Movable Bridge Design

Design and Detail Issues Unique To Movable Bridges

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Movable spans are required for bridges crossing navigable waterways to allow passage of vessels in locations where alternatives, such as a fixed bridge with sufficient vertical clearance or a tunnel, are not practical or cost effective. Despite inherent disadvantages associated with movable bridges relative to such alternatives - including increased and more sophisticated maintenance requirements; potential for operational problems; safety concerns associated with movement of the bridge; disruption to traffic when the span is drawn; and more complex design considerations that requires interdisciplinary coordination of structural, mechanical, and electrical components - movable bridges still provide the most practical solution for bridge owners at certain locations.

Figure 4

An example of such a location is the Woodrow Wilson Bridge that crosses the Potomac River. Due to community concerns with the approach height necessary to achieve a fixed bridge with sufficient vertical clearance at the channel, the structure-type selected for the current replacement project is a bascule bridge, despite the current operational problems experienced with the existing movable span of the existing bridge. See *Figure 1* for a rendering of the new Woodrow Wilson Bridge bascule span.

Figure 3

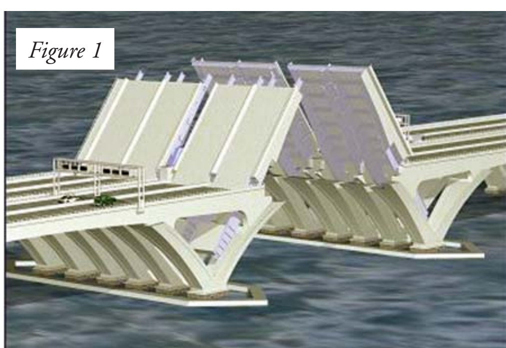

Figure 1

Figure 2

Movable Bridge Types

Three basic types of movable bridges are generally designed and built today – bascule bridges, swing bridges, and vertical lift bridges. Several sub-categories exist within each of these bridge types.

Bascule Bridges

When raising and lowering, bascule bridges pivot about a horizontal axis. Bascules fall into two general categories: trunnion bascules or rolling lifts. The Quogue Bridge in Southampton, NY, pictured in *Figure 2*, and the Berkley Bridge in Norfolk, VA, pictured in *Figure 3*, are examples of a trunnion bascule and rolling lift, respectively.

The trunnion type has a fixed point of rotation located at or very close to the center of gravity of the movable span. For this type, a shaft called a trunnion supports the main girders of the bascule span and serves as the pivot during operation. Typically the trunnion shafts are fixed to the main girders and the shaft ends rotate within bearings supported on the non-moving structure, thus the trunnions rotate with the moving span. However, an alternate arrangement keeps the trunnions stationary while the span rotates about them.

On rolling lift bridges, the center of rotation of the span moves in a horizontal line as the span opens and closes. Essentially, the movable span rolls back from the channel as it rotates open. This arrangement allows for rolling lift spans to be shorter, and require a lesser angle of opening in comparison to a trunnion bascule in order to achieve the same channel clearances.

Bascule bridges have either a single leaf or a double leaf. *Figures 2 and 3* both illustrate double leaf bascule bridges. For a photo of a single leaf bascule span, see *Figure 4*, which is the Rehoboth Bridge in Rehoboth, DE. Deciding which to use often hinges on required horizontal and vertical channel clearances, and to a lesser extent, time of span opening. A single leaf span supports dead load as a cantilever and live load as a simple span. Although each leaf of a double leaf span also supports dead load as a cantilever, the two leaves are connected at the center of the span by a lock system capable of transferring live load shear from one leaf to the other. In rare cases, the lock system is designed to transfer moment as well as shear, creating theoretical continuity across the span for live loads. Such a system was designed for the new Woodrow Wilson Bridge. The dual lock bar arrangement necessary to achieve moment transfer is shown in *Figure 5*, where a set of lock machinery is provided on each leaf of the double leaf bascule.

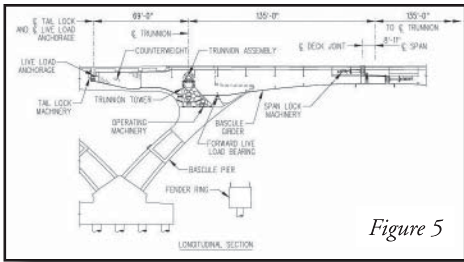

Figure 5

Swing Bridges

During span operation, swing bridges pivot in a horizontal plane about a center support, usually providing two navigation channels of equal width. Typically, the span swings open 90 degrees to allow vessels to pass, creating unlimited vertical clearance. Swing bridges are generally one of two types – center bearing or rim bearing. The Mystic River Bridge, pictured in *Figure 6*, is an example of a swing bridge in the open position.

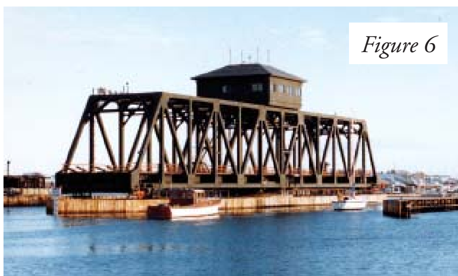
Figure 6

On center bearing swing bridges, the full dead load of the movable span is supported on a single bearing on which the span rotates when it opens and closes. Commonly, a single member oriented perpendicular to the bridge, called a pivot girder, carries the full dead load of the span from the main longitudinal members to the pivot bearing located at the center of the pivot pier. The configuration of the Third Avenue Bridge, a center bearing swing bridge in New York City currently being constructed, is shown in *Figure 7*. On rim bearing swing bridges, the full dead load of the movable span is supported on a circular drum girder, which in turn rests on a series of rollers that distribute the dead load of the span uniformly over the pivot pier. When the span operates, these rollers travel on a circular track anchored to the pivot pier.

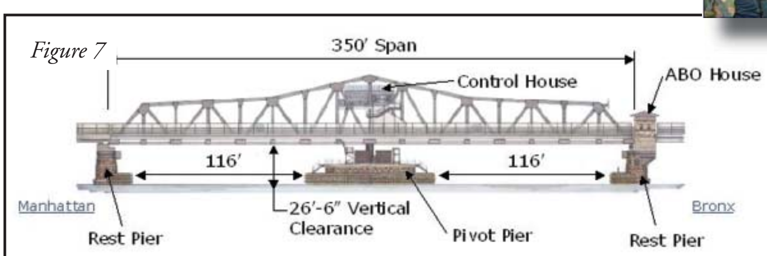

Figure 7

For center bearing and rim bearing swing bridges alike, span dead load is supported as a cantilever by the main longitudinal load-carrying members. When it swings closed, machinery lifts the ends of the span to vertically align the roadway joints with the fixed portion of the bridge and produce a positive reaction at the piers at each end of the span, called rest piers. This produces a continuous span to support live load.

Vertical Lift Bridges

Vertical lift bridges consist of simple spans that are raised vertically when the span operates. Towers at each end of the lift span contain sheaves over which wire ropes pass. These wire ropes connect to each corner of the span and to counterweights within the towers. At the tops of the towers, trunnion shafts and bearings support the sheaves, and thus the full weight of the lift span and counterweights. When the span operates, the system works in similar fashion to an elevator.


Figure 8

Two general types of lift bridges are typically designed – span drive and tower drive. For span drive vertical lifts, the drive machinery is located on the moving span itself, utilizing operating ropes that are anchored to the towers to raise and lower the span. By contrast, tower drive arrangements do not use operating ropes. Instead, drive machinery is mounted at the top of each tower, and turns the sheaves supporting the counterweight ropes directly. Examples of tower drive vertical lift bridge are the Route 7 Lift Bridge in Bellville, NJ, pictured in *Figure 8*, and the Marine Parkway Lift Bridge over the Jamaica Bay in New York City, pictured in *Figure 9*. Installation of the counterweight sheave for the Route 7 Bridge is pictured in *Figure 10*.

Design and Detail Issues

A number of design and detail issues unique to movable bridges exist that must be addressed by the structural engineer.

Span Weight and Balance

Regardless of the type of movable bridge selected, span weight and balance are critical issues. In order to minimize the size and power requirements needed to operate a movable bridge, movable spans for vertical lift and bascule bridges are typically counterweighted to produce a balanced condition. This allows drive machinery to be sized to only overcome small intentional imbalances, rather than the full weight of the movable span, in addition to frictional resistances, and wind and ice loads. As a result, the size of drive machinery can be dramatically reduced, and motors smaller than those required for a compact car commonly operate a movable span weighing millions of pounds.

Because movable spans are balanced with counterweights, the need to minimize span weight becomes more critical. For vertical lift bridges, every pound the span weighs is balanced by a pound in the counterweight, and for bascule bridges, the penalty is even more severe as typical counterweights weigh three to four times more than the weight of the movable span. For this reason, considerable attention has been paid to movable bridge decks over the years. Deck types used today include open steel grating, steel grating filled with concrete, orthotropic steel plates, and, more recently, fiber reinforced polymer systems. Because of its heavy weight relative to these deck types, solid concrete decks are generally not utilized on movable spans. However, in some cases, bridge owners desire the durability of a concrete deck and require such a system. One example of this is the new Woodrow Wilson Bridge, where extreme

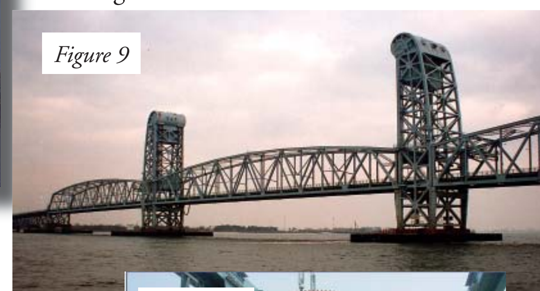
Figure 9


Figure 10

traffic demands influenced the decision to use a cast-in-place reinforced concrete deck for the bascule spans.

Balancing bascule bridges presents a unique challenge to designers, who must consider the vertical as well as the horizontal location of the center of gravity of each leaf. The elevation of the trunnions are established by passing a theoretical line through the center of gravity of the forward leaf and the center of gravity of the counterweight as it acts on the bascule girders. Only by achieving this theoretical alignment in both the vertical and horizontal directions will the span remain balanced throughout its travel. Generally, a small imbalance that results in a span-heavy condition is maintained to create a tendency for the movable span to stay in the seated position without needing machinery to accomplish this. *Figure 11* shows a simple schematic that illustrates the span balance concept for a bascule bridge, for which the center of gravity of the portion of the span

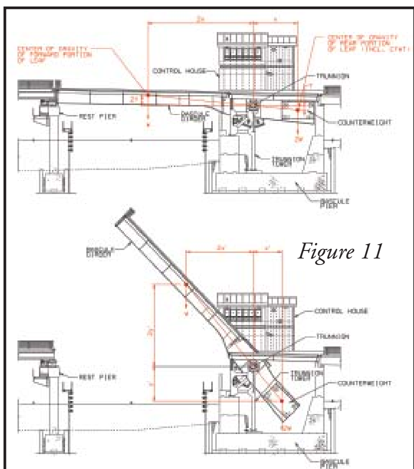

Figure 11

forward of the trunnion is located exactly twice the distance from the trunnion as the center of gravity of the rear portion of the span, including the counterweight.

Designers must provide adequate space and easily handled balance blocks in counterweight pockets to allow for simple addition and subtraction of weight to adjust the balance. This usually becomes a concern during rehabilitation projects where significant weight is added to or removed from the movable span.

Analysis in Open and Closed Positions

To design a movable bridge, additional efforts are required relative to fixed bridge design in that stress analyses must be performed with the bridge in the open and closed positions, typically requiring modeling of different support configurations for each position. Accordingly, for swing and bascule bridges, the sign of dead load stresses in the main members is generally different from the live load stresses. Seismic analysis must also be performed with the span in the open and closed positions.

Governing design codes, such as AASHTO and AREMA, define load cases for movable bridges that must be checked in addition to those required for fixed bridges. For example, AASHTO requires that when a movable span is in the closed position, the structure be designed as a fixed span for wind loads. However, with the span open, different wind loads and allowable stresses are specified, and these specifications vary further depending whether the movable span is normally left in the open or closed position. To account for forces associated with moving and stopping the span, impact forces generally specified as a percentage of dead load are included with dead load cases, and components attached to the fixed spans or substructure are designed to stop moving spans in the event of failure of the mechanical or electrical systems.

Clearances During Span Movement

Clearances during span movement are another critical issue in movable bridge design. Careful detailing of piers, deck joints, railings, parapets, and flanking spans is required to ensure that no interferences exist between the moving span and adjacent fixed bridge elements. Bridges carrying rail pose additional clearance issues associated with overhead catenary systems and mitre joints. In order to maintain reasonably small open joints and to keep designs efficient, clearances between moving and fixed components maybe as tight as an inch. Therefore, designers must consider potential variances due to fabrication and erection tolerances and the effects of temperature. Certain elements commonly require details that provide for field adjustability based on actual construction to account for this.

Due to the path they travel, bascule bridges typically present the most challenging clearance issues to designers. In addition to the noted concerns, clearance between the moving bascule girders and the fixed structure (typically towers) that supports the trunnions must be maintained. The presence of these towers restricts the designer's ability to provide lateral support for the compression flanges of the bascule girders in the highly loaded vicinity of the trunnions. This must be taken into account in the design.

Machinery Alignment and Supports

Perhaps the biggest challenge on movable bridge projects is mounting and aligning


Figure 12

machinery on the structure within required tolerances. Machinery tolerances are generally in thousandths of an inch, while the structure is built to tolerances of $^{1}/_{16}$ to ⅛ inch at best. To account for this, designers specify erection procedures and details to allow for proper machinery installation. For example, designers generally require that the structure be in its final uncambered, loaded position before final alignment of the machinery takes place. In addition, machinery supports require the use of shims and undersized bolt holes drilled to full size after final machinery alignment to provide the adjustment needed to correctly install the machinery on the structure. Also, details specify finishing of steel surfaces on which machinery mounts. These requirements ensure that tolerances associated with fabrication and erection of the structure, including camber, and actual deflections of the structure under dead load are properly accounted for when aligning the machinery.

Structural components that support machinery must satisfy requirements to ensure that the operational performance of the machinery is not jeopardized. In addition to accounting for forces from machinery and impact loads from moving and stopping the span, governing design codes such as AASHTO require that machinery supports be sufficiently stiff to limit potential deflections to levels that will not interfere with proper machinery operation. To ensure meeting these criteria, structural engineers must learn loads and permissible operational misalignment associated with supported mechanical systems. In general, stresses in machinery supports remain low.

Related to the machinery tolerance issue is the necessity for rigid movable bridge substructures. Because of tight clearances at joints and tight tolerances on machinery alignment, it is important that substructure deflections and movement after construction, due to settlement or live loads, be eliminated to the most practical extent.

Mechanical and Electrical Interface with Structure

The existence of the mechanical and electrical equipment necessary to operate a movable structure increases the efforts required by structural engineers beyond just designing members and systems to support these components. While developing an initial bridge layout, proper consideration must be given to the physicality of the mechanical and electrical equipment. In addition to providing space within the bridge structure to accommodate this equipment, consideration must be given to accessing, maintaining, and potentially replacing the equipment. Another concern is the routing and supporting of submarine cables and conduit that will run throughout the movable bridge superstructure and substructure. Most movable bridges include control houses that are integral with the structure, which is yet another consideration during bridge layout and design.

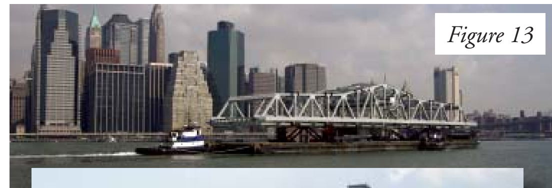
Figure 13


Figure 14

Constructing the Movable Span

The main construction issue for movable bridges is maintaining navigation traffic. Generally, this has been accomplished by erecting movable spans in the open position or prefabricating the movable span off-site and installing the span during short channel closure period, which can range from one to several days. Because of their orientation in the open position, placement of concrete for bascule decks must be performed with the span closed. This requires channel closures, although for double leaf bascules, these closures can be limited to half the channel as the concrete for one leaf is poured at a time.

Recent examples of movable spans built off-site and floated into final positions on barges include the Tomlinson Vertical Lift Bridge and the Third Avenue Swing Bridge. For Tomlinson, the 270-foot long lift span was erected just off-site and floated into position, interrupting navigation traffic for just five days. An aerial photo of the lift span being floated into place is shown in *Figure 12*. For Third Avenue, the 350-foot swing span was erected in Mobile, Alabama, placed on an ocean-going barge, and floated to New York City. The bridge will be floated into place in November, 2004, requiring only one weekend of closure to both marine and highway traffic. *Figure 13* is a photo showing the new span traveling on a barge past downtown Manhattan, on its way to the bridge site. *Figure 14* shows the Harlem River Lift Bridge raised to allow passage of this span.

An example of a movable span that was erected off-site and lifted into position by cranes is the Berkeley Bridge, shown in *Figure 3*. Each of the 110-foot long leaves of this double leaf rolling lift bridge was assembled in a nearby parking lot and lifted into position in their entirety.

Conclusion

Movable bridges have been an important part of our nation's infrastructure for centuries. They present unique challenges to the structural engineer and require extensive coordination of the structural, mechanical, and electrical systems to achieve a durable and operationally reliable structure.▪

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