1992

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Stephen E. Stump
Riverside County Flood Control and Water Conservation District

Charles H. Tate
US Army Engineer Waterways Experiment Station

Robert U. Castle
US Army Corps of Engineers

Stump, Stephen E.; Tate, Charles H.; and Castle, Robert U., "Physical Modeling of a High Velocity Covered Urban Drainage Channel" (1992). *US Army Research*. 75.
http://digitalcommons.unl.edu/usarmyresearch/75

Published in Hydraulic Engineering: Saving a Threatened Resource—In Search of Solutions: Proceedings of the Hydraulic Engineering sessions at Water Forum ’92.
Baltimore, Maryland, August 2–6, 1992. Published by American Society of Civil Engineers.

PHYSICAL MODELING OF A HIGH VELOCITY COVERED URBAN DRAINAGE CHANNEL

Stephen E. Stump[1], Charles H. Tate, Jr.[2],
and Robert U. Castle[3]

Abstract

The design of Oak Street Drain, a 3-mile-long rectangular open channel project in Corona, CA, requires a covered section with a sinuous alignment to avoid commercial development. The alignment includes a reverse 100-ft-radius curve and a long 200-ft-radius curve to convey the 100-year design flow of 7,100 cfs at velocities of 40 fps. A physical model was constructed to verify that the proposed design would pass the design flow without adverse hydraulic conditions.

The Project

The Oak Street Drain flood control project in Corona, CA, is a feature of the Santa Ana River Mainstem Project, a massive US Army Corps of Engineers (USAE) flood control project that consists of a 10-year program to construct a new dam, raise and rebuild the outlet works of an existing dam, and construct 36 miles of channel improvements on the Santa Ana River and some of its tributaries in Southern California. In general, the proposed channel will provide 100-year flood protection following the same alignment as the existing channel, which has about a 10-year capacity.

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[1] Senior Civil Engineer, Riverside County Flood Control and Water Conservation District, PO Box 1033, Riverside, CA 92502-1033.

[2] Research Hydraulic Engineer, Locks and Conduits Branch, Hydraulic Structures Division, Hydraulics Laboratory, US Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-0631.

[3] Hydraulic Design Engineer, US Army Corps of Engineers, Los Angeles District, P.O. Box 2711, Los Angeles, CA 90053-2325.

The proposed design is primarily a rectangular concrete channel. The new channel maintains, in general, the average 20-ft width of the existing rail and wire-revetted channel, but will be deepened on the average by about 5 ft.

Obstacles in a short reach include a McDonald's restaurant; a service station; a 70-ft-wide local north-south artery (Lincoln Avenue); an auto dealership; State Route 91 (SR 91), which is an 8-lane interstate-style highway; and connecting ramps between Lincoln Avenue and SR 91. SR 91 is one of two major east-west commuter routes between Southern California's inland valleys and the Orange County/Los Angeles Basin areas. Improving the channel in this reach was by far the most challenging aspect of the project.

The General Design Memorandum (GDM), which is the USAE document that lays the groundwork for the final design of the project, stated many goals for minimizing impacts during project construction. Among these were building through SR 91 without any lane closures, no access ramp closures, and allowing at least some traffic to pass through the construction area in Lincoln Avenue. Meeting these goals required tunneling about 200 ft to pass beneath SR 91 and constructing an underground reach upstream of SR 91 to avoid the existing commercial and transportation improvements. The design flow is 7,100 cfs, and the flow velocity in the channel approaching the covered reach is 40 fps.

Design Constraints

In preparing the GDM, the Los Angeles District, USAE, followed the design guidance given in Engineer Manual 1110-2-1601 (Headquarters, US Army Corps of Engineers 1991). The manual prescribes minimum curve radii to be used in designing the alignment of supercritical channels using the equation:

$$r_{min} = \frac{4V^2W}{gy}$$

where

r_{min} = radius of channel curve center line, ft
V = average channel velocity, fps
W = channel width at water surface, ft
g = acceleration due to gravity, ft/s^2
y = flow depth, ft

For the channel geometry and flow conditions of the Oak Street Drain, the minimum radius indicated was on the order of 800 ft, which made avoidance of existing improvements impossible. The manual also suggests that superelevation and spiral transitions be used at curves to minimize surface disturbances, which can result in unwanted wave propagation in downstream reaches. This was done in the GDM design. To ensure that the entire covered reach would remain in open channel flow, the roof height of the covered channel was set to maintain a little over 2 ft of freeboard.

Following this design criteria, the original design of the underground reach utilized a double box culvert to reduce the superelevation through a 13-deg and 22-deg deflection upstream of the tunnel section. The resulting decrease in velocity through this wider, divided section and the narrower top width allowed the use of 400-ft radii.

Alternatives

The project's local sponsor is the Riverside County Flood Control and Water Conservation District, who by cost-sharing rules must pay for 65 percent of the covered reach construction cost plus the full cost of right of way and utility relocations. Although the GDM design avoided all the existing structures, the restricted curvature made for a design that required the relocation of several utility and traffic signal surface improvements and the crossing of a cloverleaf offramp in two places. After considering several cost saving alternatives, the District settled on a design that changed the GDM design to a single 17-ft-wide by 14-ft-tall box culvert. The channel alignment was changed radically, steering clear of several surface improvements and going around the cloverleaf offramp to approach SR 91 in a normal direction. The new alignment used reversing 100-ft-radius curves twisting through 68 deg left followed by 72 deg right followed by a 200-ft-radius curve that bent 75 deg left (Fig 1).

Hydraulic Design of the Alternative Alignment

Conventional water-surface profile calculations for the alternative design show that supercritical open-channel flow is maintained throughout the covered reach, although considerable superelevation of the water surface occurs at the bends. However, the sizing of the culvert was done using a worst-case energy verification analysis that assumed that the head losses in the bends or the turbulence associated with the succession of curves would be sufficient to cause pressure flow starting at the downstream outlet in the closed conduit. For these assumed conditions, a cross section was determined that assured flow would not back up at the upper entrance to the covered reach should pressure flow occur within the covered reach.

While the design method provided a configuration that could successfully pass the design flow, the analysis could not predict air entrainment or wave propagation effects. Therefore it was decided to test the design by conducting a physical model study.

Physical Model

A 1:25-scale physical model was constructed of acrylic plastic. The model reproduced the channel starting 300 ft upstream of the transition entering the 14-ft-high by 17-ft-wide box culvert, through the box culvert, which ends at the downstream side of SR 91, and to a point approximately 500 ft downstream of the Pomona Road Bridge (Fig 1). The slopes in the model were adjusted to reproduce the energy gradient for a Manning's n value of 0.014 based on Froudian scaling criteria. Normal depth entering the model was controlled with a slide gate located at the exit from the head tank.

For the design flow of 7,100 cfs, approximately 1.5 to 1.75 ft of freeboard existed in the open channel upstream of sta 80+00 (Fig 2). Flow entered the box culvert with 4.25 ft of clearance below the roof. Flow rode up on the outside of the curves between sta 74+50 and sta 71+50 resulting in the flow covering approximately half of the roof on the outside of the curves while dropping off the inside walls. Cross wave action and an additional curve also caused the flow to reach the roof at approximately sta 70+30 and sta 67+00. Flow exited the box culvert with approximately 2 ft of clearance below the roof. Minimum freeboard downstream of the box culvert to the Pomona Road Bridge was 2.75 ft at sta 63+75. Flow passed under the Pomona Road Bridge with 3.75 ft of clearance. Minimum freeboard downstream of the bridge was 2.25 ft.

The maximum capacity of the box culvert was between 10,000 and 10,500 cfs, although such flows would overtop the upstream channel. Flow instability at the entrance to the culvert sealed the entrance, causing the entrance to act as an orifice, drastically raising the water surface immediately upstream of the box culvert. Leafy branches representing vegetation up to 55 ft tall and 7.5- by 25-ft boards were placed in the flow upstream of the box culvert and passed through the culvert without problems for all flows tested.

Piezometers were placed on the roof of the culvert 1 ft from the right wall at sta 74+07.5 and 73+62.75 and 1 ft from the left wall at sta 72+72.25 and 72+45.38. For the 7,100-cfs flow, the pressures on the roof at those locations were 2.3 ft, 0.7 ft, 1.5 ft, and 0.5 ft, respectively. For the 10,000-cfs flow, the pressures were 6.6 ft, 5.0 ft, 6.9 ft, and 4.4 ft, respectively.

Conclusions

Oak Street Drain, as it was designed and tested, will pass the design flow of 7,100 cfs. The roof of the box culvert will become the flow surface at some locations, but with minimal pressures. Flow will remain within the channel at all locations and there should be no problems at the Pomona Road Bridge. The maximum capacity of the box culvert will be between 10,000 and 10,500 cfs, which is greater than the capacity of the upstream channel.

Acknowledgement

The tests described and the resulting data reported herein, unless otherwise noted, were obtained from research conducted for the US Army Engineer District, Los Angeles. Permission was granted by the Chief of Engineers to publish this information.

Appendix I. Conversion Factors from U.S. Customary to SI Units

To convert (1)	To (2)	Multiply by (3)
Cubic foot per second (cfs)	Cubic meter per second (m^3/s)	0.03
Degree (angle) (deg)	Radian (rad)	0.02
Foot (ft)	Meter (m)	0.31
Foot of water (39.2°F) (ft)	Kilopascal (kpa)	2.9
Foot per second (fps)	Meter per second (m/s)	0.31
Mile (mi)	Kilometer (km)	1.61

Appendix II. References

Headquarters, US Army Corps of Engineers. (1991). "Hydraulic design of flood control channels," EM 1110-2-1601, US Government Printing Office, Washington, DC.

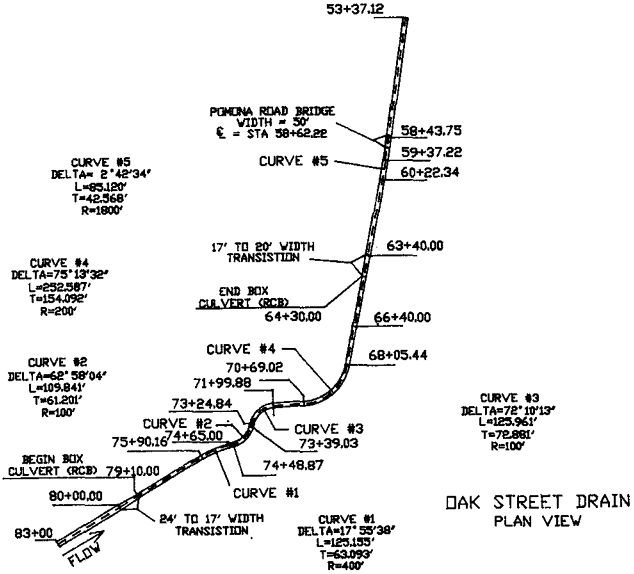

Figure 1. Plan view

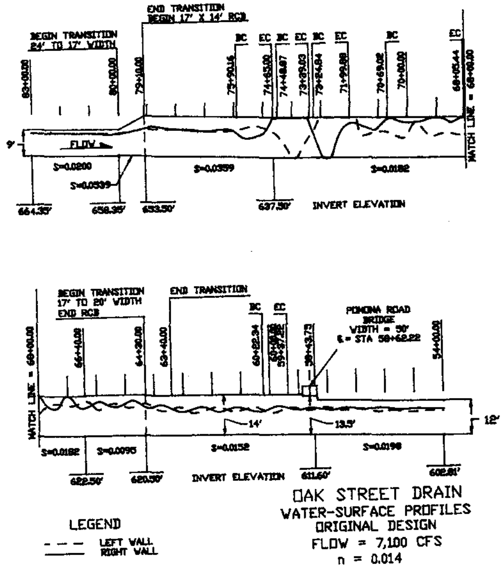

Figure 2. Water-surface profiles