiccation-stress cracks which parallel an arroyo bank. When the ground is wetted the major swelling movement is toward the unconfined or free face of the arroyo. Less swelling occurs with depth than near the surface due to moisture deficiency at depth. When desiccation occurs again, the cohesive force of the sediment is not sufficient to pull the arroyo bank back to the vertical so cracks develop which are largely parallel to the arroyo bank.

Where subsidence, due to saturation of the ground, occurs at depth in low-density earth materials such as alluvium or loess, underground cavities may result as reported by Turnbull (21). Stress cracks may subsequently open up to the surface and serve as

conduits for water to pass from the surface down to the subsided area. Given opportunity for lateral ground water flow to a nearby ditch, canal, or arroyo, pipes may then develop at depth in the formation (22).

Piping has been observed in the grass-covered alluvium of portions of Town Dump Wash and in Montana (23) and Uganda (10). In the Town Dump Wash alluvium, a large pipe outlet was found at a depth of about 8 ft in a layer of alluvium slightly more sandy and permeable than the material between it and the land surface or the exposed strata below it. Thus, the layer of higher permeability serves as a drain during snow-melt runoff or rare prolonged rains. The horizontal transmissibility appears adequate to develop a sufficient water velocity to carry dispersed clay out to the gully. Locally, the hydraulic gradient may be adequate to move silt and sand as well at the headward end of the pipe. Bishop (10) reports that "... during heavy rainfall [following a protracted dry spell] the water-table may rise rapidly and when supply exceeds drainage by a sufficient amount 'perched water-tables' build up above layers of relatively impermeable strata. If the rainfall is sufficiently concentrated the surface of the water-table develops a slope towards lines of [surface] drainage. Such a build up of ground-water results in rapid subterranean flow into gully heads, undercutting both unconsolidated beds and any surface cover of vegetation. The gullying [piping] proceeds in steps above each relatively impermeable band and temporary tunnels up to 3 feet in diameter can be seen leading off from the heads of active gullies. With the collapse of tunnels [pipes] gullies may advance headwards as much as 10 or 15 feet in a single storm."

The development of pipes away from a gully wall, without visible inlets, may also occur where a gully or drainage ditch intercepts a water table (Fig. 3). Several such instances have been noted in the irrigated areas of Wyoming and Nebraska. As the pipes grow in length and diameter, settlement of the overlying material may take place, particularly after an extended rain or snow melt which may wet the alluvium well below the surface. The water adds to the overburden weight and decreases the crumb strength as previously noted. Subsequently, surface runoff collects in the subsidence depressions causing either further subsidence or development of vertical pipes down to the more or less horizontal subsurface pipes by: (a) colloidal erosion, i.e., carrying out dispersed fines; (b) enlarging a desiccation crack; (c) enlarging a stress crack (resulting from subsidence); or, rarely (d) enlarging an animal burrow or rotted-out root

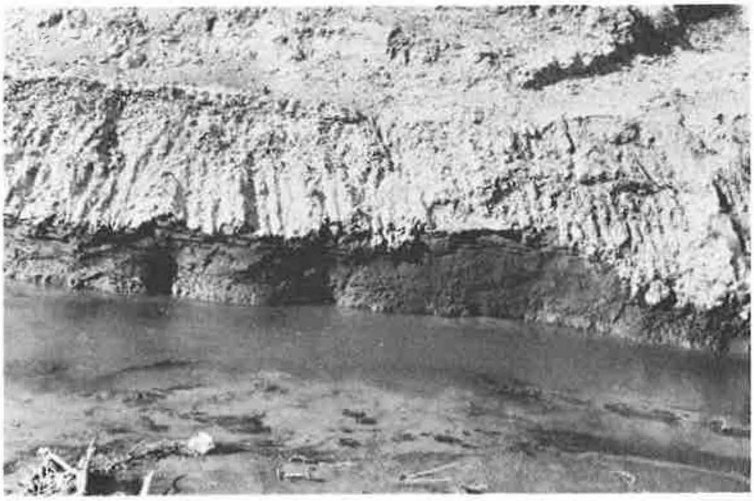

Figure 3. Pipe outlets near base of gully wall. Subsidence caused by irrigation return underflow may be responsible for development of these pipes in Oligocene Brule formation White River group.

Figure 4. Drainage ditch showing result of piping and subsidence. Ditch resulted from heavy rainstorm. Materials affected are greenish-gray silty alluvium derived from cretaceous Mancos shale.

tube. In places it appears that whole gullies have formed from the collapse of pipes of the variable permeability-subsidence type. In some situations, it appears probable that both subsidence and desiccation-stress cracks combine to facilitate piping. The drainage ditch shown in Figure 4 may have formed in this manner.

The confusion in the literature between "collapse structure," a form of subsidence, and piping is exemplified by studies of the White Silts loess area near Kamloops, B. C., Canada. Reports by Cockfield and Buckham (5), and Buckham and Cockfield (24) describe this area as a pseudokarst (although they do not call it that) produced by piping. However, a later report on this same area by Hardy (14), identifies collapse structure (subsidence) as the phenomenon responsible for the distinctive topography of this area. Without having seen the area it seems likely to us that both processes are responsible for the caved in and piped area at Kamloops. In reality, subsidence greatly increases the intensity of piping in any earth material subject to piping by: (a) concentrating runoff, (b) developing stress cracks, and (c) developing partial lateral pipes by uneven subsidence and differential consolidation between different strata.

Observations of piping phenomena and our interpretation of the processes involved allow piping to be categorized into three types: desiccation-stress cracks, variable permeability-subsidence, and entrainment. The former is the dominant type in the western drylands, although the variable permeability-subsidence type has also been observed widely; the latter type occurs only in the case of water storage or dewatered structures.

DESTRUCTIVE EFFECTS OF PIPING ON HIGHWAY STRUCTURES

The authors have not had the opportunity of making a careful and exhaustive determination of the locations of all the sites where highways, bridges, culverts, and other highway structures are imperiled by piping. However, in the course of field work related to the development of a better understanding of drylands erosion, a number of such piping sites have been observed. The locations of many of the observed sities are shown in Figure 5, and some are pictured in the photographs which follow. However, the list is far from complete. Many more sites imperiled by piping could doubtlessly be found by a systematic search along the highways crossing the geologic formations known to be susceptible to piping, or by careful study of large-scale areal photographs of these susceptible areas followed by field checking. Examples that follow are chosen to show how piping affects abutments and wingwalls, piers, drainage ditches, culverts, embankments, and roadways.

So far as we have observed, bridge abutments and wingwalls are the structures most often imperiled by piping. Deck drainage is generally permitted to drain through short vertical metal pipes and spill directly onto the abutment slope or to run down the abutment wall through joints between the bridge deck and road surface. These

THIS PLOT IS BY NO MEANS COMPLETE.

CAREFUL EXAMINATION OF BRIDGES IN KNOWN PIPING AREAS WOULD DOUBTLESSLY REVEAL MANY MORE SITES. PIPED CULVERTS ARE NOT SHOWN

Figure 5. Location of bridges, roads, and railroad embankments or rights-of-way known to be imperiled by piping.

Figure 6. Pipe intakes beginning to undermine abutment. Most water that gains access to abutment slope runs down abutment wall through crack between bridge deck and road surface. As pipes become enlarged, roofs collapse leaving gaping holes beneath and beside abutment.

Figure 7. Outlet of pipe, one of whose intakes is shown in Figure 6.

practices initiate piping in the abutment slope as shown in Figures 6 and 7 for the Meadow Valley Wash bridge. The initial result, as well as the first indication of piping on an abutment slope, is the cracking and settlement of the road surface where it abuts against the bridge. This settlement is often erroneously assumed to be the result of secondary consolidation. On the contrary, the removal of earth from under and behind the abutment walls by piping is a common cause of the settlement of the roadbed.

Figure 8 shows the location of a pipe which is endangering the wingwall of US 666 Zuni Wash bridge. As this pipe enlarges and its roof collapses, stress-desiccation cracks will appear between the pipe and the bridge. These cracks can then be expected to develop into secondary pipes which will undermine the wingwall and abutment (Arizona Highway 264 Polacca Wash bridge, Fig. 9).

Drainage ditches, even when lined with concrete, commonly fail in areas where piping occurs. A seriously piped, unlined drainage ditch is shown in Figure 4. A similar fate of a concrete lined ditch is shown in Figure 10. This is only one of several such cases where piping has destroyed the usefulness of lined drainage ditch structures.

Culvert installations are destroyed with a frequency similar to that of drainage ditches. The complete loss of a section of road adjacent to a culvert near Newkirk, N. Mex., is shown in Figure 11. Note stress cracks over pipe in foreground and small side gully in left foreground formed by collapse of a branch pipe. In Figure 12, the destructive effects of piping plus the effect of overtopping of the road by runoff is illustrated. Any concentration of runoff for passage through a culvert greatly accelerates piping between the culvert outlet and the nearest gully. By collapse of the

Figure 8. Elongate pipe intake of piping system endangering abutment.

Figure 9. Abutment and wingwall showing outlet of pipe undermining wingwall. Larger and deeper pipes are found elsewhere under abutments of bridge.

overburden, a gully may advance towards a culvert from zero to 15 or 20 ft per rainstorm. The considerable depth of some of the gullies which have grown between culvert outlets and the gully system present at the time of road building is shown in Figure 13. Here, stress-desiccation cracks extend almost to the roadbed itself and small pipes extend under the highway to discharge into an 18-ft gully. Already, cracks are present in the roadbed over this culvert as a result of subsidence and of settlement due to loss of support where the subgrade has been piped. Figure 14 shows the situation which precedes the development of a deep gully as shown in Figure 13. Note the pipe inlet directly under the culvert end in Figure 14, several feet from edge of nearest gully. Several pipe inlets appear between the culvert outlet and the short side gully on the roadward side of the arroyo. These sinkholes are interconnected by an extensive pipe system draining to the deep gully north of the highway. The major pipe outlets occur at the contact of the gully wall and the gully floor.

Surface roadbeds are most commonly damaged by increased piping caused by spilling the runoff collected by drainage structures, especially culverts and bridges, onto the land surface adjacent to these structures. Even greater difficulty is encountered in maintaining graded roads on materials subject to piping. This is illustrated in Figure 15 which shows a section of abandoned Navajo Highway 14. This stretch of road, which is one of the most intensively piped areas that we have seen, was constructed on fill derived from the triassic Chinle formation. Some strata of the Chinle formation pipe more intensively than any other bedrock we have observed. The intensity of piping of this roadbed is believed to be due to subsidence, which, as previously pointed out, greatly enhances piping intensity. Another example of an unsurfaced road in current

Figure 10. Concrete-lined highway drainage ditch, which failed due to piping. Concrete liner is now totally useless for intended purpose.

Figure 11. Culvert and drainage ditch are undermined by piping. Note collapse of ditch bed into underlying pipe. This is the beginning phase of a deep gully. Piped material is alluvium derived from triassic Chinle shale.

Figure 12. Runoff from intensive storm exceeded culvert capacity so that water overtopped road and piping developed around culvert. Culvert would have failed due to piping even if no overtopping of road had occurred as nearby road drainage ditches piped extensively.

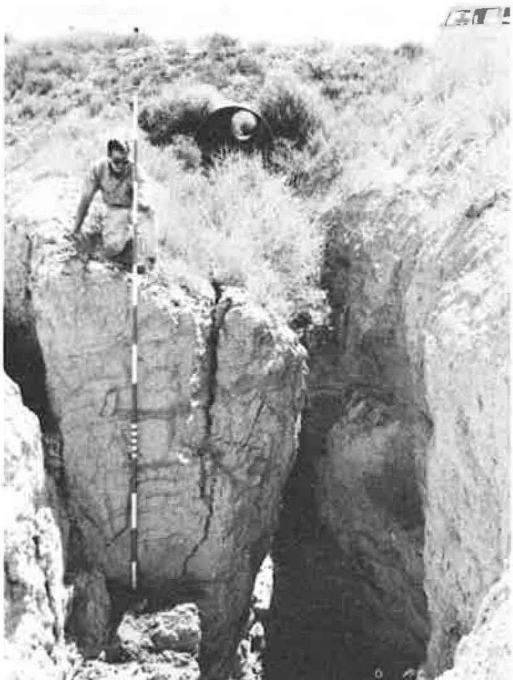

Figure 13. Culvert-concentrated drainage spill has created gully by piping and subsidence, which seriously threatens stability of roadway. (See Figs. 18 and 19, which graphically depict the conditions at this site.)

use, but that requires continuous maintenance because of piping, is shown in Figure 16.

An entire 6-mile stretch of US 140 is currently imperiled by piping. This section of road was built on Aztec Wash alluvium and is located southwest of Cortez, Colo., in the 4-Corners area (Fig. 5). This section of US 140 was only put into service in 1963, but already it is being undermined by pipes in several places (Figs. 13 and 14). Already, highway maintenance crews are making repairs to the new highway as it settles and cracks, especially on the arroyo side. The view in Figure 17 is fairly typical and shows settling and cracking of the roadbed as a result of piping and subsidence in the subjacent alluvium on the side of the road nearest to the arroyo. This figure also shows a large patch needed to restore the damaged road surface. In other places along this 6-mile stretch, several large asphalt repair patches have been emplaced one atop the other where settlement of the roadbed is even more rapid than at the site pictured.

The results of the desiccation-stress crack piping process as well as the destructive effect of piping on roadways are shown in Figures 18 and 19. The medial gully of Aztec Wash meanders from side to side in the alluvial fill of this bedrock

Figure 14. Sink, or pipe inlet, developed at toe of highway embankment as a result of spilling the collected drainage onto ground at culvert outlet. Note pipe inlets (center foreground) of culvert outlet. Note also edge of big asphalt patch in road pavement emplaced to repair damage caused by pipe subsidence.

Figure 15. A six-ft tall man is standing on ledge in pipe 10 ft from bottom of pipe inlet. Materials are red and green shale of the triassic Chinle formation. Both piping and subsidence are responsible for the erosion shown here.

Figure 16. Old US 66 is in center of photo and mainline track of Southern Pacific Railroad, which itself is undermined by piping in this area, is just beyond highway. Pipe intakes beside road in front of truck are 2 to 3 ft deep.

Figure 17. Cracks reflect settlement of roadway shoulder in response to piping and subsidence in subjacent alluvium on which highway was constructed. In the future, this roadway can be maintained only at greatly increasing costs. An alternative and cheaply maintained right-of-way may be found on stable bedrock upland on either north or south side of Wash.

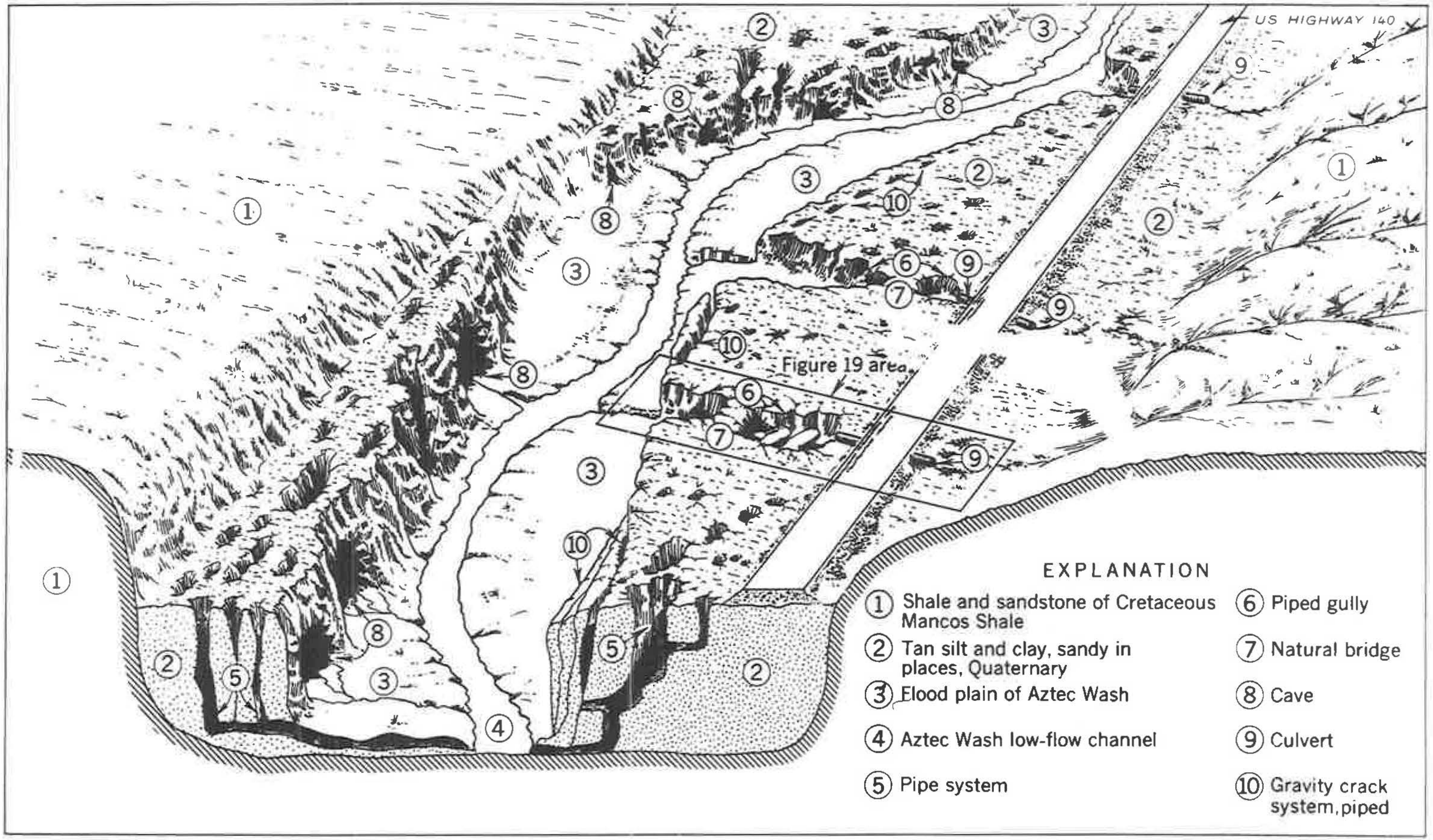

Figure 18. Idealized block diagram of Aztec Wash showing dissected and extensively piped valley fill, old bedrock surface and channel, highway, and drainage system. (See Figs. 1, 13, and 19.)

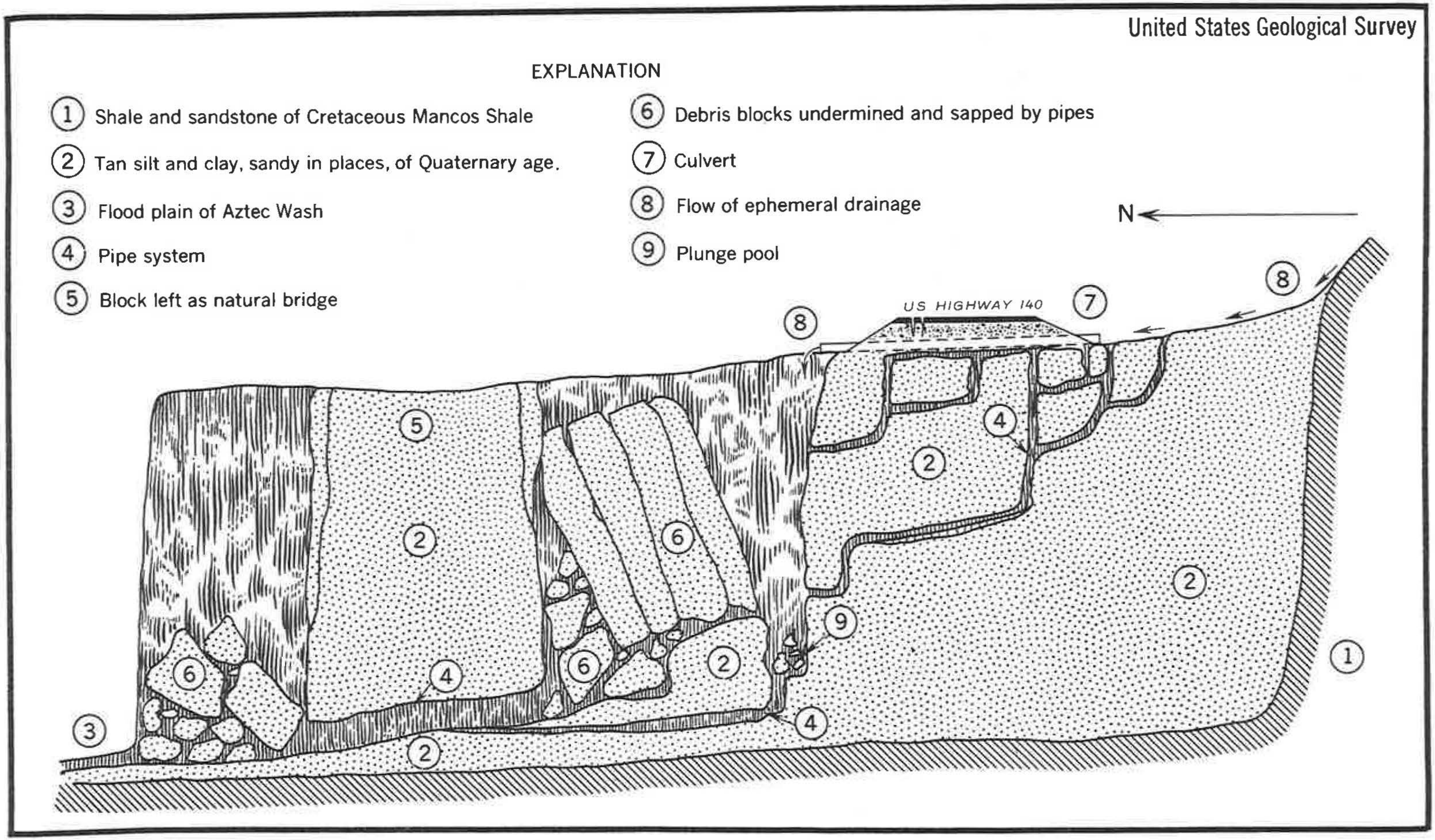

Figure 19. Idealized north-south cross section under US 140 built on Aztec Wash valley fill. Note incipient piping system beneath roadway. See Figure 18 for setting.

valley, and in places it has eroded the valley fill to expose the nonpiped bedrock. The valley erosion probably had its origin in the 1880's like other such major gullies of the Southwest. The current rate of erosion and removal of the valley fill is not accurately known but it is fairly rapid. Furthermore, the building of the highway and the concentration of surface runoff via culverts have accelerated erosion on the south side of the valley fill. Figure 19 shows a portion of the idealized block diagram of Aztec Wash in detail. In particular, the manner in which large blocks of alluvium are undercut is illustrated.

PREVENTATIVE AND REMEDIAL MEASURES

Although piping is most frequently observed in alluvium, it is by no means confined to this material. Piping also occurs on the crowns and slopes of miniature badlands formed from shales or, rarely, from other argillaceous rocks (Figs. 1 and 2). Thus, even the fact that a road is constructed on and from bedrock is no guarantee that it will not be subject to piping.

In order to minimize maintenance and relocation costs, as well as possible loss of life as a result of roadway failures attributable to piping, surveys of piping incidence should be made prior to road construction. The most desirable procedure is to select a route that will avoid construction on and with earth materials subject to piping. This could have been readily done in the case of the 6-mile stretch of US 140 which is being damaged and may be destroyed by piping. Figures 1 and 14 show that the tableland on both the north and south sides of the valley is relatively level. Since piping does not appear to attack this particular bedrock, initial choice of the tableland would have avoided both expensive maintenance and eventual relocation costs. Where suitable nonpiping bedrock is available, as in this case, relocation may be less expensive in the long run than maintenance of the present roadway. Where it is not practical to avoid building a road on materials susceptible to piping, several measures can be taken to minimize or prevent piping damage.

A difficult problem is that of leading culvert or roadway drainage to a nearby gully without increasing piping intensity in the process. One method would be to dig a sloping trench from the downslope side of the road to the nearest gully floor and to lay a closed conduit therein with a minimum slope to minimize the possibility of piping

Figure 20. Metal pipe is carrying bridge-deck discharge directly into channel where it can do no harm instead of allowing it to drop onto abutment slope. Note companion discharge pipe on opposite side of bridge.

Figure 21. Successful engineering design for combating piping under bridge abutments in area of severe and destructive piping.

beside or above it. A riser would surface on the downslope side of the road to receive the runoff from the culvert under the road. The trench would be wet compacted during back filling, to preclude piping induced by subsidence, and the area around the culvert intake on the upslope side of the road would be asphalted as would a relatively small area around the riser. Although it would be much less expensive to extend the culvert overland to allow it to discharge directly into the gully, this method might result in a structural failure due to piping under the extended conduit.

Asphalt curbs could be emplaced along both sides of the road to prevent roadway runoff from causing piping of highway fills and subjacent terrain. The collected runoff could be led along the side of the roadway via an asphalt-lined shallow drainage way which would discharge into the buried drain of the nearest culvert.

It is believed that grading of nearby arroyo walls to roughly a 1:1 slope would decrease the intensity of piping along the arroyo. However, the reduction in piping may not be sufficient to justify the expense. Grading of the arroyo banks would decrease adjacent piping intensity for two reasons: (a) development of stress-desiccation cracks parallel to the gully wall, such as are shown in Figure 17, would be greatly reduced; and (b) increased velocity of runoff would tend to cause the water to override small cracks as well as to plug them by surface erosion.

Bridge deck and adjacent roadway drainage should be collected and dropped into the channel by means of drains similar to the gutter downspouts on houses. Such a successful device is shown in Figure 20. A different, but more expensive, approach which appears to have been successful is to box the abutment slope with planking (Fig. 21).

Two unsuccessful attempts to arrest and control piping at the Arizona Highway 264 Jeddito Wash bridge on the Navajo Reservation are shown in Figures 22 and 23. As shown in Figure 22, steel fence posts and barbed wire strands were emplaced on a line parallel to and about 2 ft away from the abutment wall. This enclosure was then filled with boulders, but the piping continues unabated and the boulders are now funneling vertically into the ever-enlarging pipe system. To stop this piping, the supply of water from the overlying bridge deck and roadway pavement must be intercepted and led to the arroyo channel in downspout conduits. Grout or slurry pumped into the boulder-filled pipes would help stabilize the abutment slope. Instead of leading bridge-deck drainage to the arroyo channel through conduits at the Jeddito Wash bridge as was done at the Meadow Valley Wash bridge (Fig. 20), shallow concrete troughs were constructed to intercept the drainage at the land-slope surface and conduct it to the

Figure 22. Abutment showing unsuccessful attempt to control piping. Pipes continue to enlarge and boulders fall into pipe inlets.

Figure 23. Unsuccessful use of concrete trough to intercept surface runoff and bridge-deck drainage, and conduct it to arroyo channel. Hole about one foot in diameter has broken through the trough to the underlying pipe. Outlet of pipe system is hidden behind bridge pier in right foreground but is undermining pier.

channel (Fig. 23). Piping continues, however, and a hole has been broken through the trough, probably by livestock crossing the slope. Asphalting the total area enclosed within a 50- to 100-ft area of culvert inlets could be expected to reduce greatly the damage currently being done to culvert installations. Extension of culvert outlets to a nearby gully channel would also greatly decrease the damage being done.

SUMMARY

Piping is most commonly observed in alluvium in arid and semiarid regions. However, it also occurs in loess and in certain argillaceous bedrock, especially shales and altered volcanic ash and tuff. It frequently results in a pseudokarst topography.

Subsidence, or collapse structure as it is sometimes called, has been found both to initiate and to accompany piping. Three types of piping have been delineated depending on the mode of origin of the pipes: (a) desiccation and stress-desiccation cracks, or sometimes localized subsidence cracks or holes, with visible inlets and outlets; (b) entrainment without visible inlets but often with visible "boils" as outlets; and (c) variable permeability-subsidence, developed along a temporary perched water table, a stratum of relatively high permeability, or subsidence-caused voids with visible outlets but initially without visible inlets.

Our preliminary findings with regard to characterization of strata which are subject to piping, generally corroborate those of Quirk and Schofield (25) and Aitchison, Ingles, and Wood (26). Essentially, silty and clayey earth materials are susceptible to piping if they:

1. Contain in excess of about 20 percent montmorillonite;
2. Desiccate thoroughly, or are susceptible to localized subsidence, or have a stratum of high permeability relative to lower strata, or have a temporary perched water table; and
3. Contain a high percentage of exchangeable sodium. However, due to subsidence, loess and possibly other low-density previously unwetted earth materials may pipe even in the absence of montmorillonite and large amounts of exchangeable sodium.

Regardless of location or materials, at least four basic conditions are essential for piping to develop: (a) sufficient water either to cause drainage through cracks or to saturate a layer of higher permeability than the layers below it, (b) hydraulic head sufficient to move water through a subsurface route, (c) presence of a permeable (or deeply cracked) soil or bedrock above gully floor level, and (d) outlet for flow.

The mechanisms of piping are now largely understood, although details of the physicochemical-mineralogical aspects are still obscure. The geologic formations and geographical areas in the United States which are particularly susceptible to piping can be recognized. Based on the information presented in this report, a careful scrutiny of proposed highway routes for evidence of piping, by competent individuals, could readily avoid the increased cost resulting from the unwise selection of highway routes in areas subject to piping. However, where piping materials must be utilized for road construction, several precautions can be taken to minimize damage to highways by piping. Catchment drains under bridge deck-roadway junctions are essential and use of asphalt-mat covers may also be necessary at some sites. Culvert discharge should be carried in closed conduits to empty into a gully distant from the roadbed. Asphalting the area around culvert inlets would reduce the current damage being done to roads in areas where piping is a problem. The main rules to follow are: (a) to avoid terrain and road-building materials susceptible to piping whenever possible; and (b) to prevent the concentration of runoff, thus, preventing piping near roadways, bridges, or drainage structures.

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