Chapter 6
Trunnion Girder

6-1. General Description

The trunnion girder supports the tainter gate. The trunnion girder and associated anchorage are critical items since all loads acting on the gate are transferred from the trunnion through the girder and anchorage to the piers. The girders are located on the downstream pier face and are held in place by a prestressed or nonprestressed anchorage system that extends into the pier (Chapter 5.). Trunnion girders can be constructed of posttensioned concrete or steel. Selection of girder type (steel or posttensioned concrete) is dependent upon a variety of factors including availability of quality fabricators or precasters, site exposure conditions, economics, and designer preference. Posttensioned concrete trunnion girders are very stiff resulting in minimal deflections and offer significant resistance to torsional and impact loads. Steel girders are susceptible to corrosion and are more flexible than concrete girders but are more easily retrofitted and repaired. Due to their higher flexibility, steel girders are intended for use with smaller gates. Paragraph 6-6.c provides guidance on use of steel girders.

6-2. Components

a. Posttensioned concrete. A concrete trunnion girder may be of precast or cast-in-place construction. In either construction method, the girder is posttensioned longitudinally to control in-service deflections. (Posttensioning also increases girder resistance to flexure, shear, and torsion.) Longitudinal ducts are provided for the posttensioning tendons and recesses are commonly provided for second placement concrete pours between the trunnion assembly and pier. Conventional reinforcement is provided to resist shear, torsion, bursting, and reverse loading forces, and to control spalling. Figure 6-1 shows the upstream face of a typical concrete trunnion girder.

b. Structural steel. Steel trunnion girders are typically of welded construction and are I-shaped or box-shaped. I-shaped members can be made from plates or standard steel sections and are primarily used where torsion is not a significant concern. Box-shaped girders are fabricated from standard sections or plate steel and are much more efficient in resisting torsional loads. Box-shaped girders (especially those that include center-mounted pins) are more difficult to fabricate, coat, and inspect than I-shape girders. (Paragraph 4-1.b describes center-mounted pins.) Girder stiffeners are used to increase web stability in areas of high shear and where posttension anchorage forces are applied. Stiffeners also increase torsional stiffness and provide support for center-mounted pins. Figure 6-2 depicts a typical steel girder configuration.

6-3. Material Selection

a. Concrete girders. The minimum compressive strength of concrete shall be 33MPa (5000 psi). Higher concrete strengths may be considered; however, specifications should include requirements on material controls and fabrication procedures to ensure the required strength.

b. Prestressing reinforcement for concrete girders. The posttensioning bars shall be of high-tensile alloy steel, conforming to the requirements of ASTM Designation A722. Posttensioning strands shall be low-relaxation, high-tensile, seven-wire strands conforming to ASTM A416 with a minimum strength of 1860 MPa (270 ksi). Bars are generally preferred over strands because they are less susceptible to stress corrosion.

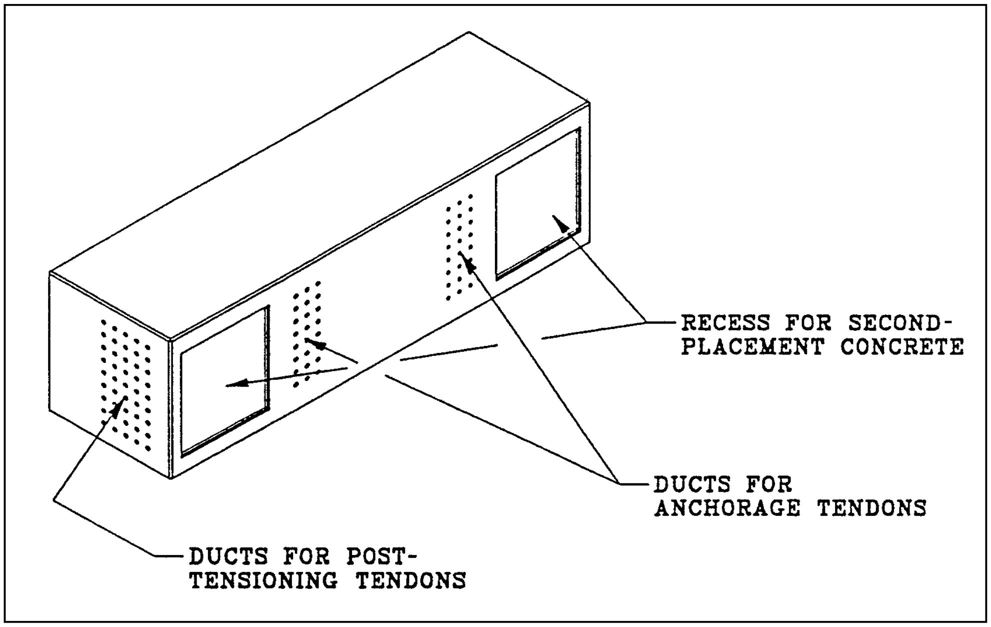

Figure 6-1. Posttensioned concrete trunnion girder

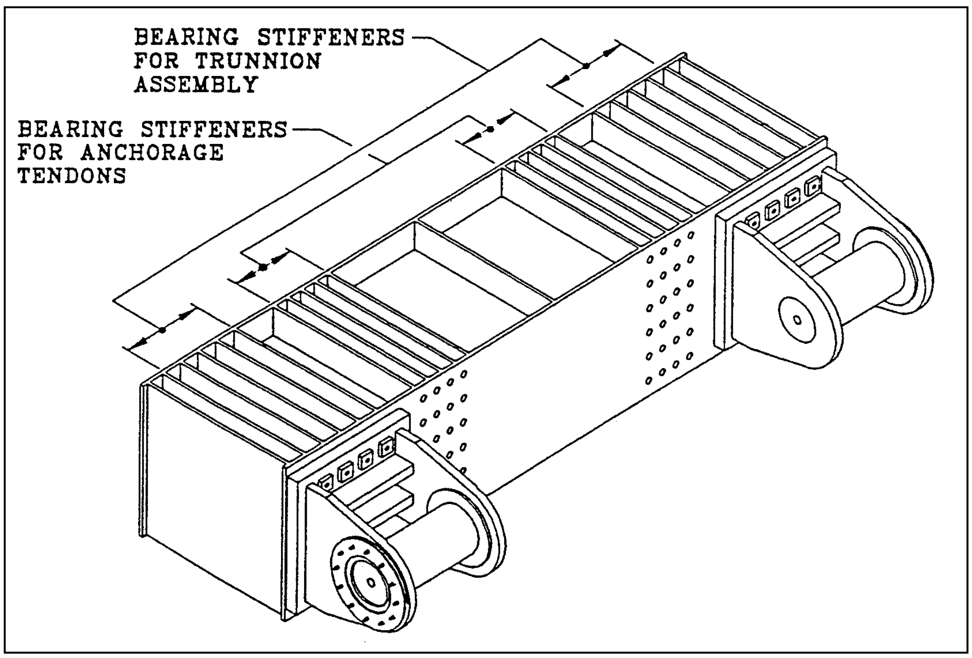

Figure 6-2. Steel trunnion girder

c. Mild steel reinforcement for concrete girders. Reinforcing steel shall be deformed bars conforming to ASTM A615, ASTM A616 including Supplementary Requirement S1, ASTM A617 or ASTM A706. ASTM A706 shall be specified when bars are welded to form a cage. The specified yield strength of deformed bars shall be 400 MPa (60 ksi).

d. Steel girder. Steel trunnion girders are considered fracture critical members (paragraph 3-8). Either ASTM A36 or ASTM A572 can be specified.

6-4. Design Requirements

Trunnion girders shall have sufficient strength to withstand combined forces of bending, torsion, shear, and axial compression due to trunnion reaction and anchorage forces. Girder torsion that occurs due to trunnion pin friction (as the gate is operated) and eccentric loads applied at the trunnion pin shall be considered. However, torsion due to trunnion pin friction shall not be considered if it counteracts torsion resulting from other loads. The design load cases shall be consistent with the operational range of the gate (i.e., consider loading from closed to open positions and intermediate positions). For multigate projects, the orientation of adjacent gates shall be considered (i.e., one gate closed, other gate open or closed or dewatered for maintenance) when evaluating the loading condition on the trunnion girder. Specific requirements for concrete and steel girders are provided in paragraphs 6-4a and b, respectively.

a. Concrete girders.

(1) Design basis. Concrete trunnion girders shall be designed based on the strength design method in accordance with ACI (1995), except as modified herein. Behavior under service loads shall be considered at all load stages that may be critical during the life of the project from the time posttensioning is first applied. The posttensioned anchorage zones shall be designed and detailed in accordance with AASHTO (1994), Section 5.10.9.

(2) Load requirements. The required strength of concrete trunnion girders shall be determined in accordance with the load combinations specified in paragraph 3-4.b, except the following load factors shall be used. A uniform load factor of 1.7 shall be applied to each of the specified loads for evaluating strength limit states and a load factor equal to 1.0 shall be applied to each of the loads for evaluating service limit states. A load factor of 1.2 shall be applied to the girder anchorage force.

(3) Limit states.

(a) Strength limit state. The design strength (nominal strength multiplied by a strength reduction factor) shall be greater than the required strength. The nominal strength and strength reduction factors shall be determined in accordance with ACI (1995).

(b) Service limit state. Service limit states are provided to limit tendon and concrete stresses at various stages including jacking (tendons only), after prestress transfer but before time dependent prestress losses, and after prestress losses have occurred (concrete only). These stages and prestress losses are discussed in Sections 18.4, 18.5 and 18.6, ACI (1995). Tendon stresses shall not exceed those specified in Section 18.5 of ACI (1995). Concrete stresses shall not exceed those provided in Table 6-1. The compressive strength of concrete at the time of initial prestress is denoted f'_{ci}, and f'_c is the specified compressive strength of concrete.

Table 6-1
Service Limit State Concrete Stresses

	Stress immediately after prestress transfer before prestress losses due to creep and shrinkage	Stress at service load after allowance for all prestress losses
Compression	0.55 f'_{ci}	0.4 f'_c
Tension	0.0	0.0

b. Structural steel.

(1) Design basis. Steel trunnion girders shall be proportioned and designed in accordance with paragraph 3-4 and EM 1110-2-2105.

(2) Load requirements. Steel trunnion girders shall be designed to resist trunnion loads due to load combinations specified in paragraph 3-4.b. A load factor equal to 1.2 shall be applied to the girder anchorage force.

(3) Limit states. Strength and serviceability limit states shall be considered in the design of steel trunnion girders.

(a) The strength limit states of yielding and buckling shall be evaluated in accordance with AISC (1994), Chapter H (for members under combined torsion, flexure, shear and axial forces), modified as required by paragraph 3-4.c. Resolved normal and shear stresses due to factored loads (i.e., required strength) shall not exceed the factored yield strength (i.e., design strength), and normal stresses due to factored loads (required strength) shall not exceed the factored critical buckling stress (design strength) of the member. When shear and normal stresses are of comparable magnitude, the affect of combined stresses can be evaluated by Von Mises stresses. The Von Mises stresses due to factored loads should not exceed the factored yield strength using $\phi = 1.0$ and α in accordance with paragraph 3-4.c. Careful consideration should be given for buckling in this analysis. Standard buckling equations apply to loads that are normal and transverse to the longitudinal axis of the member, whereas Von Mises stresses are usually not normal or transverse.

(b) The serviceability limit state shall be evaluated for maximum girder deformations. See paragraph 6-6.c for discussion of girder deformations.

(c) Fatigue limit states are typically not considered in the design of steel trunnion girders, since the number of load cycles is generally low and dynamic loading is not generally a concern. However, steel trunnion girders are considered fracture critical and proper material selection, welding procedures, joint details, and adequate quality control and testing is required. Paragraph 6-8 includes discussion of fracture considerations.

6-5. Analysis and Design Considerations

The trunnion girder shall be proportioned to satisfy the requirements of paragraph 6-4. The size of the trunnion girder is dependent on the magnitude of the flexural, shear, and torsion forces due to trunnion loads, and those forces due to anchorage jacking forces. The maximum shear and maximum bending forces act at the fixed end of the cantilever portion of the trunnion girder. These forces are combined with torsional and axial forces that result in a complex interaction of stresses. The design is accomplished by separating different stress contributions and designing for each individually. In general, shear and bending stresses due to transverse loading can be significant, while for most tainter gate configurations, axial stresses are minimal. Torsional shear stresses may be significant, especially for yoke mounted pins; however, these stresses can be limited by properly orienting the trunnion girder to minimize eccentricity. Maximum torsion will usually occur in the girder when the gate is partially raised and the pool is at maximum level. The trunnion girder should be designed with a compressible material over the center portion of the contact area between the girders and the back face of the pier as shown in Figure 5-2. This detail will provide a larger moment arm between the anchorage steel groups to resist gate reaction forces and will reduce negative bending moments in the trunnion girder when the main gate anchorage tendons are tensioned.

a. Analytical models. The trunnion girder can be modeled as a simply supported beam with cantilevered end spans. The supports are located at the centerlines of trunnion girder anchorages. The girder support is assumed to be torsionally fixed at the anchorage point. This model is shown in Figure 6-3.

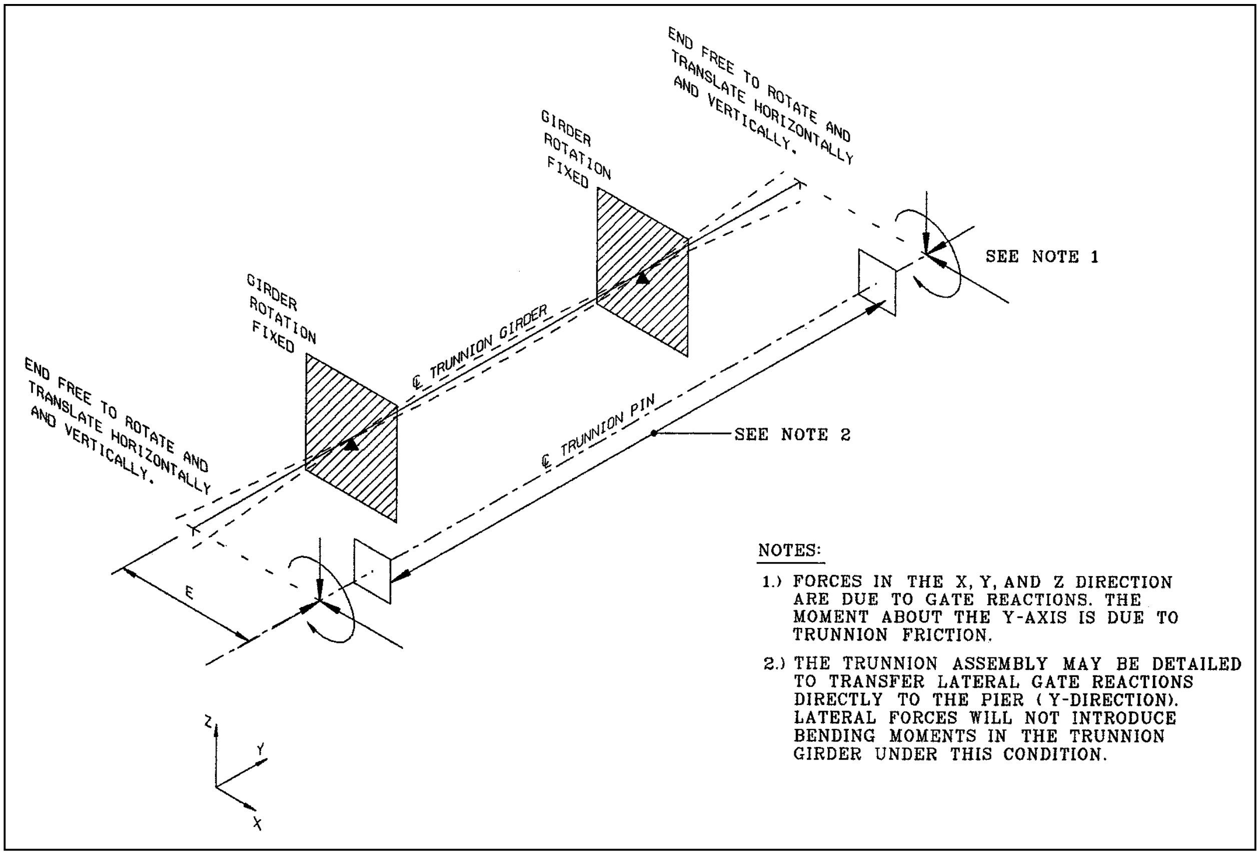

Figure 6-3. Trunnion girder analytical model

b. Concrete girders.

(1) Shear and torsion reinforcement. Shear and torsion reinforcement shall be designed in accordance with ACI (1995), Section 11.6. For design purposes, the critical section for shear and torsion shall be located at the first row of anchorage tendons closest to the trunnion. The minimum amount of web reinforcement should not be less than 0.003 *bs*, where *b* is the girder width and *s* the spacing of web reinforcement.

(2) Stressing sequence. Depending on the tendon stressing order, the controlling design stage may not be when all tendons are stressed. Consideration shall be given to bursting and spalling reinforcement needed as each tendon is tensioned in sequence. Any special requirements regarding stressing order shall be described in the contract specifications or noted on the contract drawings.

(3) Anchorage zones. Anchorage zone reinforcement to resist bursting, edge tension, and spalling shall be designed in accordance with AASHTO (1994), Section 5.10.9. This applies to anchorage zones corresponding to the girder longitudinal tendons and those due to girder anchorage forces (bearing areas between the trunnion girder and pier).

c. Steel girders.

(1) Stability. Beam flanges and webs should be proportioned to satisfy compact section requirements to avoid local buckling. Where compact sections are not practical, noncompact sections are allowed; however, slender elements shall not be used. Transverse stiffeners may be used to provide increased web stiffness. Where required, transverse stiffeners shall be designed in accordance with AISC (1994), Chapter F. The limit state of lateral torsional buckling is generally not a concern for box girders due to the relatively stiff cross sections. However, lateral torsional buckling may be a concern for I-shaped trunnion girders. In evaluating lateral torsional buckling, the unsupported length is generally determined assuming that the girder is braced at the centerlines of anchorage groups.

(2) Anchorage tendon supports. Specific members are generally required to provide support to resist the anchorage system posttensioning loads. These members may be comprised of steel plates, pipes, or tubes. Stiffener plates may be mounted on each side of an anchor and welded to the interior flanges of the girder. These plates may also serve as web or flange stiffeners. Pipes or tubes may also be mounted to the interior flanges and anchors passed through the inside of the pipes or tubes. Members shall be designed to resist jacking loads as described in paragraph 6-4.b(2). Steel plates should be designed as edge loaded flat plates, and pipes or tubes should be designed as axially loaded columns with boundary conditions that are consistent with the detailing.

6-6. Serviceability Requirements

a. Corrosion protection for concrete girder components. Ducts for tendons shall be morter tight and shall be grout-filled subsequent to posttensioning. Ducts shall be nonreactive with concrete, tendons, and grout and shall have an inside of diameter at least 6 mm (1/4 in.) larger than the tendon diameter. Anchorage devices shall be encapsulated by second-placement concrete.

b. Corrosion protection for steel girders. Corrosion protection for steel trunnion girders consists of protective coatings. I-shaped and open-end box-shaped girders may be painted, metalized, or hot-dip galvanized. Closed-end box-shaped girders may be galvanized. Box girders must include access holes for penetration of galvanizing material to the interior of the girder. The designer should locate potential galvanizers to assure that the size of girder can be accommodated. Bituminous fillers may be used to fill recesses and isolated pockets to promote proper drainage. Chapter 8 provides additional information on coatings.

c. Steel girder deflection. Deflections of steel girders due to service loads shall be evaluated for effects on tainter gate operation. Deflections shall be limited so that design stresses for bearings are not exceeded, maximum allowable bearing rotations are not exceeded (for spherical bearings), gate seal contact surfaces are maintained within acceptable tolerances, machinery loads are not exceeded, and gate and girder anchorage design assumptions are not compromised. For small gates (i.e., less than 15 m (50 ft) wide or 7 m (23 ft) high), acceptable deformations shall be determined by the owner and verified by standard engineering practice. For gates larger than this, steel girders shall be designed to achieve the same stiffness characteristics of a typical concrete girder proportioned to resist the same loading.

Alternatively, deflections may be calculated and the impact on operability determined. Such analyses shall be conducted using advanced 3-D analysis techniques such as the finite element method.

6-7. Design Details

a. Concrete girders.

(1) It has been common practice to require that the trunnion girder be completely posttensioned prior to placing adjacent pier concrete and tensioning the girder anchorage. This was done because shortening of the girder due to posttensioning would be restricted by bond to the adjacent concrete at points of bearing. This requirement can cause delays in the construction schedule. The use of second-placement concrete can be incorporated in the area between the pier and girder to eliminate this concern.

(2) Torsional reinforcement shall be provided in the form of closed stirrups. As an aid in construction, it is suggested that the conventional reinforcement be assembled as a cage with the web steel fabricated in a welded grid arrangement and welded to surrounding hoops and longitudinal steel. The longitudinal bars should not be too large since the posttensioning of the girders will have a tendency to cause buckling of these bars and may cause spalling of the concrete.

(3) The tendon spacing for the longitudinal posttensioning steel must be offset with respect to the trunnion girder anchorage tendons, allowing adequate clearance for concrete placement between ducts for longitudinal and anchorage steel. A 178-mm (7-in.) grid spacing for both the longitudinal girder and main gate anchorage tendons has been used satisfactorily in previous designs.

b. Steel girders.

(1) Consideration should be given for working room by selecting web depths and spacing of tendon supports and stiffeners so that welding can be performed without difficulty. It is recommended to provide a minimum of 200 mm (8 in.) of working room at a 45-deg angle to perpendicular members at a weld joint. If tighter working room is required by other constraints, potential fabricators should be consulted for requirements. Consideration should also be given for working room for weld test equipment.

(2) I-shaped girders are easier to fabricate than are box-shaped girders. Weld joints for flange-to-web welds and tendon support members are easily accessed. Box-shaped girders are more difficult to fabricate when center-mount trunnions and tendon supports are incorporated. The top plate may be installed in sections if welding to intermediate plates is required. Allowance for welding access may control member selection and sizing so that adequate working room is provided and quality welding can be assured.

6-8. Fracture Control

a. Material selection. Proper material selection and fabrication details and procedures will aid in control of brittle behavior of steel girders. To enhance ductile behavior, specified materials should either include mild carbon steels or maintain a carbon equivalent conducive to good welding. Weld metal should meet AWS matching filler metal requirements. Stringent toughness requirements should be considered for cold regions and where large welds (welds greater than 1 in.) are used. Toughness requirements shall be in accordance with EM 1110-2-2105.

b. Weld details. Girder end and interior stiffener or support plates should be coped at the corners to avoid intersecting welds and to provide access for coating materials. Where possible, large welds should be avoided by specifying double-bevel, full-penetration or partial-penetration groove welds, and by replacing single thick plates with multiple thinner plates. For all welding, AWS requirements should be specified for weld details, heat treatment, and matching filler metal. Stress relieving should be considered for girders with thick plates and high restraint.

c. Nondestructive testing. All structural joints and large welds should be 100 percent tested using ultrasonic or radiographic testing. Appendix B provides additional information on welding.