Movable Bridge Engineering

Pavement Technology Advisory
Maintenance, Repair and Rehabilitation Series
PTA-M5 (Eff. 12/2014)
DECEMBER 2014

Reprinted with the permission of the publisher, Zweig Group, the publisher of civil + structural magazine.

If you have any questions regarding this advisory, please contact:

Engineer of Bridge Investigations
Bureau of Materials and Physical Research
126 East Ash Street Springfield, IL 62704-4766
(217) 782-7200

Illinois Department of Transportation

Bureau of Materials and Physical Research
126 East Ash Street / Springfield, Illinois / 62704-4766

Movable Bridge Engineering

cenews.com/article/9944

December 2014 » Project + Technology Portfolio » Transportation

Proper alignment, fit, and materials keep bridges — and traffic — moving.

Christopher Hahin, MetE, CorrE, P.E.

Figure 1: The principal components of a rolling lift bridge. The tracks and racks are not connected within a highly rigid common frame with respect to the movable portion of the bridge.

This article describes the advantages of movable bridges, the origins of misalignment in these bridges, and the various problems created by misalignment in rolling lift, vertical lift, and trunnion bascule bridges. The need to use tough and durable materials to construct movable bridges is also discussed.

Advantages of movable bridges

The choice of a bridge design for a specific location is determined by several factors, including the criticality and importance of the highway and the availability and cost of land acquisition. Movable bridges are compact electro-mechanical structures. Movable bridges are appropriate for locations where a limited amount of land is available, particularly for urban locations where tall fixed spans would require graded approaches to provide clearance over a navigable waterway. Because they have relatively short spans, they only open to river traffic when needed. In general, movable bridges have a lower cost because of their size limitations and limited land requirements compared with fixed bridges, which require greater clearances and longer approaches.

Movable bridges have a low initial cost, but must have operators when needed. If a movable bridge must be attended around the clock, the cost of operators has to be taken into account. Some bridge owners choose to operate movable bridges on specific timetables to conserve on labor, particularly if the river traffic is only recreational and movement would disrupt commercial and highway traffic.

Misalignment in movable bridges

The principal causes of misalignment are derived from errors in machining, layout during construction, misunderstanding of the need for tolerance control by designers, and improper installation of racks, bearings, shafts, tracks, tread plates, pinion gears, and track pintles.

Figure 2: The track uses pintles to establish correspondence with the movable tread plate to permit straight line motion of the pinion gear. The circular tread plate enables raising and lowering of the bridge span. The position correspondence of these pintles is critical to ensure proper closure of the bridge.

Structural elements used in construction of movable bridges are another source of misalignment. Rolled sections and plates all have some degree of lack of straightness, twist, and camber, and weldments contain substantial residual stresses. The relief of residual stresses during longer-term operation of the bridge can also cause plastic deformation and distortion. Structural elements of bridges are joined together by bolts, welding, rivets, and concrete foundations. The long-term mechanical action and vibration of machine elements and structures can lead to loss of rigidity. This relaxation of original as-built rigidity results in small but appreciable changes in geometry of the machinery, foundations, or structure. Moreover, continuing mechanical action on key components can lead to wear and loss of section, which is further exacerbated by misalignment. Because movable bridges use heavy, massive counterweights, they are subject to subsidence over long periods, particularly if the tracks or foundations have insufficient capacity to handle concentrated loads typically not experienced by fixed bridge piers.

Alignment in older movable bridges was originally carried out by use of optical transits, where measurements had an accuracy of 0.01 foot, which is equivalent to 0.12 inch. Foundations were generally laid out using spirit levels, which have limited horizontal accuracy. Taut wires were also used for alignment, along with dial indicators to measure run-out and deviation from required straightness of rotating machinery. Laser theodolites typically have in-line distance accuracy of 0.002 inch at 90 feet, and horizontal accuracy of 0.005 inch at 100 feet. Their typical angular accuracy is about 0.0008 inch/foot. Modern precision laser levels have an accuracy of 1/8 inch at 100 feet; machinist levels only have an accuracy of 0.005 inch/foot, whereas master precision machinist levels are accurate to 0.0005 inch/foot.

Most alignment papers and textbooks concentrate on direct in-line alignment of two machine components with couplings. The accuracy required for true alignment is often ignored by use of flexible couplings, which supposedly lessen the effects of misalignment. However, flexible couplings still result in bearing wear, overheating, and coupling failure. For movable bridges, coupling alignment is addressed by the important concept of machinery being anchored to a “common frame,” which may be a heavy massive foundation, a thick floor plate, or a rigid steel structure. The difficulty with movable bridges is that drive components are often separated not by a few inches, but by distances of 35 to 60 feet or more, depending on the number of lanes carried by the bridge.

The use of modern laser positioning and laser theodolites has markedly improved our understanding of misalignment in movable bridges. Lasers have revealed that even though movable bridges appear to be massive, seemingly rigid structures, they are not always truly stationary, particularly during operation of the bridge. Vibration and deflections arise from raising and lowering the bridge spans, along with deviations from intended alignments and fits dictated by various codes, which in turn can cause abnormal behavior, wear, and fatigue of critical components. These aspects are described for rolling lift, vertical lift, and trunnion-style bascule bridges.

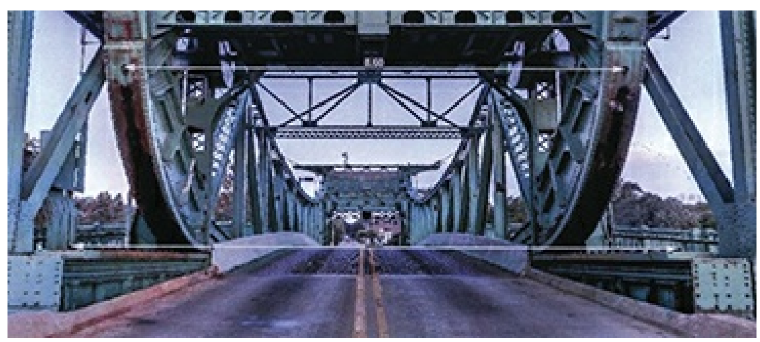

Figure 3: From this longitudinal view of a rolling lift bridge obtained by laser scanning, it is apparent that tracks, tread plates, pintles, and racks must have complete parallelism to provide good operation and closure. The photo shows differences in the centers of the pintles versus the tread plate sockets, leading to clashing when they interface. Photo: Falk PLI

Rolling lift bridges

A rolling lift bridge is a structure that rolls on tracks. The principal components of a rolling lift bridge are (1) a counterweight for each span and (2) rolling tread plates that are joined to (3) semi-circular sector plate assemblies that have (4) a drive pinion located right in the center of each sector circle (Figure 1). Drive machinery is housed inside this movable structure that rolls on two separate tracks. Each track has steel cones called pintles bolted to it that act as drive cogs for the tread plates, which have socket holes spaced on the same travel distance as the pintle spacing (Figure 2). This permits the tread plate to move forward uniformly and in a directly linear fashion.

Each center drive pinion engages a straight-line rack, which causes the bridge to move. Because the pinion drive gears are supposed to be in the exact centers of the sector circles, the pinion gear moves back and forth along a straight line. This permits the pitch line of pinion gear teeth to be in line with the pitch line of the rack. If the tread plate is a perfect circle, there should be no deviation of the correspondence of the pitch lines of the rack and the pinion gear, which is supposed to move in a perfectly straight and level line.

The rolling portion of the bridge is an integral entity composed of a counterweight, a circular-shaped sector with a tread plate connected to the span that moves up or down in an angular motion, typically to a maximum angle of 70 degrees. The greatest stresses are sustained on the rack and pinion gear teeth when the bridge is beginning to open, especially if the balance is "span heavy." The rolling portion of the bridge is separate from the fixed portion of the bridge, which consists of tracks and rack supports and the overhead live load bearings. The live load bearings restrain the live loads of road traffic and transfer them onto the fixed portion of the bridge when the opposing spans are center-locked, rather than transferring truck axle live loads through the drive train machinery.

There is no actual "common frame" of the machinery inside the movable portion of the bridge with respect to the independent tracks, racks, and pintles, which leads to misalignment. The term "common frame" is defined as a very rigid housing by which gears transfer mechanical forces without excessive variation of position, thereby providing alignment, proper mesh, and translation of motion. There are multiple sources of misalignment caused by the separation of the drive system with respect to the tracks on which the movable portion of the bridge rolls, and the racks by which span motion is induced.

The layout of each track must be completely parallel on one side of the bridge versus the other. For example, this means when bridge traffic runs east and west, the north and south track plates must be completely parallel. The importance of parallelism is shown in Figure 5. Each track plate must also be collinear with the other side of the river, so that when the east and west spans close, there is proper correspondence for center locking and uniformity of clearance. This is particularly important if finger joints are used for closure.

If a 20-foot track only deviates from parallelism from the other track by 3/8 inch, that results in a very slight skew of 0.0895 degree, which initially does not seem to be much deviation. However, if the span is 100 feet long, and assuming that the structural truss is straight, the shift from transverse parallelism at the center lock is 1.875 inches. Angular deviation of this magnitude results in lack of center lock fit and finger joint clashing.

If the rolling tread plate is not perfectly circular, there will be deviations from the pitch line of the rack versus the pinion gear. If the circle is too large, there will be insufficient engagement of the rack teeth. This is especially a problem if the rack has stub teeth. If the circle is of insufficient radius, the pinion gear teeth can be literally riding on the bottom lands of the rack, causing fatigue of the rack teeth at their roots.

Pintle misalignment is also problematic. If the pintles are not in perfect correspondence on one side of the track versus the opposite side, this can also lead to misalignment and improper clearance at the center locks. An out-of-correspondence pintle displacement of 3/8 inch for a 35-foot-wide track for a span of 100 feet results in 1.07 inches of transverse center lock displacement.

Pinion drive shaft alignment is important, whereby each shaft must be collinear with its counterpart on the opposite track side. A misaligned shaft can result in insufficient pinion gear tooth contact with the rack, as shown in Figure 6. This misalignment is probably the most critical of all because if tooth stresses are too high, fatigue or outright tooth rupture can jam or stop bridge operation. If the balance is markedly weighted toward the span and teeth rupture, this would result in a load transfer to the pinion gear on the opposite side rack. If the remaining single rack and pinion cannot sustain the entire balance load while the span is in motion, it could lead to machinery brake overload. A jammed span leaf could result in blockage of the channel.

Misalignment of the pinion gears and the racks can also lead to fatigue damage to drive shafting and pinions due to unnecessary stresses on the keyways, resulting in premature shaft life. If the drive shafting is skewed with respect to its supporting journal bearings, this can result in excessive wear and improper distribution of lubricants on the main drive shaft bearings. Many older bridges often do not have sufficient openings in the movable structure to permit a determination of alignment of the opposite side drive shafting by taut wire or optical or laser methods. What results is that the pinion gear is being mated with rack teeth, but is essentially accommodating the misalignment on one side of the bridge versus the other side. Laser methods have shown that such misalignment can be severe if the tracks are not perfectly aligned, the racks have separate alignments, or the drive shafts can be also misaligned.

Balance in rolling lift bridges is important because the span-versus-counterweight balance determines the level of stresses encountered in the rack and pinion gear teeth as the bridge spans are raised and lowered. A balanced bridge has lower rack and pinion tooth stresses, decreased bearing wear, longer motor drive life, and reduced power consumption.

Vertical lift bridges

Vertical lift bridges are capable of longer span lengths over a navigable channel. They are often augmented by additional fixed approach spans over parts of the river or channel where navigability is limited. Vertical lift bridges consist of two raised towers that support the movable span by means of wire ropes suspended from large-diameter sheaves (Figure 5). The spans are raised and lowered by drive systems. The drives may be located on the span where shafts transfer their rotation through pinion gears onto vertical racks on opposite towers of the bridge. Alternately, the drive motors may be located on the top of the towers, transferring rotation to large-diameter sheaves. In either case, the weight of the span is balanced by counterweights suspended on opposite towers.

Figure 4: A rack section showing signs of major misalignment of the pinion gear with the rack section. Continued operation would have caused severe wear and high tooth stresses. This situation resulted in abnormal main drive pinion bearing wear, but was reset by repositioning the rack to correct the misalignment. Shims were also added to correct the pitch line mismatch.

The bearings that cradle the large-diameter sheaves must be aligned so that they are exactly 90 degrees transverse to the longitudinal axis of the span. The AASHTO tolerance for these bearings is RC6. For example, for a 10-inch-diameter shaft that is shrunk-fit into the hub of the sheave has a maximum clearance of 0.013 inch between the bearings and the shaft. Any marked deviation from the 90 degree orientation can result in excessive wear on the wire ropes, eventually causing fatigue of the outer strands and abnormal bearing wear. Bearing block misalignment can lead to wear on the tower span guides and inability of joints to properly mesh when the bridge is seated and closed to river traffic.

In addition, the sheave bearings must be parallel to their cousins on the opposite side of the bridge, preventing skewing of the span. Cable length inequality can lead to incomplete seating of the bridge on its live load bearings, causing transfer of truck loads through the wire ropes and onto the sheaves.

Misalignment of span drives occurs when the drive shafting couplings are not properly connected, do not have a straight-line alignment, or if the shafting is not balanced. Long drive shafts used in span drives are often unbalanced because they were fabricated directly from hot or cold rolled rounds, which have straightness issues. This can result in vibration and fatigue of speed reducers. To prevent this, drive shafting should be machined before installation to ensure complete straightness. If pinion gears are misaligned with the vertical racks, abnormal pinion wear will result in early replacement.

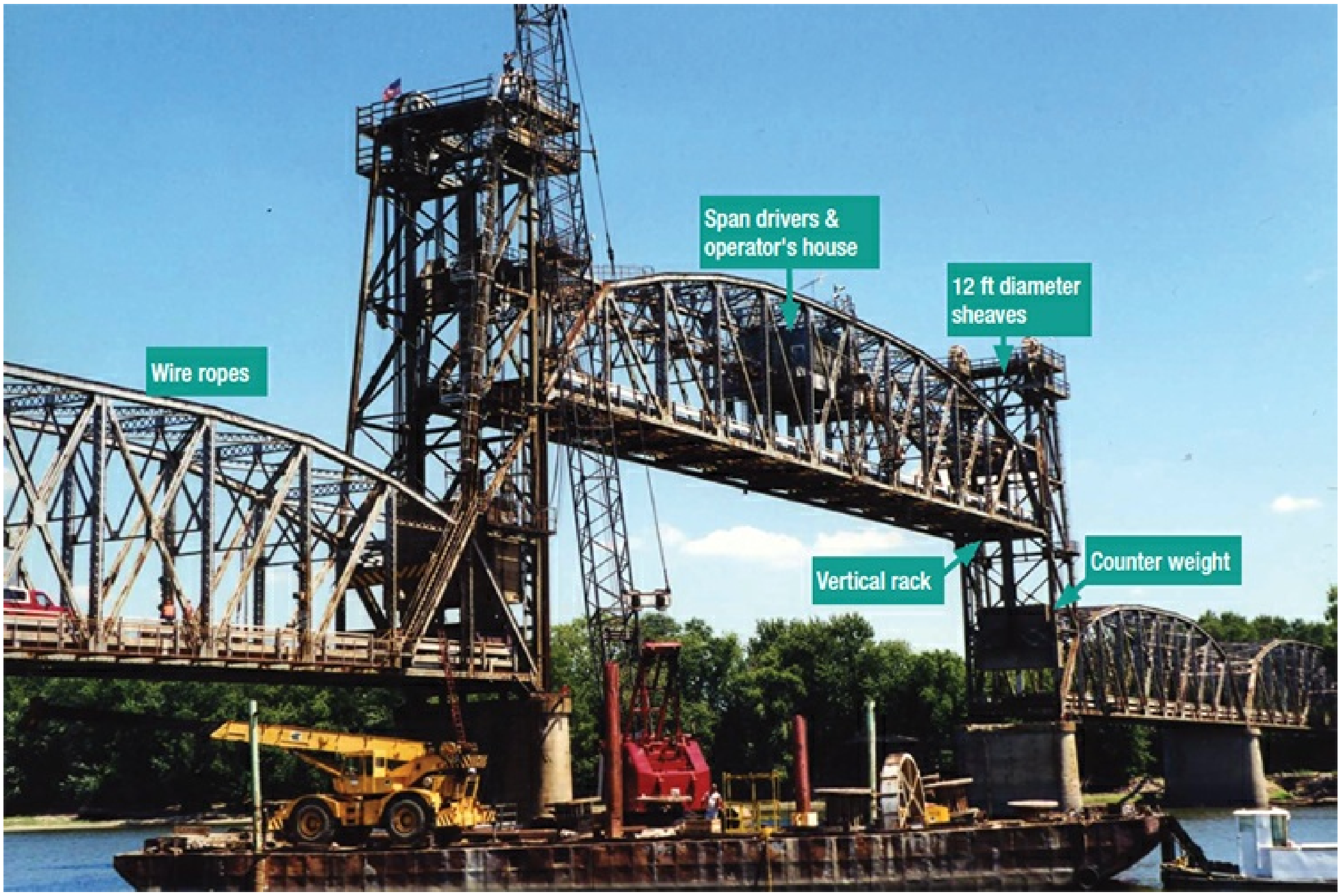

Figure 5: Major components of a vertical lift bridge with a span drive motor located in the operator’s house. The bridge is raised and lowered by shaft drives acting upon vertical racks on each tower. In this picture, new triple-web sheaves are replacing the severely cracked cast steel sheaves that had been in operation for 65 years.

Tower motor drives must have proper alignment to transfer motion without incurring vibration or stresses in couplings and shafting. Tower drives rely on exact synchronization so that all four sheaves are operating in unison. Otherwise, the span will be subject to loss of transverse and/or longitudinal levelness, triggering position sensors to shut down or result in incomplete seating of the span. Modern day towers have increased rigidity and stability compared with older versions, improving their reliability of operation.

Trunnion style bascule bridges

Trunnion style bridges differ from rolling and vertical lift bridges and have definite advantages. The larger-diameter trunnions are fixed and placed in a foundation of heavily reinforced concrete and structural steel that acts as a common frame. This continuous foundation houses the counterweight pit, drive motor foundations, speed reducers, and gearing. The design is stable because the unified foundation also provides a higher degree of rigidity for the drive gears and trunnions. The structures typically have curved racks on both sides of the movable span.

A good example of a classic trunnion style design is found in the Ruby St. Bridge over the Des Plaines River located in Joliet, Ill. In Figure 6, a composite drawing taken from the original plans shows the fixed and movable portions of the bridge.

TYPE OF MOVABLE BRIDGE	ALIGNMENT PROBLEM	PERTINENT DIMENSIONS AND VARIABLES	ANGULAR ERROR	DISPLACEMENT
Rolling Lift	Lack of pintle correspondence	Track width = W Difference in pintle correspondence = d* Span of bridge leaf = L Center lock displacement = D	$\tan \Theta = d \div W$	$D = L \times \sin \Theta$
	Track parallelism	Track width = W Deviation from track parallelism = d Track length = L_1 Span length = L_2 Center lock displacement = D	$\sin \Theta = d \div L_1$	$D = (L_1+L_2) \sin \Theta$
	Pinion gear misalignment	Tolerance of tooth dimension = T Gap difference between tooth & pinion at gear ends = G Tooth face = F; amount in contact = F_1	$\tan \Theta = G \div F$	Amount of face contact $F_1 = T \div \sin \Theta$
	Pitch line deviation	Levelness of rack = $E_1 - E_2 = \Delta E$** Radius of tread plate through roll = ΔR*** Distance from Pitch Line = ΔL	Not applicable	$\Delta L = \Delta E \pm \Delta R$
Vertical Lift	Lack of sheave collinearity	Span length = L Displacement from collinearity = D Wire rope length = L_w	$\tan \Theta = D \div L$	Span displacement = f (Θ, L_w)
	Span elevation	Wire rope length L_1, L_2 Inequality of levelness = $L_1 - L_2$ Span width = W Out-of-level displacement = D	$\tan \Theta = (L_1 - L_2) \div W$	$D = \sin \Theta \times W$
Trunnion Bascule	Transverse elevation difference of trunnion bearings	Elevations of trunnion bearings = E_1, E_2 Distance between bearing centers = W Vertical displacement = D	$\sin \Theta = (E_1 - E_2) \div W$	$D = W \sin \Theta$
	Lack of bearing perpendicularity to bridge center line	Deviation from perpendicularity = d Distance between bearing centers = W Span of leaf = L Transverse center lock displacement = D	$\tan \Theta = d \div W$	Transverse center lock displacement $D = L \sin \Theta$

Table 1: Displacements due to misalignment in movable bridges.

**This is a linear out-of-correspondence pintle displacement from one side of the track to the other.*

***Depends on position of deviation from level; minimized by making rack sections shorter.*

****Lack of radius equality can vary along the tread plate; typical pitch line coincidence variation is ±0.010”.*

Alignment in this style of movable bridge is dependent on the transverse orientation of each trunnion bearing such that it is perfectly transverse by 90 degrees to the longitudinal truss axis of the bridge. When the Ruby St. Bridge was first constructed, the trunnion elevation of the west side of the bridge was 2 inches higher than that of the east side. This was apparently corrected by the use of shim plates on the live load anchors, but center lock problems still persist today because of this oversight at original construction.

Because of bearing wear or any inherent trunnion misalignment, the fit-up at the center lock cannot be guaranteed to perfectly mesh. This can trigger problems with center lock closure. If center locks are not properly engaged, forces from truck loading are transferred to brakes and gears. Another problem arises if there is deviation of straightness in the truss span. If center lock fit is not proper, thermal expansion can prevent closure on very hot days. Misaligned or poorly lubricated trunnion bearings can result in abnormal shaft or bearing wear and increased motor drag due to excess friction. Each of these problems can lead to downtime, necessitating temporary support of the span, repositioning bearing mountings, and replacement of bronze bearing bushings.

Alignment of drive systems is equally important. Because these drive shafts and their bearings are not as stout as the trunnions, they must have excellent alignment, suitable couplings, and straightness to prevent vibration. Abnormal wear of spur and bevel gears is typically due to misalignment and lack of full face contact, necessitating their early replacement.

Importance of durable and tough materials

Fracture and impact toughness in movable bridge structures and drive systems are important material properties that are vital keys to bridge durability and safety. Many older bridges have non-redundant truss spans, but are generally well-tied together with large floor beams and stringers. However, many have open-grid decks, permitting dirt, salt, and debris to collect and cause corrosion of the stringers and connections. Movable bridges are subject to impact from barges and other vessels, particularly at night when visibility is poor. Steels with high impact toughness are required for bridges operating at lower operating temperatures for both structural and mechanical components because they can tolerate longer crack lengths under stress. Use of lower-carbon (0.10 percent or less), weldable alloy structural steels painted with durable coatings can prolong the life of these bridges. Steels such as ASTM A710 Grade B (50 or 70 ksi) or A709 HPS 50W are good examples.

Counterweight balancing is an important factor in decreasing stresses on spans, racks, and drive systems. Racks are often non-redundant, since many of the earlier designs apparently did not envision their potential fracture. Since rack teeth are in tension, bridge code requirements dictate that they must have sufficient fracture toughness at the lowest operating temperatures. The loading speeds of gears are faster than 1 Hz, so use of V-notch impact toughness as a function of yield strength at the lowest known operating temperature is appropriate. A V-notch impact toughness of 15 ft-lbs is an absolute minimum, and should be increased if the yield strength of the specified steel is above 50 ksi.

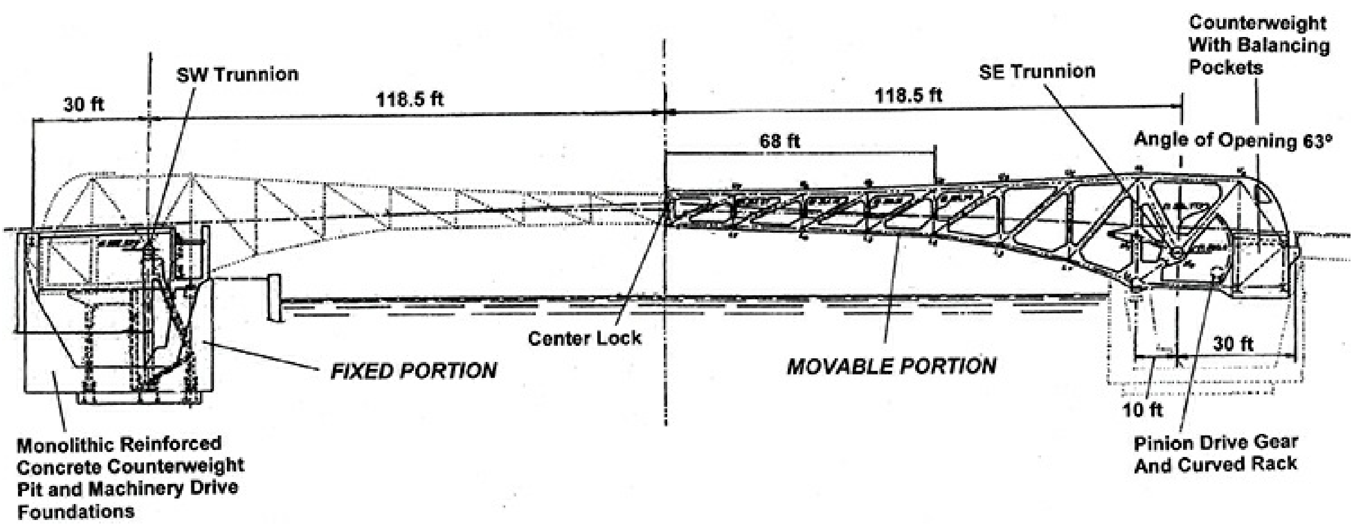

Figure 6: A composite diagram shows the fixed foundation and movable portions of a trunnion bascule bridge. All the weight of each span and counterweight are distributed over two large-diameter SAE 1045 steel trunnions attached to the movable structure.

The use of quenched and tempered alloy steels such as SAE 4130, 4140, and 4340 are most suitable for pinion gears and drive shafting containing notches or shoulder steps when alternating stresses in shafting are greater than 20 ksi. Shafts should be designed to avoid any sharp radii, and keyways should not be cut into shaft shoulders. Both of these design errors decrease fatigue life.

Wear of drive gears and racks are constant problems. Carburizing of SAE 8620 or other tough steels can sometimes relieve excessive wear on pinion gears. Avoid use of softer alloys such as ASTM A36 for racks; alloy steels are preferable. Use of brittle high-tin bronzes for bearings or center lock receiver slots invites premature cracking or failure if they are misaligned. Center locks are particularly susceptible because they are subject to frequent impact upon closure. Bearing bronzes that contain small percentages of lead can help provide lubricity during times when lubrication is lacking or unavailable.

Summary

Misalignment relationships for the three principal types of movable bridges are summarized in Table 1.

Fortunately, misalignment usually becomes a problem for movable bridges after many years of service due to changes in structural rigidity, machinery wear and fatigue, shifts in foundations due to subsidence, or barge impact, which causes permanent structural distortion or rupture. However, in general, steel movable bridges are economical, compact, and useful transportation structures if they are well designed and built, properly maintained, and suitably aligned. They have honorably served many American states, cities, and counties for more than 100 years.

References

- SKF USA Inc., 2010, “Don’t Let Shafts be an Afterthought,” Motion System Design, November, pages 30-31.
- Piotrowski, John, 2013, Shaft Alignment Handbook, Third Edition, CRC Press, Boca Raton, Fla.
- FARO Technology, 2013, Scanning of the Cass St. Bridge, Falk PLI, Portage, Ind.

Christopher Hahin, MetE, CorrE, P.E., is engineer of structural materials and bridge investigations with the Illinois Department of Transportation.

The author appreciates the contribution of several photographs cited in this article from Truman Price of IDOT District 1 and Bill Crosby of Falk PLI.