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Moving Substrate in an Ephemeral Stream

Case Study in Bridge Survival

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A case study concerns a small bridge site in an arid area where ongoing inhibition of the transport of bed load sediment has caused chronic problems and maintenance issues for many years. The crossing of Guadalupe Arroyo by US-62–180 exhibits many unusual and important characteristics that are seldom seen in one place. Guadalupe Arroyo is an ephemeral stream in a very arid area. The stream originates high on the east slopes of the Guadalupe Mountains of Texas, where the watershed is subject to rainfall generated by orographic lift. The stream traverses several miles of arid land and ultimately disappears into a dry lake. It is subject to severe flash flooding because of the slope and orographic effects of the mountains, and it apparently transports large amounts of widely graded material (silt to boulder sized). A bridge across this stream was constructed for US-62–180 in 1959. Since that construction, the stream has exhibited symptoms of instability in the reach around the bridge, manifesting as chronic, severe aggradation accompanied by widening, avulsion, and bank erosion. Evidence exists of large magnitude transport of very large particles on a regular basis, to the extent of requiring protection of the piles from boulder impacts. Maintenance forces have continually removed accumulated bed material from the bridge opening and the reach immediately upstream. A large lens of bed material has accumulated upstream and extends approximately 1,000 ft (305 m) from the bridge. This site presents a rare opportunity to study an extreme case of the inadvertent inhibition of the transport of bed material in an ephemeral desert stream by the construction of an otherwise ordinary and innocuous highway bridge.

Guadalupe Arroyo is an unusual Texas stream, with several interesting qualities. Streams that flow into dry lakes are not uncommon in states like Arizona and Nevada, but there are few in Texas. This ephemeral stream arises from the southeastern flank of the Guadalupe Mountains and the adjacent Delaware Mountains to the east, traverses a region of Chihuahuan desert at the foot of a mountain known as El Capitan from east to west, and disappears into a dry lake. It is characterized by relatively steep slopes, sparse desert scrub vegetation, and the flash flood response typical of streams in arid regions.

This area of west Texas is arid and sparsely populated. There are few rainfall measurement stations and even fewer streamflow gauging stations. Although the mean annual precipitation in the area is low, the nearby Guadalupe Mountains exert a strong orographic effect, locally increasing rainfall on the mountain flanks contributing to this stream. Flash floods at the site are anecdotally considered more common and severe than in the surrounding desert. These floods often occur from rainfall confined to the mountains, resulting in flows at the bridge in the absence of rainfall at the site itself.

HYDROLOGY

A reliable method of hydrologic estimation for this watershed does not exist because of the unusual and relatively unique nature of the stream. Statistical methods, such as regression equations, rely on consistency between the watershed being analyzed and gauged watersheds used to develop the equations. Such consistency does not exist in this case. Watershed modeling requires a similar consistency between rainfall measured at weather stations and the rainfall that generates runoff on a watershed. Again, that condition cannot be met for this watershed because of the orographic influence on the dominant flood-producing rainfall.

The contributing watershed area to the site is about 40 mi^2 (104 km^2) (Figure 1). The crossing is approximately at elevation 3,850 ft (1,174 m). The uppermost point of the watershed is Guadalupe Peak, the highest point in Texas, at approximately 8,550 ft (2,606 m). The total drop is on the order of 4,700 ft (1,433 m) in about 12.5 mi (20 km) of stream, with 3,500 ft (1,067 m) of that elevation change occurring in the upper third of the drainage. The physical characteristics of this watershed are therefore unusual. Such a stream can be considered a conveyor belt of the mass-wasting process; the stream exists mainly to move the products of mass wasting downhill.

SITE CHARACTER

In 1959 the existing bridge crossing Guadalupe Arroyo on US-62–180 was constructed. During the 50 years since that construction, the maintenance effort necessary to keep the bridge serviceable has been increasing. Recently, erosion of the south bank of the stream to the east of the bridge has presented a threat to the south abutment. For many years (as long as current maintenance employees recall), there has been a chronic need for maintenance forces to remove bed material from the bridge opening and the reach immediately above it. The lateral migration of the south bank and other visible indicators suggest that bedload sediment is inhibited from passing this site on the stream and has clogged and aggraded the streambed. These observations further suggest that instability in the reach adjacent to the crossing is related to the crossing in some way, possibly from the influence of the crossing on the transport potential of bedload sediment.

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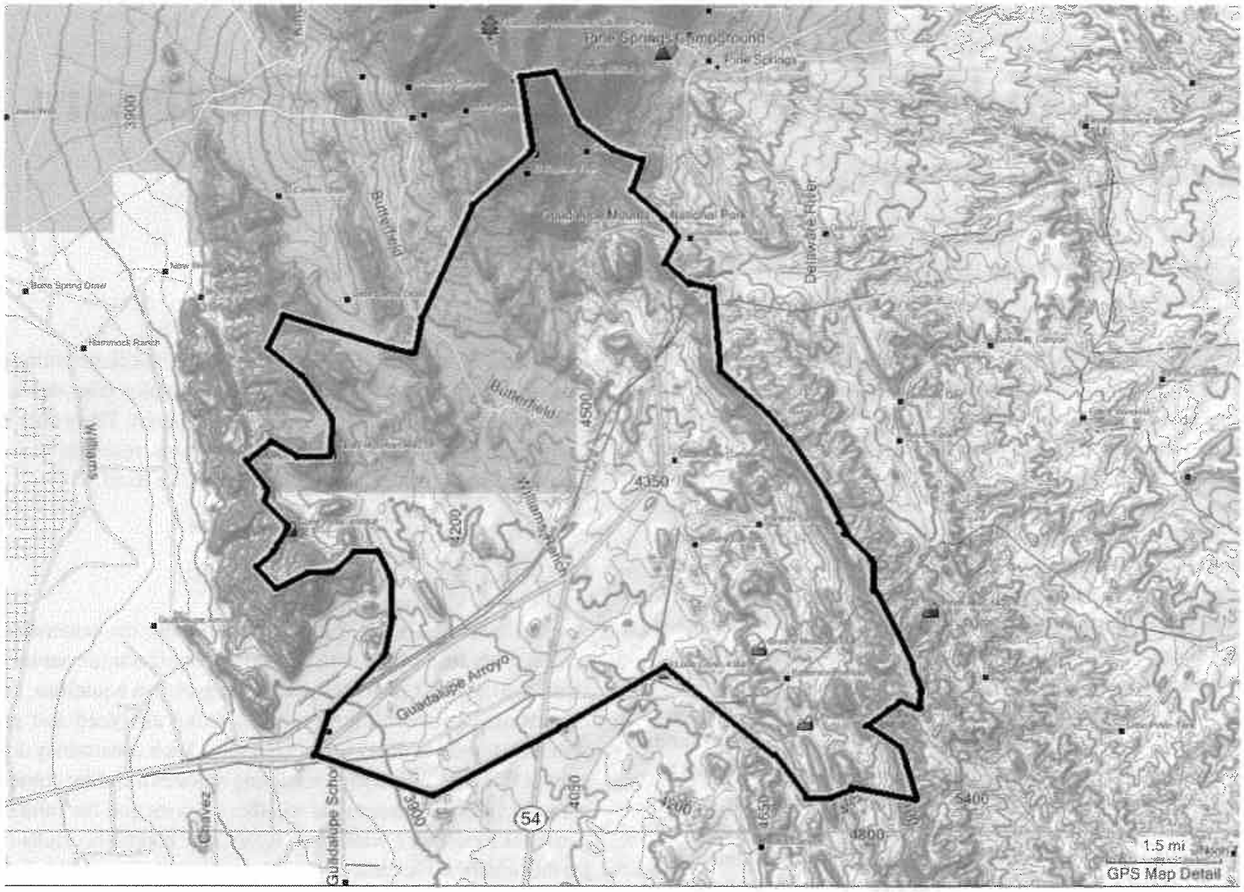

FIGURE 1 Drainage area map. (Source: Garmin Ltd.)

A trace of darker material appears on the surface of the widened bed in a meandering pattern that coincides with areas of apparent bank erosion in overhead imagery. That meander pattern appears to be of shorter wavelength and smaller radius of curvature than the rest of the stream, at least until the stream gradient drops as it enters the terminal lake downstream. Unusual widening of the visible streambed is often an indicator of localized aggradation, and a shortening of the meander wavelength can be an indicator of lessening of relative stream gradient.

The particular problem at the site has developed as bank erosion along the outside of a gentle meander, adjacent to and threatening the adjacent south abutment of the bridge. An important observation about this site is found in the overhead imagery (by Google Earth). Tracking Guadalupe Creek along all tributaries from origin to destination, the stream reach immediately adjacent to the crossing of US-62–180 stands out as anomalous. The stream exhibits an obvious widening at the crossing, which continues downstream approximately 300 ft (91 m) before disappearing and extends upstream approximately 1,600 ft (488 m). This widening is seen in Figure 2.

The image shows that an already conspicuously wide reach of the stream is further widening to the south. No similar reach is in evidence from imagery along this stream. This widening appears to be associated with the highway crossing. Numerous other sites have been identified in recent years where highway stream crossings have exhibited an adverse impact on stream stability in central and west Texas (*1–4*), so such an association is not unusual.

At this site, the highway crosses the stream at a fairly acute angle (greater than 45 degrees) and in a bend of the stream. The exact angle of skew is ambiguous because of the curvature of the stream and because the streambed is tapering at this point. The bridge bents are skewed with respect to the roadway to more nearly align with the stream. The supporting foundations are driven steel H-piling.

FIGURE 2 Current overhead image (note overwidened section upstream of bridge and appearance of shorter meander wavelength).

HYDRAULIC FACTORS

The original design of the bridge clearly attempted to align the bents with flow streamlines, but the location of the bridge in a bend of the stream is a complicating factor. Approaching and departing streamlines are at angles to the bents and to each other. A further complication is that flow under the existing conditions appears to converge through the bridge opening.

Hydraulic geometry at the crossing has been altered from the natural conditions by construction activities such that arriving bedload material does not readily proceed through to the adjacent reach. The approach reach has become a sediment sink; as more sediment arrives, it adds to sediment already there. The accumulation has caused streambed aggradation, forcing widening and avulsion.

A review of the bridge layouts indicates that the stream cross section through the bridge opening may have been shaped or improved to provide enhanced hydraulic capacity. This well-intentioned effort to provide hydraulic capacity is common and often adversely affects the hydraulic geometry, a critical variable in bedload sediment transport (*5*), and disrupts stream power at the point in the stream profile occupied by the bridge.

This particular stream is apparently extremely sensitive to such changes, since it appears to have been destabilized at that time, with chronic problems resulting. The nature of the existing bents and the angles of approach and departure of water and sediment are compounding factors to an unknown degree. Altogether, the result is severe stream instability.

Streams are invariably the avenues of movement of at least two media: water and sediment. Sediment is composed of two components—suspended load and bed load. In ephemeral streams such as this one, the fraction of total sediment load that moves as bed load is necessarily higher than it is in perennial streams, simply because bed load movement is a result of flood flow, and all flow in an ephemeral stream is flood flow. What specific condition triggered the onset of aggradation and the subsequent destabilization of the stream is now difficult to determine.

The ability of a stream to move bed material is apparently related to both velocity and depth. When a stream aggrades and widens, stream power available to move bed material is reduced. However, at locations downstream where more favorable geometry exists, the stream may be thought of as deficient in bed load sediment. Under those conditions, the stream will still mobilize the available material from the bed and banks, resulting in scour or degradation of the streambed in that reach. Such scour may also manifest itself as lateral movement and erosion of the streambanks.

At the site in question, the streambed in the immediate vicinity of the crossing [600 ft (183 m) upstream and 300 ft (91 m) downstream] has been further influenced by ongoing mechanical efforts to prevent further damage to the bridge. Unknown quantities of bed material have been moved from the stream under and near the bridge to the banks. There are physical indications that material has been approximately 4 ft (1.2 m) deeper at the bridge itself in the recent past (see Figure 3) than when the site was visited. Material has been mechanically removed in order to enlarge the bridge opening.

The construction plans for the bridge indicate a general height of the bridge low chord above the streambed at the time of construction of 12 ft (3.6 m). The roadway profile at the bridge is both on a grade and in a superelevated curve, making reference to such a height ambiguous. Thus it is difficult to state with certainty how much the streambed has aggraded. A rough estimate based on observation is that net aggradation at the bridge has been, in the recent past, bed material between 5 and 8 ft (1.5 and 2.4 m) deep, which has been mechanically removed. As the removal of such material has apparently been ongoing for many years, the amount of material that has already passed through the reach cannot be estimated. However, on the basis of this degree of aggradation at the bridge and the distance upstream that the impact is visible, the amount of material remaining in a lens upstream of the bridge is estimated at between 10,000 and 20,000 yd^3 (7,650 and 15,300 m^3). A minimum of approximately 300 yd^3 (230 m^3) of bed material per year appears to be the average arriving at the site and being detained since the bridge was constructed in 1959.

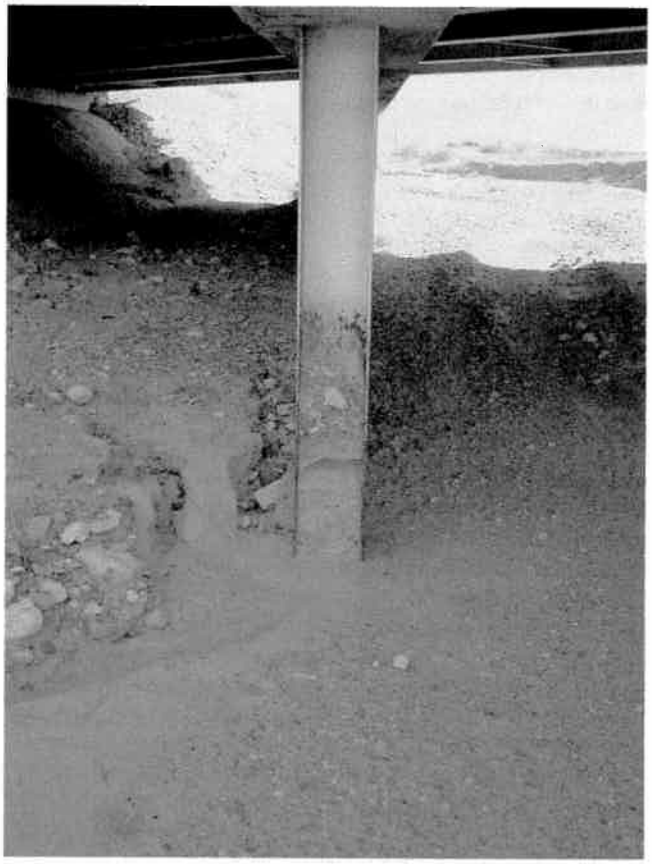

FIGURE 3 Bridge pile (note evidence that bed material has been at least 4 ft higher than it is under conditions at time of the photograph).

The steel H-pilings supporting the bridge bear indications of having been buried numerous times and of damage indicating impacts from boulders. Some time after the original construction, concrete walls were constructed connecting the piling of each bent and semicircular nose elements on the upstream side of the upstream pilings, evidently to prevent damage from boulder impacts or machine impacts during removal operations.

A hydraulic study conducted of this site by others with step-backwater techniques, extending approximately 300 (91 m) ft upstream and downstream of the structure, indicated very high calculated velocities [20 ft/s (6.1 m/s)]. An ad hoc study by the U.S. Geological Survey indicated that out of 58,724 measured velocity values in Texas, roughly 20 exceed 10 ft/s (3 m/s) and none approach 20 ft/s (6.1 m/s). Although this is an unusual case, it was concluded that the simplifying assumptions necessary for such hydraulic analyses are incompatible with actual flow conditions. In particular, the assumptions of rigid channel boundaries and single-phase flow are likely not representative of sites such as this. High-magnitude bed load movement may be a transitional phenomenon between ordinary fluid flow and debris-type flow.

BED MATERIAL

Site reconnaissance demonstrated that the bed material is composed of particles ranging from silt size up to several feet in size (Figures 4 and 5). This gradation is also an indication of the magnitude of the forces driving their movement; such particles are not moved easily. Conditions permitting their movement would necessarily result in the movement of huge quantities of cobbles and gravel as well. By volume, the preponderance of material is fine sand. Larger particles, including a wide range of gravel, cobble, and boulder sizes, appear embedded in a matrix of fine sand. One plausible model is that the apparent extreme throughput of material might be related to some optimal proportion of large particles embedded in a matrix of more easily mobilized sand.

In locations where the undisturbed streambanks that are subject to erosion were visible, the material in them appears to be alluvium consistent with the bed material—sand, gravel, and cobbles. Erosion of the banks results in material indistinguishable from that already in the streambed (Figure 6); thus at least some of the material present at the site is material recently liberated from these banks. However, considerable quantities of material have had to be removed mechanically; this necessity argues in favor of a net positive change in storage of the bed material in this reach over time as opposed to simply liberating it from adjacent alluvial deposits.

Imagery indicates that the overwidened reach dissipates in less than 400 ft (122 m) downstream of the bridge. A reconnaissance of that distance and further downstream revealed that features consistent with bankfull geometry emerge from the bed material and are consistently maintained proceeding downstream. With these features, a bankfull width of 50 ft (15 m) and a depth of 4 ft (1.2 m) is estimated to be the natural stream channel configuration near the crossing.

Upstream approximately 1,200 ft from the bridge, similar features of similar dimension to those from the downstream bed emerged. Using a parabolic approximation for area of flow and assuming a Froude number of 0.5 (*2*), these dimensions result in a bankfull discharge of approximately 600 ft^3/s(17 m^3/s). In the reach adjacent to the bridge, no such features are in evidence. Morphologic structures that existed before the bridge construction may be buried under bed material or may have been obliterated by construction and maintenance efforts. Rather than being streambanks, the features now defining the channel have probably been floodplain terraces until recently. Similar terraces exist in the reaches where the smaller bankfull features are visible. The bank on which erosion is currently a problem appears to actually be a floodplain terrace rather than a streambank associated with bankfull channel geometry dictated by current climatic and runoff conditions.

The stream reach adjacent to the bridge approximately 300 ft (91 m) downstream and 600 ft (183 m) upstream has been severely altered by maintenance activities such that identification of bankfull features is impossible.

Locating actual bankfull features and geometry is important for several reasons. In diagnosing stream instability, it is essential to estimate what the bankfull geometry should be. In addressing unstable sites, it is desirable to reestablish and maintain bankfull geometry

FIGURE 5 Large bed material (Philadelphia level rod for scale).

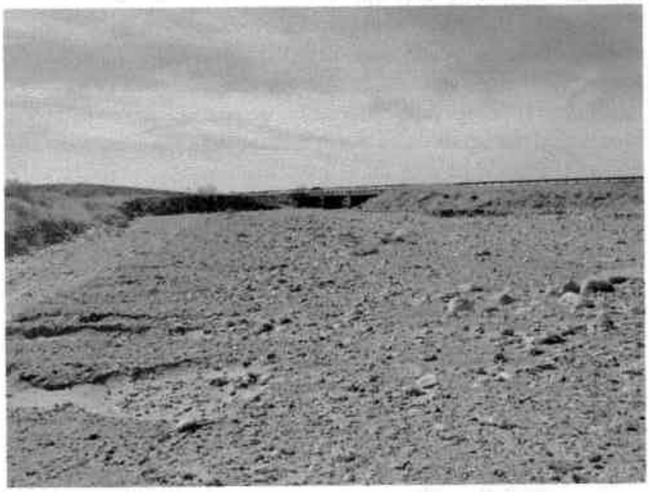

FIGURE 4 Streambed material (view of streambed looking downstream toward bridge).

FIGURE 6 Undisturbed streambank showing character of bank material.

approximating what should occur at a location in order to stabilize the stream. It is logical that the bankfull configuration through the bridge reach was similar to the configuration above and below the bridge where features are still identifiable today.

STREAM MORPHOLOGY AND SURROUNDING TERRAIN

Several miles above the site in question, Guadalupe Arroyo is crossed by Texas State Highway (SH) 54, which ends where it intersects with US-62–180 several miles east of the bridge in question. At this crossing, bed material is predominantly sand-sized. The boulder-sized particles seen at the US-62–180 site are not in evidence in quantities similar to those of the problematic site, although occasional large cobbles do appear (Figure 7).

The watershed contributing to the SH-54 site primarily drains from the Delaware Mountains, an adjacent range much lower, less impressive, and geologically different from the Guadalupes. Several tributaries cross US-62–180 between the intersection of SH-54 and flow into Guadalupe Arroyo upstream of the site of interest. These crossings allow the examination of associated streams in similar conditions but with other crossing types. It is evident from the examination of one of these crossings that the cobble- and boulder-sized particles seen at the site of interest are the result of concentration of those particles in the area of a crossing by preferential transport. The smaller particles move through the crossing more easily, whereas the large particles are delayed, resulting in an anomalously large amount of them at the site of a crossing. This feature was observed at the SH-54 site also.

The crossings at SH-54 and of US-62–180 at a tributary to Guadalupe Arroyo present comparisons to the crossing in question. The former is an open-span bridge, similar to the structure of interest but smaller. In that location, the bankfull width is approximately 40 ft (12 m). The latter crossing is a six-barrel 10-ft by 10-ft (3-m by 3-m) box culvert, and the bankfull width is approximately 35 ft (10.7 m) (Figure 8).

Meander amplitude is usually confined to a meander belt between floodplain terraces or the valley banks that define the floodplain, and meander wavelength is related to the overall topographic slope of the valley. Steep valley slopes are characterized by small meander amplitude relative to the meander wavelength. When aggradation occurs, a localized decrease in stream slope accompanies it. The meander wavelength tends to diminish, and meander amplitude tends to increase, in response to that change in slope.

FIGURE 7 Guadalupe Arroyo at upstream crossing of SH-54, looking downstream (larger material in bridge vicinity; bankfull configuration is evident in stream adjacent to this bridge).

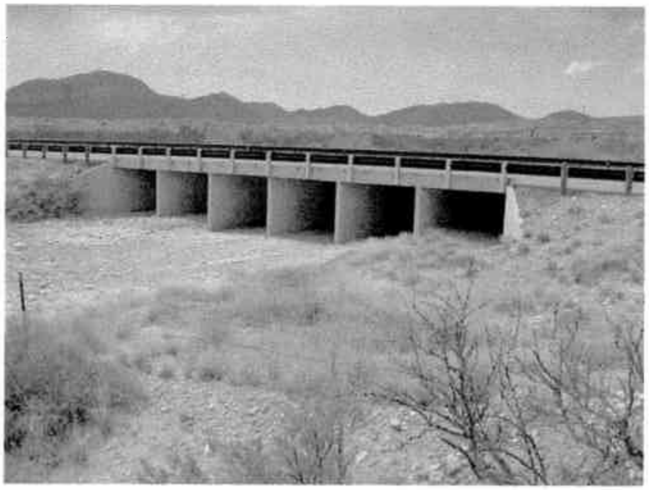

FIGURE 8 US-62–180 at a tributary to Guadalupe Arroyo.

According to the Rosgen classification system (*6*), this stream is classified as G3. This classification is noted as being "highly unstable due to the very high sediment supply available from both upslope and channel derived sources." It is further described as "very sensitive to disturbance and tend[s] to make significant adverse channel adjustments to changes in flow regime and sediment supply from the watershed." These descriptions encapsulate the problem as it is presented here quite thoroughly. A relatively slight disturbance (the construction of a bridge and change in hydraulic geometry) 50 years ago has echoed with instability and channel adjustments ever since. Of this stream type, Rosgen also states: "The ratio of bedload to total sediment load often exceeds 50%." Such large bedload movement is consistent with observation and history at this site.

A series of overhead images extending back in time approximately 13 years shows that the stream immediately above the bridge has been exhibiting essentially identical instability at least that long. Imagery from 1996 (Figure 9) indicates that the meander character of the stream immediately upstream of the bridge is in a state of change. Where there had previously been a long, gentle meander, meander reversal has occurred, resulting in the development of a short-wavelength meander anomalous for the stream. The avulsion attendant with this meander change has been seen and interpreted only in the context of bank erosion that threatens the southwest bridge abutment.

This image and others from the years between 1996 and the present show the signs of repeated and chronic attempts to rebuild and stabilize the streambanks, as well as to remove material from the bridge opening itself. Figure 10 is an image from 2005, which shows bed material piled adjacent to the stream from efforts to deal with the accumulating bed material.

DISCUSSION AND CONCLUSIONS

The site described here has been a chronic maintenance problem for many years, possibly decades. In 1996, the problem was already well developed. Thus far, efforts to keep the bridge in service have done

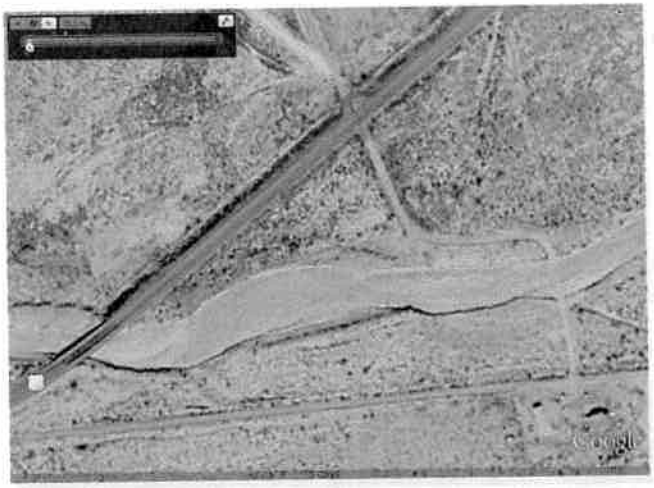

FIGURE 9 Image from 1996 (shortening of meander wavelength is evident at this time).

so but have clearly not solved the problem. Indications are that the problem is getting worse with time; the severity of bank erosion along the southwest abutment of the bridge increases with each flood event. Repeated efforts to rebuild and reinforce the banks have failed. This long and chronic history of problems should be an indicator that the situation has not been understood. The visible problem is one of bank erosion; however, the underlying problem is one of stream stability.

Stability and instability with regard to stream geomorphology are terms that are much more commonly thought of in the context of perennial streams, fisheries biology, and riparian habitat. Many would view the application of these terms to an ephemeral stream in a desert area such as this with some doubt. However, this case demonstrates that the terms are applicable and that ephemeral desert streams may be even more sensitive to disturbance than those streams where the science of fluvial geomorphology evolved. General fluvial geomorphic concepts such as the progression of riffles, runs, pools, and glides and the relationship of these profile features to plan features such as meanders and a bankfull channel are much more difficult to identify with certainty when a stream is not subject to base flow.

Stream restoration is an activity that is of increasing importance in the general civil engineering field. In its traditional form, dealing with the preservation or restoration of habitat and the mitigation of environmental damage, it has often been used to address the long-term aftermath of prior civil engineering works. As the general civil engineering profession has begun to examine the long-term implications of their work, stream stability and stream restoration have begun entering the vocabulary of the profession. However, it is still difficult to accept that these concepts might extend to desert streams like Guadalupe Arroyo.

Nevertheless, it appears that an approach to this problem should be sought through stream restoration. Clearly, the simple armoring of the banks has not solved the problem, and there is no reason to believe that it will in the future. A more thorough solution would involve the manipulation of the stream geometry in a manner that would allow bed material arriving at the site to pass and would encourage bed material accumulated at the site to remobilize and continue downstream.

Both hydrology and hydraulic analysis at this site (and others like it) are particularly difficult because of a lack of appropriate data under similar conditions. At this time, a computational approach to stream restoration is severely hampered by those difficulties. However, the "reference reach" approach to stream restoration would be a viable option for addressing this site. The reference reach approach involves locating a similar reach of stream in close proximity and transferring certain physical characteristics from that stream to the stream of interest. In this case, reaches immediately above and below the affected reach were examined for features including bankfull channel and potential riffles. At intervals along the stream in the reaches upstream and downstream of the bridge are features thought to be riffles during flow events. The nature of the material, as well as visibly higher slopes over short distances, is thought to be indicative of riffles. Figure 11 shows one of these locations.

Riffles are important features in the profile of any stream and are used as important points of reference for the assessment of a stream. Locating them is a vital part of finding a reference reach.

The important conclusion that can be drawn from an examination of this site is that stream type, stability, and sediment transport

FIGURE 10 Image from 2005 (note bed material piled along stream upstream of bridge location, indicated by closed shapes).

FIGURE 11 Riffle location (looking downstream from a location thought to be head of a riffle).

considerations should be emphasized to engineers designing and constructing bridges and roadways. Although it is easy to dismiss such factors in an arid area subject to 10 in. of rainfall per year on average, to do so obviously risks severe long-term problems and maintenance costs.

The authors contend that the ultimate cause of the problem plaguing the crossing of Guadalupe Arroyo by US-62–180 is the reshaping of the stream channel that occurred during the construction of the bridge. This reshaping was compounded by the severe skew of the crossing, which extended the affected area along the stream for more distance than would be found in a normal crossing. Such reshaping is a common practice in bridge construction, under the hypothesis that it increases the conveyance through the bridge. Streams, particularly ephemeral ones, are often reshaped to a simple trapezoid, destroying the shape that the stream has assumed in order to transport bed sediment. Although it should increase conveyance of water, this reshaping destroys the natural hydraulic geometry for a distance. Sediment transport through the reach involved is inhibited, and the reach becomes a sink for sediment. All bed sediment is inhibited, but particles that are most difficult to move (the largest ones) reside in the reach for long periods, effectively segregated from the remainder of the load as it moves through the reach. This situation has been perpetuated and compounded by continued reshaping by maintenance activities.

This segregation hypothesis is supported by the presence of large particles in the structure vicinity at the other two sites examined, where a more natural bed form and sediment gradation could be observed. At the SH-54 location, maintenance is necessary but to a much smaller degree than at US-62–180. At the nearby tributary stream, maintenance activities are not in evidence at all. Both of these structures cross at smaller or nonexistent skews, and the structures are closer to in length to the bankfull width of the stream at their locations.

This site should be periodically reexamined or monitored long term. Large particle movement and ongoing maintenance activities endanger traditional monitoring equipment placed at the site, and data collection may require innovative monitoring techniques.

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The Culverts and Hydraulic Structures Committee peer-reviewed this paper.