June, 1969

TABLE OF CONTENTS

FREE WATER SURFACE DESIGN (G 400)

SECTION NO.	SUBJECT	DATE
G 401	**Design Procedure**	June, 1969
G 402	**Roughness Coefficients**	"
G 410	**GEOMETRIC DESIGN**	"
G 411	**Alignment**	"
G 411.1	Horizontal Curves	"
G 411.2	Vertical Curves	"
G 412	**Cross-Sections**	"
G 413	**Invert Grades**	"
G 414	**Preliminary Plan and Profile**	"
G 415	**Freeboard**	"
G 420	**HYDRAULIC DESIGN**	"
G 421	**Control Points**	"
G 422	**Balanced Design-Water Surface**	"
G 422.1	Water Surface Computations	"
G 423	**Head Loss at Structures**	"
G 423.1	Junctions	"
G 423.2	Transitions	"
G 423.3	Bridge Piers	"
G 423.4	Inlets and Outlets	"
G 424	**Special Design**	"
G 424.1	Spiral Easement Curve	"
G 424.2	Superelevation	"
G 424.3	Bulking from Air Entrainment	"
G 424.4	Hydraulic Jumps	"
G 425	**Summary of Hydraulic Design**	"
G 430	**HIGH VELOCITY DESIGN---SAMPLE PROJECT**	"
G 431	**Conduit and Debris Basins**	"
G 432	**Velocity and Freeboard**	"
G 433	**Manholes and Access Structures**	"
G 434	**Junctions and Transitions**	"

LIST OF FIGURES

NUMBER	TITLE	DATE
*G 402	Roughness Coefficients	June, 1969
G 411.2	Vertical Curves for High Velocity Flow	"
G 422.1	Water Surface Computations-Backwater	"
G 422.1A	Water Surface Computations-Downwater	"
G 423.3	Class of flow at Bridge Piers	"
G 423.3A	Bridge Pier Loss Calculations	"
G 423.3B	Bridge Pier Loss Algebraic Solution	"
G 424.1	Spiral Transition Curve for Supercritical Flow	"
G 424.3	Approximate Bulking from Air Entrainment	"
G 424.4	Hydraulic Jumps	"
G 425	Summary of Hydraulic Design	"

* Figures preceded by asterisks are in text. All others are at ends of chapters.

G 400 FREE WATER SURFACE DESIGN

Free water surface design, as used in this chapter, means any conduit, closed or open, which is designed to flow with a free water surface at peak flow for a designated storm frequency. An improved storm drain open channel usually consists of a rectangular or trapezoidal concrete conduit of constant cross-sectional area, designed for uniform flow. The choice of an open channel in Lieu of a pipe or box is based principally on economic considerations and location. Generally, because of esthetics and land use, a closed conduit is preferable to an open channel.

G 401 DESIGN PROCEDURE

The general procedure for free water surface design is basically the same as that for full flow conduits. The applicable sections of the design procedure outlined in the flow diagram (Figure G 314) may be used as a guide to coordinate the design. Only those functions which apply to free water surface flow will be discussed in this chapter.

A typical open channel serves as the main line for a drainage system, which may also include closed conduit laterals and catch basin connections. All parts of the system other than the free water surface design should be as shown in the chapter for pressure flow conduits (Chapter G 300).

The recommended sequence for free water surface design is as shown below. The functions covered in this chapter are in italics.

1. Project Review (Section G 321), Field Survey (Section G 322), Preliminary Engineering Report (Section G 323), Notice to Traffic and Street Lighting (Section G 324).

2. Hydrology (Chapter G 200, Section G 332).

3. Alignment (Section G 411), Survey and Substructure Plat (Section G 331), Main Line Location where applicable (Section G 333).

4. Cross-Section (Section G 412), Invert Grade (Section G 413), Preliminary Plan and Profile (Section G 414). Freeboard (Section G 415).

5. Joint Field Meeting (Section G 334), R/W Sketch (Section G 335), Test Borings (Section G 336), Main Line Centerline Calculations (Section G 337), Substructure Excavation (Section G 339)

6. Hydraulic Control Points (Section G 421), Balanced Design-Water Surface (Section G 422), Head Loss at Structures (Section G 423), Special Design (Section G 424), Summary of Hydraulic Design (Section G 425).

7. Catch Basin Hydrology (Section G 351) Catch Basins (Section G 352), Connector Pipes (Section G 353).

8. Preliminary Plans (Section G 360).

9. Final Plans (Section G 370).

G 402 ROUGHNESS COEFFICIENTS

The roughness coefficient used in design for storm drains, earth channels, or natural streams shall be Manning's "n" values shown in Figure G 402.

If a part of the channel cross-section is not lined, or the linings are composed of different materials, a weighted average coefficient (n_W) shall be determined (using "n" values given in Figure G 402) as follows:

$$n_w = \frac{P_a\ n_a + P_b\ n_b + Pc\ n_c\ ....}{\sum P}$$

where a, b, c, etc., represent types of lining materials and P is the wetted perimeter.

For more specific applications of "n" values, the University of California Institute of Transportation and Traffic Engineering (ITTE) booklets Street and Highway Drainage (1965) offer tables as follows:

Table III-3, Page III-1B, Volume 1
Table I-7, Pages I-8 to I-11, Volume 2

G 410 GEOMETRIC DESIGN

The general procedure for free water surface design is shown in Section G 401. For open conduits, this procedure does not show the relationship between alignment, grade, and cross-section. These factors control the geometry of the conduit and must be resolved concurrently as shown below. For closed conduits, the controlling factors which determine the shape and size of the conduit are street grade, clearance of physical obstructions, and velocity.

G 411 ALIGNMENT

A good alignment should be as straight as possible and provide economical construction. Open channels are usually aligned along an existing watercourse to take advantage of natural drainage conditions and less expensive property, considering the cost of severance damages.

An economic alignment study across property should include the following considerations:

1. The use of existing right of way, bridges, and culverts.

2. The use of existing natural channels to minimize excavation and fill and minimize surface and subsurface obstructions.

3. The use of a covered conduit open channel to decrease right of way requirements and maintenance, eliminate fencing, and retain surface use of the land.

4. The use of horizontal curve radii consistent with the channel velocity (see Subsections G 424.1 and G 424.2).

A trial alignment of the channel centerline is plotted on the plan (Section G 331) and adjusted to best fit the above considerations. This alignment, however, is preliminary only. The horizontal curve radius must be adjusted to the calculated design channel velocity to maintain the superelevated water surface at or near the finished ground surface.

The need for subdrains must also be considered in the choice of one alignment over another.

Reaches of constant section along the alignment are determined between major changes of grade or quantity of runoff. The grade of the proposed channel is tentatively set parallel to the average watercourse flow line (or street grade). Runoff quantities are taken from the hydrologic tabling. The cross-section (or conduit size) of the proposed channel is next determined.

G 411.1 Horizontal Curves: Changes in the horizontal direction of a storm drain alignment shall be accomplished by circular curves (for subcritical flow) or by a combination of circular curves with spiral transitions (for supercritical flow) rather than by angle points. Reversing curves with no intervening tangent and a series of curves in the same direction with intervening tangents should be avoided. Vertical curves should not be located within the limits of a horizontal curve.

Radii of horizontal curves shall be as large as possible consistent with the general terrain in

ROUGHNESS COEFFICIENTS

	Manning's "n"
LINED CHANNELS:	
Concrete (poured in place)	.013
Gunite Concrete	.016
Asphalt	.015
Flush Grouted Cobbles	.020
Medium Weight Levee Riprap	.035
Jetty Type Riprap	.050
EARTH CHANNELS:	
Fine Sand, Silt, or Loam	.020
Usual River Sand and Gravel	.025
coarse Gravels	.030
Coarse Gravels with Boulders	.035
Earth Channel with Pipe and Wire Revetment*	.025
NATURAL STREAMS:	
Valley with Light Vegetation and Gravel	.040
Mountain with Moderate Brush and Boulders	.050
Mountain with Heavy Brush, Boulders, and Trees	.070

* Flow assumed rectangular prism within revetment
CONDENSED FROM ITTE (1965)
STREET AND HIGHWAY DRAINAGE

Figure G 402

Order to reduce the superelevation of the water surface and preserve freeboard. In some cases it will be necessary to increase the wall height on the outside of the curve when the superelevated water surface encroaches into the freeboard. Spiral easement curves (Subsection G 424.1) shall always be used when the resulting decrease in superelevation will produce a significant reduction in the height of the curve outside wall. In computing the additional wall height which is required without the use of spirals, it should be remembered that the waves of maximum superelevation continue far downstream from the EC of the circular curve.

Horizontal curves in unpaved channels should have a minimum radius of five times the base width to reduce spiral flow, which is a major concern of channel erosion in subcritical flow.

G 411.2 Vertical Curves: Changes in grade for low velocity free water surface flow do not require vertical curves. A grade break is usually sufficient for all conduits: pipe, box, or open channel. (For pipes, see Subsection G 333.4.) However, changes in grade for a free water surface flow of 18 fps or higher must retain the flow on the invert to avoid cavitation.

Major grade changes in all conduits with high velocity free water surface flow shall be connected by parabolic vertical curves in accordance with Figure G 411.2. Circular vertical curves should not be used because of the difficulties in calculating elevations and because the circular curve does not conform to the trajectory of the jet. The length of curve as computed from Figure G 411.2 should be increased a reasonable amount to provide a factor of safety for retaining the flow on the invert.

The majority of grade changes of less than 5% will not require vertical curves, since the length computed as shown on Figure G 411.2 will be insignificant. For grade changes greater than 5%, a minimum radius of 200 feet should be used with a parabolic vertical curve. For R=200 feet, the minimum length of curve (L) for a grade change (A) of 5% is 10 feet and the distance between grade breaks (D) is 4.0 feet (use 2.50 feet).

The profile should show stations and elevations of BVC, PI, EVC, invert grades, algebraic angle (A), length of curve, and intermediate elevations to define the curve adequately.

G 412 CROSS-SECTIONS

The most efficient cross-section, assuming slope, n, and area are constant, is a rectangular section in which the depth is one half of the width. This produces a maximum hydraulic radius and Q, and a minimum amount of concrete, since the wetted perimeter is at a minimum. However, the section chosen must be adaptable to existing field conditions.

In selecting a cross-section, the following factors should be considered:

1. Areas available for R/W acquisition and clear of surface and subsurface obstructions. The right of way required should include consideration for an access road, as shown in Figure G 122.

2. Minimum excavation and fill.

3. Foundation and side slope soil stability.

4. Clear width between bridge piers or other structures.

5. Slope of channel and velocity of flow. A trapezoidal cross-section should not be chosen for supercritical flow.

The cross-section for each reach may be determined when the values of Q, n, and S_g are known, assuming normal depth. Starting with a hydraulically efficient rectangular section, a ratio of depth to base width (d/b) that best fits the average cross-section of the natural channel is estimated. Assume the natural channel is approximately 12 feet wide by 5 feet deep. Enter Office Standard No. 117 (Appendix D) with d/b = 0.417, Q = 750 cfs, and S_g = .0020, and calculate A (58.6 sq. ft.), V (12.8 ft./sec.) and S (0.0021). Compare calculated S (0.0021) to average ground slope S_g (0.0020).

For changes in cross-sections, see Transitions, Subsection G 423.2.

G 413 INVERT GRADES

Before the invert is plotted on the profile, certain hydraulic and alignment checks should be made to ensure that the chosen cross-section meets all design criteria. These checks are as follows:

1. Establish whether the flow is subcritical or supercritical and compare the trial radius of vertical curve to the requirements of Figure G411.2.

2. Apply width of right of way required along the proposed alignment on the plans to check clearance to existing improvements. Compare proposed channel to existing bridges or culverts for clearance in width and height. Check radius of horizontal curves. Adjust the alignment where required to provide the needed clearance.

3. Plot water surface parallel to the finished average ground line and below the depth of freeboard. Plot invert at normal depth below the above water surface. Check for substructure clearance and vertical curves, and adjust the depth where required. The preliminary plan and profile may now be completed in preparation for the water surface computations.

G 414 PRELIMINARY PLAN AND PROFILE

Before the water surface computations can be made, the junction and transition structures must be tentatively chosen and located on the plan, the alignment must be scaled for stationing, invert grades must be calculated, and all data must be plotted on the plan and profile. Also, the alignment should be reviewed in the field (if necessary, in a joint field meeting; see Section G 334) to resolve any problems that may arise.

The junction and transition structures are chosen as shown in Sections G 622 and G 623. They should provide for a smooth flow and continuous water surface through the transition by adjusting the width and/or invert slope of the transition.

After the alignment is scaled, stations should be provided at the following points:

l. The intersection of the lateral and channel centerlines

2. Both ends of transition structures

3. All BC's and EC's of horizontal curves

4. All BVC's and EVC's of vertical curves

5. All grade changes and manholes Show the stations in plan and profile.

Next, the invert slopes and elevations are calculated as shown in Subsection G 333.3. Invert elevations should be provided at the inside face of the channel wall at junctions, at both ends of transitions, and at all grade changes. Plot all elevations to scale on the profile.

G 415 FREEBOARD

Freeboard, as applied to free water surface flow, is additional wall height above the calculated water surface. Freeboard shall be incorporated in all open channel design in accordance with the design frequency.

A. The recommended freeboard for rectangular channels is as follows:

l. For 50-year frequency-

a) 2.0 feet of freeboard for velocities of 35 fps or less, including superelevation.

b) 3.0 feet of freeboard for velocities higher than 35 fps, including superelevation.

However, in areas where channel overflow is hazardous to life and property for a 50-year storm, set the freeboard above the maximum superelevation. The use of spiral transitions will reduce superelevation by 50%.

2. For l0-year frequency-2.0 feet freeboard. Superelevation shall not encroach into the freeboard. Open channels shall not be designed for a l0-year storm unless it is definitely determined that overflow from a 50-year storm will cause no damage whatsoever.

B. The recommended freeboard for trapezoidal channels, subcritical flow only, is as follows:

l. For 50-year frequency-2.0 feet freeboard.

2. For l0-year frequency-2.5 feet freeboard. Superelevation shall not encroach into the freeboard for either frequency.

C. The recommended freeboard for closed conduits is one foot minimum, but must be sufficient to provide a friction slope equal to or less than the construction slope with full wetted perimeter. This prevents a decrease in capacity at full flow.

Bridge soffits shall have a minimum clearance of two feet from the calculated maximum water surface at 50-year design peak flow.

G 420 HYDRAULIC DESIGN

The hydraulic design of free water-surface flow consists mainly of water surface computations. These computations determine the adequacy of the preliminary design. They provide a hydraulically balanced design for the full length of the project by trial and error hydraulic calculations and grade (or size) adjustments on the profile. The final design is summarized and submitted to the supervisor for review and approval.

G 421 CONTROL POINTS

A control point is a point along a storm drain where the water level or depth is limited to a predetermined level or can be determined directly from the quantity of flow (Q). Other depths of flow along the profile are established from hydraulic calculations based upon these control points. Known depths of flow or water surface elevations are usually found at the following locations:

1. At critical depth (dc) when the flow changes from subcritical to supercritical (usually at a grade break or expansion of channel width).

2. At a predetermined outlet water elevation;

3. At a predetermined headwater elevation (such as at culvert inlets);

4. At normal depth (d_n) when the flow has been calculated to be uniform (usually a long reach with little change in runoff volume).

5. At a hydraulic jump (downsteam is d_n unless another control point is in close proximity).

The class of flow and the location of the control depth are determined as follows:

1. When $d_n > d_c$, the flow is subcritical

Control is downstream. Any change in quantity of flow or change in cross-section will be reflected back upstream.

2. When $d_n < d_c$, the flow is supercritical.

Control is upstream. Any change in flow downstream cannot be reflected back upstream.

**G 422 BALANCED DESIGN-
WATER SURFACE**

The design of open channels must be hydraulically balanced. That is, the water surface calculations must meet all hydraulic requirements given below and the top of wall must be located at or near the finished ground line for the full length of the alignment. This may be obtained by varying the size and/or grade of the channel by trial and error in conjunction with the water surface computations. A balanced design attempts to minimize grading, wall height, and right of way use.

The hydraulic requirements of a balanced design are as follows:

1. The hydraulic gradient elevation at inlets must not exceed the highest water surface allowed to prevent backwater or inundation at sumps. This highest water surface is generally set from a determination of flood damage which would be incurred thereby.

2. The hydraulic gradient elevation must be at the water surface of the channel or conduit into which the storm drain discharges. The channel or conduit water surface will normally be the point of control for the start of hydraulic computations.

3. The construction slope of the storm drain conduit should be sufficient to provide a minimum self cleansing velocity of 5 fps. Also, steep construction slopes should be avoided so that excessive velocities do not cause cavitation or abrasion in the conduit.

4. The depth of flow must be calculated for the full length of the channel in successive reaches and in proper sequence at a control. A reach is generally a length of channel which has constant discharge, grade, and cross-section. The water surface at structures may be calculated as shown in Subsection G 422.1 and by Appendix C, Office Standard No. 115.

5. All controls must be integrated with the water surface calculations. Some controls, such as flow through critical depth, are inherent in the channel geometry; other controls, such as predetermined depths required for flow, must be matched by the calculated water surface. For each stage of flow only one control prevails, the downstream control for subcritical flow and the upstream control for supercritical flow.

6. After the depth and velocity have been computed for the full length of the conduit, superelevation at horizontal curves (Subsection G 411.1), bulking due to air entrainment (Subsection G 424.3), and freeboard (Section G 415) must be determined and added to the calculated depth (if applicable) to determine the wall height above invert.

The hydraulic calculations must be correlated to field conditions by trial adjustment of the channel on the preliminary profile. The channel invert grade for the first reach (see No. 4 above) is plotted on the profile at a depth equal to the height of wall before superelevation. The invert, water surface, and energy gradient elevations shown in the hydraulic calculations must be adjusted to field conditions before the calculations for the second reach are made. This procedure is continued, reach by reach, to completion of project. The original slopes (based on the finished ground lines) and cross-sections (based on economical cut and fill) should be maintained throughout the alignment if possible, provided the laterals at junctions are not incapacitated. Should a change in slope and/or cross-section be required, the hydraulics for that reach must be recalculated.

G 422.1 Water Surface Computations: When the flow in an open channel is non-uniform, the depth varies and must be calculated. This calculation can be done as shown for the backwater curve (Figure G 422.1) and the downwater curve (Figure G 422.1A). This method is applicable to natural streams and is adaptable to computer applications (see Section G 920).

The procedure for the sample computation shown on Figure G 422.1 is as follows:

A. List Q and n. Calculate and list Q_n and $b^{8/3}$. Show cross-section and base (b). Select control and list its depth (d) and station. List channel grade (S_i). Calculate and list critical depth (d_c) and normal depth(d_n). Compare d_n to d_c to determine whether flow is subcritical (backwater) or supercritical (downwater). The water surface will increase or decrease toward d_n.

B. List d/b and from O.S. No. 117 calculate area (A), velocity (V), and K2. Calculate velocity head (hv), energy head (E = d + hv>, and friction slope (St). List all values on line 1.

C. To set a reach limit based on 5% change of velocity, multiply V on line 1 by 1.05. Set a depth (8.0) on line 3 that produce a velocity equal to or less than the limiting velocity (13.25<13.41). Calculate all values on line 3 for that depth similar to B shown above.

D. Calculate the difference of energy head between lines 1 and 3 and list ΔE on line 2. Calculate the average friction slope between lines 1 and 3 and list average S_f on line 2. Calculate ΔS (S_I-AveS_f) and the reach L(ΔE/ΔS) and list on line 2. Add L to station on line 1 and list new station on line 3.

E. Repeat steps B, C, and D above for each consecutive reach until either uniform flow, a structure, or a grade change is reached. At this point, the new conditions (Q, section, grade, etc.) are listed and the water surface computation continues (Section G 422).

The above sample calculation assumes a depth and determines the reach required to realize that depth. In some instances, such as grade changes or structures at fixed locations, the reach must be set and the corresponding depth calculated. This requires a trial and error computation assuming a depth and calculating its reach until the calculated reach matches the set reach.

G 423 HEAD LOSS AT STRUCTURES

The structures for which head losses are determined in free water surface design are junctions, transitions, bridge piers, outlets, and inlets. An independent head loss determination for each structure is presented in this section. These head loss calculations are required in the water surface determination.

The friction head loss in an open channel shall be averaged for non-uniform flow as shown in Figure G 422.1. The head loss due to bends in an open channel is negligible. See Spiral Easement Curves Subsection G 424.1.

G 423.1 Junctions: The analysis of junctions for open channels is based on the Pressure Momentum method presented in Appendix C, Office Standard No. 115, Hydraulic Analysis of Junctions, Part III. The head loss at junctions (h_j) is as follows:

$$h_j = \Delta Y + h_{v_1} - h_{v_2}$$

where h_v is the velocity head at points 1 and 2, and Sy is calculated as shown in Appendix C, Office Standard No. 115. For the geometric design of junctions, see Section G 622.

G 423.2 Transitions: The head loss at transitions for free water surface subcritical flow is computed by equations based on Hind's experiments as follows:

1. Contraction: $h_t = 0.10\left(\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right)$

2. Expansion: $h_t = 0.20\left(\frac{V_2^2}{2g} - \frac{V_1^2}{2g}\right)$

The head loss at transitions for free water surface supercritical flow is computed by equations based on Gibson's experiments on enlargers as follows:

1. Contraction: $h_t = \dfrac{0.10\,(V_1 - V_2)^2}{2g}$

2. Expansion: $h_t = \dfrac{0.20\,(V_2 - V_1)^2}{2g}$

See Section G 623 for the geometric design of transitions.

G 423.3 Bridge Piers: The head loss at bridge piers (or multiple box culverts) for open channels can be computed by the Pressure Momentum method shown on Figures G 423.3A and G 423.3B, ignoring friction.

The change in depth of flow which results from the bridge pier constriction is shown on Figure G 423.3. The three types of flow are classified as follows:

1. Class A-subcritical flow. Control is downstream, d3 is known, solve for d1 and d2.

2. Class B-critical flow (at constriction). Control is downstream, d8 is known, solve for d_1 and d_2

3. Class C-supercritical flow. Control is upstream, d1 is known, solve for d3 and d2

The procedure for applying the Pressure Momentum method (as shown on Figure G 423.3A) is as follows:

1. From the calculated normal depth (dn), critical depth (dc), and known water surface, assume a class of flow (Figure G 423.3).

2. Select depths above and below the known water surface and calculate the pressure and momentum values.

3. Plot the above values and draw smooth curves.

4. Locate the known water surface depth on the upstream curve I or downstream curve III. A vertical line passing through the three curves and the known depth will give a direct solution for the unknown depths.

If the vertical line drawn through a known depth on curve I or III does not cross curve II (plots to the left of d_{c2}), control is at the pier and d_2 is assumed at dc. The vertical line is drawn through d_{c2} to determine the unknown depth (d_1 or d_3). If the known depth is subcritical, the unknown depth is subcritical and if the known depth is supercritical, the unknown depth is supercritical unless there is a change in channel slope.

An alternate and more direct solution of bridge pier losses by the momentum method is an algebraic solution by trial and error presented by D. Thompson, Chief Engineer of Design, as shown on Figure G 423.3B.

A solution of losses at bridge piers by the use of coefficients is presented in the Institute of Transportation and Traffic Engineering (ITTE) Street and Highway Drainage, Volume I (1965), pages III-39 to III-46.

Another method of determining the head loss at bridge piers is Yarnell's method. The use of this method, however, is restricted to subcritical flow in rectangular channels. The solution gives the depth upstream only; no depth is given for the constricted section.

G 423.4 Inlets and Outlets: An inlet for an open channel is in effect a transition from a natural channel to an improved channel. The head loss for an inlet shall therefore be determined in the same manner as head loss is determined for a transition (Subsection G 423.2).

The head loss at an open channel outlet into a still pond is equal to the change in velocity head. Otherwise the outlet loss shall be determined in accordance with Office Standard No. 115.

G 424 SPECIAL DESIGN

Items of special application in the design of open channels are spiral easement curves, superelevation, bulking from air entrainment, and hydraulic jumps. The design criteria and a short discussion on the use of these items are given in this section.

G 424.1 Spiral Easement Curves: Spiral easement curves are alignment transition curves, placed both upstream and downstream from circular curves in open channels. They are used for supercritical velocities only. They alter the transverse slope of the water surface in such a way that the water prism is kept in constant static equilibrium with the centrifugal force throughout the entire length of the easements and central circular curves. This achieves minimum heights of superelevation and eliminates wave disturbances downstream on an unspiraled curve.

Figure G 424.1 presents a sample problem of a short method of calculating a spiral transition curve. This method was derived by D. Thompson, Chief Engineer of Design, City of Los Angeles, to alleviate the cumbersome calculations inherent in a spiral curve. See Subsection G 424.2 for the application of superelevation with spiral easement

G 424.2 Superelevation: The amount of superelevation of raised water surfaces on walls of horizontal curves of open channels shall be calculated and the height of the channel wall shall be increased accordingly to protect against overflow.

The maximum amount of superelevation is about twice as much for supercritical velocity as it is for subcritical velocity, except where easement curves are introduced. With easement curves, the amount of superelevation for supercritical velocity can be held to substantially the same amount as at subcritical velocity.

The terms and definitions used in the equations are as follows:

s.e. = Superelevation (in feet). The maximum height of water surface above the depth "d."

d = Depth of water (in feet) as calculated for a straight alignment.

d' = Average depth (in feet) of trapezoidal section.

b = Base of channel (in feet). The width of a rectangular channel or the bottom width of a trapezoidal channel.

g = Acceleration due to gravity.

$V^2/2g$ = Velocity head (in feet).

V = Average velocity (in feet/sec.) for the flow cross-section.

V_c = Critical velocity.

Z = Embankment side slope ratio

$$\left(\frac{\text{horizontal distance}}{\text{vertical distance}}\right)$$

S_c = Slope of superelevated water surface (feet per foot)

R_c = Radius (in feet) of centerline of circular curve.

$F = \dfrac{V}{\sqrt{gd}}$ Froude number.

Ls = Length of spiral transition curve (in feet).

The recommended superelevation is as follows:

A. For Rectangular Channels:

1. Superelevation for subcritical velocity ($V<V_c$) or for supercritical velocity ($V>V_c$) with easement curve:

$$s.e. = \frac{V^2 b}{2g\,R_c}$$

2. Superelevation for supercritical velocity without easement curve:

$$s.e. = \frac{V^2 b}{g\,R_c}$$

3. L_s = 1.82 (F) b

B. For Trapezoidal Channels-subcritical flow only: The approximate superelevation is as follows:

$$s.e. = 1.15\frac{V^2}{2g}\left(\frac{b+ZD}{R_c}\right)$$

(15% safety factor included)

G 424.3 Bulking from Air Entrainment: At high velocity flow, turbulence produces a rough water surface which entraps air. This air entrainment phenomenon increases the depth of flow in the approximate relationship shown in Figure G 424.3. This increased depth requires additional wall height to contain the flow. The designer shall check for air entrainment in the design of free water surface flow.

The critical velocity at which air entrainment usually begins is

$V_a = (5gR)^{1/2}$ where R = hydraulic radius
g = 32.2 ft./sec./sec.

However, should turbulence be caused by a bridge pier or similar object, air entrainment can occur earlier.

For concrete surface channels, determination of total depth including air entrainment (d_a) can be made by determining the percentage of entrained air (u) from Figure G 424.3 using a known velocity (V) and hydraulic radius (R).

G 424.4 Hydraulic Jump: A hydraulic jump occurs in an open channel when the flow passes from a depth less than critical to a depth greater than critical. In this section, the causes of some common hydraulic jumps encountered in open channel design are discussed to help the designer recognize and control jump situations.

A hydraulic jump generally occurs near one of the following locations:

1. Near a change of invert slope from supercritical to subcritical in a uniform channel (see point 2, Plate "A," Figure G 424.4)

2. At a constriction or obstruction to supercritical flow, such as accumulated debris at an outlet or a bridge pier.

A hydraulic jump may be calculated by the method of pressure plus momentum. The relationship between pressure plus momentum, energy, and depth is illustrated in Plate "B," Figure G 424.4. This relationship is independent of the channel slope or friction factor. The momentum curve shows sequent depths of equal pressure plus momentum. The energy curve shows conjugate depths of equal energy exclusive of the head loss due to the jump. Note that the two curves diverge rapidly for subcritical flow. This shows that the jump head loss increases rapidly- as the height of the jump increases.

Unbalanced forces (pressure, friction, gravity, etc.) cause a change of pressure plus momentum (AM), which results in a jump and a loss of energy (h;) . The jump occurs when the upstream and downstream depths reach a point of equal pressure plus momentum.

This point can also be located by the intersection of the downstream depth and the upstream conjugate depth when both are plotted on a profile. Three typical cases are shown on Figure G 424.4. Note how the jump location varies and how it is located.

If several determinations of depth after jump are required for the same discharge, it may be advantageous to obtain them by plotting a graph similar to Plate "B." Figure G 424.4.

In the design of wall heights at hydraulic jumps, consideration must be given to the length of jump. This length is approximately five times the downstream depth of the jump and extends upstream from the calculated jump location.

For more information on the use of hydraulic jumps as energy dissipators and the solution of hydraulic jump problems, refer to Hydraulics of Open Channels by Bakmatef and Hydraulic Energy Dissipators by Elevatorski.

G 425 SUMMARY OF HYDRAULIC DESIGN

Before the hydraulic design is submitted to the supervisor for review, the final water surface calculations must be complete and legible. Also, the preliminary plan and profile must be revised to comply with the final design, and the final calculations must be compiled in the Summary of Hydraulic Design (Figure G 425). Another designer must check all calculations (which should be made on the forms illustrated by the figures). The preliminary plan and profile must also be checked against the calculation results.

The final water surface calculations submitted should include the following:

1. Water surface computations (Subsection G 422.1),

2. Head loss calculations at structures (Sections G 423 to G 423.4),

3. Superelevation (Subsection G 424.2), and air entrained depth calculations (Subsection G 424.3), and

4. Summary of Hydraulic Design (Figure G 425).

The Summary of Hydraulic Design figure provides a quick reference showing all the data required by the supervisor in checking the design. All depths and slopes are converted to elevations for the channel invert, the water surface, and the top of wall. All structures, hydraulic jumps, inlets, clearance at bridges, and other pertinent data are listed under Remarks. The critical depth should be listed under the section drawn to show the relationship between critical depth, normal depth, and the calculated depth.

Upon approval of the design by the supervisor, the procedure outlined in Section G 401 is continued to completion of design.

G 430 HIGH VELOCITY DESIGN-SAMPLE PROJECT

The design of open channels for flow at high velocity requires the consideration of hydraulic phenomena which are not entirely known and upon which control of flow may depend. Examples of these are surface waves at curves or transitions, concrete cavitation when the flow separates from the channel surface, and increased depth from entrained air due to turbulence. The criteria and techniques utilized for the Santa Ynez Canyon Storm Drain (Plan D-19357), where flows of approximately 45 fps occur, are presented herein as an example of high velocity flow design.

G 431 CONDUIT AND DEBRIS BASINS

The project utilizes a multiple box closed conduit, constructed with steel forms which have the rough areas ground smooth to reduce turbulence. The invert is flat in cross-section and steel troweled. Since no windows are allowed between barrels, the center section of the triple box is designed for larger flow at the upstream end to compensate for side inlets into the outside sections. Air ports are provided between barrels in the freeboard area to ventilate all sections. Windows are omitted to minimize turbulence.

A debris basin is required to protect the main inlet and each side inlet where incoming flow exceeds 50 cfs. The removal of debris is necessary to prevent damage to concrete and to minimize turbulence.

G 432 VELOCITY AND FREEBOARD

The maximum design velocity is 45 fps. This velocity approaches the velocity which may cause cavitation at wall or floor irregularities.

The minimum freeboard is 1 foot, but the freeboard must be sufficient to provide a friction slope equal to or less than the construction slope with full wetted perimeter. Air entrainment and superelevation were not considered critical in this design because of the allotted freeboard in a closed conduit. For an increase in grade at a grade change, the vertical curve criteria (shown in Subsection G 411.2) are used when required to retain the flow on the invert and thus prevent cavitation.

G 433 MANHOLES AND ACCESS STRUCTURES

Manholes are provided at major inlets and/or at 500-foot intervals. In multi-section conduits, each section is provided with a manhole, since no windows are constructed.

Vehicle access is provided at 5000-foot intervals Material access is provided either between the vehicle access or at 2000-foot intervals.

G 434 JUNCTIONS AND TRANSITIONS

Junctions are designed according to the head loss criteria given in Section G 423. With a main line (M.L) Q of 5572 cfs in the Santa Ynez Canyon storm drain, the inlets were designed as follows:

For Inlet Q is equal to or less than 10 cfs:
angle A = 90°, enter at center of M.L.

For Inlet Q is equal to or less than 50 to 75

cfs: angle A = 45°, enter at center of M.L.

For Inlet Q > 75 cfs: angle A = 30°, enter at

1 ½ feet above starter wall construction joint.

Side inlets should be kept as high as possible without creating bulking in order to reduce effect of cavitation on junction trailing edges.

Transitions are designed according to the criteria for high velocity flow given in Section G 623

The pier leading and trailing edges should be fabricated with A242 (ASTM) steel plate for protection against cavitation.