PHYSICAL MODELING ON THE EFFECT OF A HORIZONTAL ARMOR BLANKET FOR GRADE CONTROL STRUCTURES

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ABSTRACT

Grade control structures are often used in alluvial channel to limit the extent of channel-bed degradation and are economical compared to the stilling basins which would otherwise be required for similar hydraulic structures. The buoyant jet associated with the flow over the crest of these structures will impact the downstream streambed and dissipate energy by excavating a scour hole. An important aspect of the design for grade control structures is the prediction of the local scour that will occur downstream of the structure since adequate precaution must be provided to prevent failure, especially from undermining. Numerous empirical relationships and methods have been developed to predict the depth of local scour associated with the falling jet from a grade control or drop structure, however, none of these procedures addresses the application of a horizontal armor blanket downstream of the structure crest to reduce the effect of scour. This study presents a physical modeling program completed to **compare** the erosion associated with various design alternatives of grade control structures in alluvial channels

The experimental setup evaluated and compared the erosion patterns in a moveable streambed with several different alternatives designs. The intended objective of the modeling program is to utilize the results in developing engineering judgements for the design of grade control structured toe-down requirements if a horizontal armor blanket is applied. The model will assist in providing design requirements for (1) the minimum length of armor blanket, (2) armor gradation requirements, (3) allowable toe-down reduction for condition without armor, and (4) armor blanket thickness. The dimensions and scale of the model are based upon providing similitude through the application of the Froude Law. The general design of the model requires selecting scales and materials that will result in bed movement similar to that in the prototype for the estimated discharge range. The stream bed material selected for the model was based upon utilization of the fall velocity for the similitude criterion. The moveable bed model utilized a scale of **1:16** and evaluated the performance of one grade control structure located in a portion of the channel between two other grade control structures. An optimization program was developed for the design of the armor blanket so that the length minimized the potential failure hazards and would result in a cost effective configuration. The results of this study are discussed with relationship to current standard empirical designs associated with grade control and drop structures, also the field application to a large regional flood control project in Indian Wells, California.

INTRODUCTION

Control of long term channel degradation in alluvial streams with high sediment transport capacities and excessive velocities can be accomplished through incorporation of grade control structures into the channelization program. In-stream grade control structures establish fixed elevation in the alluvial streambed which assists in long-term stability through development of the anticipated "equilibrium slope" and limits the maximum potential streambed degradation. Grade control structures may also be incorporated to provide protection to in-stream facilities which may be susceptible to scour such as bridges. The location or spacing of the crests for each grade control structure is limited by the maximum allowable drop height. An important consideration in the design is prevention of a common failure mechanism through undermining downstream from the erosive action of the local scour and also the general long term scour. Common features which can be incorporated into the design of the grade control structure to prevent failure from undermining include a toe-down or cutoff which extends to the maximum anticipated scour depth and the use of a rock armor blanket in the scour hole area. These designs rely on accurately evaluating the magnitude of the anticipated local scour depth through the application of a variety of available empirical scour equations which generally provide considerable variation of the results.

The general hydraulics involved with the formation of the scour hole downstream of the grade control structure relies of the dissipation of the energy associated with the jet impacting the streambed. The free jet disperses upon entering the tailwater, but the diffused flow velocity exerts shear stress on the streambed particles. Sediment is removed from the impingement region and local scour progress when the applied shear stress exceeds the critical shear stress. Scour occurs when the rate of particle removal exceeds the transport rate into the scour hole. An equilibrium condition is reached for the hole formation as the rate of scour approaches zero.

AVAILABLE LOCAL SCOUR PROCEDURES AND EQUATIONS

Numerous investigator have developed empirical relationships regarding estimates for local scour under a falling jet. Mason and Arumugam (1985) provide an excellent summary of the available formulas, over thirty, which have been generally classified in several basic forms. The flow conditions associated with all local scour phenomena has a large influence on the extent of scour. This geometric dependance has been a major reason for the large number of scour equations, each equation being developed for a different flow geometry. A large group of formulas express scour depth, D, in terms of the head drop from upstream to downstream water level H, the unit discharge q, and in some cases the characteristic particle size of the bed material, d. These formulas generally take the form:

One of these general local scour equations which follows this format is the Veronese method (1937) which is illustrated in publications by the USBR as follows:

The updated formula by Mason and Arumugam (1985) indicated that the most sccurate form of the expression for calculating scour depth is:

A more recent evaluation of scour associated with grade control structures was prepared by Borman and Julien (1991) who based their relationship on two-dimensional jet diffusion and particle stability. The advantage of this relationship is that it accounts for the angle of the jet impingement on the stream bed, which is useful in the case of a sloping/chute grade control. The equation is valid for structures with a downstream face between vertical and 1.3. The relationship for the equilibrium scour depth was given as follows:

Application of any of the empirical formulas for a particular design will yield variable results. In addition, none of the procedures provide a method to quantify the effect of artificial armoring to reduce the depth of the scour hole.

PROJECT BACKGROUND AND PHYSICAL MODEL OBJECTIVE

The design of flood control facilities utilizing a series of grade control structure were required for a new development, The Reserve, within the City of Indian Wells and Palm Desert (California). The project site is located on a large active alluvial fan with a tributary regional watershed area of over 46 square miles that is subject to historic flooding, carrying significant amounts of sediment and debris. Protection of the proposed development from these flood hazards was addressed through the planning of a comprehensive flood control program which will utilize a combination of structural control measures and channelization to achieve long term stabilization for this portion of the alluvial fan. Flood protection is a key feature controlling the project design and results in one of the dominant construction cost items. A physical modeling program was prepared to evaluate the design requirements for the **twelve grade control structures**, each with a net vertical drop of 6.5 feet, in the alluvial channel system. The proposed grade control structures would consist of a reinforced concrete crest which would extend across the full channel width (220 feet) and a 1:1 sloping chute which would be embedded below the streambed to provide adequate toe-down. The model specifically investigates the modification to the erosion patterns associated with alternative designs for the grade control structures. One of the primary alternatives evaluated was the application of a horizontal armor blanket downstream of the structure to develop an artificial armor of the scour hole.

The environmental permitting agencies required that the project maintain the existing stream alignments as alluvial channels, which eliminated the application of a rigid channel system. The alluvial stream mechanics became one of the principal effects which were carefully analyzed through the application of empirical relationships and sediment routing models. Grade control structures were recommended as a principal influences to achieve a long-term stable alluvial channel through the project because of the existing steep channel gradient of approximately S_o = 0.030 and the high sediment load from the alluvial fan. An important design requirement of grade control structure is to ensure that failure will not occur from the erosive action of the flowing water which produces significant downstream local scour and can potentially undermine the structure. The maximum local scour depth for the initial design of the proposed grade control structures was calculated through the application of available empirical procedures developed for the hydraulics of vertical drop structures and estimated approximately 26 feet. However, the proposed grade control structures associated with this project have a different geometry than utilized by the original investigators that developed the empirical relationships for scour depths. In addition, none of the empirical procedures addresses the effect from the application of a horizontal armor blanket downstream of the structure crest.

The physical modeling program for the Lowe Reserve was developed to (1) evaluate the hydraulics of different grade control geometric configurations, (2) evaluate the erosion patterns, and (3) determine the effect on the local scour from the introduction of a horizontal armor blanket. The model was developed to compare the erosion for alternative designs to the erosion pattern without the application of the armor blanket. **The intended objective of the modeling program is to utilize the results in developing engineering judgements for the design of the grade control structure toe-down requirements if a horizontal armor blanket is applied.** The model will assist in providing design requirements for the minimum length of armor blanket, armor gradation requirements, and armor blanket thickness.

MODEL DESCRIPTION AND EXPERIMENTAL SETUP

A linear scale ratio of $\mathbf{L_r = 1:16}$ was selected as the geometric scale between the model and prototype to provide the minimum dimension which the erosion features could be adequately observed and measured. This model scale was considered the smallest model size which quartz could be used to represent the prototype channel bed material. The corresponding discharge scale for the model was $Q_r = 1:1,024$ ($Q_r = (L_r)^{5/2}$), time scale of $T_r = 1:4$ ($T_r = (L_r)^{1/2}$), and velocity scale was $V_r = 1:4$ ($V_r = (L_r)^{1/2}$).

A 24" wide and approximately 80-foot long flume, with a 40-foot segment with plexiglass sides, was constructed. The combination of the flume width and pumping the maximum flow from the two pumps allowed testing conditions equivalent to the SPF discharge. The flume's aluminum structural frame was installed on a sloping concrete foundation specifically constructed for the flume. The experimental setup was located outdoors in an abandoned highway patrol substation, under a covered metal carport area, which provided protection from direct sunlight and desert heat. The flume discharged into a large artificial storage reservoir which was created through earthen ring embankment and was then covered with a plastic membrane. The reservoir provided storage for the circulating flows and allowed periodic sediment removal from the system. Prototype and model data are compared in the following Table No. 1.

Table No. 1 - Prototype / Model Data

Description	Prototype	Model
Modeled Portion of	32 feet	2.0 feet

Table No. 1 - Prototype / Model Data		
Description	Prototype	Model
Channel Width		
SPF Design Discharge	5,380 cfs	5.25 cfs
Structure Net Invert Elevation Drop	6.5 feet	4.88 inches
Modeled Portion of the Hydrograph	480 minutes	120 minutes

Flow measurements were performed utilizing ultrasonic electronic meters attached to the circulating pipeline. In addition, a clear standpipe was attached to the circulating pipeline in order to guide the operation of the pump while throttling to various discharges of the design hydrograph. Flow depths and streambed configurations were monitored relative to the fixed top of the flume.

Flume: An 80-foot long flume which included a plexiglass sided portion, the constant head tank area, and outlet to the storage reservoir area. The flume inside width was 24" and a height of 42". The moveable bed portion of the flume included the plexiglass sided flume 24" wide and 40-feet long with aluminum structural frame on a fixed sloping concrete foundation. The longitudinal slope of the concrete foundation was approximately 3.75%, equivalent to the steepest natural slope at the project site for the prototype.

Pump System: Two pumps with an intake located at the storage reservoir were utilized to develop the required flowrate. The pumping system consisted of two -10 horsepower pumps, each had a rated capacity of 1,800 gpm at 16-feet of head.

Water Supply: A water storage reservoir was constructed below the discharge end of the flume through an earthen ring embankment covered by a plastic membrane or liner. The reservoir also served as a sedimentation area to trap sediment discharged from the flume. The ability to remove a majority of this sediment assisted the operation of the pumps. There was adequate water volume for the flume operation at the maximum pumping discharge, while providing sufficient submergence at the pump intakes location.

Sand Bed Material: The sand bed material utilized for the alluvial bed portion of the model included a mixture of medium to coarse sand which was combined with coarse gravel material to reflect the high percentage of cobbles and boulders in the prototype streambed. The design of the model sand-bed material was based upon the principle that the settling velocity ratio to be the same as the Froudian velocity, which is equal to the square root of the length ratio. The settling velocity for representative bed material can be determined from relationships such as the Rubey equation:

Application of similitude regarding the fall-velocity allows the development of an engineered gradation for the model bed material which should have similar properties. The design of the bed material was discretized into three categories to simplify the manufacture of the bed material for the model. The moveable bed protion of the flume will have a 2.5-feet depth of sand material. The geotechnical consultant had indicated the percentage of cobbles and boulders at the project site from field measurements appeared to be approximately 25-30%. The corresponding alluvial bed material utilized in flume was developed through a mixture of 60% medium and coarse sand, 20% pea gravel, and 20% medium gravel. The percentage of gravel in the model was less than the corresponding percentage of boulders and cobbles in actual streambed, providing a more conservative analysis.

Armor Blanket Material: The resulting rock material used in the model to simulate the artificial armor blanket in the prototype consisted of angular cobbles ranging in size from 3" to 5" in diameter. Numerous rock gradations were introduced in different experiments setups until the optimum gradation was developed which provided adequate erosion resistance and longevity. The final configuration rock armor blanket consisted of a five-inch thick blanket of the angular cobbles over a bed of 1/4" to ½" gravel which simulated a gravel and rock filter blanket. The length of the rock blanket was varied for different experiments to evaluate the effects on the scour hole development. The geometry of the rock armor blanket was developed to allow the maximum possible energy dissipation. The resulting configuration of the rock armor blanket closely resembled the scour hole geometry. A loose sill or thickened section was created at the downstream end of the blanket and the rock extended to the concrete chute face.

Circulating Pipe System: The circulating pipeline system consisted of a 12"-diameter PVC above ground pipeline extending from the twin pump discharge location at the reservoir to the flume inlet.

TESTING PROCEDURES

The testing procedures applied during the different experiments evolved over the operation of the model in order to allow optimization of the experiment setup, and to provide the most useful and accurate data during this process. The procedures associated with the operation of the model which were common to the various experiments included the following:

- Setup of the experiment in the flume first required the mixing and placement of the alluvial bed material. The bed material created a level channel bottom up to a level equal to the anticipated ultimate streambed elevation and slope.

- The proposed configuration of the armor blanket downstream of the grade control structure was placed in the bed material. The variables which were modified in the

experiments included: (1) gradation, (2) blanket thickness, (3) length, (4) cutoff depth, and (5) configuration or geometry of the blanket.
· Water was introduced into the flume to saturate the bed material then the experimental setup was ready to proceed with the actual test.

· Flow was then introduced into the flume which followed the design SPF hydrograph. The hydrograph was simulated through discretizing the calculated hydrograph for the watershed into small time intervals. The flow delivered by the pumps was adjusted at 7.5 minutes incremental over a 120 minute period of the experiment. The adjustment of the streambed at the downstream of the grade control structure was monitored and measurements of the maximum depth of the scour geometry was recorded at the end of each 7.5 minute flow increment

TESTING PROGRAM HISTORY

Numerous experiments were conducted during the initial operation trials of the model and preliminary setup in order to perform qualitative evaluations which would assist in developing the final experiments. These initial experiments resulted in observations which modified model operation during the experiments and developed the final geometric configuration of the grade control structure, but are not listed in the summary of experiments.

Table No. 3 - Summary of Model Experiment Set-ups

Experiment Date	Discharge (Prototype)[1]	Model Blanket Configuration [2]	Actual Prototype Rock Length	Model Max. Scour Depth Measured
Nov. 21, 1996	100-year	37.5" length rip-rap	50-feet	9.0 inches[3]
Dec. 4, 1996	SPF	19.5" length rip-rap	26-feet	7.75 inches
Dec. 4, 1996	SPF	None	None	21 inches (flume bottom)
Dec. 11, 1996	SPF	13.5" length rip-rap	18-feet	failed (flume bottom)
Jan. 3, 1997	SPF	23.5" length rip-rap	31.3-feet	5.75 inches
Jan. 8, 1997	SPF	19.5" length rip-rap	26-feet	failed (flume bottom)

Note: 1. Scaled discharge to reflect the specific storm hydrograph of prototype
2. Rock blanket measured from bottom of the concrete chute at the channel invert
3. Test prior to adjusting bed material with 20% gravel addition

Several modifications were incorporated into the model during construction and after the results of the initial trial runs which are different from the original model proposal. These items primarily reflect adjustments to proposed channelization program and additional data on field conditions of the prototype. The items include the following:

1. Streambed Material: The original material recommended for the movable bed portion of the model was selected to represent the prototype material through similitude relationships. The bed material initially selected for the model utilized the similitude relationship regarding the fall-velocity to select gradation. The recommended material was manufactured at the model site and used in several of the initial preliminary set-ups. However, additional information from the geotechnical consultant indicated that there was a higher percentage of cobbles and boulders in the streambed at the project site than initially reported in the mechanical analysis. The bed material for the model was modified based upon this information and the final media utilized corresponded to a mixture of 60% medium and coarse sand, 20% pea gravel, and 20% medium gravel.

2. Flume Width: The initial flume width recommended in the model proposal was 18" but was modified to 24" based upon the available pumping capacity. This flume width provides less influence of side effects and allows better observation of the erosion pattern development. The initial primary limitation in the selection of the flume width was the pump capacity in delivering the required peak design discharge, but adequate size pumps were obtained for the experiments.

3. Grade Control Structure Geometry: The initial design of the grade control structure on the improvement plans had included a concrete chute with a 4:1 slope for the net drop and the remainder of the chute was embedded to the cutoff depth was at a slope of 1.5:1. The cutoff depth for the grade control structure in Channel "A" extended 17.5 feet below the ultimate channel streambed elevation based upon empirical relationships used to estimate the local scour depth. The crest of the structure also had a 16-foot wide concrete horizontal crest. The dimensions and geometry of the chute were modified based upon the results encountered from numerous experiments in an attempt to optimize the performance of the structure. The slope of the chute on the downstream face of the structure was changed to a 1:1 slope and the crest of the structure was reduced to a horizontal width in the prototype of 8-feet. The cutoff depth of the chute was also reduced based upon the effectiveness of the rock blanket.

SUMMARY OF DATA AND OBSERVATIONS

The final experiments investigated the effects of various configurations and sizes of the horizontal armor blankets for the grade control structure with a maximum net drop of 6.5 feet in the prototype. Each of the experiments was monitored to determine the effects of the scour hole downstream of the grade control structure. The variation or migration of the scour hole geometry was recorded for the portion of the simulated SPF hydrograph in the model. Experiments conducted without the use of the rock armor blanket downstream of the grade control structure developed scour holes to depths similar to those predicted by the empirical equations previously applied. Experiments with the rock armor blanket significantly reduced the maximum depth of the scour hole downstream as indicated by the attached data. The configuration of the armor blanket was adjusted in the different experiments in order to optimize the energy dissipation occurring at this location. If an inadequate length for the armor blanket was utilized, then failure would generally occur during some point of the design hydrograph. Applying just a horizontal armor blanket did not yield the optimum results for energy dissipation of the grade control structure, but it also required adjusting the rock in the configuration which resembled the scour hole.

RESULTING DESIGN RECOMMENDATIONS

The model provided dramatic results regarding the benefits of the application of a horizontal armor blanket to reduce the local scour erosion associated with a grade control structure. A specific experimental program was developed based upon the initial results observed from the model. The model evaluated the extreme design flow conditions for this particular facility design with the Standard Project Flood (SPF) hydrograph and the effect to the potential erosion patterns. Numerous lengths and configurations of the armor blanket were utilized in experiments to determine the point at which failure occurred with the maximum discharge hydrograph. The observations from each experimental set-up provided insight into necessary modifications to the grade control structure and the rock armor blanket to develop the optimum configuration. The optimization of the armor blanket design was developed so that the length minimized potential hazards and was cost effective.

The experiments performed with the model indicated the following conclusions which are recommended to be incorporated into the design requirements of the prototype of this particular facility, however, some features would be common to any installation:

· A rip-rap armor blanket should be provided downstream a minimum of 30-feet in length. The blanket should be configured such that it resembles the shape of the scour hole. This minimum length also ensures that the calculated distance for flow impingement will occur on the armor blanket. This length of armor blanket has a desired safety factor incorporated into the design based upon the other lengths which failure will occur.

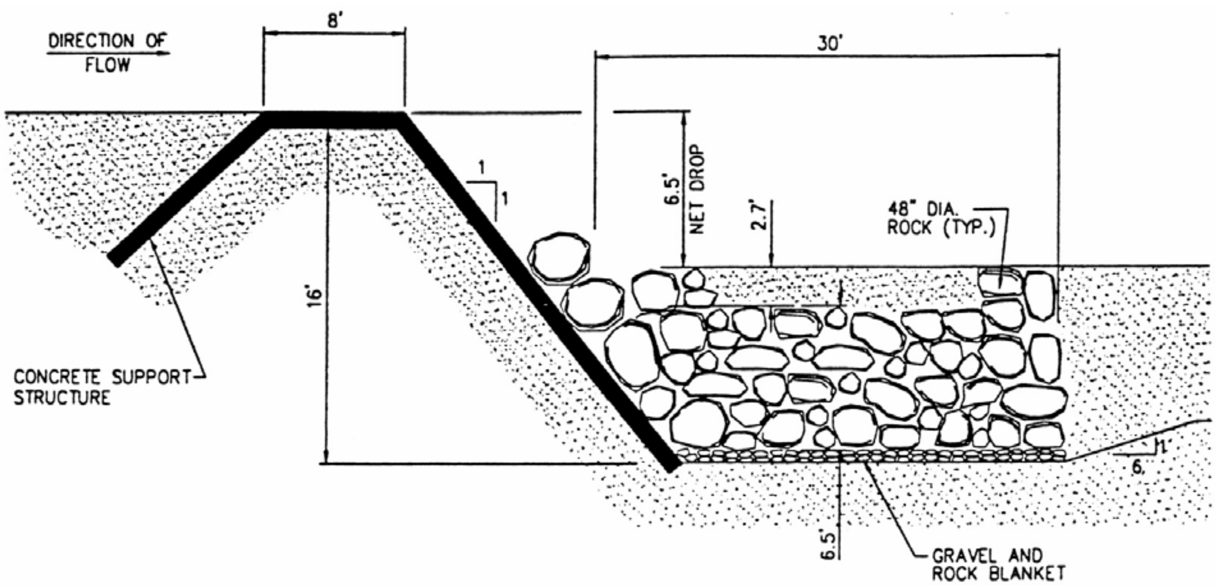
· The thickness of the rock armor blanket should be a minimum of 6.5 feet and utilize a rock gradation maximum rock diameter of 48".

· The armor blanket should incorporate an inverted gravel and rock filter at the interface with the streambed, along with a geotextile filter fabric.

· The placement of the rock is very important and requires the development of the rock geometry which is resembles the scour hole. The rock should be placed so that they are interlocking. A thickened rock sill should be created downstream which is approximately 3.0 feet in height.

· The maximum vertical height of the concrete chute for the grade control structure is recommended to be a total of **16-feet** measured from the crest of the grade control structure. This vertical height includes the **6.5-feet of net drop**. The chute should be constructed at a 1:1 slope.

The following figure summarizes the design recommendations for the layout of the grade control structure and the revetment.



SUMMARY AND CONCLUSION

The physical model developed specifically to evaluate the proposed flood control project in Palm Desert provided important data to guide the development of the final design for the twelve grade control structures to be utilized for this project. The primary benefits associated with the model includes verification of the expected response of the prototype rather than relying on empirical relationships from other investigators. Also, it is difficult to apply the empirical equations to this particular design application since the relationships were based upon specific properties which may not all be applicable. There is very limited data on evaluating the effect of armor blankets on the magnitude of the scour hole associated with grade control structures. The proposed grade control structures are located in a steep channel and a hydraulic jump will not occur, however, there will be significant energy dissipation associated with each structure. The energy loss associated with each structure cannot be directly calculated with hydraulic relationships, but the effects can be verified in the model. The final configuration of the grade control structure and the armor blanket was developed to allow the optimum energy dissipation of the structure. It appears that the recommended design of the grade control structure with the armor blanket will provide a more **cost effective** design rather than constructing a concrete cutoff to the anticipated unarmored scour depth. The modified structure with the armor blanket should provide the desired level of flood protection even with the extreme conditions utilized and minimize the long-term maintenance requirements.