Case Study: Movable Bed Model Scaling for Bed Load Sediment Exclusion at Intake Structure on Rio Grande

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Abstract: Results of a laboratory modeling study are presented for excluding bed load sediment from a diversion/intake structure on the Rio Grande in Albuquerque, New Mexico. To achieve model similitude, crushed coal was used to model the prototype sediment in a 1:24 scaled model with an exaggerated slope such that shear force is adequately modeled. The Shields parameters and critical Shields parameters were matched between the prototype and the model, resulting in similar grain Reynolds numbers. Twenty-four tests, where guiding walls, submerged vanes, and/or the angle of the intake bay were altered, were conducted for a single river and diversion flow rate to develop the best performing sediment exclusion system at the intake structure. Independent vanes with 45° rotated intake bays were recommended for the most effective sediment exclusion at the intake structure.

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Background

A 1:24 scale distorted movable bed model of the Rio Grande diversion structure was constructed and tested at the U.S. Bureau of Reclamation, Water Resources Research Laboratory in Denver, Colorado. The diversion structure is composed of overshot gates that extend across the channel, a river intake structure, and a fish passage (Fig. 1). The physical model allowed for a variation in gate operations and intake structure design. Fig. 1 shows the estimated prototype two-dimensional surface velocity vectors in front of the intake structure for a river flow rate of 28.3 m^3/s with 3.7 m^3/s diverted. The initially designed intake structure, positioned perpendicular to the river, consisted of two 7.3-m-wide intake bays to divert a maximum of 5.2 m^3/s. An intake guiding wing wall and 0.5-m-high bottom weir were initially designed to prevent sediment transport into the intake bays. The actual structure is expected to be in full operation in 2009. The purpose of this modeling study was to reproduce prototype sediment transport of the diversion structure on the Rio Grande to determine the best sediment exclusion intake structure design.

Movable Bed Model Similitude

The Shields diagram is often used for analyzing the ratio of channel bed shear force to sediment buoyant weight for a range of grain Reynolds numbers, $R^*=u_* d_s/\upsilon$, where u_* is the shear velocity, d_s is the sediment diameter, and υ is the fluid kinematic viscosity. The curve indicates when significant movement of bed particles is likely to begin, though it is not an exact threshold condition for incipient motion (ASCE 2000). Pugh and Dodge (1991) suggested that the difference of the Shields parameter (τ^*, dimensionless shear) to the critical Shields parameter (τ_c^*) should be the same in the model and prototype to achieve similarity of sediment transport between the model and the prototype

$$\frac{(\tau^*-\tau_c^*)_m}{(\tau^*-\tau_c^*)_p}=1;\quad \tau^*=\frac{\tau_0}{(\gamma_s-\gamma)d_s} \tag{1}$$

where subscripts m and p represent model and prototype, respectively; $\tau_0=\rho u_*^2$=bed shear stress, with ρ being the fluid density; γ_s and γ=specific weights of sediment and water, respectively. Their scaling technique was applied to a 1:10 scaled sediment erosion model and verified with prototype measurement. Mefford (2004) followed the suggestion of Pugh and Dodge (1991) in a 1:20 scale movable bed model for a river surface water intake structure hydraulic performance test. The prototype bed shear was reproduced using a distorted material for prototype sediment. Similarly, for this study, the prototype τ^* was compared with a different scaled model τ^* as shown in Fig. 2. The R^* of the prototype particle (d_s=0.51 mm) and τ^* for eight hydraulic radii ranging from 0.03 to 2.4 m are plotted with the hollow circular dots. Particles are in

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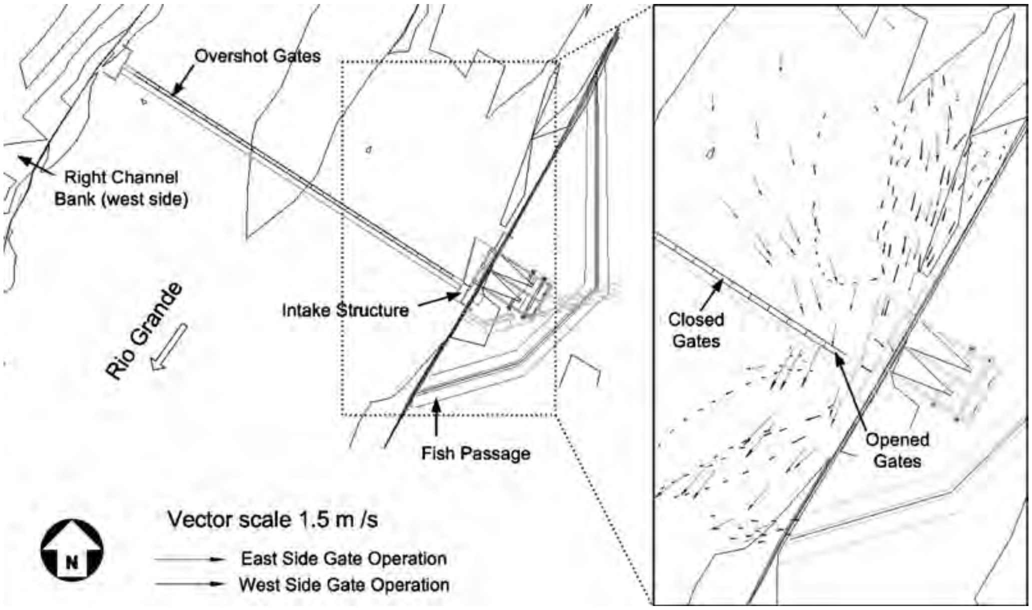

Fig. 1. Rio Grande diversion structure and surface velocity vectors

motion for $\tau^* > \tau_c^*$. Geometrically scaled particle diameters are plotted with hollow squares. These particles, classified as medium silt, can be cohesive, misrepresenting the prototype sediment. Using grain sizes with equivalent fall velocity results in increased R^* (solid squares), but the corresponding difference between τ^* and τ_c^* is not great enough for the desired sediment transport. Crushed coal with lower density allows larger d and hence increases R^* (hollow triangles), but the corresponding τ^* is still lower than prototype. To increase τ^*, the model bed slope was adjusted to be 6.5 times steeper than the prototype to match the prototype τ^* as shown in the solid circles. Crushed coal, with a much lower specific weight, is used in the steeper model for sediment transport model similitude. Resulting grain Reynolds numbers of prototype and model are similar. Prototype and model parameters are given in Table 1. The prototype parameters are design values since the diversion structure was only proposed when this modeling study was performed. To reproduce the prototype sediment incipient motion and transport in the scaled model, the sediment grain Reynolds number was matched between the prototype and the model, rather than achieving Froude or Reynolds number similitude. Both model and prototype are fully turbulent and subcritical. The model measurements should not be used to estimate prototype variables because the Froude similitude is not achieved. Although the shear relationship is matched between the model and the prototype for particle incipient motion, the actual settling velocity of the model particle is 56% of the scaled prototype settling velocity, keeping an entrained bed load that will not be present in the prototype. Since the bed load sediment was the object of the exclusion of the intakes, particle settling velocity similitude, which is commonly used for suspended sediment oriented models (ASCE 2000), was not achieved in this study.

The Meyer-Peter and Muller bed load transport equation was used to estimate sediment bed load discharge rates of the model

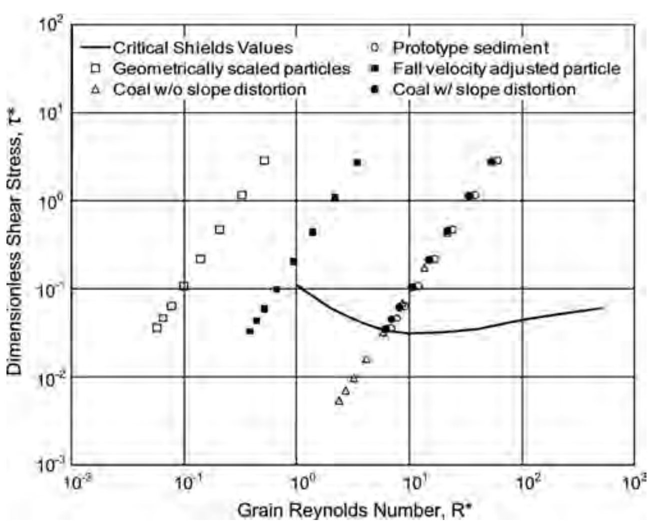

Fig. 2. Shields parameter for sediment materials and scale distortion

Table 1. Hydraulic Properties of Prototype and Model

Hydraulic properties	Prototype	Model
Channel flow rate, Q_{ch}	$28.3\ m^3/s$	$10.02^3\ cm^3/s$
Diversion flow rate, Q_{div}	$3.7\ m^3/s$	$1.31^3\ cm^3/s$
Approach water depth, H_{app}	0.7 m	2.9 cm
Approach velocity, V_{app}	1.2 m/s	24.5 cm/s
Sediment diameter, d_s	0.51 mm	0.88 mm
Sediment specific weight, γ_s	$2.6^4\ N/m^3$	$1.24^4\ N/m^3$
Sediment settling velocity, V_{st}	8.0 cm/s	18.4 cm/s
Sediment bed load rate, g_s	12.6 g/m	0.2 g/m
Channel bed slope, S	0.001	0.0065
Approach Froude number, F	0.20	0.46
Approach Reynolds number, R	55,630	470
Approach Grain Reynolds, R^*	11.67	10.48
Approach Shields parameter, τ^*	0.11	0.11
Critical Shields, τ_c^*	0.03	0.03
Velocity ratio (settling/shear)	2.65	11.94

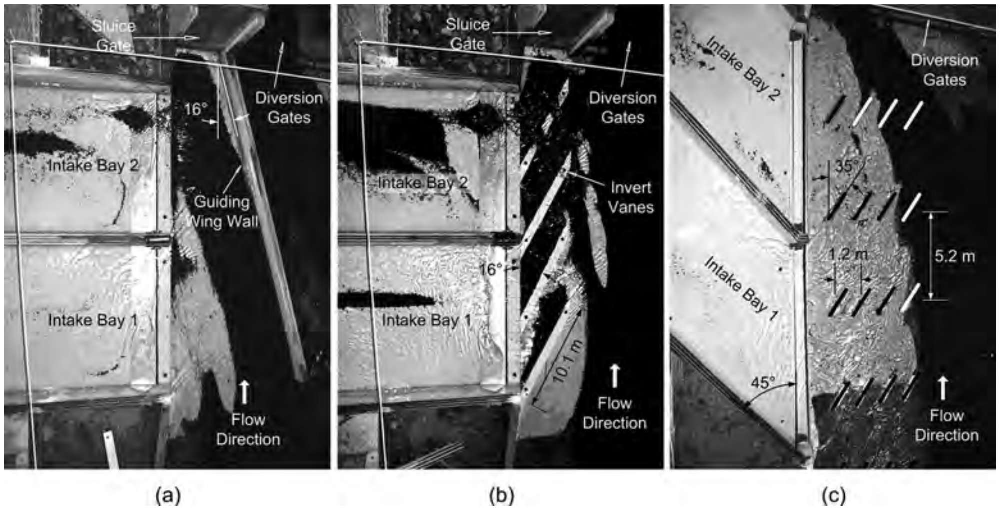

Fig. 3. Sediment exclusion system: (a) initial intake structure; (b) invert vane; and (c) independent vane at 45° rotated intake bay, recommended

and the prototype. Shen (1971) recommended a bed load scaling for sand and gravel dominated systems using the Meyer-Peter and Muller equation because sediment particle densities of model and prototype as well as model slope distortions can be considered. The equation may be expressed as (Vanoni 1975)

$$\left(\frac{k_r}{k_r'}\right)^{3/2}\gamma R_h S = 0.047(\gamma_s - \gamma)d_m + 0.25\left(\frac{\gamma}{g}\right)^{1/3}\left(\frac{(\gamma_s-\gamma)}{\gamma_s}\right)^{2/3} g_S^{2/3} \tag{2}$$

where k_r represents a roughness coefficient; $k_r' = 26/d_{90}^{1/6}$; R_h and S=hydraulic radius and bed slope, respectively; d_m=mean sediment diameter; g=acceleration due to gravity; and g_S represents a unit bed load rate in metric tons per meter per second. This equation was manipulated to estimate g_S for both model and prototype, and then multiplied by respective channel widths, as a basis for scaling the transport rate given differing prototype/model sediment densities as well as model slope distortions (Gill 2004). The linear relationship, $[g_S]_p = 63.2 \times [g_S]_m$, between the bed load rate of the prototype and the model was derived. Crushed coal was continuously and uniformly distributed at the entry of the experimental box (12.7 m upstream of the intake) using electric operating feeders according to the derived bed load rate relationship. The crushed coal resulted in a 4-cm layer simulating bed load in the river. One hour after initiating an experiment, diverted coal at the intake bays was collected for 30 min and wet weighed to determine the sediment transported. The experiment was repeated for a total of three measurements that were averaged for each intake design. Although the modeling approach cannot yet be verified by prototype comparison, it was verified with a numerical model of the prototype (Ho 2006).

Sediment Exclusion at Intake Structure

For the case of a river flow rate of 28.3 m^3/s and an intake diversion flow of 3.7 m^3/s, a total of 24 tests, consisting of various walls, vanes, gates, and different angles of the intake bays, was performed. Wet weight of sediment diverted to the intake bays was measured for each test. Fig. 3 shows three of the sediment exclusion models. The initial intake structure model has a guiding wing wall and a sluice gate without sediment vanes [Fig. 3(a)]. Flow separation from the left wall at the entry of both intake bays sets up a counterclockwise eddy in each bay. However, most sediment moved to the wing wall once it was diverted into the intake bay over the 0.5-m height of the bay entry weir. An average of 18.4 g/m of wet sediment concentration was obtained experimentally. Invert vanes were installed and the guiding wing wall was eliminated as shown in Fig. 3(b). In this case, the separation of flow passing over the sharp downstream edge of the vanes created a low pressure zone that caused bed load sediments to be pulled around the end of the vanes and back toward the intake bays resulting in an extremely high sediment concentration rate (25.9 g/m) in the intake bays. The recommended model is shown in Fig. 3(c) with submerged (30% of design water depth) independent vanes and 45° rotated intake bays. Similar vanes have been studied by Nakato and Ogden (1998) and Barkdoll et al. (1999). Five clusters of four rows of vanes (0.46 m high by 1.83 m long) were installed at 35° oriented with the front of the intake bays. The angled intakes with the associated wider intake opening provide enhanced diversion capability and diminished recirculation in the intake bays. Odgaard and Spoljaric (1986) found that these submerged vanes change the magnitude and direction of bed-shear stresses and cause a redistribution of the flow and sediment transport in the area by generating a secondary circulation in the flow. A 0.20 g/m of wet sediment concentration was observed.

Conclusions

Effective sediment exclusion of an intake structure for the Rio Grande diversion structure was developed using a movable bed laboratory model. Crushed coal was used to represent sediment particles on a 1:24 scaled model with a distorted slope to achieve similitude for the prototype sediment transport. The sediment grain Reynolds number was similar between the prototype and the model. Independent vanes with 45° rotated intake bays were recommended for the sediment exclusion system of the intake structure. Because of right-of-way issues, the rotated intake bays were not included in the design. The effectiveness of the vanes in the prototype cannot be determined until the dam and intake structure are in full operation later in 2009.

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