COACHELLA VALLEY WATER DISTRICT
GUIDELINE K-3
SCOUR CALCULATION GUIDANCE

K-3.1 General Requirements

The calculation of scour will be required for the design of flood control channels with erodible beds and for structures proposed for the CVWD's existing stormwater facilities – such as bridges, bank protection, pipelines, encroachments, or other instream features. These calculations may also be required to assess potential impacts of projects on existing facilities. For instance, an encroachment into a stormwater facility might result in lower minimum scour elevations that will require additional stabilization for existing bank protection structures.

K-3.2 Description of Scour

Scour generally refers to the fairly localized lowering of the channel bed by flowing water, often during a single flood. It is often defined as a lowering of the channel bed below its normal level. Scour includes the bed lowering that occurs over sizeable areas of bed from that occur during the passage of a large flood (often called "natural" or "general" scour) and the bed lowering over small areas that results from the interaction of the flood with structures or features within the channel (local scour).

Scour is classified into various processes or types. For the purposes of this guideline, we have adopted the following categories:

- Natural or general scour, consisting of the bed adjustments that occur during the passage of a flood. These adjustments may be more severe where bends or other natural features interfere with flow patterns
- Constriction scour, where a river or channel is narrowed by structures such as bridges, encroachments or natural features or where levees or berms now contain flow within the channel that previously spilled onto the floodplain
- Local scour, that results from the flow interacting with a structure such as a bridge pier, abutment, intake, spur or other structure
- Channel incision (profile degradation), defined as a long-term lowering of the stream bed towards an equilibrium gradient. Incision may be a result of geological or human-induced changes in flow, sediment supply or sediment character, or other factors.

Channel incision is different from the first three scour processes. It is progressive and often occurs slowly. On the other hand, natural, constriction and local scour generally reach a maximum near the peak of large floods and the bed may subsequently re-fill or re-deposit to about previous levels on the falling limb of the hydrograph. This pattern of scour and fill is particularly common in sand bed channels.

Scour depths are often calculated separately for the four processes above and then are summed to calculate the total maximum depth of scour. For instance, at a bridge crossing, the maximum scour depth is the sum of the channel incision, the natural scour (or constriction scour if the bridge narrows the waterway), and the local scour (if piers and abutments are in the waterway) that occurs below the bed elevation reached by incision and natural scour.

Plunging jets or complex flows over the crests of drop structures or grade stabilization structures, such as are found along the WWR/CVSC, may also be an important source of scour.

The depth (and length) of the scour hole downstream of the structure will be calculated separately from the scour components described above. Note that bed profile incision may considerably increase the maximum depth of the scour hole calculated below these structures by lowering tailwater levels.

K-3.3 Previous Predictions of General Scour or Toe Down Depths

Predictions of toe down depths for bank protection along the WWR/CVSC were previously prepared by Bechtel Corporation (1995). In their report, the general or natural scour component was calculated from HEC-6 sediment transport studies for the design flood hydrograph. Where required, local scour associated with bends, bridges, drop structures or other features was then added to the general scour to predict toe down depths for bank protection.

Their results show maximum depths of scour or toe down depths of about 6 to 12 feet below the observed channel bed. While CVWD does not recommend this method for calculating maximum scour depths, the recommended scour depths provide a starting point for further analysis.

K-3.4 Definitions and Design Standards

The following subsections provide CVWD's recommended definitions for scour depths and their flow standards for the design of different structures.

Definitions
CVWD has adopted the following definitions for terms that describe scour:

- Scour (or scoured) depth: The depth from the water surface to the lowest scoured point below the bed for a particular flow or discharge. This scour depth may be the sum of the scour from several different components.
- Maximum scour (scoured) depth: The scour depth calculated or predicted from the design flow and adopted for design of a particular structure.
- Minimum scour elevation: The minimum scour elevation is calculated by subtracting the maximum scour depth from the design water surface elevation and is expressed with its associated vertical datum.
- Depth of Scour: The elevation difference between the design or normal bed elevation and the minimum scour elevation.

CVWD requires that scour depths are expressed as “minimum scour elevations” in order to simplify comparison to toe elevations of existing structures, top of pipeline elevations, or other features along the channel.

The general design condition for protection of the CVWD stormwater facilities is to assume the maximum outflow from the storm drain, both with and without flow in the stormwater facility and to provide appropriate protection to sections of the bank or bed that might erode under these design conditions, considering how flow will be directed once it leaves the outlet.

Design Flows for Maximum Scour Depth
The CVWD has adopted the following standards for design flows for particular structures:

- Bank Protection: Maximum scour or toe down depths (see Guideline K-2) are calculated for the 100-year peak flood
- Bridges, Grade Stabilization Structures or other Control Structures: Maximum scour depths are calculated for the Standard Project Flood (SPF)

K-3.5 General Discussion of Scour Calculations

The prediction of scour is very complex at the theoretical level. Local scour has been studied experimentally for structures like bridges and piers and satisfactory empirical techniques for calculating design maximum scoured depths are available from a number of publications. The US Federal Highway Administration (Arneson et al 2012), as well as number of other publications, provide satisfactory methods for estimating scour at bridges.

General or natural scoured depths in arid, semi-natural channels such as the WWRSC/CVSC, where banks are often protected and flows are contained by channel banks or levees, have been less frequently studied and design guidance is limited. There is also no local experience with scour during extreme floods. CVWD recommends a regime approach to scour depth calculation in this situation. Details are provided below; further background on the regime approach is provided in TAC (2004) and May et al (2002).

CVWD is willing to consider other approaches to scour depth calculation. However, it is important to note that the descriptions of scour calculations provided in some general guidebooks are incorrect. We recommend referring to the original publications to ensure that formulae are expressed correctly and that the approach is suitable for the particular application. It is particularly important to recognize that some scour calculations developed for naturally-formed alluvial channels will not be appropriate along sections of the WWR/CVSC where channel widths are constrained by bank protection and are much narrower than would be expected for an alluvial channel with that peak discharge.

CVWD is generally not willing to consider sediment transport and bed level calculations (based on HEC-6T or HEC-RAS) over the design hydrograph as an estimate of maximum scour depth. The hydraulic calculations that underlie the sediment transport calculations are not of sufficient detail to provide useful or reliable predictions of scour associated with structures nor will they provide reliable predictions in bends. It is possible that sediment transport calculations will provide estimates of general or natural scour in straight sections of the WWR/CVSC that are distant from any structures, bends or constrictions. Here, scour depths would be estimated as the difference between the normal and the minimum bed level during passage of the hydrograph (not the bed level following the flood). Such a calculation procedure is very expensive and is likely only to be accepted if it is consistent with the regime calculations described above.

K-3.6 Maximum Scour Depths for Bank Protection

The typical situation for calculating maximum scour depths for bank protection works will be in relatively straight section of channel, distant from bridges or other structures, where the maximum scour depth results mostly from natural or general scour. The first subsection discusses the recommended procedure for the typical situation discussed above. The following sections describe adjustments for channel curvature and channel encroachment and discuss channel incision (profile degradation).

Natural Maximum Scour Depths

CVWD has adopted the Blench regime equation, as follows, for calculating scour depths:

$$d_{fo} = (q_f^2/F_{bo})^{1/3} \qquad \text{(K.3-1)}$$

In this equation, d_{fo}, is the regime depth (feet) below the design water surface, q_f is the unit design discharge (ft^2/sec) calculated from the 100-year water surface width and the 100-year design discharge, and F_{bo} is the zero-bed factor (ft/sec^2), which is a function of the median grain size of the bed material. The regime depth is the expected channel depth for the particular median grain size and discharge, assuming that these materials extend to the depth of scour and that the flood hydrograph is of sufficient length to move the material required to achieve the depth. Inerodible or less-erodible subsurface sediments may limit development of this depth.

Median bed sediment sizes vary along the WWRSC/CVSC. Based on samples from the surface and five feet below the bed, Bechtel (1995) determined that median sizes declined from about 0.9 mm near Palm Springs to about 0.2 mm near Rancho Mirage, and then to 0.15 mm near the Thermal Drop Structure. Bechtel's Figure 4-1 provides general guidance on median sizes for calculation of the zero-bed factor. However, we recommend sampling of bed material near the project site to calculate a depth-weighted median size and inspection of boring logs to identify subsurface materials that might limit scour. An example is described below.

Logs of subsurface soils to 25-foot depth in the WWRSC/CVSC from trenches near the Fred Waring and Jefferson Street Crossings (LandMark 2006) showed depth-weighted median sizes of 0.26 and 0.1 mm. The trench near Fred Waring Drive exposed erodible sand deposits to maximum depth and the median size from this excavation was adopted for calculations of the zero-bed factor, which was estimated to be almost 1. The zero-bed factor for a particular median size can be obtained from TAC (2004) or Pemberton and Lara (1984). CVWD will provide advice on calculating the zero-bed factor, if required.

The trench near Jefferson Street exposed silty clay at depths of about 14 feet below the bed, below a layer of silt sand, which lowered the depth-weighted median size to less than 0.1 mm. This lower median size will reduce the zero-bed factor and increase the calculated regime or scour depth compared to the previous trench. However, it is likely that the silty clay will slow the development of the depth of scour and that scour will not necessarily penetrate the silty clay strata. Assuming that soil characteristics are such as to limit erosion, it could be assumed that geological characteristics will limit scour to no more than 14 feet below the bed. For this example, the maximum scour depth would be the lower of the calculated maximum scour depth or the 14 feet limit imposed by the less erodible subsurface material.

The maximum scour depth, d_s, is then calculated by applying a Z-factor to the regime depth from Equation K3-1. The maximum scour depth below the design discharge water surface is then:

$$d_s = Z^* d_{fo} \qquad \text{(K3-2)}$$

In the above equation, Z varies depending on the general situation in the channel. For the reasonably straight reaches under discussion CVWD recommends Z = 1.25. Adjustments for bends and constrictions are discussed in the following subsections.

As discussed above, this maximum scour depth is the maximum that could be achieved in erodible material of the typical size adopted for the zero-bed factor calculation. Where subsurface investigations have identified inerodible or less-erodible strata the maximum scour depth may be adjusted to the lesser of the calculated scour depth or the depth to the top of the less erodible strata from the bed plus the 100-year water depth. Where subsurface investigations have not been undertaken, CVWD recommends adopting the maximum scour depth calculated from Equation K3-2 for design of bank protection.

CVWD requires that “maximum scour depths” be expressed as “minimum scour elevations” that are calculated by subtracting the maximum scour depth from the appropriate design water surface elevation.

Adjustments for Curvature

It is generally recognized that maximum scoured depths in bends will be greater than maximum scour depths in upstream straight sections. Consequently, adjustments for bend curvature or tightness will need to be incorporated when calculating maximum scour depths for cutoff walls on the outside or concave bank of bends.

A number of different procedures have been developed to estimate scour depths for stabilized bends and Maynord (1996) provides a recent summary. Many of these procedures were developed for alluvial channels and are not necessarily applicable to the WWRSC/CVSC where natural widths are often much constrained. Instead of adopting these procedures, CVWD recommends extending the regime approach described above, by adjusting the Z-factor in Equation K3-2 to correct for deeper potential scour. The recommended Z-factors (TAC 2004) are:

- Moderate bend, Z=1.5
- Severe or tight bend, Z=1.75
- Right angle bend or direct impingement, Z=2.0

While the above method has been satisfactorily applied in various situations, it has not been confirmed that it will apply to the stormwater facilities in the Coachella Valley. Other methods may be appropriate; however, we recommend that the design engineer consult with the CVWD before adopting alternative ones.

Adjustments for Contraction or Constriction

Where a proposed project will encroach into a stormwater facility and narrow the waterway or where overbank flow will be maintained in the channel by constructing berms or levees, it is expected that maximum scour depths will increase over those calculated for existing conditions. For long constrictions where the design flow is maintained within the channel and where new regime conditions will establish, the with-project maximum scour depth can be re-calculated from Equations K3-1 and K3-2 by adjusting the topwidth for the unit design discharge. Alternatively, the following equation from Neill (1973) can be adopted to calculate the revised regime depth:

$$d_p = d_{fo}(q_p/q_f)^m \qquad \text{(K.3-3)}$$

Here, d_{fo} and q_f were defined earlier; d_p is the with-project regime depth, q_p is the with-project unit discharge, and m is an exponent, set to 0.67 for sand channels. The project unit discharge may require adjustment for a narrower top width or for increased flows where overbank flows are now contained. The re-calculated regime depth will be multiplied by the appropriate Z-factor to calculate the with-project maximum scour depth.

CVWD will consider alternative procedures to calculate the maximum scour depth under contraction. Melville and Coleman (2000) provide a chapter on constriction scour and this topic is also addressed in other publications.

Bed Incision (Profile Degradation)

Bed incision refers to the long-term adjustment of the bed profile towards some equilibrium gradient. It occurs over long reaches and is progressive, so that it does not reverse after the passage of a flood. The lowering of bed levels tends to start just upstream of a hard point or grade control structure and progress upstream towards the next hard point.

Very little is known about the adjustments that are underway along the WWRSC/CVSC in response to geological or man-induced changes. Studies of historical profiles near Jefferson Street have indicated flattening of bed profiles between grade control structures or hard point such as low water crossings over the past forty years or so. It is very useful to compare historical profiles along the WWRSC/CVSC and CVWD recommends such an analysis as part of studies of proposed channel modifications in order to gain an understanding of long-term trends and project them into the future.

NHC (2011) provides an evaluation of the combined effects of local scour and incision between grade control structures on the Coachella Valley Stormwater Channel (CVSC) on selection of toe down depths and provides recommendations for analysis. CVWD recommend referring to this document as guidance for considering the bed incision component of total scour for the CVSC and as general guidance for bed incision analysis on other flood control channels.

There may be special situations, such as downstream of sediment traps, where sediment supply has been greatly reduced, which may result in very rapid bed incision in easily erodible sediments. At these sites, slope profile adjustments during the design flood should be considered carefully as part of the total scour depth.

K-3.7 Maximum Scour Depths for Bridges and Control Structures

At bridges and at control structures, the CVWD recommends that maximum scour depths be calculated for the Standard Project Flood. This standard has been adopted to ensure that these structures will survive extreme floods. The maximum scour at the bridge with no grade stabilization works will then consist of incision, general or natural scour in the channel as calculated from the Blench regime equation, an adjustment for contraction scour through the bridge opening (if applicable), and the local abutment and pier scour (if applicable). Where a grade stabilization structure has been or will be constructed beneath the bridge, separate calculations are required to consider toe down depths downstream of the bridge.

The following subsections provide CVWD recommendations for scour calculations at bridges and other structures and for determining the transitions between the maximum scour depths for bridges and structures and the upstream or downstream bank protection.

Scour Depths at Bridges
CVWD recommends that constriction scour and the maximum local depths of scour at piers or abutments be calculated following the procedures described in Arneson et al (2012). General or natural scour will be first calculated with the procedures in Section K.3.6.

Scour Depths for Other Structures
The most common structures for scour calculations will be grade control structures. These structures generally consist of inerodible cross-channel sills with upstream and downstream sloping faces. They are often referred to as “grade stabilization structures”, “drop structures” or “hard points”.

For scour analysis, they can be treated as “low head” structures where scour will result from a jet plunging over their downstream faces (Breusers and Raudkivi 1997; May et al 2002). Scour calculations focus on the maximum (equilibrium) depth and length of the scour hole that develops downstream of the structure. The maximum depth and length are used to define the minimum elevations for the downstream face of the structure and the depth and extent of toe down for concrete slope protection on the banks downstream of the structure.

A variety of specialized publications describe procedures for calculating scour depths for grade control structures. The various equations produce quite different results, depending on the values selected for coefficients and exponents, and there does not appear to be reliable guidance on this topic. Previous grade control design studies for the CVSC adopted Bormann and Julien (1991) for scour calculations but other publications may provide better results in other parts of the regional flood control system. We recommend checking calculations from one equation against other applicable ones and verifying the equations from the original sources. For preliminary estimates of scour depths, we recommend calculating the natural scour for the SPF with the unit discharge based on the width of the grade control crest, the downstream water levels, and $Z = 1.25$. This also will provide a rough check on maximum scour depths calculated from equations developed for grade control structures.

Given the uncertainties in these calculations, the CVWD recommends a physical model for major projects, for non-standard designs, or where a serious hazard might potentially occur from scour downstream of the structure.

Transition from Bridge or Structure Maximum Scour Depths

Given that minimum scour elevations at a bridge or grade control structure will be based on the SPF and that upstream and downstream bank minimum scour elevations will be based on the 100-year peak flow, it is necessary to define the extent of SPF scour in order to design transitions from one to the other.

For bridges that are not associated with a grade control structure, the extent of SPF scour protection should be about 25 times the channel depth to the downstream side and about 15 channel depths to the upstream side. For typical SPF depths of 20 to 25 feet, the SPF protection will extend about 500 feet downstream and 300 feet upstream of the bridge. These distances should be measured from the downstream and upstream edges of the bridge, along the channel centerline.

For a grade stabilization structure or a bridge with a grade stabilization structure, the SPF scour elevations will not need to extend upstream. Instead, the toe of any bank protection can be set to the 100-year minimum scour elevation.

On the downstream side, the extent of the SPF scour elevations will be defined by the typical geometry of the scour hole associated with the grade stabilization structure. Based on observations in Bormann and Julien (1991) and D’Agostino and Ferro (2004), the geometry of the scour hole is a function of the maximum scour depth, ds. For design, the longitudinal scour geometry would be:

- Minimum Distance to Bottom of Hole = $2d_s$ to $3d_s$
- Typical Distance to Bottom of Hole = $5d_s$ to $6d_s$
- Typical Distance to Downstream end of Hole = $10d_s$ to $12d_s$

The above dimensions provide starting information for extension of the SPF scour protection downstream of the stabilization structure. We recommend discussing analytic procedures with CVWD prior to starting any detailed analysis.

K-3.8 Submissions

The scour analyses for the particular project will be incorporated in the Hydraulic Design Report prepared as the preliminary submittal for the project. If appropriate, separate reports may be submitted for existing conditions and with project conditions.

K-3.8 References

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