**HEAVY MOVABLE STRUCTURES, INC.**
**THIRTEENTH BIENNIAL SYMPOSIUM**

October 25-28, 2010

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# Movable Bridge Balance and Counterweight Design Considerations for Designers and Constructors

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# INTRODUCTION

Movable bridge balance is an essential consideration when constructing a new movable bridge or rehabilitating an existing movable bridge, as inattention to balance can result in overloading of the machinery and/or electrical drives, unacceptable operational behavior, unacceptable stability when seated or an inherently unstable bridge when seated any of which can result in damage to the structure or injury to construction personnel or the traveling public. This paper is intended to give an overview of considerations for balancing trunnion bascule bridges and shall discuss:

- The fundamentals of bascule bridge balance.
- Current balance criteria for bascule bridges, including AASHTO and DOT guidelines.
- The fundamentals of performing the balance calculations and considerations for calculating the make-up and design of the counterweight as part of the balance calculations and the benefits of considering materials and pocket locations.
- Two case studies are presented detailing balance calculations performed as part of new construction and the subsequent resulting counterweight design and final balance condition achieved.

The concepts presented in this paper can be applied to other movable bridge types with some modification.

# MOVABLE BRIDGE BALANCE FUNDAMENTALS

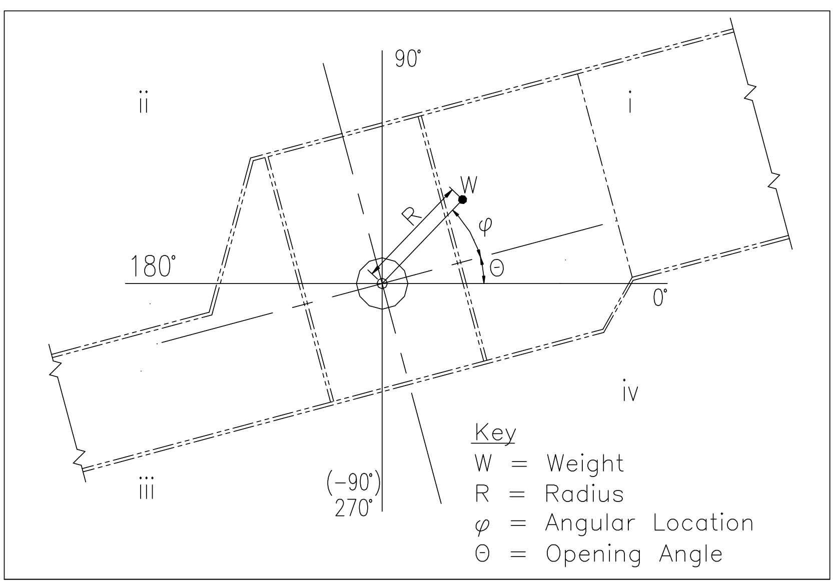


**Figure 1 – Identification of Imbalance Variables**

A trunnion bascule bridge may be represented as a rotating mass with the entire weight of the bridge acting at its center of gravity (W). The balance of the bridge is dependent upon the offset (both radial and angular) of the center of gravity of the bridge from the point of rotation. See Figure 1 for a depiction of the imbalance variables used. In practice, it is not desirable for the c.g. of the bridge to coincide with the center of rotation. Due to the complexity of bridge construction, there is invariably deviation of the c.g. from the calculated location, so that it would not be practical to achieve a perfectly balanced bridge. In fact, it is always desirable to maintain a span heavy moment when the leaf is in the seated position so that the leaf is stable under traffic and does not exhibit any tendency to open due to imbalance, as would be present under a counterweight heavy condition. Therefore, the term bridge imbalance is commonly used interchangeably with bridge balance when discussing this subject as the ultimate objective is to establish a known leaf imbalance.

The fundamental balance equation is expressed as:

$$WX = WR \times \cos(\varphi + Q)$$

where:

WX = Imbalance Moment, represents the moment that causes leaf rotation due to the influence of gravity.

WR = Imbalance Constant, represents the total weight (W) of the bridge multiplied by the radius (R) to the c.g. As will be subsequently discussed, each component of this constant can be individually calculated when performing detailed balance calculations. However, when measuring bridge imbalance it is only possible to determine the combined constant.

$\varphi$ = Angular Location of Center of Gravity, represents the location of the center of gravity relative to the center of rotation. A positive phi angle is measured from a horizontal line passing through the center of rotation (i.e., the trunnion) in the direction of leaf opening.

Q = Leaf Opening Angle, represents the actual opening angle of the leaf referencing a horizontal line passing through the center of rotation (i.e. trunnion) with positive values established in the direction of leaf opening..

It is common practice to equate the Imbalance Moment (WX) to an equivalent force applied at the toe of the leaf which is typically referred to as the Toe Reaction and can be expressed as:

$$\text{Toe Reaction} = WX \div \text{Leaf Length.}$$

One additional factor that is invoked in any discussion of bridge balance is system friction, which is that friction developed at the point of rotation which resists rotation. From a calculation standpoint, this friction is addressed in the machinery design and does not need to be evaluated in the bridge balance calculations. However, during measurement of leaf balance, system friction must be considered and compensated for as it impacts all of the current balance measurement techniques. System friction is typically presented similar to the Imbalance, both as a moment applied about the center of rotation (Friction Moment) and as an equivalent force applied at the toe of the leaf (Friction Toe Reaction).

# MOVABLE BRIDGE BALANCE DESIGN CRITERIA/CONSIDERATIONS

Due to the presence of the Leaf Opening angle (Q) in the governing balance equation, the balance of a movable bridge changes throughout bridge operation. Therefore, suitable balance parameters must be selected and specified in the design documents to obtain bridge behavior that is consistent with the design intent. The primary balance parameters which must be selected are the desired angular location of the c.g. (φ) and the desired magnitude of leaf imbalance. Selection of the φ parameter governs the rate at which the imbalance changes with leaf opening angle, and determines when the imbalance will achieve its maximum and minimum values. The magnitude of leaf imbalance is typically presented to specify the desired imbalance with the span seated, as well as the maximum allowable imbalance over the operational range of the bridge.

In the governing balance equation, the Imbalance Moment will be a maximum when the Imbalance Constant passes the horizontal axis through the center of rotation [(φ + Q) = 0°, 180°], and the Imbalance Moment will be a minimum, effectively 0, when the Imbalance Constant passes the vertical axis through the center of rotation [(φ + Q) = 90°, 270°]. Historically, there have been two primary schools of thought on how to specify the ideal location for the angular center of gravity, and they differ in where the maximum and minimum imbalance moments occur through the allowable range of travel.

According to the first school of thought, the c.g. should be located at the complement of the opening angle so that the leaf is in its maximum span heavy balance state when seated and then the imbalance should decrease over the operational range until the span is neutrally balanced in the full open position. See Figure 2. Under this criterion, the span is never in a counterweight heavy balance state, and the machinery is able to exert its full capacity to counter the maximum wind load at the fully open position. This balance state facilitates manual lowering of the bridge in the event of an electrical or control failure.

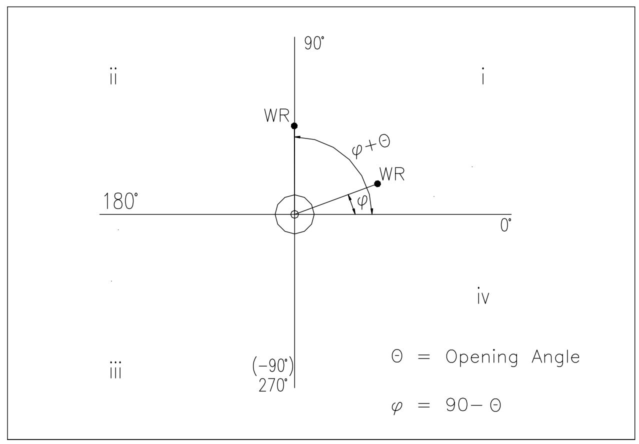


**Figure 2 – Ideal Location of C.G.**

Current AASHTO LRFD Movable Highway Bridge Design specifications provide guidelines that are generally consistent with the first school of thought.

> "For all bascule bridges, the movable leaves should be balanced such that the center of gravity with the span fully seated is located towards the channel at an angle no greater than 20 degrees above or below a horizontal line passing through the trunnion." (AASHTO LRFD article C1.5.1)

It is notable that the AASHTO guideline allows for the range of imbalance to remain more span heavy than originally discussed under the first school of thought. In its most stringent application, where the c.g. would be located at 20 degrees below horizontal with the span closed, the loading resultant from imbalance would be more constant than in the first school, however, a distinct span heavy imbalance state would exist with the leaf fully open (i.e., the span heavy imbalance would remain at 68% of its original value (for a 70° opening angle)) so that consideration would need to be given in the design of the machinery to the imbalance being additive with the maximum wind load. This imbalance state could be appropriate for a hydraulically operated bridge where a clear benefit can be obtained with regard to cylinder sizing and maintaining positive control of load. Note that the current FDOT Structures Design Guidelines with regard to hydraulically operated bridges requires a span heavy balance condition throughout the entire range of operation.

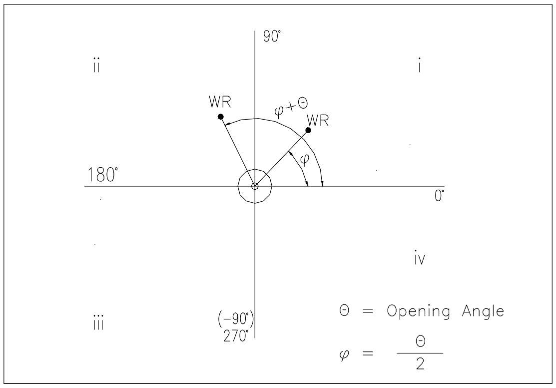


**Figure 3 – Ideal Location of C.G.**

According to the second school of thought, the c.g. should be located to produce a span heavy balance state when closed, and a counterweight heavy balance state when open. See Figure 3. Under this school of thought, the imbalance ensures that the leaf remains closed when fully lowered and open when fully raised. This school of thought also provides more equal loading of the machinery and ensures that the machinery sees loading in both directions of operation. However, the counterweight heavy condition when open is additive to the maximum wind load and must be considered in the selection of the power requirements and machinery design.

Many bridges on the West Coast are balanced according to this school of thought, and the Florida Department of Transportation has recently updated their guidelines to conform to this balance criterion (with the exception of hydraulically operated bridges as noted above):

> "a. The center of gravity is forward (leaf heavy) of the trunnion and is located at an angle 20° to 50° above a horizontal line passing through the center of the trunnion with the leaf in the down position.
> b. The leaf shall be tail (counterweight) heavy in the fully open position."
> (FDOT Structures Design Guidelines article # 8.5.3, #2)

Note that FDOT has changed their balance guidelines over the years. As recent as the 2000 FDOT Structures Design Guidelines, the recommended guideline provided for a more span heavy balance condition throughout operation than provided under the current AASHTO. The FDOT guideline specified that "A rule of thumb is to insure that the center of gravity is located at minus one half (-1/2) the total bridge opening angle with the leaf in the down position and rotates to plus one-half (+1/2) of the total bridge opening angle with the leaf in the full open position." This guideline provides for the most constant power output and machinery loading under normal operating conditions, but it also results in a significant span heavy balance condition when the span is fully open.

Ultimately the location of the center of gravity is a matter of preference to the owner and engineer for any number of valid reasons for a specific bridge. However, due consideration should be given when changing the balance of an existing structure that the machinery and drive/controls are capable of operating under the new requirement.

The primary objective in specifying the magnitude of leaf imbalance is to obtain a bridge which is stable when seated under the live load of traffic, which can be reasonably controlled during operation and which does not require excessively large machinery or power to operate the leaf. The range of acceptable span imbalance can vary with bridge type and is dependent upon many factors including whether the bridge utilizes a single or double leaf, whether the break in the roadway falls forward or behind the center of rotation, and whether span locks are utilized which employ a positive reaction to restrain the tip of the leaf. Current AASHTO guidelines specify a toe reaction of approximately 1,500 lb. per girder for a double leaf bascule and 1,000 lb. per girder for a single leaf bascule. However, we have performed actual bridge balance tests where the measured seated toe reactions due to imbalance range from 750 lbs. to 11,000 lbs.

System friction should also be considered when selecting an imbalance magnitude to anticipate the effect of the proposed imbalance on leaf behavior. Where system friction exceeds leaf imbalance, which may occur in a design which utilizes plain bearings, the leaf will have no tendency to rotate under the influence of gravity. Such a system is inherently stable in the absence of external loading. Conversely, if the system friction is very small relative to the leaf imbalance, such as may occur in a design which utilizes roller bearings, the leaf will tend to accelerate under gravity in the direction of the imbalance. With the increasing usage of roller bearings for the primary support bearings, system friction has been greatly reduced allowing reductions in power requirements and machinery size; however, it is duly noted that the decreased system friction places greater demand on the control system to maintain control of the movable leaf during operation. A significant imbalance coupled with minimal system friction can result in a bridge that is difficult to control if the brakes and controls are not properly sequenced.

# MOVABLE BRIDGE BALANCE CALCULATIONS

In order to ensure that a movable bridge meets the desired balance parameters settled on by the designer and owner, detailed balance calculations must be performed to calculate the weight and center of gravity of each component that makes up the movable leaf and sufficient adjustability must be provided in the design to allow placement of weight as required to achieve the target. Meeting the balance parameters should be a collaborative result of the designer having performed sufficient advance work to ensure that the design provides the required adjustability to compensate for material allowances and construction variations and the contractor having performed the detailed calculations in sufficient detail to finalize the counterweight design and make adjustments as necessary.

To that end, the designer is tasked with specifying: the envelope dimensions of the counterweight as well as the generalized location of the counterweight pockets, the density of concrete required for the counterweight, the type of permanent ballast material, and the type of adjustable balance blocks. For the purpose of obtaining a uniform bid, it is beneficial to specify anticipated quantities of each material.

The contractor is tasked with performing detailed balance calculations based on shop drawings for each component to be used on the bridge and then designing the actual layout of the counterweight, including locating both the permanent ballast material as well as the adjustable balance blocks. AASHTO provides guidance on the design of counterweights to ensure sufficient adjustability to compensate for typical construction allowances.

> "Counterweights shall be made so as to be adjusted for variations in the weight of the span and in the unit weight of the concrete. Pockets shall be provided in the counterweights to house the balance blocks necessary to compensate for not less than 3.5 percent underrun and five percent overrun in the weight of the span. Each completed counterweight shall contain not less than one percent of its weight in balance blocks, arranged so as to be readily removable for future adjustments. Additional blocks for future adjustment in the amount of 0.5 percent of the weight of the counterweight shall also be provided and shall be stored at the site as specified by the Engineer." (AASHTO LRFD Movable Highway Bridge Design Specifications, Article 1.5.2)

A reading of this section makes clear that AASHTO intends for counterweight pockets to be sized, and adjustment blocks provided, to compensate for material allowances and construction variations. However, where the intent of the section is readily applicable to a vertical lift bridge due to the 1:1 relation between the balance of the span and counterweights, its application for bascule bridges can result in varying interpretations due to the moment calculation inherent in bascule bridge balance. Varying questions may be asked, including whether the intent of the allowance is only to consider the weight of the span forward of the trunnion centerline or if it should be applied to entire leaf including counterweight and whether balance blocks should be provided in an amount equal to the specified tolerance or should be provided to compensate for the moment resultant from the specified tolerance in which case the location of the blocks will have a significant impact on the number of blocks required. So as not to leave this open to interpretation during construction, it is preferable for the design documents to specify the quantity and general location of the counterweight adjustment blocks.

Detailed balance calculations are typically performed in three distinct phases:

1) Steel Skeleton – Calculations should be performed to determine the imbalance of the steel skeleton for the bascule leaf based on the approved shop drawings. The location of each component's center of gravity is determined relative to the center of rotation relative to three axes, X, Y, and Z. The X direction is typically parallel to the longitudinal axis of the bridge, with X = 0 at the center of rotation. The Y direction typically runs vertically with Y = 0 at the center of rotation. The Z direction typically runs transverse to the longitudinal axis of the bridge, with Z = 0 at the midpoint between the bascule girders. For leaves that are symmetrical about the Z-axis, the Z balance calculation can be neglected due to a symmetric assembly resulting in no imbalance moment about the Z-axis. The weight of each component is multiplied by the distance to the component's center of gravity to determine the moment about the respective axis. Once the moment for each component is determined, all of the components moments are summed to determine the resultant moment for the leaf as a whole.

2) Counterweight – Once the imbalance due to the steel skeleton has been calculated, the counterweight can be designed. Counterweight design should consider the following factors: variation in concrete density (if allowed by contract), quantity and location of ballast material, and quantity and location of counterweight pockets. As previously indicated, the counterweight pockets and associated balance blocks are intended to compensate for variations and/or changes during construction. Typically, designs provide for varying the concrete density and/or installing ballast material in order to assist in meeting the theoretical balance requirement without disturbing the adjustable balance blocks. If there is no such provision in the design, then alteration in the size of the balance block pockets and addition or removal of balance blocks would be required.

3) Construction Changes – Once complete, all of the itemized calculations should be entered into a common spreadsheet which may be used to monitor the balance of the span throughout construction. If variations in material weights are identified, or construction changes are implemented, the spreadsheet should be updated and the balance adjusted accordingly. In order to provide the best adjustability to the balance at the completion of construction, the counterweight design performed under item 2 must incorporate balance block pockets which provide for blocks to be located both above and below the center of rotation so as to achieve the best adjustability of the Phi angle.

Having complete balance calculations does not guarantee that the project balance parameters will be met, but they do increase the likelihood that discrepancies with the specification will be identified prior to construction when corrective actions can be taken to correct or mitigate the problem.

# MOVABLE BRIDGE BALANCE CASE STUDIES

The following two case studies illustrate the forestated balance considerations and methodology as experienced over the course of two completed projects from design plan through to final balance testing. Each case shall present the desired balance condition, balance calculations results, adjusted balance condition, counterweight design modifications required to meet the adjusted balance target, and the final balance condition measured via the dynamic strain gage method.

## Case Study 1. Single Leaf Bascule Bridge– New Construction

This project was a complete bridge replacement where an existing deteriorated single leaf trunnion bascule bridge was replaced with a new single leaf trunnion bascule bridge. Construction was completed in the spring of 2009 with the final balance testing conducted in April 2009.

The bridge design comprised steel girder construction with floorbeams and stringers supporting a steel grid deck half-filled with concrete. The counterweight consisted of a steel box containing concrete, permanent lead balance block ballast material, and adjustable cast iron balance blocks. The contract plans required complete balance calculations to be performed by the contractor, and that the final locations and quantities of balance material in the counterweight be determined by the contractor based on the calculations.

| Case Study 1 | | | | |
|---|---|---|---|---|
| | WR | Phi | WX | WY |
| | kip-ft | degree | kip-ft | kip-ft |
| Initial Target (Contract Specifications) | [99.2] | [60.9] | 48.2 | 86.7 |
| Initial Target (Contract Plans) | <147.5 | 20 to 40 | 54 to 63 | --- |
| Adjusted Target | <147.5 | 20 to 53 | 54 to 74 | 19 to 98 |
| Balance Calculation Result | 73.6 | 28.9 | 64.4 | 35.6 |
| Measured | 84.0 | 17.0 | 80.4 | 24.6 |

**Table 1 – Balance Target and Results, Case Study 1**

Calculations were performed in accordance with the previously identified methodology where first the steel skeleton was prepared, and then the counterweight design was formalized. Several balance issues were identified in the preparation of the calculations which enabled several significant adjustments to be made prior to construction and thereby prevented a very undesirable balance state following construction. Table 1 provides a summary of the bridge balance from design to completion.

The balance calculations identified the following:

1. A discrepancy was noted between the balance state called for in the contract plans versus the specifications with regard to the angular location of the center of gravity. This discrepancy was rectified through provision of an adjusted target.
2. Weight of the steel skeleton, and corresponding span heavy moment, was greater than indicated on the design plan. As a result, the moment provided by the counterweight needed to have a corresponding increase in order for the bridge to meet the overall balance requirements. Per the original design, the steel counterweight frame provided multiple bays which were to be filled with concrete, lead plates and cast iron blocks in varying proportion. See Figure 4.

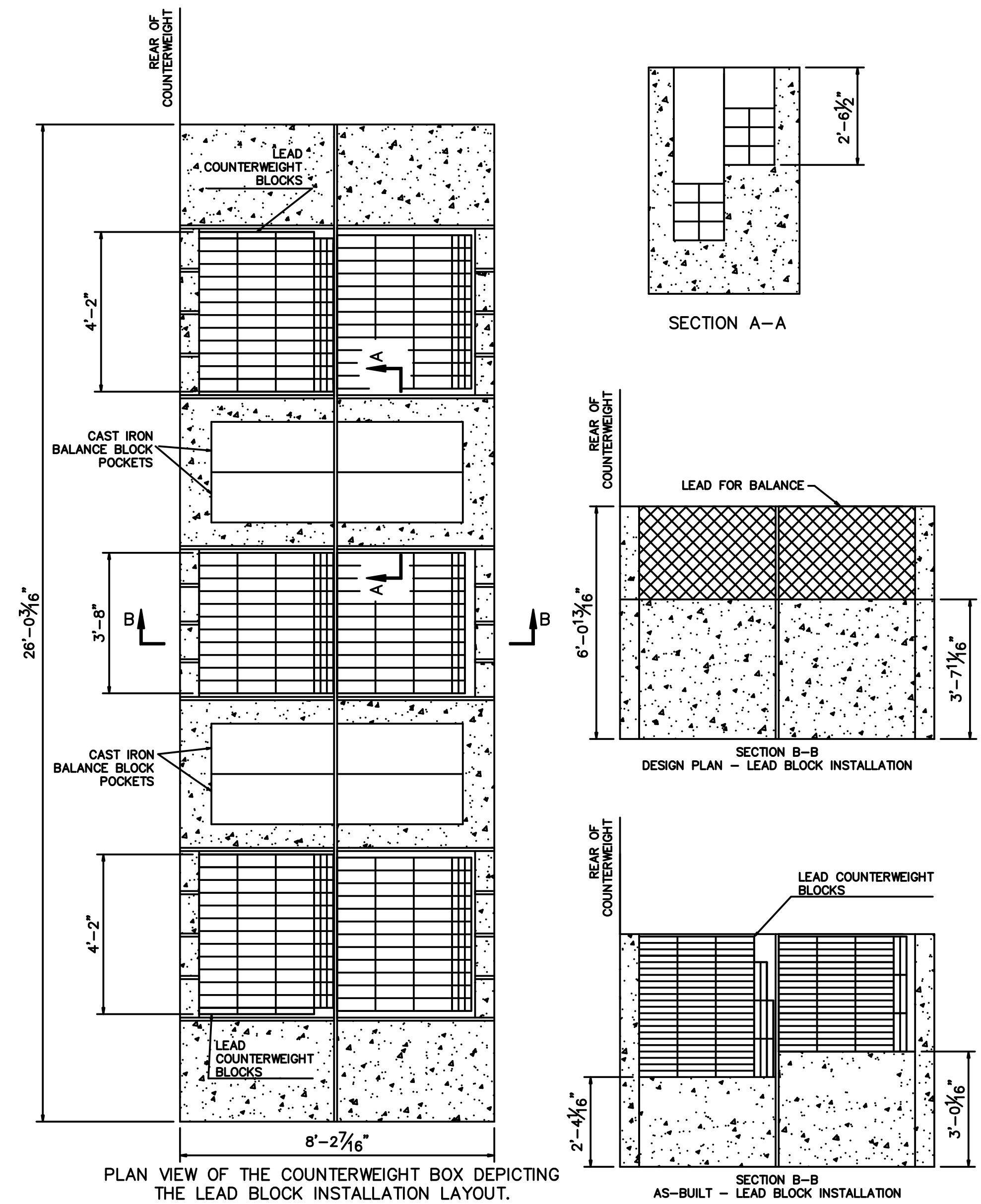


**Figure 4 – Counterweight Pocket Layout**

Working within the confines of this frame, the increase in the counterweight moment could be achieved through adding additional ballast, increasing the moment arm of the counterweight c.g., or some combination of the two. Due to the confines of the steel counterweight box and the limits on the acceptable range for the angular center of gravity, it was not possible to gain additional counterweight moment by shifting weight to the back of the counterweight box without falling outside the allowable angular range for the c.g. Therefore, it was necessary to provide additional ballast weight in the counterweight. Again, working within the confines of this frame and maintaining each material in its originally specified bay, the decision was made that providing additional lead was the most effective means of providing for the required balance while minimizing the impact on the angular location of the center of gravity. The cast iron balance blocks were maintained in their original quantity to compensate for construction changes. The following table presents a comparison of original vs. as-calculated and constructed quantities of the ballast material:

| Case Study 1 | |
|---|---|
| Balance Blocks and Ballast Weight in the Counterweight | Weight kips |
| Cast Iron Balance Blocks | |
| Original Design | 19.05 |
| As-Constructed Design | 19.19 |
| Lead Block Ballast Material | |
| Original Design | 169.42 |
| As-Constructed Design | 189.60 |

**Table 2 – Comparison of Original vs. As-Constructed Ballast Weight**

3. The original counterweight design placed the lead ballast as high in the counterweight as possible. As a result, the additional lead used to ballast the additional span weight by necessity had to be placed lower and resulted in a lowering of the c.g. of the structure. See Section B-B in Figure 4. While this lower c.g. still provided an overall theoretical balance state within the allowable tolerance, it was not at the midpoint of the tolerance. As indicated in Table 1, the highest c.g. which could be produced following the addition of the lead ballast was 28.9 degrees as opposed to an optimal target of 37 degrees which would split the tolerance. This in effect limited the ability to compensate for changes which occurred during construction.

4. It is notable that the design of the pockets for the cast iron balance blocks provided a shelf within each pocket so that blocks could be added at differing elevations as depicted in Section A-A in Figure 4. This design provides superior adjustability to the vertical c.g. than if the pockets had only provided one common elevation.

At the completion of construction, the actual leaf balance was measured via dynamic strain gage testing. The actual balance condition was comparable to the calculated balance, however it is notable that material allowances and/or discrepancies between the theoretical calculations and actual construction resulted in an angular location of c.g. that was lower than calculated and outside the target range. The lower c.g. also resulted in the seated imbalance being slightly greater than the target imbalance range. A subsequent weight change analysis revealed that notwithstanding the provision of the bi-level counterweight pocket, the adjusted target balance condition could not be met without altering the entire block configuration of the pockets. Due to the nominal overrun on the target condition and verification through review of the strain recordings that all strains were well within 100% Full Load Motor Torque (See Figure 5), the balance condition was accepted without further modification.


**Figure 5 – Strain Gage Testing Strip Chart**

It is notable that if the theoretical balance condition of the leaf could have been set so that the angular location of the c.g. fell at the midpoint of the tolerance range, then the deviation between actual and theoretical conditions noted during this project would have fallen within the target tolerance.

# Case Study 2. Single Leaf Bascule Bridge– New Construction

The project involved the construction of a new single leaf trunnion bascule. The movable portion of the bridge was completed in early 2010 with the final balance testing conducted in March 2010.

The bridge design comprised steel girder construction with floorbeams and stringers supporting a concrete filled steel grid deck. The counterweight consisted of a steel box containing concrete and lead balance blocks for adjustment. The contract plans required complete balance calculations to be performed by the contractor, and that the final locations and quantities of balance material in the counterweight be determined by the contractor based on the calculations.

Calculations were performed in accordance with the previously identified methodology where first the steel skeleton was prepared, and then the counterweight design was formalized. In the preparation of the balance calculations, a significant issue was identified with the quantity and location of the lead balance blocks which required adjustments to the pocket size and location, the quantity of blocks, as well as to the target balance condition. The identification of this issue prior to construction enabled corrective action to be taken prior to construction and also adjusted expectations as to the final balance state. Further explanation of this balance issue follows.

Table 3 provides a summary of the bridge balance from design to completion. The balance calculations were prepared and submitted in three distinct phases. Phase I calculated the imbalance due to the steel skeleton only, and the imbalance presented in Table 3 is correspondingly high as the leaf is not counterweighted. Phase II calculated the imbalance due to the steel skeleton, concrete counterweight and the concrete filled deck, however, phase II does not take into account the lead balance blocks. Phase III calculated the final balance of the leaf, including the steel skeleton, concrete and lead balance blocks.

| Case Study 2 | | | | |
|---|---|---|---|---|
| | WR | Phi | WX | WY |
| | kip-ft | degree | kip-ft | kip-ft |
| Initial Target | 500 max | >5 | 400 to 500 | --- |
| Balance Calculation Result - Phase I | 13,104.8 | 4.6 | 13,063.1 | 1,044.8 |
| Balance Calculation Result - Phase II | 4,224.9 | -0.2 | 4,224.9 | -13.8 |
| Balance Calculation Result - Phase III | 448.7 | -9.6 | 442.5 | -74.7 |
| Adjusted Target | 453 max | -20 to 20 | 339 to 453 | --- |
| Initial Balance Test July 2009 | 347.7 | -18.5 | 329.7 | -110.3 |
| Final Balance Test March 2010 | 469.7 | 8.8 | 464.0 | 71.9 |

**Table 3 – Balance Target and Results, Case Study 2**

As a tie-in between Phase II and Phase III, a calculation was performed to determine the theoretical location and magnitude of lead blocks necessary to achieve the target balance condition; the calculation revealed that the magnitude of lead balance blocks was greater than originally called for and that the required location for the lead blocks was above the top of the counterweight and therefore could not be physically achieved. Through coordination with the EOR, the balance block pockets were modified to optimize their impact on the span balance. The original design had provided for 2 pair of counterweight pockets: one pair was provided to facilitate the WX adjustment and one pair was provided to facilitate WY adjustment. The modification implemented as a result of the calculation was to increase the dimensions of the WY pocket so that a greater quantity of weight could be placed higher and further back in the counterweight than provided for under the original design. See Figure 6.

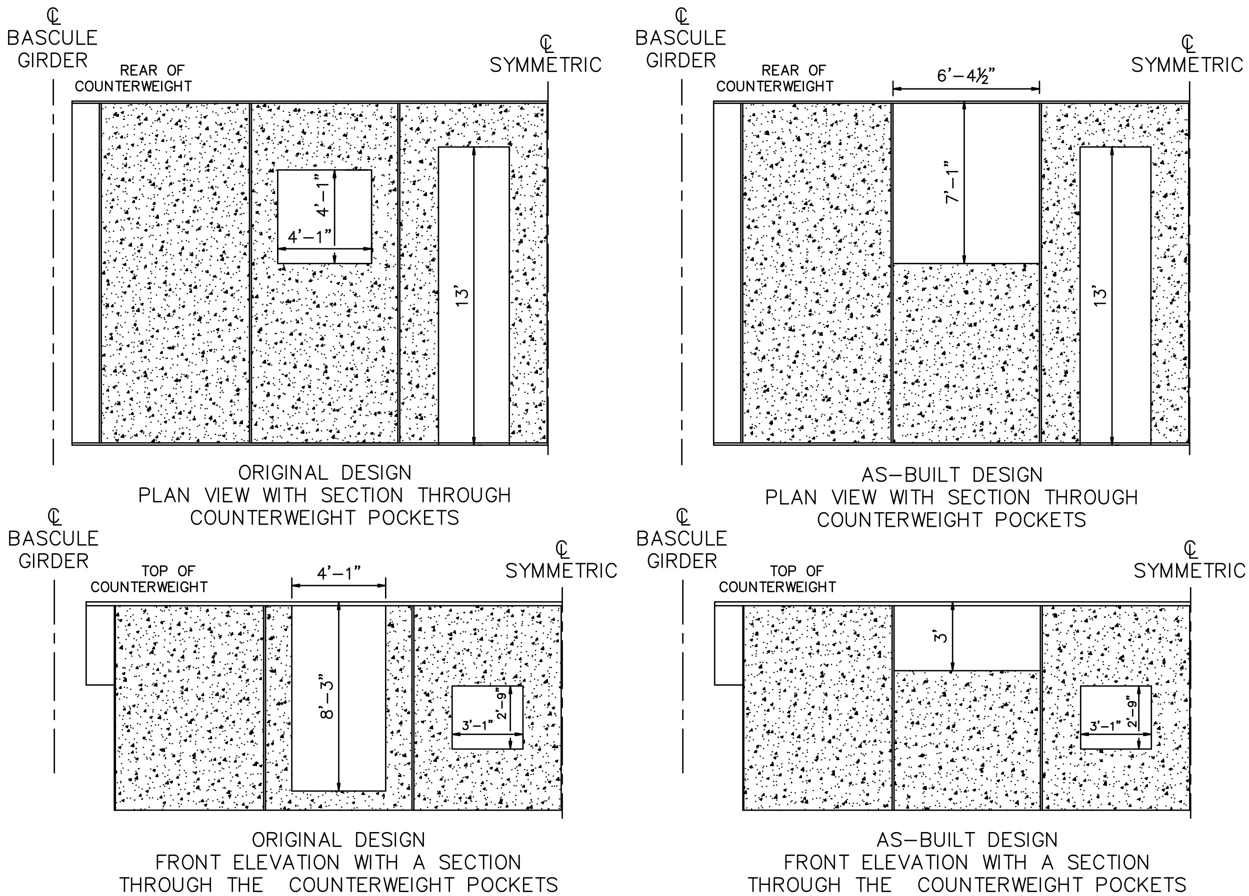


**Figure 6 – Counterweight Pocket Layout**

The net result of this modification to the counterweight pockets was that while a greater quantity of lead balance blocks would be required to achieve the final balance condition than originally called for, the quantity was much lower than would have been required if blocks could have been placed at the theoretical location above the top of the counterweight identified in the calculations performed following Phase II. See Table 4.

| Case Study 2 | |
|---|---|
| Balance Blocks in the Counterweight | Weight |
| | kips |
| Lead Balance Blocks | |
| Original Design | 135.36 |
| As-Constructed Design | 153.91 |

**Table 4 – Comparison of Balance Blocks**

In addition to the modification to the size of the counterweight pockets and the required quantity of lead blocks, the balance target was modified to accept a lower center of gravity than originally specified in recognition that the best theoretical balance condition which could be achieved after completely filling the modified WY pocket with lead balance blocks still yielded a c.g. that was lower than originally specified.

At the completion of construction, the actual leaf balance was measured via dynamic strain gage testing. Testing was actually performed at two different time intervals. Testing was initially performed in July 2009 under the auxiliary drive in order to validate the leaf imbalance prior to the setup of the electrical drives; the leaf construction was not complete at this time, however only several miscellaneous tasks remained. Final testing was performed in March 2010 at which time all construction was complete and the bridge was functional on its main drive. It is notable that the test results from July 2009 corresponded very well with the anticipated balance condition (both with respect to WX and Phi), taking into account those items which remained to be completed. Likewise, it is notable that the final test results from March 2010 saw an unexpected jump in the Phi location which could not be readily explained by the remaining work that was completed following the July 2009 test. However, this change in the Phi location did not appreciably effect the bridge operation, did not contribute to increased machinery loading during operation, and was consistent with the initial target.

The final balance shift between the July 2009 and March 2010 reinforces the need to set a theoretical target at the middle of a desired target range to guard against the potential influence of construction and/or other physical activities which may not be entirely predictable.

# MOVABLE BRIDGE BALANCE SUMMARY

Movable bridge balance is an essential consideration when constructing a new movable bridge or rehabilitating an existing movable bridge. From a design perspective, balance parameters must be specified which are consistent with the owner's desire and the machinery and drive capacity, and the design must provide sufficient adjustability that the intended parameters can be met during construction. From a constructor's perspective, care must be taken to perform balance calculations in sufficient detail to ensure that the specified balance condition can be met utilizing the available ballast material, or alternate ballast schemes can be proposed prior to construction. Based on the experience cited in this paper, it is advisable that the theoretical balance condition of the completed leaf should target as close as possible to the middle of the allowable tolerance range to afford the greatest variance in construction without exceeding the balance parameters. Additionally, bridge balance can and should be monitored throughout construction utilizing a balance spreadsheet that has been compiled based on the detailed calculations to ensure that a severe imbalance does not develop due to construction methods which could jeopardize the safety and stability of the construction plan.