Sediment Transport Modeling for the Colorado River Aqueduct Conduit Erosion Control Improvement Project

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Introduction

The Colorado River Aqueduct (CRA), which is a reinforced concrete subsurface conduit, is experiencing erosion and loss of adequate cover at various locations along its alignment through the San Gorgonio Pass in Riverside County, California. Consequently, the Metropolitan Water District of Southern California (MWD) desired analyses to inform erosion protection design recommendations at nineteen (19) identified areas of concern (see Figure 1). The CRA's location within alluvial fan morphology presents sediment transport challenges that needed to be addressed to analyze the scour conditions and develop appropriate mitigation measures. This study focuses on the sediment transport modeling approaches, methodologies, and software (e.g., HEC-RAS) implemented to design erosion protection for this critical piece of infrastructure.

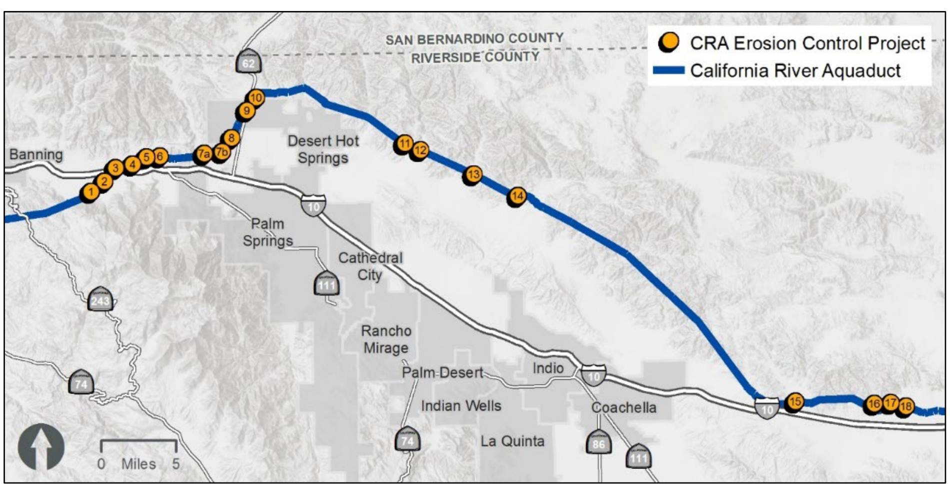

Figure 1. Study Location Map

Hydrology

Using the United States Army Corps of Engineers (USACE) HEC-RAS (version 6.3.1) software, hydrologic calculations were prepared for the 10-, 25-, 50-, 100-, and 500-year storm frequencies and 6-hour and 24-hour durations. The rain-on-grid functionality of HEC-RAS was implemented to account for the impacts of the alluvial fan morphology, as well as other diversionary features such as guide levees, roadways (e.g., Interstate 10) and hydraulic structures. NOAA Atlas 14 precipitation depths, combined with guidance in the currently effective Riverside County Flood Control and Water Conservation District (RCFC&WCD) Hydrology Manual (dated 1978), was used to prepare the storm hyetographs and infiltration curve numbers. The 24-hour duration storms consistently produced larger peak flow rates and volumes at selected CRA concentration points compared to the 6-hour durations. Due to the critical nature of the CRA, the more conservative 24-hour storm events were used for the subsequent hydraulic models.

Hydraulics

Two-dimensional (2D) HEC-RAS (version 6.3.1) hydraulic models were developed for the 19 identified study areas to inform the sediment transport modeling. The 10-, 25-, 50-, 100-, and 500-year, 24-hour hydrographs were extracted from the ROG hydrology models and input as inflow boundary conditions for the hydraulic models. The preliminary results indicated supercritical flow was present throughout most of the primary flow paths. The generally medium caliber sand to gravel available in the bed, combined with the forcing hydraulics, led the project team to believe that supercritical flow might only persist for a small period of time. The roughness values were then adjusted within a specified tolerance to create a subcritical/transitionary flow regime that was felt to be representative throughout the storm event duration. Limited avulsion analyses were also performed for high-energy channels to either bolster design values at the known problem areas or identify potential flow paths which may cause future degradation issues at the CRA.

Sediment Transport

General and Long-Term Scour

General and long-term degradation were the primary mechanisms determined to govern the scour depths for the proposed design mitigation measures. To quantify these depths, quasi-unsteady one-dimensional (1D) sediment transport models were developed using HEC-RAS (version 6.3.1). The 2D hydraulic models were used to inform the flow rates specified in the sediment transport models: The 500-year resultant hydrographs were used in the general scour model and a series of 10-year hydrographs, representing the approximate channel forming discharge in a semi-arid environment, were used to simulate the long-term scour potential at the CRA.

2D hydraulic model stream power spatial maps were generated to help identify the most geomorphically active areas of the alluvial fans. Typically this indicated that the stream channels identified through the CRA locations of concern were subject to the most critical scour events. Therefore, ineffective flow boundaries were designated at the approximate channel forming discharge limits because this was both physically and numerically (e.g., it reduces the hydraulic complexities of transitioning a 2D to a 1D model in an alluvial fan environment) supported.

The upstream and downstream model limits were located far enough away from the CRA crossing to remove potential boundary condition impacts. In general, this resulted in models which extend approximately 2,000 to 6,000 feet upstream and approximately 100 to 2,000 feet downstream of the crossing. The upstream freeboard is particularly important due to the uncertainty of the inflowing load's gradation and concentration.

The project team performed field investigations in May and June 2021 to document the morphological features at the crossings. Sediment samples were also collected during these investigations to understand the bed and inflowing sediment load gradations; bed samples were collected at depths up to approximately one foot and where available and samples at depositional feature (e.g., mid-channel bars) were collected to approximate the inflowing sediment load gradation. Figure 2 illustrates a representative bed sample at one of the CRA site locations.

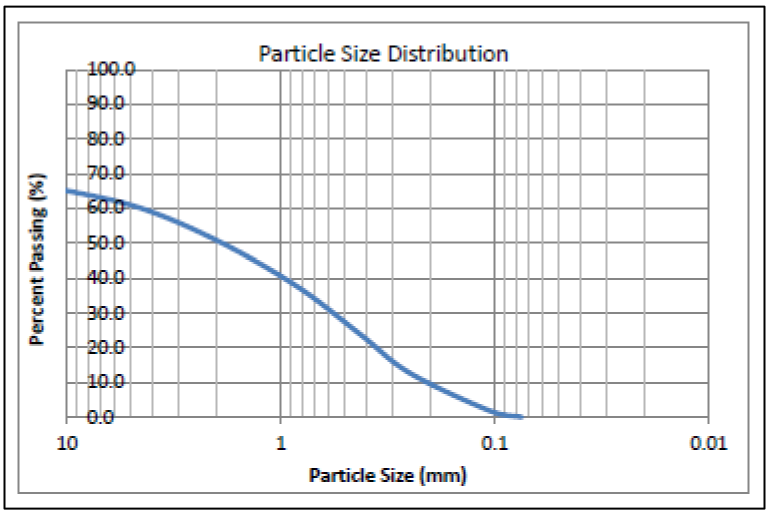

Figure 2. Sediment bed gradation at selected site

Review of sediment samples from the 19 study areas indicated bed material in the range of coarse sand to coarse gravel, with inflowing load approximated as a medium sand (where applicable). The concentration of the inflowing load is also source of uncertainty. For conservatism, a very low concentration of approximately 500 mg/L was set for the entire range of flow values. Additionally, the approximately 2,000 feet to 6,000 feet of freeboard from the upstream model boundary to the CRA crossing provides opportunity for the model to generate its own load, further reducing modeling subjectivity.

The selected model transport functions at each site were based primarily on the sediment caliber and hydraulics. For example, it was noted that the eastern site bed material was generally coarser than the western sites. Therefore, Laursen-Copeland, Wilcock-Crowe, and Meyer-Peter Müller were the functions typically evaluated for more eastern sites. Yangs total load equation, which is applicable and oft used for sand sized particles, was usually selected for the western site locations. Figure 3 and Figure 4 illustrate the channel bed profile results of various sediment transport functions from preliminary 500-year storm event and long-term simulations, respectively, at selected locations.

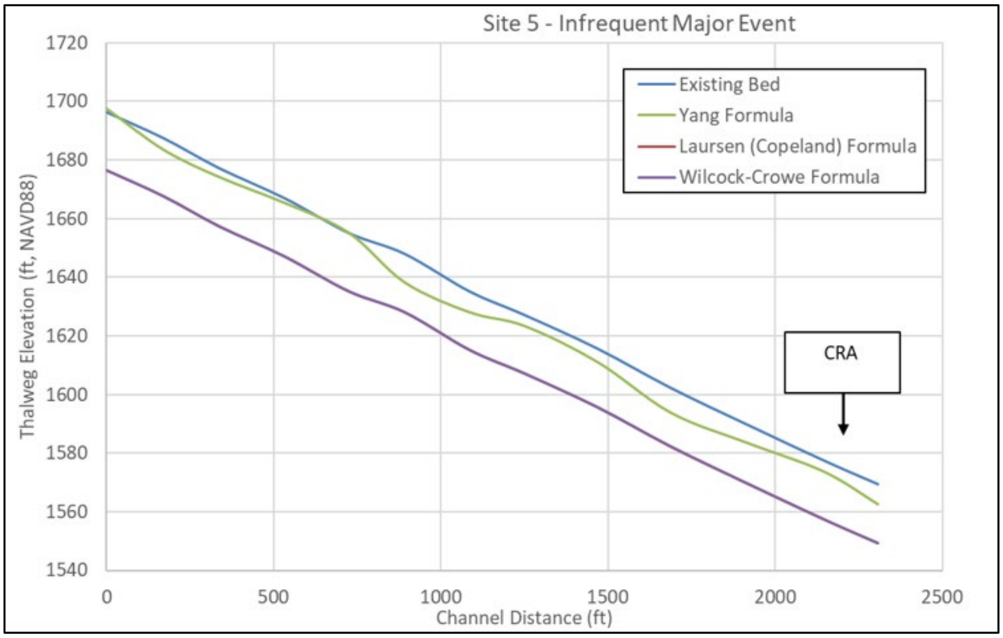

Figure 3. Maximum Preliminary Channel Invert Profile for the 500-year Storm

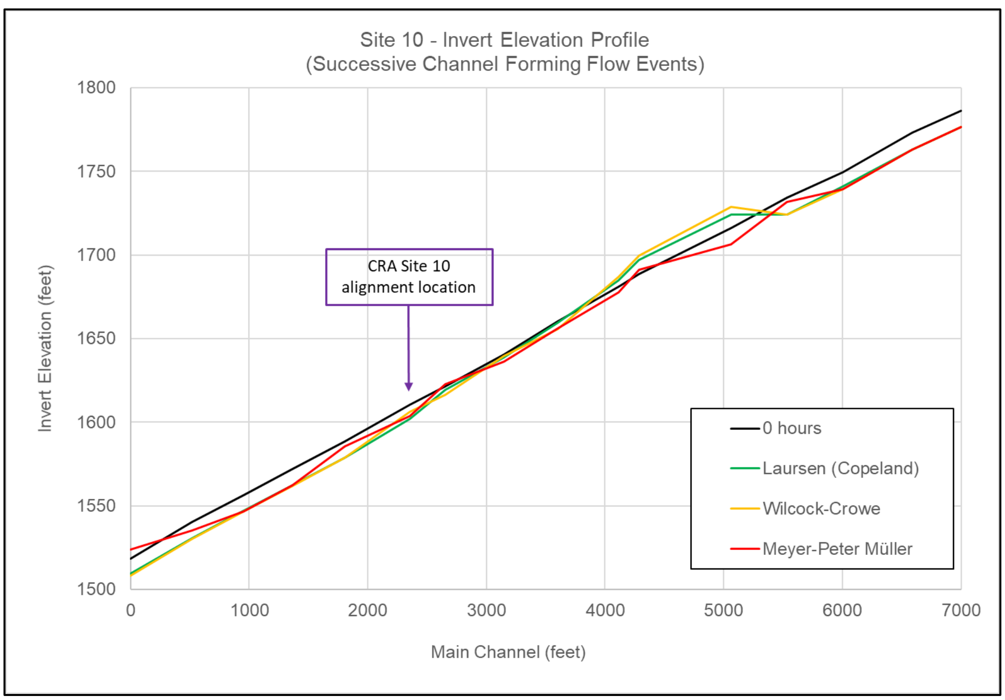

Figure 4. Preliminary Channel Invert Profile at conclusion of Long-term Simulation

Other Scour Mechanisms

Depending upon the site location, other scour mechanisms (e.g., contraction and bend scour) were considered for inclusion in the final design depth. For all sites, bed form scour and low-flow incisement were considered. Kennedy's antidune equation was implemented as follows to consider bed form scour:

$$h_a = 0.014(2\Pi V^2)/g \quad (1)$$

$$y_s = 0.5h_a \quad (2)$$

where:

h_a	=	antidune height (feet)
V	=	velocity (feet/second)
g	=	gravitational acceleration
y_s	=	scour depth (feet)

Due to the critical nature of the CRA, the low-flow incisement depth was assigned a value of two feet.

Conclusions

The total scour depths at each site (i.e., 1 through 19) were determined from the summation of the various scour components (e.g., long-term, general, bedform, low-flow incisement). These depths were then used to inform the mitigation design at each site.

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