Review of Headcut and Tailcut Methodologies

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Headcuts and tailcuts are natural occurrences but are often associated with uncontrolled sand and gravel mining in river channels or near channels when the pit is captured by the river. Headcuts and tailcuts have both been observed and documented to occur as a result of the removal of material from a stream bed. Headcut and tailcut problems have become more prominent since large sand and gravel mining operations have taken up residence near bridges and other infrastructure. This report has been prepared to review the current methodologies to estimate the length and depth of headcuts and tailcuts.

Figure 1. Headcut on Santa Cruz River in Pinal County. These headcuts can move Several Hundred Feet in a Single Small Event.

Most headcuts are not caused by sand and gravel mining. The occurrence of headcuts is a natural phenomenon that has been occurring as long as water has been flowing down a slope. This document focuses primarily on pits that are excavated within the river channel rather than in the floodplain away from the channel. Pits in overbank areas have been postulated to have a different sediment transport regime and less potential for headcuts and tailcuts as long as the river does not capture the pit (Zeller 2010). The physics of the process governing the erosion are identical although the flows and sediment loads would be different from the main channel.

There are numerous natural causes of bed lowering (headcutting) but when the downstream reach of a river bed lowers, the bed of the river upstream must adjust to the lower grade. The point where the river begins to change from the old, higher grade to the new, lower grade is often called a **knickpoint**. This point may be as subtle as a riffle or set of rapids in a sand / gravel bed river or can be vertical and as spectacular as Niagara Falls. This headcut associated with the knickpoint naturally moves upstream – rapidly in a sand bed river and very slowly in a river that has a rock bed.

The lowering of stream beds is often accompanied by a vertical face separating a natural looking stream upstream from a stream downstream that may look like a disaster area and is almost wholly dissimilar to the channel upstream. (See Figure 1.) This vertical or near vertical drop is normally called a **headcut**[1]. The terms headcut, **over steepened reach**, and knickpoint are often

[1] The term headcut is associated with both vertical headwalls and grade lowering with no vertical wall. It may be used to describe both conditions at times in this report although normally the term over-steepened-reach (OSR) will be used to describe a channel lowering with no vertical headwall.

used interchangeably[2] and applied to all types of bed lowering causing confusion as to what constitutes a headcut and what differentiates a headcut from an over steepened reach and a knickpoint. In hard rock these headcuts are known as waterfalls but in softer soils they may be something still spectacular but less permanent as shown in Figure 1. In softer material these headcuts move too rapidly to be considered permanent and may move dozens or hundreds of feet during a single flood event. A headcut on the Santa Cruz River near Redrock, Arizona in fine soils (near Figure 1) moved several hundred feet during a flood that was perhaps a five year event. Even in hard substrates a head cut may move dozens of feet in a single event. A headcut on Tiger Wash moved over a hundred feet during an approximate 100-year event through strongly cemented caliche. (See Figure 2.)

Figure 2. Tiger Wash Headcut Moved over a Hundred Feet in one Event through Cemented Material

The area downstream of the headcut is often lowered by several feet (or even tens of feet) with a deep channel and eroding banks. As water traverses the narrow channel below the headcut, the velocity is higher, there is little resistance to erosion and banks tend to undercut and fail as can be seen in Figure 1. Further down the channel, below the headcut, the banks widen and become more stable, the flow slows, and sediment begins to deposit in the lowered bed of the channel. The result is normally a permanent lowering of the stream with terraces along the lowered channel indicating where the stream used to be. These terraces normally erode back over longer periods of time until a new floodplain is established for the lowered stream. At some point downstream the increased sediment load is deposited with sometimes devastating results.

[2] Even though the terms are used interchangeably it should be noted that both processes result in bed lowering and are normally easily recognized by vertical eroding walls on both banks of the river in the areas where the lowering has taken place – i.e. downstream of the headcut or over steepened reach. The term headcut will be used to describe both types of lowering.

The type of headcutting prevalent on the rivers that are mined for sand and gravel in Maricopa County consist of **over steepened reaches (OSR)** rather than vertical headcuts[3]. In Maricopa County the larger rivers consist of either gravel or sand beds with no hard (or clay) layer to generate the vertical face that is normally indicative of a headcut. Since the river beds are gravels and sands, a vertical wall does not form and the bed lowering occurs over a longer reach of the river which may not be obvious to the casual observer. The end result of this process is identical to the process associated with headcutting, i.e. a lowered channel bed; but since there is no vertical wall it can be overlooked (Figure 3 and Figure 4). The lowering of the river can still be significant even though there is no vertical wall associated with the lowering. The over steepened reach may not be readily distinguished in local rivers due to the similarity between a riffle and an over steepened reach.

Figure 3. Knickpoint Lowering on Hassayampa River due to pit Capture during January 2010 Flood Event. Note vertical banks along both sides of River Branch.

Figure 4. Over Steepened Reach (Knickpoint) on the Salt River Downstream from Gilbert Road Bridge.

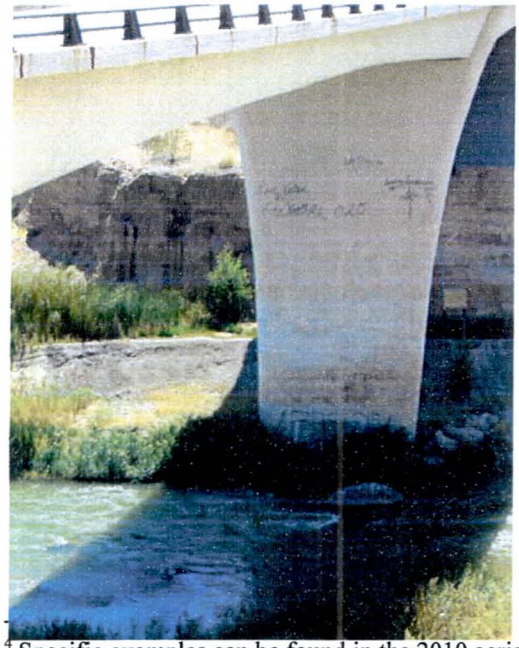
The differences between bed lowering in the presence of a "hard" layer and a bed lowering with no hard layer are readily seen. Figures 1 and 2 represent a traditional head cut with a vertical or near vertical headwall. Figure 3 and Figure 4 show a long riffle or over steepened reach that is indicative of a bed lowering in an alluvial channel with no hard layer. Figure 4 is the Salt River at Gilbert Road where a headcut/knickpoint (approx 13 ft high at Gilbert Road) has propagated from the downstream gravel mining

[3] Numerous vertical headcuts exist in Maricopa County but they normally do not occur with sand and gravel deposits.

operation when the protective berm failed and the pit captured the river flow (2005). Figure 3 shows an over steepened reach associated with an over-steepened-reach (OSR) propagated by the capture of a stream side pit on the Hassayampa River in 2010. These over steepened reaches can be significant with lengths of 1,400 to 3,500 feet[4] being noted on the Salt River (a gravel bed system) with longer lengths observed on the Hassayampa (a sand bed system).

The headcut process can be seen in numerous rivers in Arizona including the Agua Fria River in Prescott Valley. The headcut on the Agua Fria river (See Figure 5) was arrested by a golf cart crossing in the golf course at the Villages at Lynx Creek. These headcuts can cause hundreds of millions of dollars in damages to upstream infrastructure if left unchecked and may cost similar amounts to contain if allowed to propagate for extended periods of time in urban environments.

Figure 5. Headcut on Agua Fria River in Prescott Valley. Figure at left is looking upstream from golf cart path (2005) and Figure at right is looking upstream with golf cart path just out of sight around bend past excavator. Headcut is on the order of 8-10 ft in depth. Bed downstream is hard clay layer that fails in blocks when undercut.



Las Vegas Wash exemplifies the impacts of uncontrolled headcuts. A headcut that originated when a culvert was replaced near Lake Mead has resulted in major impacts upstream. The original estimate to construct drop structure to eliminate the upstream erosion was $270,000 but for whatever reason it was not constructed. The Southern Nevada Water Authority had, by 2005, spent $110 million to construct enough grade control structures along the wash to simply stabilize the wash in its current configuration (up to 40 ft lower than the original bed elevation). The total estimated cost was $140 million (Hester 2005) and does not include bank protection

Figure 6. North Shore Drive Bridge Pier on Las Vegas Wash. Upper Graffiti is 30 ft above current grade and marks the location of the original wash elevation when the bridge was constructed in the 1970s

[4] Specific examples can be found in the 2010 aerial photos of the Salt River at Mesa Drive (approx. 2,000 ft), Salt River at Stapley Dr. (1,600 to 2,000 ft), Salt River at Center St (1,400 ft), Salt River at Alma School (1,400 ft), and Salt River at Alma School Road FY 95/97 Aerials (3,500 ft).

required to keep the wash from causing further damage by widening beyond its current path.

It should be noted that this particular problem was not caused by sand and gravel mining but the wash illustrates the problems that can occur from uncontrolled headcuts regardless of their source. The bridge pier shown in Figure 6 has experienced approximately 30 ft of degradation since its construction in the 1970s. (Hester 2005) The bridge is currently protected by a soil cement drop structures and bank protection to prevent further degradation. The original bed elevation was at the top of the vertical bank in the background and just below the upper graffiti on the pier.

Sand gravel mining can cause headcuts as serious as those triggered by a natural lowering of the streambed depending on the pit depth, length, and the type of river system (sand, gravel or cobble bed). Local examples of significant headcuts associated with sand and gravel mining operations are readily available. A headcut of at least 3,000 ft can be seen in Figure 7 at Gilbert Road from the aerial photos taken at the end of 2008. The depth of the headcut at Gilbert Road is approximately 13 ft[5]. Another example of a headcut is on the Salt River at 35th Avenue. This headcut was approximately 1,600 ft long at the end of 2006 and can be seen in Figure 8. Headcuts can be easily found by reviewing the various aerial photos of the rivers.

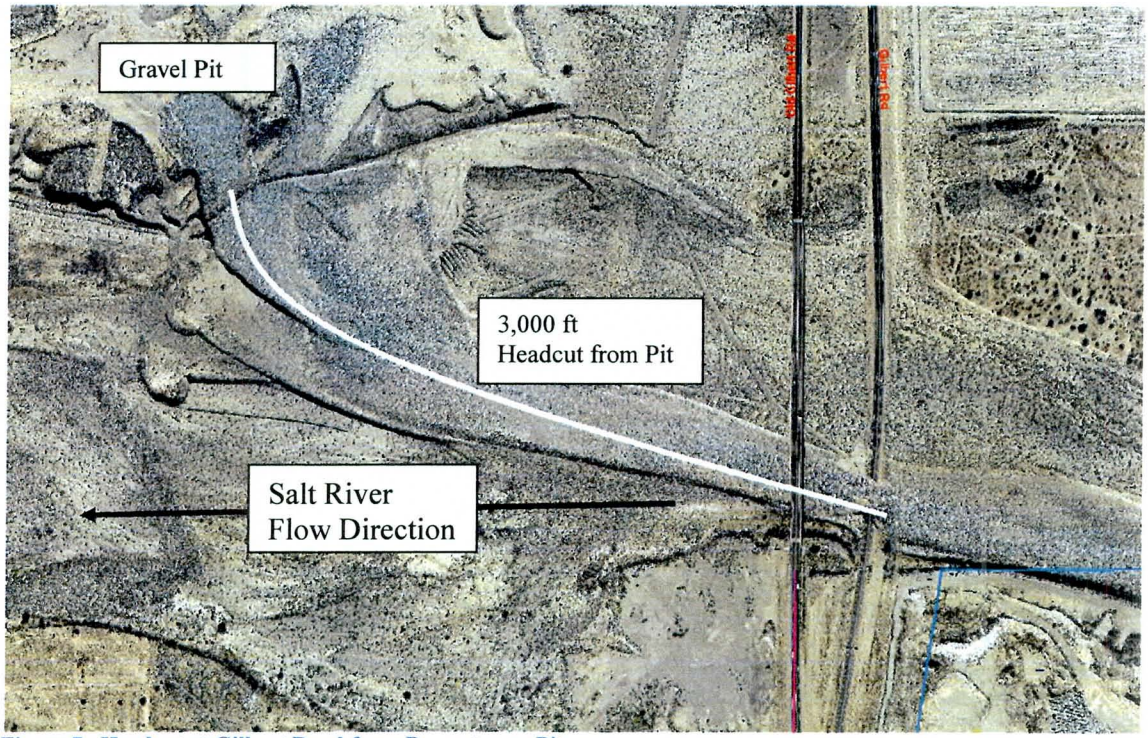


Figure 7. Headcut at Gilbert Road from Downstream Pit.

[5] Howard Chang's report (2009) reported a headcut of approximately 10 ft but the 2009 cross sections shows a maximum depth of approximately 13 ft at Gilbert Road Bridge when compared with the 1994 elevation data.

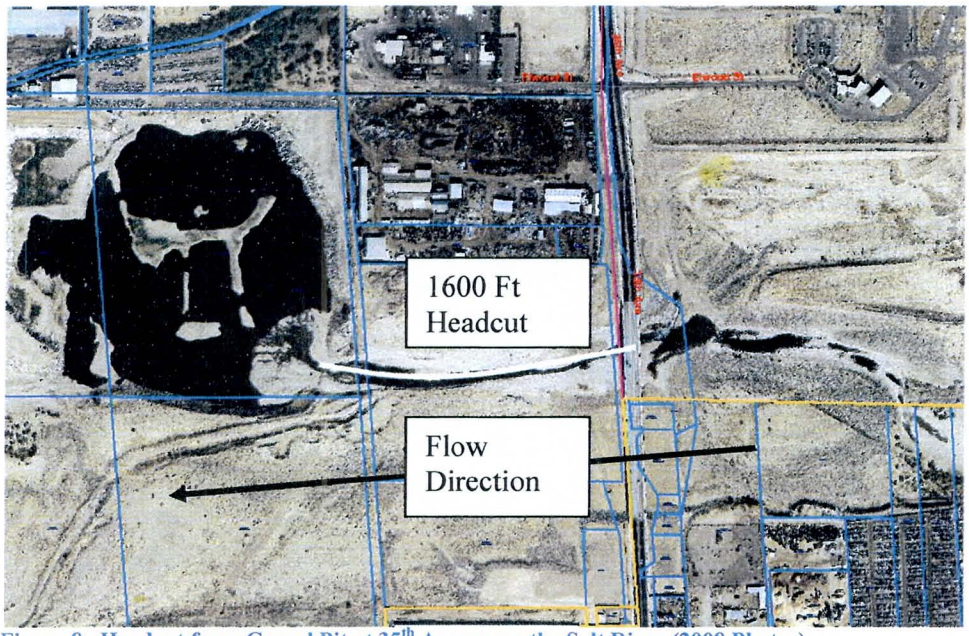


Figure 8. Headcut from Gravel Pit at 35th Avenue on the Salt River (2008 Photos).

Once headcuts start they can propagate throughout the entire watershed. Examples of this are the Las Vegas Wash, the Santa Cruz River downstream from Tucson (as well as last century through Tucson), and the Agua Fria in Prescott Valley. Headcut propagation is especially problematic and rapid in sand bed or fine gravel bed rivers and streams where no bedrock controls are present[6]. Most headcuts have historically been triggered by stream channelization, the cutting off meander bends or otherwise shortening or confining the flow area of a stream. The mining of very large pits in sand bed rivers or in gravel bed rivers where the bed material is not sufficient to armor at the steeper slope found upstream from gravel pits may very well trigger significant headcuts that move upstream until bedrock control is reached.

Methods for Predicting Scour Due to Headcuts and Over Steepened Reaches

A number of methods have been developed for the calculation of erosion due to headcut / knickpoint erosion. The most problematic to calculate is the headcut with a vertical or near vertical face. This is due to the much higher erosive forces and the impact of the hard layer on the rate of erosion and movement of the headcut. The methods used to calculate the movement of vertical face headcuts involves calculation of the impact of a water jet into a pool of water, the undercutting of the headwall, and may involve large pressure fluctuations due to turbulence and air entrainment. Numerous papers have been written on this subject over a number of decades.

The USDA Agricultural Research Service in Stillwater, Oklahoma has been active in this field for several decades due to the importance of gullying on the production of sediment from agricultural fields and the reduction of productivity on fields where gullying takes place. As a part of the on-going research at the Stillwater facility, Hanson, Robinson and Cook in 2001

[6] A headcut on the White River in Arkansas started at the Mississippi River and moved 200 miles up the Arkansas River and the White River, drained 7 miles of lakes in a wildlife refuge and is now moving 400 lb stones in the headwaters of the system (Derrick 2010).

reported an equation to predict the advance of headcuts in fine grained soils that appears to work well based on their experimental results. The method requires knowledge of the physical properties of the soil through which the headcut is progressing. They have also performed work on levee breaches and spillway channel erosion. This work may be adaptable to use in the analysis of gravel pits but would require on-site soils data and analysis to verify its applicability. Hanson indicated that in its current form it would not likely be applicable to sand and gravel mining applications (Hanson, 2010).

Knickpoint Erosion

The impacts of sand and gravel mining on the larger rivers in Maricopa usually appear more as over steepened reaches or knickpoints since the river beds are predominately made up of sands and gravels. In streams where a hard or erosion resistant layer exists (such as shown in Figure 1 and Figure 2) the methodology for vertical or near vertical headcuts come into play (i.e. Hanson, Robinson and Cook 2001). Since the focus of this project is the mining of sand and gravel from the rivers in Maricopa County the focus of this paper was limited primarily to the calculation of erosion due to over steepened reaches of the local rivers (as opposed to vertical headcuts).

Over Steepened Reach Theory and Physics

Over steepened reaches are stretches of the river where a higher slope connects two reaches of river with lower average slopes. In the case of a headcut this is easily observed as a vertical wall or a near vertical drop. In gravel bed systems, however; it may be somewhat problematic to find these reaches visually since they resemble rapids and riffles that occur naturally in gravel/cobble bed rivers. The visual clue in sand and gravel bed rivers is eroding vertical banks downstream from the knickpoint. In sand bed streams these over steepened reaches will likely move rapidly (in engineering time) upstream and the area downstream of the knickpoints will exhibit vertical cut banks on both banks of the river or, if braided, on all or most of the banks. In order to better understand how these over steepened reaches function and how to model them we need to understand some of the physics and theory that govern their formation and function.

Lane (1955) found that a relationship exists between the product of the amount and size of sediment transported in a stream and the product of the flow rate and slope of the stream transporting the sediment. He explained it as a balance between the four factors as shown in Equation 1:

$$Q_s * D_{50} = k * Q_{water} * S_o \qquad (1)$$

When we look at this equation in terms of a headcut / over steepened reach we see that both the flow rate (Q_{water}) and material size (D_{50}) are fixed (assuming all of the bed is naturally transportable). The proportionality coefficient (k) is also constant (or nearly so). This means if we greatly increase the slope (S_o) we also greatly increase the sediment transport (Q_s). In sand bed and gravel streams where all of the material can be transported under natural conditions the response of the river in reaction to the steepened slope is an increase in the amount of material being transported since that is the only variable that can adjust in response. In the case of

gravel/cobble streams the size of the material being transported can also increase to some extent if there are materials that could not be transported under the natural flow conditions so it is hard to generalize all rivers into one summary. For the sake of simplicity the discussion is simplified and all material is assumed to be transportable (i.e. the river bed does not armor under higher velocity conditions associated with headcuts/over steepened reaches).

When flow reaches the bottom of the pit the slope is sharply reduced and the sediment transport must reduce sharply to maintain balance in the equation. This means that once the material eroded from the upstream face of the pit reaches the bottom of the pit it will be quickly deposited since the slope is dramatically reduced. In very long pits the slope of the water surface in the pit will be determined by the slope of the pit bottom. In small pits the downstream slope may be near zero as the pit fills and behaves like a pond. The change in slope between the headcut slope and the slope in the pit is abrupt in large pits and creates a slope break and a deposit (very similar to an alluvial fan in its early stages) which forms at the base of the knickpoint[7].

During the very early stages of the entry of water into a gravel or sand pit the process resembles the gullying process with a very steep or even near vertical headwall. The steepness of the headcut will be determined by the resistance to the underlying material to erosion. In areas where gravels are packed tightly or where the surface armors for a given flow, a headwall may form until the armor layer is removed or the resistance to erosion is exceeded by the incoming flows. As erosion progresses into a pit a narrow incised channel will form along the flow path that will quickly widen due to the failure of over steepened banks as they become geotechnically unstable. In sand bed rivers the flow into the pit quickly erodes this gulley or trench back from the vertical face and the erosion process becomes dominated by erosive transport (as opposed to vertical headcut erosion) on a widening, over-steepened reach of the river immediately upstream of the pit (See Figure 9 and Figure 10.)

The sediment eroded upstream from the pit from the over-steepening of the upstream river and the widening of the initial headcut/OSR is in additional to the natural process of sediment transport in the river. The larger components of both of these sources are almost immediately deposited on the floor of the pit at the base of the eroding face of the pit while the finer materials move further into the pit.

As the material is eroded from the top of the face and deposited at the base the slope of the headcut/over-steepened reach is reduced. As more and more material is eroded from the pit face and the area upstream, an alluvial fan/delta forms in the pit. This fan/delta increases in depth as material is eroded from upstream and deposited on the surface of the fan/delta As this deposit grows the elevation of the bottom of the headcut increases due to the deposition and the depth to the bottom of the headcut/OSR reduces. The knickpoint (leading edge of the lowering) also moves up the river away from the pit face. The combination of the extension of the upstream edge of the knickpoint and the deposition at the downstream end of the over-steepened-reach reduces the slope on the over steepened reach and reduces sediment transport due to the headcut (See Figure 9). This process continues until the pit fills with water to a level above the top of the deposition/fan area and the depositional process switches from an alluvial fan type process to a

[7] This deposit looks like an alluvial fan in its very early stages but as the pit fills and water covers the alluvial fan it quickly becomes similar a delta or topset/foreset deposit at the upstream end of a reservoir.

delta forming process with a steep foreset at the leading edge of the deposit similar to a delta at the head of a reservoir. For a large event the time that the deposition area resembles an alluvial fan may be very short but the very earliest stages of deposition are identical to the formation of an alluvial fan. It is, however; true that the significant deposition in the pit does not occur while the deposit is behaving as an alluvial fan but starts once the deposit begins behaving as a river delta.

The capacity of the water to transport sediment into the pit per unit volume of water reduces as the headcut slope flattens and the ability of a unit volume of water to transport sediment is reduced. In the middle stages when the pit is filling this is due to the reduction in the slope of the knickpoint due to both the lengthening of the over steepened reach upstream and the filling of the pit by the eroded material. Once the water surface elevation upstream of the knickpoint becomes controlled by the elevation of water downstream of the pit (i.e. the flow into the pit and across the knickpoint becomes subcritical – see top drawing in Figure 10) the former headcut area primarily becomes depositional. If the pit never fills to the point where downstream backwater controls the inflowing water surface elevation – i.e. the pit does not drown out – the knickpoint will likely continue to move up the river. In channels with high velocities the rapid flow expansion at the knickpoint and gravel pit entrance may cause additional erosion due to three-dimensional currents set up by the high velocities. Whether or not a knickpoint will continue to migrate or not will depend on the slope of the channel, the length of the pit as compared with the depth of flow and whether the bed of the channel upstream of the pit will armor or not. It may be pointed out that the headcut may continue to develop even after the pit is drowned out if the pit's upstream face is erosional due to high local velocities along the channel bed.

As stated above, another factor in the propagation of the upstream headcut/over steepened is whether the bed armors – i.e. the D_{50} increases due to the selective removal of fines until the remaining material is too large for the flow to transport (see Lane's Equation (1)). Under these conditions the D_{50} increases and the increase in slope (S_o) can be offset to some extent by an increase in the particle size being transported (D_{50}) rather than entirely by an increase in the sediment transport rate.[8]

[8] An armor layer can be predicted to occur when the D_{90} of the bed is large enough to be stable under the design flow rate.

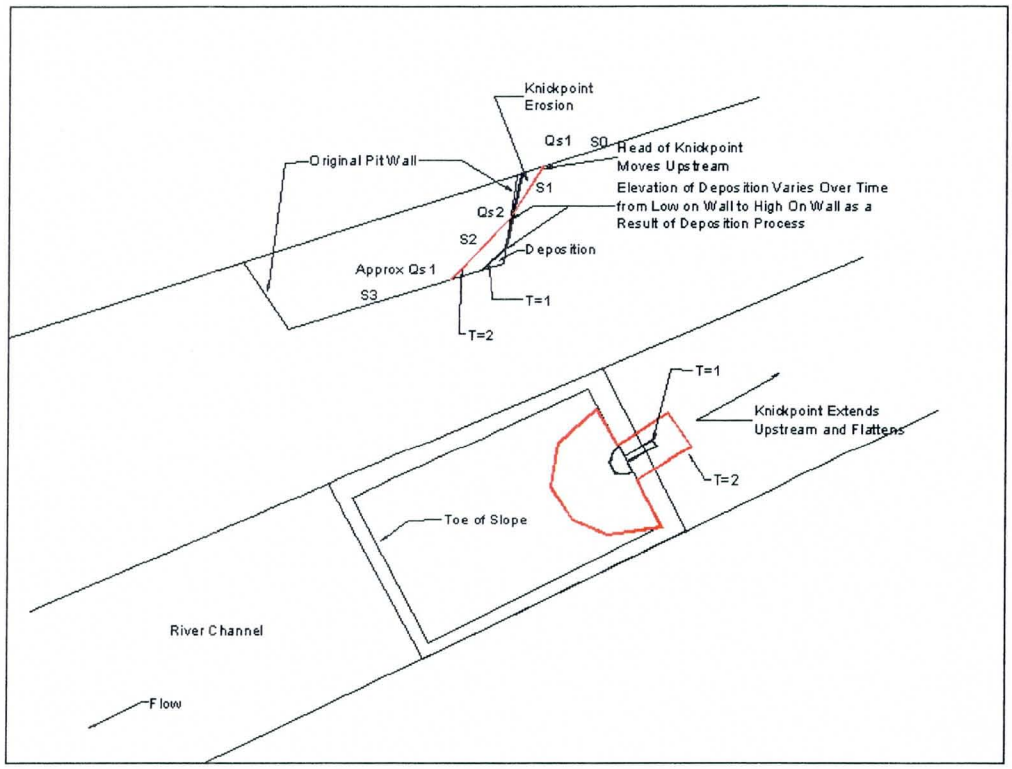


Figure 9. Progression of Knickpoint (Over Steepened Reach) During Pit Filling.

Once the pit fills with water and the flow out of the pit is equal to the flow coming into the pit the physics of the process will depend on the length and depth of the pit and the slope of the river. If the pit is hydraulically short (i.e. the pit is short and the river has a low slope or the hydraulic jump at the upstream end of the pit is drowned out after the pit fills) as shown in upper Figure 10, the water surface profile along the length of the pit will be similar to that found in the river prior to the excavation of the pit. The pit then acts like a lake and inflowing sediment is deposited into the pit as well as into the newly formed headcut/over-steepened-reach.

If the sediment load is high enough to fill the pit and knickpoint with sediment, the bed will be restored to something similar to its natural elevation and flow again resembles the natural conditions prior to excavation of the pit. If there is little sediment inflow there may be some movement of the knickpoint upstream after the pit has been drowned out as the river seeks a new, lower equilibrium condition. If sudden expansions or contractions remain as flow enters the pit there may be additional erosion due to the turbulence and/or eddies formed by flow into the drowned out pit.

If the pit is hydraulically long (i.e. the pit is long, the flow is shallow, and/or the river is steep and the hydraulic jump does not drown out – see lower Figure 10) the pit and headcut will not fill and the headcut/over steepened reach may continue to move upstream if the river bed does not armor. These headcuts/over-steepened-reaches can continue not only up the main channel of the river but up all of the tributaries. The result of this headcutting process in natural channels can be seen in numerous places in Maricopa County as well as across the southwestern and Midwestern United States. While most of the headcuts that can be seen in Maricopa County are the result of more natural processes, once the headcut is started in a system that does not armor and where no bedrock controls are present, the headcut may propagate up the river until bedrock control is reached or a drop structure is constructed. The challenge is determining when a headcut/over-steepened-reach (OSR) will drown out, when the bed will armor to arrest the movement of the headcut/OSR, and when the headcut/OSR will continue up the channel.

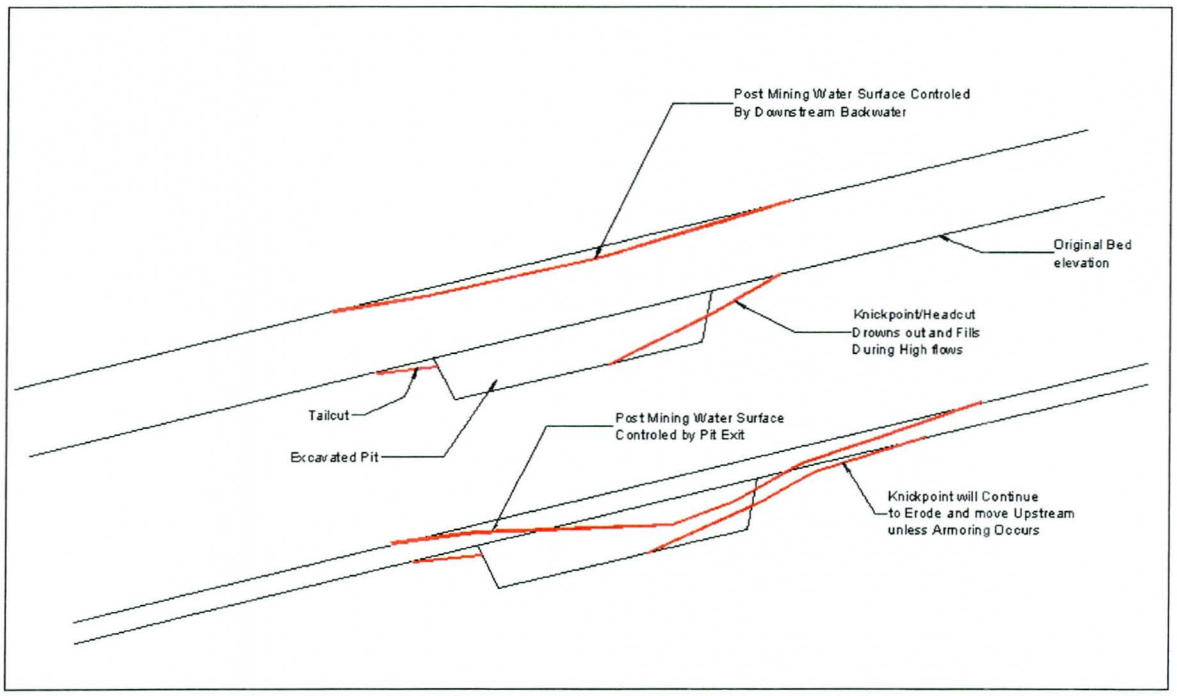


Figure 10. Diagram of when pits will fill with sediment without Triggering Upstream Bed Lowering via Headcut. Upper Pit will fill with Sediment over time and not trigger upstream headcut movement whereas lower pit will not likely fill back to original bed elevation and will trigger upstream headcut/knickpoint. (See Bovolin and Ponce, 2003 for similar discussion, Kondolf 1994)

The situation in the lower drawing in Figure 10 illustrates the conditions downstream from Gilbert Road on the Salt River when flow breaks into the downstream pit; while the upper drawing may be more representative of conditions for a small pit on the Gila River in Buckeye, for example.

Headcut Depth

Conventional wisdom holds that the maximum depth of erosion is approximately one-half the height of the headwall – i.e. one-half the difference in elevation between immediately upstream of the pit and the bottom of the pit. From the video produced by Chen it appears that the initial maximum scour depth is near the bottom of the pit – maybe in excess of 75% of the depth of the pit. This very deep scour appeared to be downstream from the brink of the pit and was quickly filled by sediment entering the pit from the headcut/OSR. As the pit fills this maximum scour depth (i.e. pivot point) moves higher as the headcut propagates upstream from the pit face. The elevation of this point is controlled by the balance between the amount of sediment eroded from upstream and the amount of sediment deposited in the pit. A feature similar to an alluvial fan builds in the pit and by the time the headcut/knickpoint erosion reaches the upstream edge of the pit (i.e. a vertical line extending down from the original pit brink) it is likely on the order of half the pit depth for pits that drown out.

For pits that are very long or where the natural depth of flow is low (as shown in the lower drawing in Figure 10) the maximum headcut depth at the pit brink could exceed one half of the pit depth depending on the flow conditions in the pit. The depth of the headcut under these conditions may be controlled by the elevation of the downstream brink since there could be limited or no backwater in the pit. In the case of a series of pits the depth of the headcut could be controlled by normal depth flow conditions through the pit downstream. This would be an extreme condition but is not impossible given the physical length and size of pits currently being mined.

In most historically sized pits, the water fills the pit and provides backwater to drown out (or at least seriously reduce) the headcut and thus reduces the erosion depth. In the case of very long pits a condition could exist where no backwater forms in the upstream portion of the pit. Under these conditions the upstream boundary would function as a man-made headcut and propagation of something close to the entire pit elevation could occur. In the case of pits that drown out or pits that fill to one-half the original depth or more the estimate of maximum scour at one half the pit depth appears to be reasonable.

Tailcut Erosion

Tailcutting refers to the erosion of river/stream bed and bank sediments and the accompanying lowering of the channel downstream of a sand or gravel pit. The process of tailcutting begins at the point where water begins to leave the downstream end of the pit – i.e. upon pit filling. Once water begins to flow from the pit it needs to replenish the sediment that it lost as it entered the pit. Kondolf (1997) refers to water exiting the pit as "hungry water" – i.e. water hungry for the sediment it just deposited in the pit. The exiting water obtains this sediment from the bed until armoring occurs or from the banks as they begin to fail due to geotechnical failures and/or undercutting by the flow. The sediment to bring the sediment load back into balance can only come from these two sources.

The impact of armoring on the tailcut is very different from the result of armoring of the headcut/knickpoint. If the stream above a headcut/knickpoint armors, upstream erosion will

stop. The impact of armor on a tailcut is simply to delay the erosion to a point where no armor is present or to cause the river to remove the needed sediment from the banks of the river downstream of the pit rather than the river bed. When flow exits a pit where the channel has armored downstream from the pit the water is still "hungry" and it will seek to obtain sediment from any available source to balance the water's actual sediment transport with the water's capacity to transport sediment. If the bed downstream armors the river may instead remove material from the banks until it reaches sediment equilibrium. Otherwise as soon as the flow reaches an area that is not armored or if the armor layer is disrupted, sediment transport will again move towards equilibrium by removing material from the bed.

The tailcutting process is, in some regards, similar to the headcutting process in that the water exiting the pit will find the lowest and/or weakest point to exit the pit. As the flow exits the pit erosion occurs along the downstream edge of the pit. The scour width will be in relation to the amount of flow leaving the pit and can be estimated by various regime equations that relate channel width to flow rate. As the flow rate increases, the width of the exit channel will increase either by surface erosion of the new channel bed or failure of the banks of the newly forming low flow channel out of the pit. The formation of the tailcut can lead to a narrower, eroded channel exiting the pit, or if the entire downstream face is resistant to erosion, to a very wide shallow outflow area that may armor. If the bed armors, the influence of the tailcut will extend until the sediment load is in balance – i.e. until the "hungry water" is back in balance with its sediment load.

The tailcut volume should not exceed the volume of material deposited in the pit from upstream based on the physics involved. The sediment transport rate is governed by the physics requiring sediment continuity. The continuity equation simply states that sediment transport upstream of the pit will equal the sediment transport downstream from the pit plus the erosion from the headcut upstream from the pit and minus the sediment stored in the pit. Unless the river conditions change in the vicinity of the pit the sediment transport upstream and downstream of the pit's influence will be equal or nearly so. The tailcut volume thus should not exceed the amount of sediment in the river upstream of the headcut that was captured by the pit.

The assumption of sediment continuity across the pit is not unrealistic but does have limitations. If the bed upstream of the pit is armored it is also likely that the bed downstream will be armored and sediment transport will be less than the capacity of the water both upstream and downstream. Under armored conditions the downstream transport could be substantially less than the sediment load flowing into the pit but will normally come back into equilibrium with the upstream sediment transport as material is removed from the river's bed and banks. If the entire reach of the river is armored the river may not recover for many miles downstream.

It should also be noted that while a drop structure can prevent the migration of the headcut/ knickpoint upstream from the pit, the construction of a structure at the downstream end of the pit will have no impact on the tailcut since the physics of the tailcut are different from the physics of the headcut. The headcut is an adjustment of the river to the bed lowering and the full upstream sediment load is available to maintain the channel elevation upstream. The tailcut will continue to form downstream from the pit regardless of structures, protection, or other treatments since the

cause of the tailcut is the reduced sediment load caused by the gravel pit (i.e. the "hungry water" exiting the pit).

Overbank Pits

Zeller has indicated that, in his opinion (and based on the observation of floodplain pit behavior during large floods); pits in overbank areas appear to have a different sediment transport regime and much less potential for headcuts and tailcuts as long as the river does not capture the pit (Zeller 2010). When water starts to enter a pit which is in an overbank area, the physics for the headcut process is identical to the process in the main channel in that the local acceleration of the flow tends to erode the upstream face of the pit. The overbank areas normally have shallower flows, lower velocities and may be depositional away from the pit's influence. The excavation of a deep pit in overbank areas can change this general situation because of local acceleration of velocity at the headcut/OSR along the upstream edge of the pit. The overbank flows are also complicated by the reduction of the upstream sediment inflow in the floodplain as compared with the channel.

Since the physics are the same – i.e. high velocity flow down a steep bank a headcut will develop for pits on overbank areas. However, since the main channel has more frequent (and larger) flows than overbank areas, one would expect more rapid (and and perhaps longer) headcutting for pits in the main channel. For tailcuts, since overbank areas normally do not carry as much sediment as in the main channel and have lower velocity, the overbank pit's tailcut should also be much smaller than that for the pits in the main channel. It should be remembered, however; that overbank pits can cause major erosion and stability problems if the pit is captured by the main channel or one of the channel braids. When overbank pits are captured the headcuts and tailcuts are at least as large as if those pits were located in the main channel originally. The capture of overbank pits also impacts the lateral stability of the river away from the pit.

Headcut Studies and Prediction

A number of studies have been performed to estimate headcut depths and lengths as well as tailcut impacts. A few studies stand out after a review of numerous papers on headcuts and headcut propagation. Among these are the Simons & Li / ADOT Methodology (Simons & Li, 1989), a study done at Colorado State University in 1980 by Yung Hai Chen, and another ADOT study reported in 1986 by Dust, et al).

Chen 1980 Physical Modeling Reports (Chen 1980a, Chen 1980b)

In 1980 Yung Hai Chen reported on physical moveable bed model studies performed at Colorado State University for the Salt River Channelization Project at Sky Harbor International Airport (Chen 1980a). The project involved levees and other changes along the Salt River adjacent to the Sky Harbor Airport. The report examined the Salt River from Priest to just above I-10 (about 3.7 miles). A second report in December of that same year added guide dikes and a drop structure associated with I-10 at the downstream end of the model and evaluated potential gravel pits just upstream of I-10. The model study examined several pit locations and depths as shown in Figure 11. The physical model was scaled to achieve geometric, kinematic and dynamic

stability which allows the model results to be directly compared to the river when properly scaled. Results reported by Chen were the scaled values that applied directly to the Salt River. Since the values are specifically for the Salt River the results provide useful data and can be used as data points in a larger set of data that could then be extended to other locations.

The pits modeled consisted of pits in the main channel at two locations – one near the I-10 bridge and one further up between levees, both inside and outside of the low flow channel with depths of 20, 40 and 60 ft below the channel elevation[9]. The effort also included tests with a second run with the same hydrograph with the pit re-excavated between runs to view the impacts of a second flood on the channel.

Chen found that the "maximum headcutting depth occurs at the initial stage when water starts to enter the pit". This is reduced as sediment is transported into the pit from erosion of the headcut upstream. This can be seen in Figure 12. Chen also stated that, for the gravel model he tested, the headcutting action almost stopped when the pit filled. In reviewing video of the test it is apparent that while headcutting had certainly slowed from earlier rates, there is a significant knickpoint upstream from the pit as shown in Figure 13. This area will continue to erode if the bed doesn't armor or if the knickpoint doesn't drown out during higher flows. The photo in Figure 13 was not taken during the highest flow rate and the pit did drown out during high flows.

The early photos of the pit headcutting process show a very narrow and deep channel that rapidly deepens and widens as adjacent banks either become geotechnically unstable due to their height or are undercut and fail.

The Chen video shows the pits nearly filled with sediment at the end of the tests but with an over steepened reach remaining upstream and a tailcut downstream. The source of the sediment that filled the pit was the upstream channel which was lowered by the headcut to provide the sediment necessary to fill the upstream portion of the pit. This is further evidence that the headcutting/ movement of the knickpoint in Chen's model did not stop at the time the pit filled with water.

The photos shown in Figure 12 are all from the rising limb of the hydrograph. The later portion of the video (after the completion of the test) indicates that the pit and knickpoint were drowned out under high flow conditions. The upper end of the pit tended to fill during high flows later in the simulation. The Chen model did not have a sediment inflow so under natural conditions the headcut/knickpoint may have fill to some extent under natural conditions due to sediment supplied from upstream. Given the amount of mining that has occurred upstream this is not an unreasonable assumption.

[9] It should be noted that Chen's work used a physical model that was scaled to represent a 20, 40 and 60 ft deep pit and not actual field work on pits.

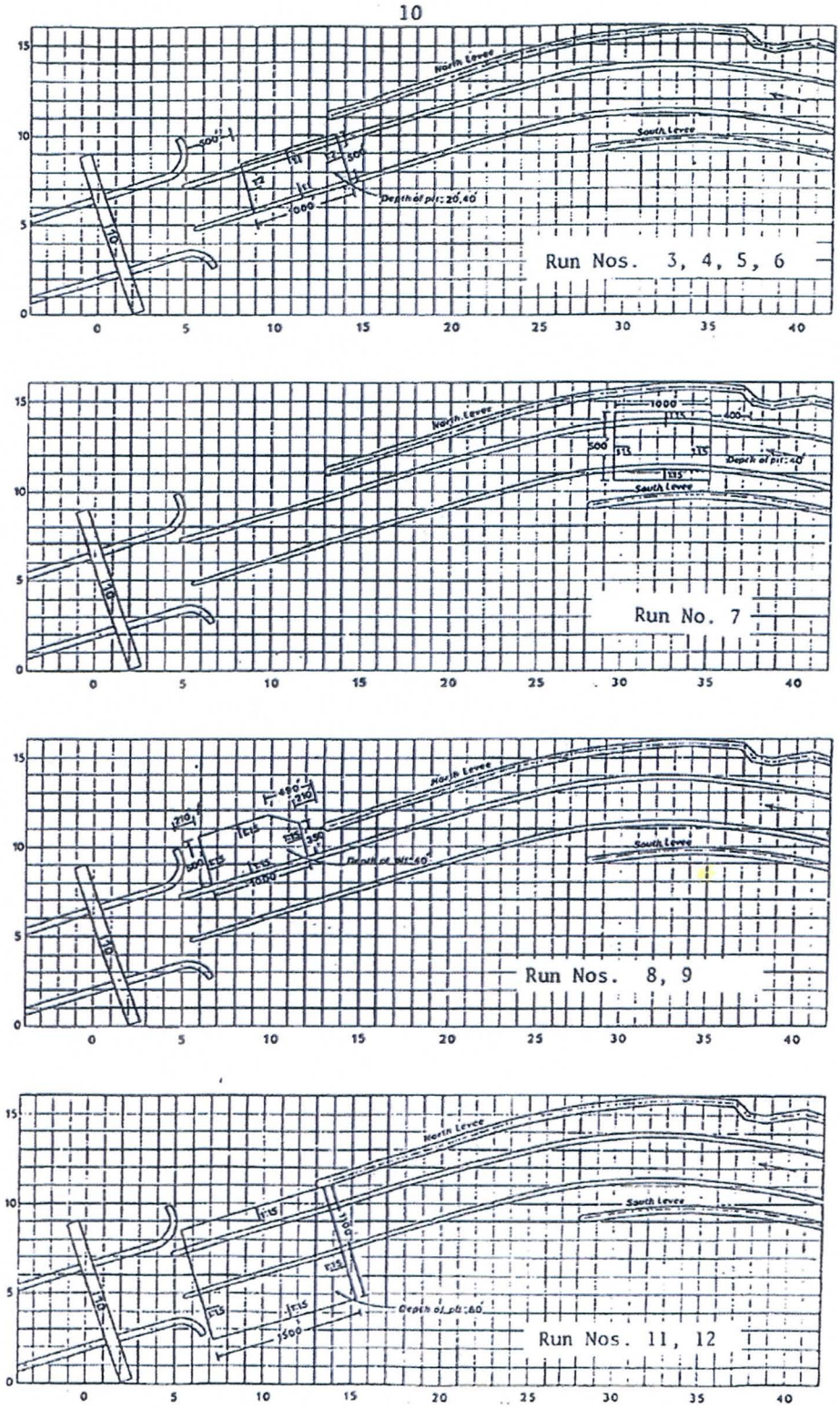


Figure 11. Layout of Gravel Pits Tested by Chen in 1980 Physical Model Study.

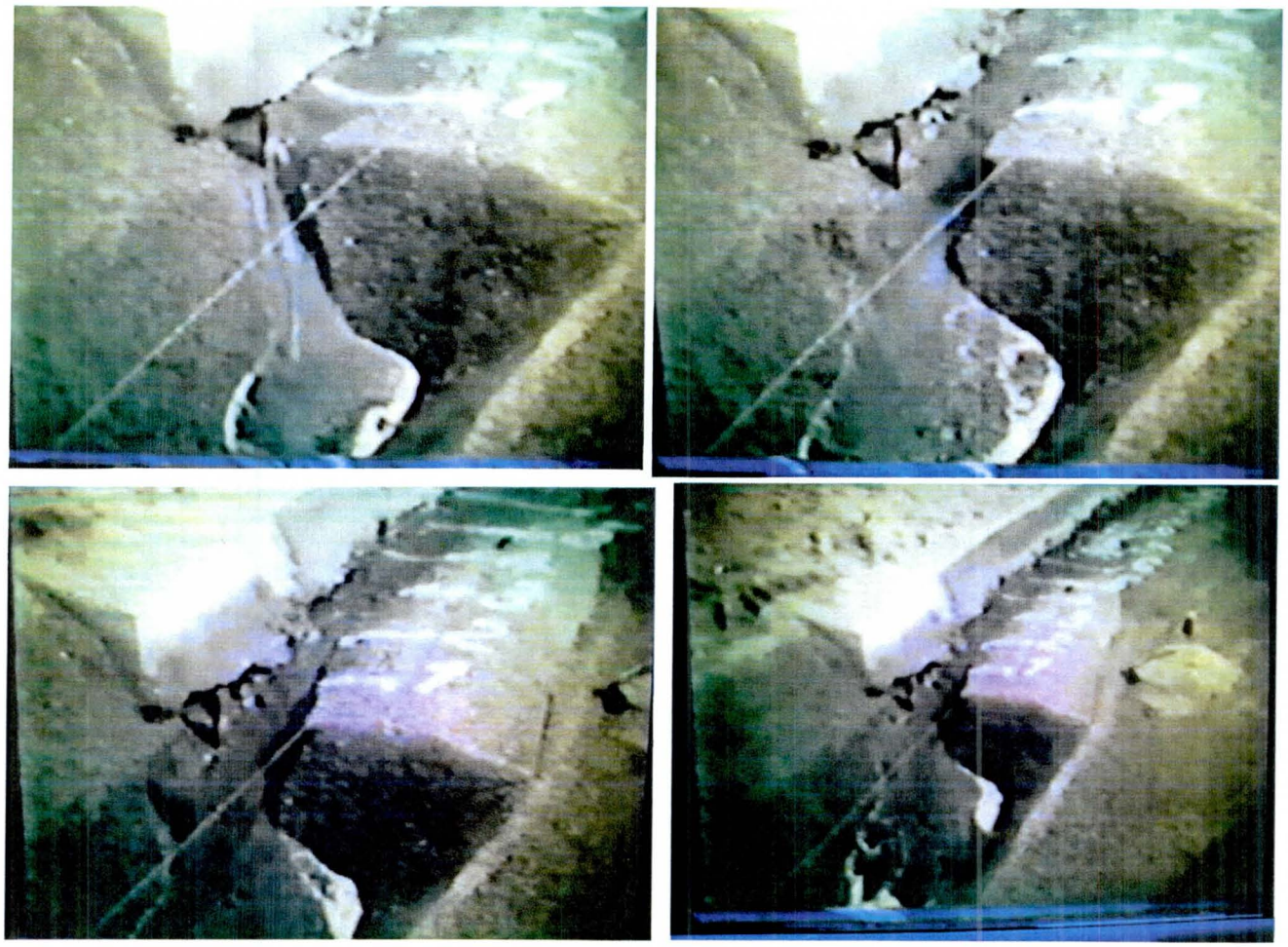


Figure 12. Knickpoint propagation for a 40 ft pit from Chen Physical Model Video (1989b). Time series moves left to right and shows oversteepened knickpoint but no vertical headcut except perhaps at very initialization of headcut.

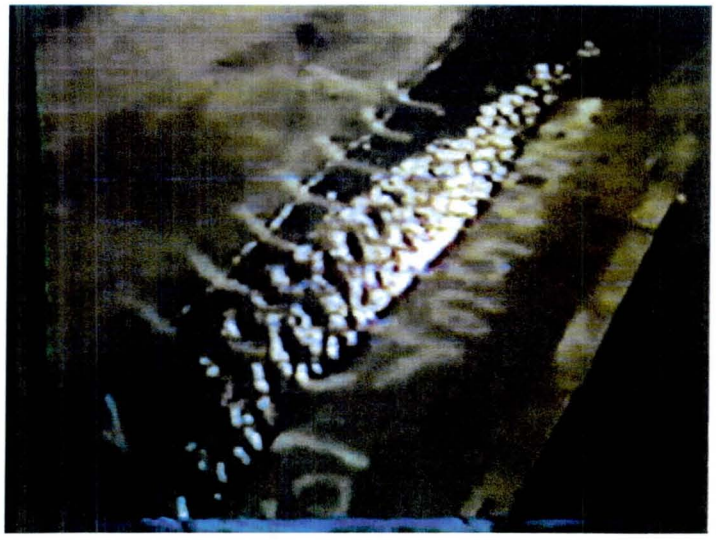


Figure 13. Over-Steepened-Reach Remaining for pit shown at top of Previous Figure after 40 ft pit fills in Chen Video (5:54 minutes into Video). Pit is at upper right and flow to upper right in this photo.

Chen developed several charts showing headcut and tailcut lengths from his study. His study found that the depth of the headcut varied with the depth of the pit and that headcut length varied with the pit size. He found that a 60 ft deep pit would produce a maximum headcut depth of approximately 23 ft with a headcut (over-steepened reach)

that extended about 2,900 feet upstream (Figure 14). Chen measured the maximum headcut depth vertically at top of the upstream slope of the pit (immediately upstream) while the video shows the scour on the face of the pit which would account for the differences in maximum scour depths between Chen's report and the observations of the video.

Chen also found that the pit migrated laterally (i.e. widened) for a downstream distance of about 300 ft for a 60 ft pit as shown in Figure 15. Chen's results for the tailcut (called downstream migration in his report) are shown in Figure 16 and show a tailcut length of approximately 1,000 ft for a 60 ft deep pit. The maximum depth was approximately 12 ft at the downstream pit brink.

The Chen video is very informative and of extreme interest in predicting the behavior of erosion in the early stages of flow into pits.

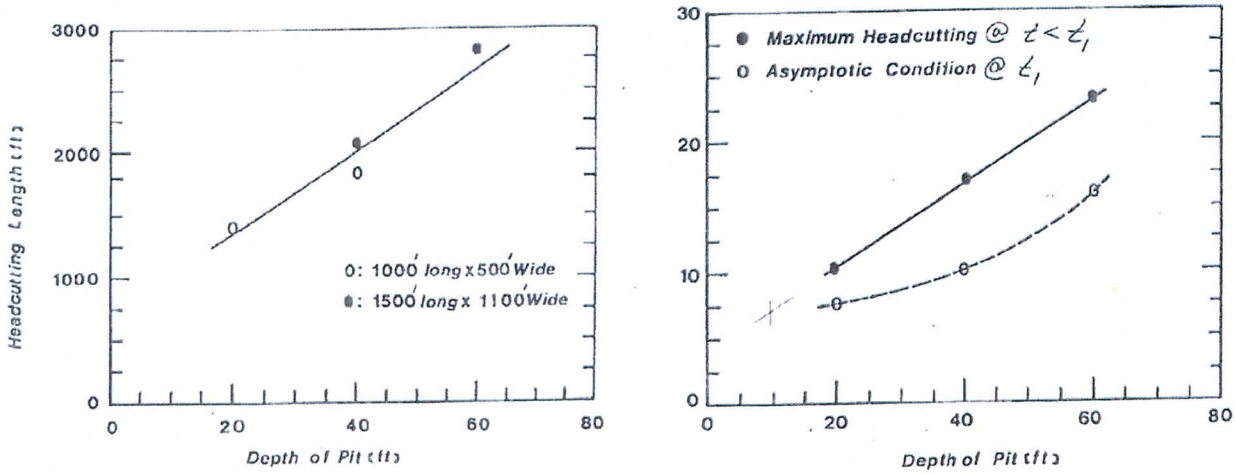


Figure 14. Chen's Results for Headcut Depth and Length from his Physical Model Testing for the Salt River at Sky Harbor Airport.

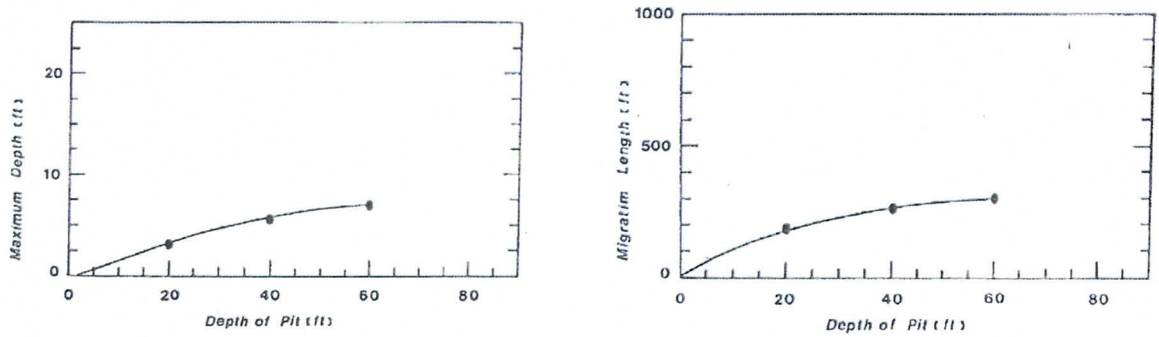


Figure 15. Chen's Physical Model Results showing Lateral Migration Length and Depth for pits in the Salt River at Sky Harbor Airport.

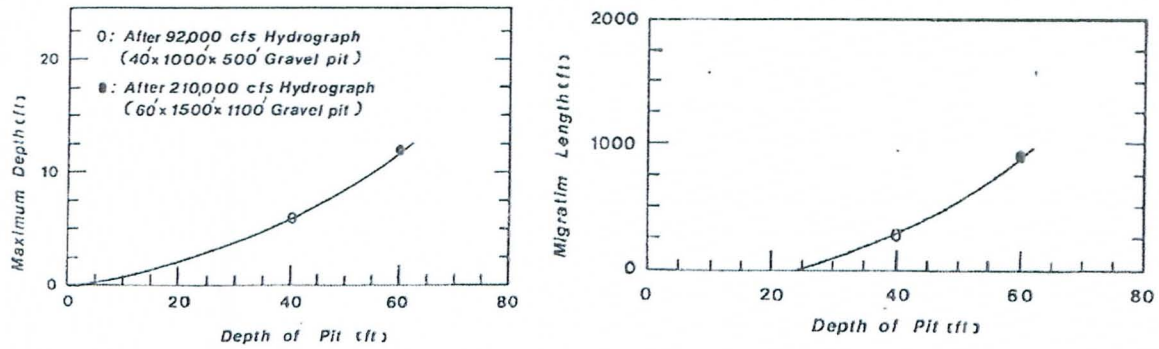


Figure 16. Chen's Physical Model Results for Downstream Pit Migration (Tailcut) for the Salt River at Sky Harbor Airport.

ADOT 1986 Study

ADOT (Dust, et al, 1986, Appendix F) modeled a generic 15 ft deep pit in the Agua Fria using the 1979 geometry and bed sediment data. One of the test pits was 1970 ft long and 570 ft wide – the full width of the moveable bed limits in the HEC-6 model of the river reach. The area modeled was at mile 24 of the river (about Happy Valley Road) and used Yang's stream power function for sediment transport. The results looked promising and predicted a headcut (knickpoint) extending 2000 ft upstream from the 15 ft deep pit (See Figure 17). The authors found that:

1. The figures show deposition and headcutting patterns that might reasonably be expected
2. Headcutting effects extended more than 2,000 ft upstream, and
3. Water surface elevations are always above the elevation of deposited sediment.

In the end the study did not recommend the use of HEC-6 stating "although the results are intuitively pleasing" the results were not based on "all of the complicated hydraulic conditions and sediment transport processes associated with headcutting". The complicated hydraulic conditions referenced included the notching effect that Chen's videos clearly show.

The results they obtained are shown in Figure 17. The results do indeed look "intuitively pleasing" and it appears that the HEC-6 model did capture the major processes involved in the problem, at least from the big picture. Later applications of HEC-6T (an updated and proprietary model based on HEC-6) have shown the model has the ability to model the major processes of headcuts and tailcuts associated mining with reasonable accuracy (WEST 2002). It should be noted that most, if not all, of the pits were large enough to entirely cover the active channel width in the HEC-6T model. The HEC-6T model does not, however; currently model the notching/gullying that occurs early in the erosive process of headcutting. This feature is expected to be added in some form the near future but has not been utilized in modeling performed to date.

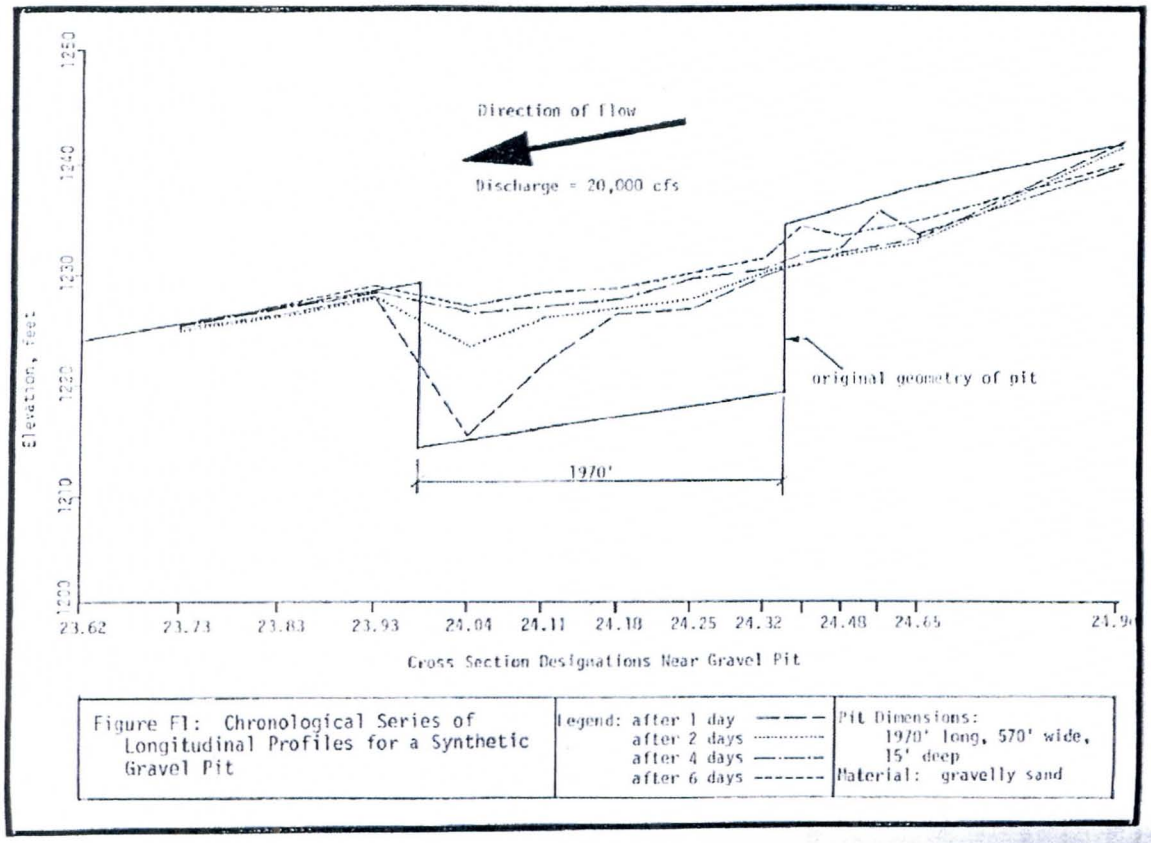


Figure 17. ADOT's 1986 HEC-6 Model of the Agua Fria River.

ADOT Methodology (Simons & Li 1989)

One of the most cited reports on the calculation of the depth and length of the headcut/OSR and associated downstream tailcut is the Simons & Lee report prepared for ADOT in 1989. This report presented a method to calculate both the headcut and tailcut for rivers in Arizona. Simons & Li performed a detailed analysis of sand and gravel mining in Arizona for ADOT in 1989. This study used two methodologies to look at the impact of sand and gravel mining on river stability. They differentiated them as a short term methodology and a long term methodology.

Simons & Li also reviewed a number of sediment transport models that were available at the time for applicability to the problem and found that the models of the day did not generally represent the processes well. Simons & Li had developed several models that addressed the problem but little, if any, mention of the models can be found in recent literature. In their research they found headcuts on the order of 3,000 ft above pits on Arizona Rivers but their short term methodology does not appear to produce results of this magnitude.

Long Term Methodology

The methodology utilized by Simon, Li & Associates in their long term assessment was to discretize a reach of the subject river using topographic maps. The area was broken into two-dimensional cells where average bed elevation was calculated. This was compared with earlier topography to determine the amount of material that had been removed from the reach. The area that was impacted by mining was also determined for each individual cell.

Their findings included a statement that gravel bed rivers in Arizona are not being replenished from upstream sources and gravels bed streams showed no recovery during the time period of the study was noted (see p. 77 of their report). Thus it would appear sand and gravel resources should be considered to be a limited resource rather than a renewable resource. Given the extensive mining that has occurred along the Salt River at this point and the upstream dams this statement is certainly valid for any remaining material below Granite Reef Dam.

The long term methodology looked primarily at clusters of mining pits rather than at individual pits and focused on tailcut calculations. Their methodology gave good results when comparing the predicted and observed values for the pits studied. They noted that in their data set the tailcuts from sand bed rivers were shorter than for those from gravel bed rivers.[10]

Short Term Methodology

Simons & Li also developed a short term methodology to estimate both headcut and tailcut depths and lengths for sand bed rivers but only headcuts for gravel bed rivers. This methodology assumed that the pits would drown-out during the hydrograph (Zeller 2010). This methodology was reproduced by the Flood Control District personnel in a beta software package. The ADOT methodology in the beta software package was used to calculate headcuts/knickpoints and tailcuts for mines on the Hassayampa and Salt River and produced results that did not match the observed data. The headcut data appears to be at least one or two orders of magnitude too low and the tailcut appears to be highly variable but perhaps of the right order of magnitude for a sand bed stream. The short term methodology does not predict tailcuts for pits in gravel bed streams since "it was felt that the armoring process along gravel bed rivers would arrest the tailcutting at the downstream brink of the pit" (Zeller 2010). Gravel bed streams are defined as those with an armor layer visible on the bed – if no armor layer is visible the stream is considered a sand bed channel. Results from the District beta software package based on their method are presented in Tables 1-4.

The data shown in Tables 1-4 strongly indicates that either the headcut calculations are not correct in the Simons & Li short term methodology or the pits in question did not drown out as was assumed in the development of the method. The values appear to be short even for the limited time in which the pit fills with water but may be more accurate if one assumes the pits do

[10] The extended tailcuts in gravel bed streams may have been due to armoring of the beds downstream of the gravel pits. This would extend the length of the tailcuts as the water would travel for longer distances before reaching a full sediment load. Otherwise their relationship between headcut and tailcut lengths in this method appears to be out of proportion. Also incoming sediment loads were neglected as insignificant or being represented by any differences between observed data and calculated data.

not drown out. The limited headcut distance is also confirmed by the pits tested by Chen in his physical model. The headcut from the pit shown in Figure 12d is described as being approximately 2,000 ft in length. This would be much higher than that predicted by the ADOT (Simons & Lee) methodology for the same pit.

Zeller (2010) recommended that in the calculation of tailcuts for gravel bed rivers, the notching effect should be considered for the calculation in gravel bed rivers. This would mean that the width of the notch would be calculated using a regime method and hydraulics would then be calculated for the flow through the notch. Using the velocities for flow through the notch the depth to armor could then be calculated and used as the depth of the tailcut at the downstream brink of the pit. If the bed would not armor the river would be considered to be a sand bed stream for tailcut calculations. Mr. Zeller also indicated that the equations presented in the ADOT methodology could be adapted to account for the conditions where the pit did not drown out and the equations would then predict much longer headcut and tailcut lengths than those obtained using the ADOT methodology as presented in the report. Mr. Zeller served as project manager for the 1989 Simons & Lee study for ADOT.

Table 1. Results for ADOT Methodology for Pioneer Sand Pit on Hassayampa River. Calculation used 2010 I-10 Hydrograph.

Sand Bed Headcut and Tailcut Profiles

Pit Information Summary	
Hydrograph File	HassayampaHydrograpsh.csv
Time Unit	Hour
Alluvial Material	Sand Bed
Pit Length	2,200.00 (ft)
Pit Width	500.00 (ft)
Pit Depth	35.00 (ft)
Effective Pit Depth	35.00 (ft)
Ground Water Depth	0.00 (ft)
Drown-out Water Depth	0.00 (ft)
Pit Volume	28,861,579.22 (cubic ft)
Pit Side Slope	3
Channel Slope	0.0042
Fill Time	13.23 (hr)

Dimensionless Scour Profile		Headcut Profile	
Ys/Ysbrink	*Ls/Ls5*	*Ys (ft)*	*Ls (ft)*
0.05	1.00	0.72	333.05
0.25	0.60	3.61	199.83
0.50	0.30	7.23	99.92
0.75	0.15	10.84	49.96
1.00	0.00	14.46	0.00

Dimensionless Scour Profile		Tailcut Profile	
Ys/Ysbrink	*Ls/Ls5*	*Ys (ft)*	*Ls (ft)*
0.05	1.00	0.42	5493.47
0.25	0.50	2.09	2746.73
0.50	0.25	4.17	1373.37
0.75	0.10	6.26	549.35
1.00	0.00	8.35	0.00

		Predicted		
	Observed	Simons & Lee/ADOT	Rule of Thumb	Boyle
Headcut	Approx. 4,300 ft	333 ft	4,170	1,750
Tailcut*	4,000+ ft	5493 ft		

* Tailcut merged into headcut from downstream pit.

Table 2. ADOT Methodology Applied to the Hassayampa Pit North of Tonopah-Salome Road. The 2010 I-10 Hydrograph was used.

Sand Bed Headcut and Tailcut Profiles

Pit Information Summary	
Hydrograph File	HassayampaHydrograpsh.csv
Time Unit	Hour
Alluvial Material	Sand Bed
Pit Length	1,250.00 (ft)
Pit Width	1,450.00 (ft)
Pit Depth	10.00 (ft)
Effective Pit Depth	10.00 (ft)
Ground Water Depth	0.00 (ft)
Drown-out Water Depth	0.00 (ft)
Pit Volume	17,326,965.35 (cubic ft)
Pit Side Slope	3
Channel Slope	0.0047
Fill Time	11.00 (hr)

Dimensionless Scour Profile		Headcut Profile	
Ys/Ysbrink	*Ls/Ls5*	*Ys (ft)*	*Ls (ft)*
0.05	1.00	0.07	72.99
0.25	0.60	0.35	43.79
0.50	0.30	0.71	21.90
0.75	0.15	1.06	10.95
1.00	0.00	1.41	0.00

Dimensionless Scour Profile		Tailcut Profile	
Ys/Ysbrink	*Ls/Ls5*	*Ys (ft)*	*Ls (ft)*
0.05	1.00	0.19	1697.22
0.25	0.50	0.93	848.61
0.50	0.25	1.86	424.31
0.75	0.10	2.79	169.72
1.00	0.00	3.72	0.00

		Predicted		
	Observed	Simons & Lee/ADOT	Rule of Thumb	Boyle
Headcut:	Approx 4,500 ft*	73 ft	1,060 ft	500 ft
Tailcut:	Undeterminable	1700 ft – Merged with headcut from lower pit and drained upper pit.		

* Headcut merged into tailcut from upper pit.

Table 3. ADOT Methodology Applied to the Hassayampa River Pit Located South of Tonopah-Salome Highway. The 2010 I-10 Hydrograph was used.

Sand Bed Headcut and Tailcut Profiles

Pit Information Summary	
Hydrograph File	HassayampaHydrograpsh.csv
Time Unit	Hour
Alluvial Material	Sand Bed
Pit Length	1,200.00 (ft)
Pit Width	850.00 (ft)
Pit Depth	10.00 (ft)
Effective Pit Depth	10.00 (ft)
Ground Water Depth	0.00 (ft)
Drown-out Water Depth	0.00 (ft)
Pit Volume	9,596,808.29 (cubic ft)
Pit Side Slope	3
Channel Slope	0.0047
Fill Time	8.33 (hr)

Dimensionless Scour Profile		Headcut Profile	
Ys/Ysbrink	*Ls/Ls5*	*Ys (ft)*	*Ls (ft)*
0.05	1.00	0.07	81.46
0.25	0.60	0.35	48.88
0.50	0.30	0.70	24.44
0.75	0.15	1.05	12.22
1.00	0.00	1.40	0.00

Dimensionless Scour Profile		Tailcut Profile	
Ys/Ysbrink	*Ls/Ls5*	*Ys (ft)*	*Ls (ft)*
0.05	1.00	0.24	2480.40
0.25	0.50	1.22	1240.20
0.50	0.25	2.45	620.10
0.75	0.10	3.67	248.04
1.00	0.00	4.89	0.00

		Predicted		
	Observed	Simons & Lee/ADOT	Rule of Thumb	Boyle
Headcut	Approx 3,500 ft*	81 ft	1,060 ft	500 ft
Tailcut	Perhaps 6,000 ft**	2480 ft		

* Headcut merged with tailcut from upper pit & drained upper pit.

** The eroding together of these two pits appears to have functioned more like a dam break when the channel between the two pits near the Tonopah-Salome Highway eroded out emptying the upper pit rapidly (based on initial impressions and subject to further evaluation).

Table 4. ADOT Headcut Method for Gravel Pit Downstream from Gilbert Road. The 2005 Hydrograph at Priest Road was used.

Gravel Bed Headcut Profiles

Pit Information Summary	
Hydrograph File	SaltHydrograpsh.csv
Time Unit	Hour
Alluvial Material	Gravel Bed
Pit Length	5,970.00 (ft)
Pit Width	1,500.00 (ft)
Pit Depth	30.00 (ft)
Effective Pit Depth	30.00 (ft)
Ground Water Depth	0.00 (ft)
Drown-out Water Depth	0.00 (ft)
Pit Volume	248,707,241.51 (cubic ft)
Pit Side Slope	3
Channel Slope	0.0034
Fill Time	21.42 (hr)

Dimensionless Scour Profile		Headcut Profile	
Ys/Ysbrink	*Ls/Ls5*	*Ys (ft)*	*Ls (ft)*
0.05	1.00	0.30	327.28
0.25	0.60	1.52	196.37
0.50	0.30	3.04	98.18
0.75	0.15	4.56	49.09
1.00	0.00	6.08	0.00

		Predicted		
	Observed	Simons & Lee/ADOT	Rule of Thumb	Boyle
Headcut	>3,000 ft	327 ft	4,400	1,500
Tailcut	No method for calculating tailcut for gravel bed rivers. Downstream of pit and pit cluster also subject to mining so no way to determine tailcut from this pit.			

Rule of Thumb Methods

The conventional rule of thumb estimates a maximum scour depth of one half the pit depth. The length of the headcut is determined by calculating the distance required for a slope of twice the natural river slope to daylight from the maximum scour depth (one half the pit depth) (Williams, Hu, Doeing and Phillips, 2002). This distance equates to the distance for the river to drop half the distance of the pit depth. The equation for the length is:

$$\text{Length} = (\text{Depth} / 2) / \text{Natural River Slope.} \quad (2)$$

or

$$\text{Length} = \text{Depth} / (2 \times \text{Natural River Slope}) \quad (3)$$

This calculation is shown graphically in Figure 18.

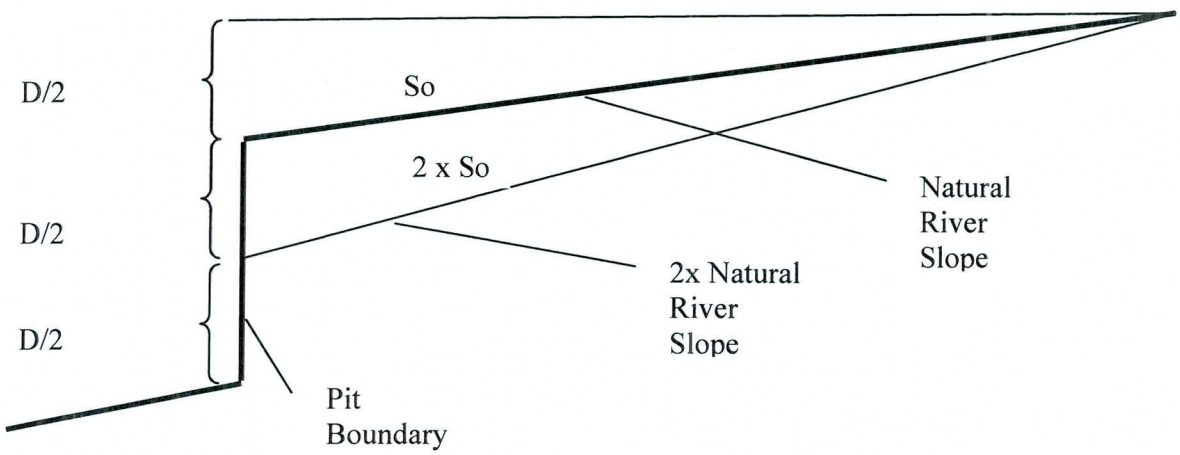


Figure 18. The Rule of Thumb Method shown Graphically.

This calculation determines how far the river's natural slope would take to drop the equivalent of the difference between one-half the pit depth and the original bed elevation). When added to the original slope the total slope is twice the river's natural slope. The conclusion of the William's paper was that the methods they reviewed varied widely but that the rule of thumb may be the upper limit. A pit on the Hassayampa River with a depth of 35 ft would produce a maximum scour depth 17.5 feet (35/2) with a maximum headcut length of 3700 ft (17.5/0.0047). The headcut depth for the pit on the Salt River below Gilbert Road would be 15 ft (30/2) and 4400 ft long (15/0.0034). These are the best headcut prediction results obtained for non-modeling methods during this review (See Tables 1-4).

Boyle Engineering Report (1980) and U.S. Army Corps of Engineers (1987)

The Boyle Engineering Corporation performed computer simulations to study the effects of in-stream gravel mines in the Salt River and demonstrated that for pits 15 to 50 ft in depth the maximum headcut distance was when the bed slope was about 1%. The equation for the length of the headcut is (assuming the bed slope is less than 1%):

$$\text{Length} = (\text{Pit Depth} / 2) * 100 \quad (3)$$

They also predicted the maximum depth of headcutting to be half the depth of the pit. Using this methodology the maximum headcut distance for the above conditions would be significantly reduced. This method does not appear to match the observed data as well as the rule of thumb method above. This methodology produces a headcut/knickpoint length of 1,750 ft for the Hassayampa pit and 1,500 ft for Salt River pit as described above. These estimates are shorter than the headcut lengths observed in the field and shorter than those calculated using the rule-of-thumb methodology described above (See Tables 1-4 for results).

Mathematical Models

A number of mathematical models have been developed to model event or long term sedimentation in rivers and streams. A number of models developed by Simons & Li were cited in their report (1989) but are no longer widely available. A few models have become the standards of the industry and are widely used. The most widely used is probably HEC-6 and HEC-6T since HEC-6 is free and HEC-6T is reasonably priced among the various proprietary modeling packages. FLUVIAL-12 is also widely applied by Dr. Howard Chang and others. Many other models have been developed but have not become as widely accepted as those reviewed here.

The current numerical models (HEC-6/6T and FLUVIAL-12) do not model the early stages of erosion as water enters a sand or gravel pit. The models all assume flow is continuous from the upstream end of the model to the downstream end of the model. This means that the pits are modeled as being full of water when the model starts the simulation and any erosion during pit filling is not modeled.

The HEC-6/6T models also do not currently allow the incorporation and modeling of the notch effect that occurs early in the headcutting process. Depending on how fast the hydrograph builds and how wide the pit is in comparison to the active channel width (i.e. the portion of the channel where active erosion is taking place) this early erosion may or may not be an important portion of the total erosion and sedimentation. For large floods this may not be too important but for smaller, more frequent floods (or for large pits that that either don't drown out or take long periods to fill) this notching effect may be a primary factor in the movement of the headcut upstream from the pit.

HEC-6 / HEC-6T

HEC-6 and HEC-6T are both widely used in sediment modeling and relatively well understood by the consulting community. HEC-6 has been used since the 1980s but has not been updated since the 1990s and has mostly been replaced by HEC-6T for modeling in Maricopa County. HEC-6T was updated by one of the original developers of HEC-6 (Mr. Tony Thomas) and has been maintained and adapted since Mr. Thomas retired from the U.S. Army Corps of Engineers. Mr. Thomas continues to update and maintain the HEC-6T model. It is based on the stepped backwater method and uses a series of stepped continuous flows to model sediment transport.

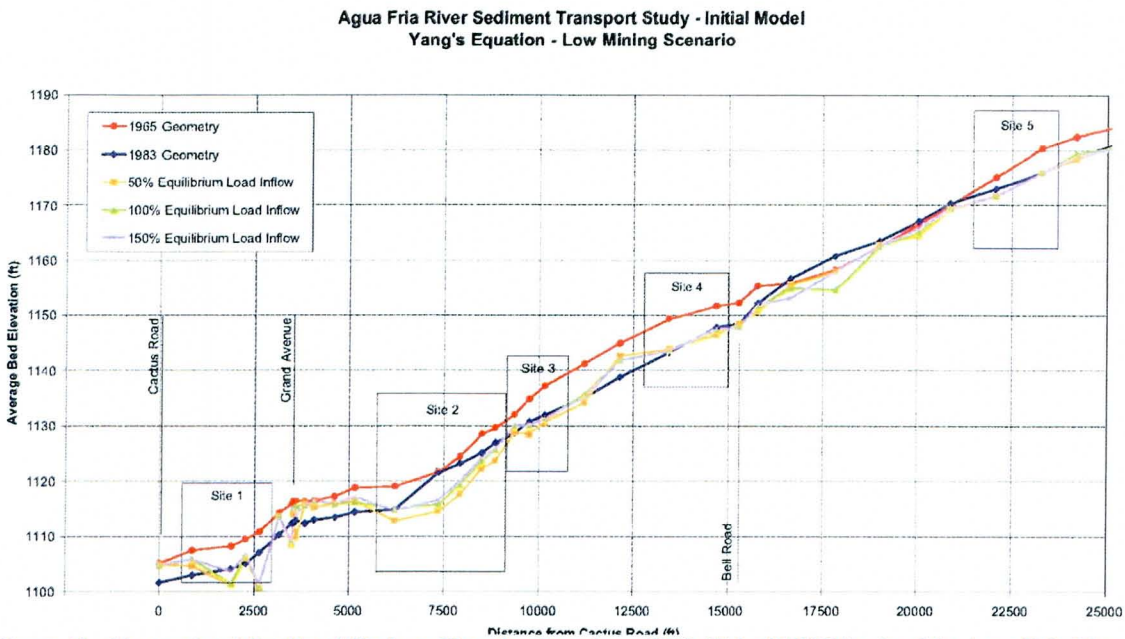


Figure 19. Observed and Predicted Thalweg Elevation Data from HEC-6T for WEST Study of the Agua Fria River from 1965 to 1983.

This means that the model is not truly fully unsteady; but results have been widely shown to be reasonable and the model is much more stable than most fully unsteady hydraulic models.

The models have been used to model challenges associated with mining including the introduction of mine tailings (sand) into a stream in Mississippi, sediment transport in the Mississippi River, and sediment transport in numerous Arizona streams and rivers. The models have been widely used not only across the United States but in Arizona and Maricopa County. The District has been using HEC-6T to assist in the regulation of sand and gravel mining operations in the rivers and washes in Maricopa County since at least 2006.

The HEC-6/6T models calculate an average erosion and deposition across the entire active bed width but only for portions of the channel which are wet. This may tend to under estimate maximum scour depths but often the average bed change is used for comparison which tends to allow a more accurate comparison of bed changes along a modeled reach. The use of the average bed elevation at a cross section will definitely underestimate maximum scour depth since it is based on an average of the wetted portion of the bed at a specified flow. Average depth values should be compared only for identical flows if meaningful results are to be obtained.

HEC-6T has been widely used by the District and was successfully applied by WEST consultants to reproduce the rivers response to gravel mining along a reach of the Agua Fria River from just upstream of Pinnacle Peak Road to Cactus Road for three different topographic data sets. Unfortunately the time period between the second and third topographic data sets (1983-1993) experienced only minor flow events but good results were obtained for the first period as shown in Figure 19. The model was set up with a dredging option turned on to remove sediment (sand and gravel) from the mined areas and reproduced the pit development. The results produced by

the HEC-6T model gave a reasonable prediction of the bed conditions between the first and second topographic data set when a significant flow event did occur. Their results are shown in Figure 19 for varying inflowing loads (WEST 2002).

Today HEC-6T is moderately suited for modeling sediment transport outside of the initial entrance of water into the pit. The normal use of HEC-6T would assume that the pit has filled with water since flow is not fully unsteady. Thus the model will not predict any erosion that occurs during the stage when the pit is filling with water. Depending on pit size this may be relatively insignificant when compared with the sediment transport during a large flood event. For small events the amount of sediment transported in the gullying and channel widening stage during pit filling may be important to the process. The maximum depth of scour at the upstream edge of the pit during a long duration smaller event could possibly be greater than the scour depth that occurs during a larger event when the pit may fill more rapidly. The extent of the active channel width must currently be set prior to the run and does not vary with flow rate.

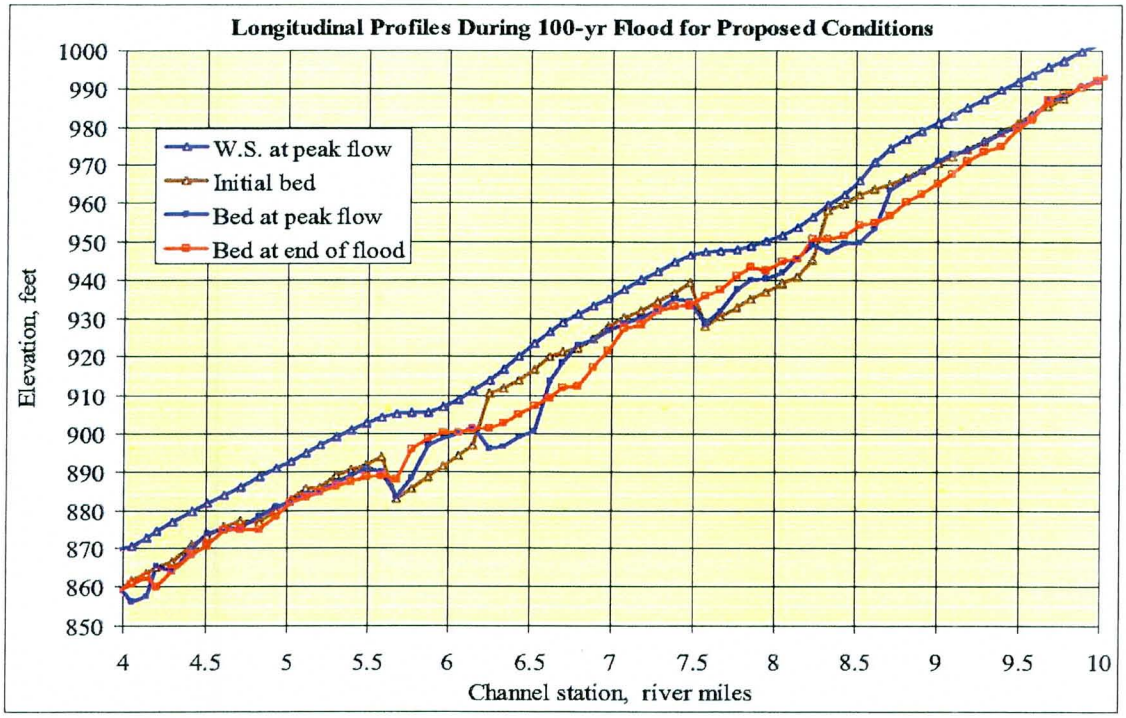
HEC-6/HEC-6T are currently recommended for long term transport modeling of pits but not for calculating maximum headcut depths or lengths during the early stages of pit filling pending further analysis and the inclusion of the notching effect in the model.

FLUVIAL-12

Dr. Howard Chang has developed a series of models over a number of years to calculate sediment transport. These models have been applied to a large number of rivers and give good results. The model has the same limitations as HEC-6/6T given above – the model does not calculate sediment transport while the pit is filling but only during conditions after the pit has filled.

FLUVIAL-12 is advertised as being a movable boundary model rather than just a moveable bed model so that the model adjusts the bed width due to erosive processes rather than having a fixed active channel width. This feature should better model the incision (notching) associated with the formation of the headcuts and tailcuts associated with sand and gravel pits. The model allows banks to fail when they exceed the angle of repose similar to HEC-6T. The FLUVIAL-12 Model appears to give good results as shown in Figure 20 for the Hassayampa River but has not, as yet, been checked against flood events with existing pits on the Hassayampa River. This task is being conducted as a part of an ongoing Hassayampa River study.

The FLUVIAL-12 model has been also been used by the District and by consultants in the Phoenix area. Areas modeled on the Salt, Hassayampa, Gila and other Rivers show good results.



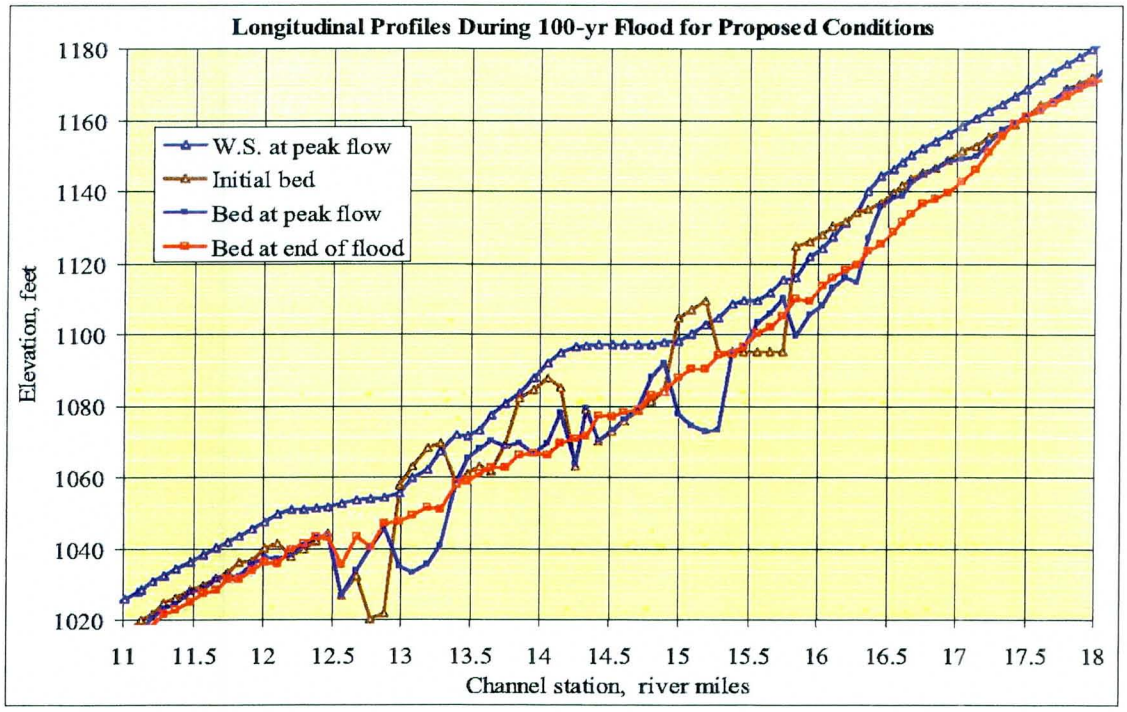


Figure 20. Predicted Bed Elevation Data for proposed mines on the Hassayampa River from Chang Report (2009).

HEC-RAS Version 4.1

A new version of HEC-RAS has been developed that calculates sediment transport. The basic approach to modeling is similar to HEC-6T since it was developed in conjunction with Mr. Tony Thomas, the developer of HEC-6 and HEC-6T. This performance of this model will also be tested in a companion task focused on the Hassayampa River.

Model Summary

HEC-6, HEC-6T, and FLUVIAL-12 have been used and accepted in Maricopa County for modeling the erosion impact due to the sand and gravel mining operations as part of floodplain use permit process. The new HEC-RAS with sediment transport feature is being evaluated for its applicability. Engineers who want to use other models for obtaining a floodplain use permit in Maricopa County should obtain prior approval from the Flood Control District of Maricopa County.

It may be noted that HEC-6 and HEC-RAS are public domain software and are available for free download from the U.S. Army Corps of Engineers Hydrologic Engineering Center in Davis, California (http://www.hec.usace.army.mil/software/legacysoftware/hec6/hec6.htm; http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html). HEC-6T and FLUVIAL-12 are proprietary software and are not free (http://www.mbh2o.com/hec6t.html; http://chang.sdsu.edu/fluvial.html).

Summary and Recommendations

A large number of papers were reviewed as a part of this process. Many of those papers discuss the geomorphic impacts of sand and gravel mining on rivers but contain no basis for predicting the magnitude of the impacts. Most research into the propagation of headcuts/knickpoints in recent years has concentrated on the movement of headcuts in agricultural fields or as it relates to levee failure or the erosion of earth and soft stone emergency spillways. This data is not as applicable to the problems of predicting the impacts of mining in sand and gravel bed rivers in Maricopa County.

It appears that it may be time for a comprehensive compilation of headcut and tailcut data that was not available to Simons & Li that may either validate the tailcut methodology or show the need for the development of new methodology. The calculated headcut lengths for the current methods have been shown to be too short by one to two orders of magnitude. It is anticipated that with available data a better methodology could be developed that will better predict headcuts lengths in central Arizona rivers.

The erosion of material downstream of the pit (tailcuts) should be adequately handled by existing sediment transport models since it is a standard erosional process downstream of a sediment sink. The long term migration of knickpoints should also be handled adequately by existing sediment transport models since the problem is a typical riverine modeling problem. It is interesting that the most basic methods currently seem to produce the best results with the rule-of-thumb method and the original Boyle study appearing to produce results which best match the

field observations. A significant challenge is predicting the maximum scour depth near the pit if the pit doesn't drown out.

The use of methods similar to those developed by Hanson et al. (2001) may be of value but have not been evaluated to this point since they were developed for vertical or near vertical headcuts. The process is based on the physical properties of the soils and may be extendable to the conditions that exist at the entrance to gravel pits. A discussion with Dr. Hanson resulted in his recommendation that as currently formulated his method would likely not apply to the situation in Maricopa County.

In the interim a recommended method might be to use the ADOT methodology to estimate erosion during the time the pit is filling and then to use either HEC-6/6T, FLUVIAL-12, or the new version of HEC-RAS to model the sediment transport processes once the pit has filled.

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