# STEEL PLATE GIRDER DEFLECTIONS

A look at the Development and Implementation of a Simplified Procedure to Predict Dead Load Deflections of Skewed and Non-Skewed Steel Plate Girder Bridges

# OVERVIEW

- Why NCDOT is modifying their dead load (non-composite) deflection policy for Steel Plate Girder Bridges
- What is Non-Composite girder dead load deflection
- Current analysis of deflection
- NCSU Research on Dead Load Deflection for Steel Girders
- Design Examples

# Why NCDOT is modifying their method for predicting dead load deflections

Inaccuracies in predicting the actual dead load deflections

- Steel bridges are being constructed with longer spans and higher skews
- Bridges are often erected in stages to limit traffic interruptions or to minimize environmental impacts

# What is Non-Composite girder dead load deflection

It’s the Deflection resulting from loads occurring during construction, prior to curing of the deck (prior to composite action between the steel girders and concrete deck)

# Current Analysis

- Predicted deflections are based on a single girder line (SGL) analysis
- Transverse load distribution transmitted through intermediate cross frames and/or the SIP forms are not taken into account
- Predicted deflections are dependent on the calculated dead load, which are determined according to the tributary width of the deck slab
- The predicted deflection for equally spaced interior girder will be the same and the predicted deflection for exterior girder is a function of the overhang slab

# Problems with the Current Analysis

- Construction issues may result from the use of traditional SGL analysis
- When girders deflect less than expected, the deck and/or concrete cover may be too thin
- When the girders deflect more than expected, the dead loads are greater than accounted for in the design
- Unexpected girder deflections may cause misaligned bridge decks during stage construction

# NCSU Research

Primary objective to develop an empirically based simplified method to predict non-composite deflections of skewed and non-skewed steel plate girder bridges

# NCSU Research

## How this was accomplished:

- Ten Steel Plate Girder Bridges were Monitored
  - Seven simple span
  - Two two-span continuous
  - One three-span continuous
- Girder deflections were measured in the field during the concrete deck placement
- Developed 3-Dimensional finite element models to simulate deflections measured in the field. The field measurements were used to validate the modeling technique
- Investigated alternate, less sophisticated modeling techniques and a general analysis program (SAP 2000)
- Utilized the 3-Dimensional finite element models to conduct a parametric study for evaluating key parameters and their effect on non-composite deflection behavior
- Developed a simplified procedure from the results of the parametric study
- Verified the method by comparing all predicted deflection to those measured in the field

# NCSU Research

## Conclusions

- The traditional SGL method does not accurately predict dead load deflections of steel bridges
- Finite element models created according to the technique presented in the research are capable of predicting deflections for skewed and non-skewed steel bridges
- Finite element models with SIP forms generate more accurate results, and should be included in the finite element models
- Skew, the exterior-to-interior girder load ratio, and the girder spacing-to-span ratio affect girder dead load deflections for simple span bridges
- Cross frame stiffness and the number of girders within the span do not have a significant effect on girder dead load deflections for simple span bridges

# NCSU Research

## Final Recommendation

- Developed the simplified procedure (SP), alternative simplified procedure (ASP), and SGL straight line (SGLSL) procedure to accurately predict girder dead load deflections

# Implementing the Research Recommendations

## Simplified Procedure (SP)

- To be used on simple span bridges with equal exterior-to-interior girder load ratios, or where the difference between the two ratios is less than or equal to 10%
- This procedure is applied to half of the bridge cross-section and the predictions are then mirrored to the other half

# Implementing the Research Recommendations

## Alternative Simplified Procedure (ASP)

- To be used on simple span bridges with unequal exterior-to-interior girder load ratios (load ratios that exceed 10%)
- Introduction to ‘high ratio’ and ‘low ratio’ which refers to the greater and lesser of the two exterior-to-interior girder load ratios

# Implementing the Research Recommendations

## SGL Straight Line (SGLSL)

- To be used on continuous span bridges with equal exterior-to-interior girder load ratios or where the difference between the two ratios are less than or equal to 10%

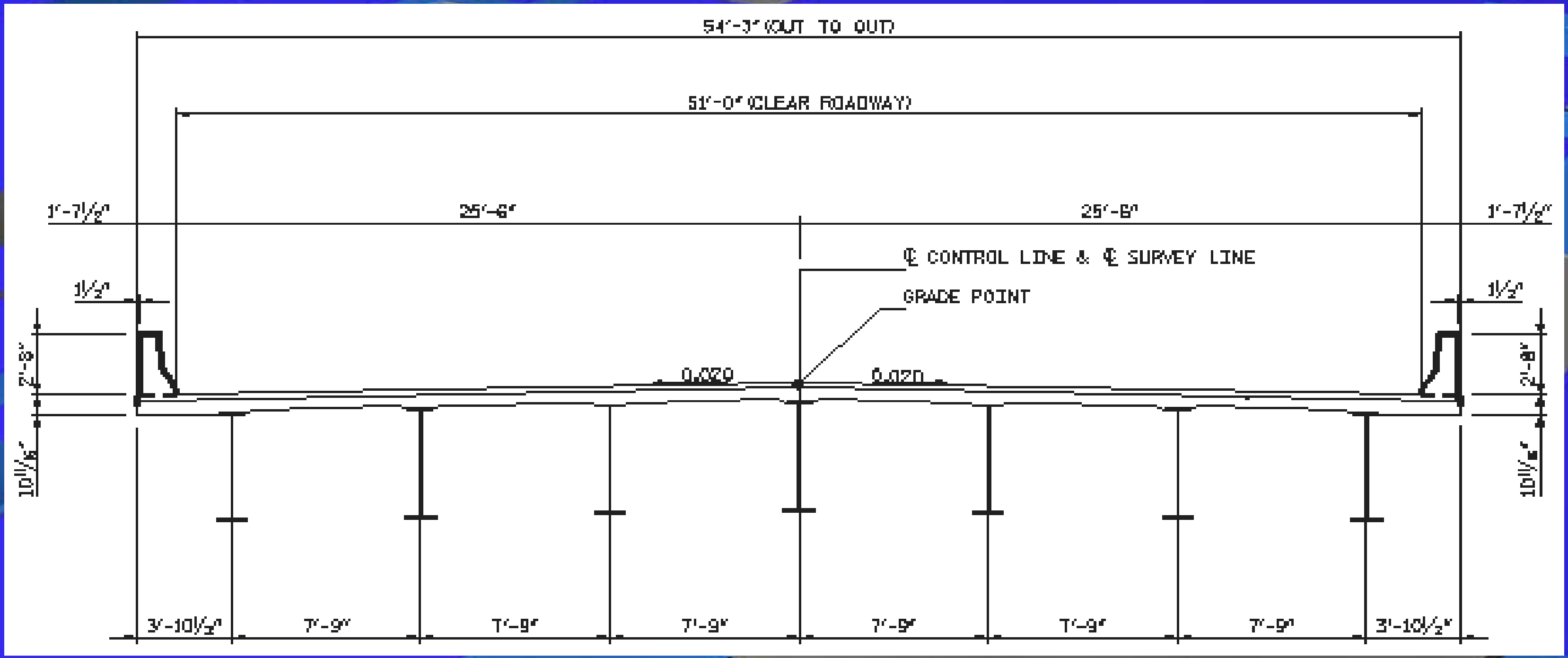
# LIMITATIONS

- Maximum span length 250 feet
- Maximum girder spacing 11.5 feet
- Maximum number of girders is 10 (this applies only to the ASP method)
- Girder spacing-to-span ratio can not exceed 0.08

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

### Typical Section



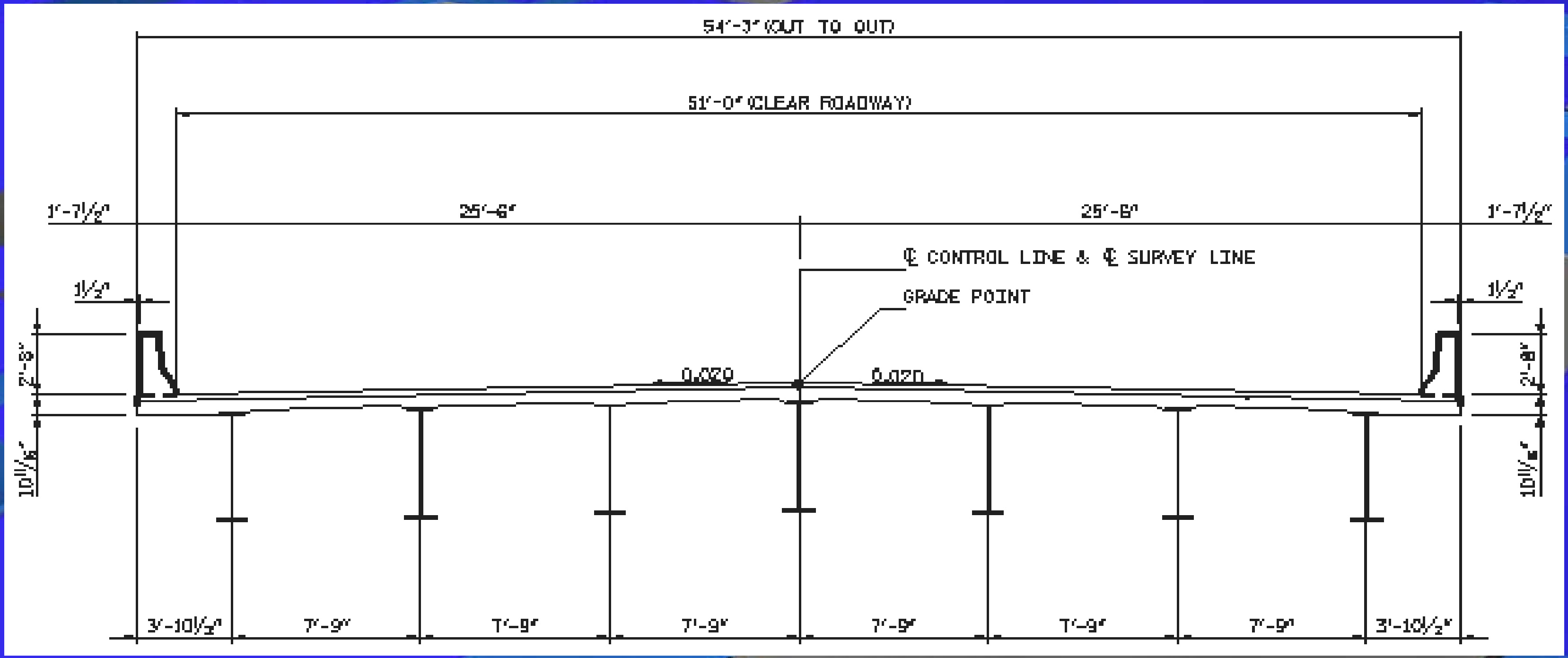

Number of Girders = 7
Skew Angle = 46 degrees
Girder Length = 123.83 ft

Interior girder load = 2.0 k/ft
Left Ext. girder load = 1.7 k/ft
Right Ext. girder load = 1.7 k/ft

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

### Typical Section




Number of Girders = 7
Skew Angle = 46 degrees
Girder Length = 123.83 ft

Interior girder load = 2.0 k/ft
Left Ext. girder load = 1.7 k/ft
Right Ext. girder load = 1.7 k/ft

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

### Step 1 - Calculate load ratio, expressed as a percentage

$$Rl = \frac{\text{Left Ext. girder load}}{\text{Interior girder load}} = \frac{1.7\ k/ft}{2.0\ k/ft} = 85\%$$

$$Rr = \frac{\text{Right Ext. girder load}}{\text{Interior girder load}} = \frac{1.7\ k/ft}{2.0\ k/ft} = 85\%$$

Difference in Ratios = Rl - Rr

▲ = 85% - 85%

▲ = 0% ← Use SP method

* If the difference in ratios (▲) exceeded 10% you would need to use the ASP method

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

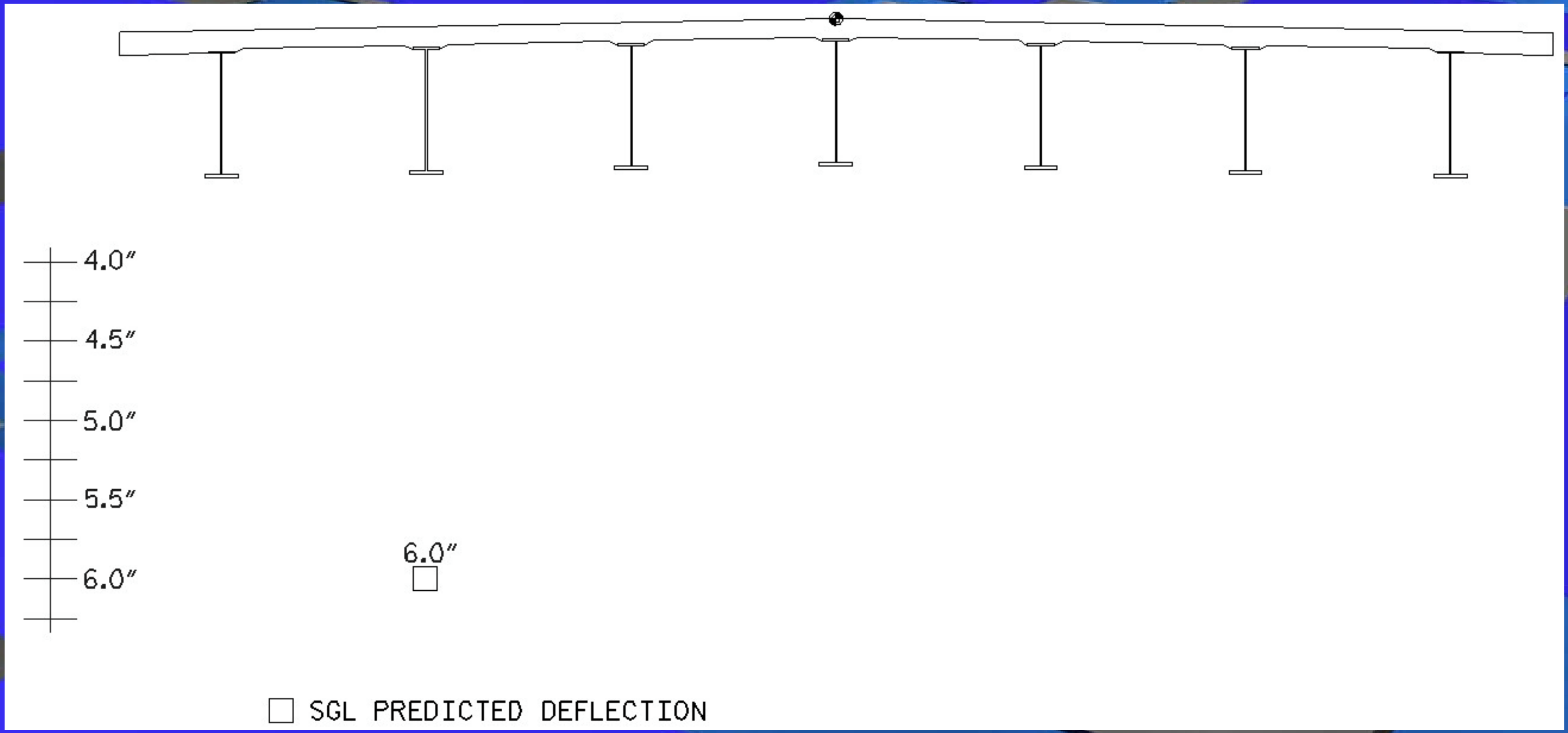
Step 2 - Retrieve interior girder SGL predictions for dead load deflection along the span, 1/10 or 1/20 points.

(For this example we will assume an interior girder deflection of 6” and an exterior girder deflection of 5.1”at midspan)

$$\delta_{SGL\_INT} = 6''$$
$$\delta_{SGL\_EXT} = 5.1''$$

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios



# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

Step 3 - Calculate the predicted exterior girder deflection at each location along the span using the following equation:

$$\delta_{EXT} = [\delta_{SGL\_INT} - \Phi(100-R)][1 - 0.1\tan(1.2\theta)]$$

**$\delta_{EXT}$ is a function of:**

- $\delta_{SGL\_INT}$ - interior girder SGL predicted deflection
- $\Phi$ - correction factor
- **R** - load ratio
- $\theta$ - skew offset (degrees)

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

$$\delta_{EXT} = [\delta_{SGL\_INT} - \Phi(100\text{-}R)][1 - 0.1\tan(1.2\theta)]$$

where: $\delta_{SGL\_INT}$ = interior girder SGL predicted deflection at locations along the span (in)

$\Phi = 0.03 - \alpha^*\theta$

where: $\alpha = 0.0002$ , if $(g \leq 8.2)$

$\alpha = 0.0002 + 0.000305(g - 8.2)$ , if $(8.2 < g \leq 11.5)$

where: g = girder spacing (ft)

R = exterior-to-interior girder load ratio (%)

$\theta$ = skew offset (degrees) = |skew - 90|

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

$$\delta_{EXT} = [\delta_{SGL\_INT} - \Phi(100-R)][1 - 0.1\tan(1.2\theta)]$$

where: $\alpha = 0.0002$ if $(g \leq 8.2)$

$R = 85\%$

$\theta = |skew - 90| = |46 - 90| = 44$

$\Phi = 0.03 - \alpha * \theta$

$\Phi = 0.03 - 0.0002*44$

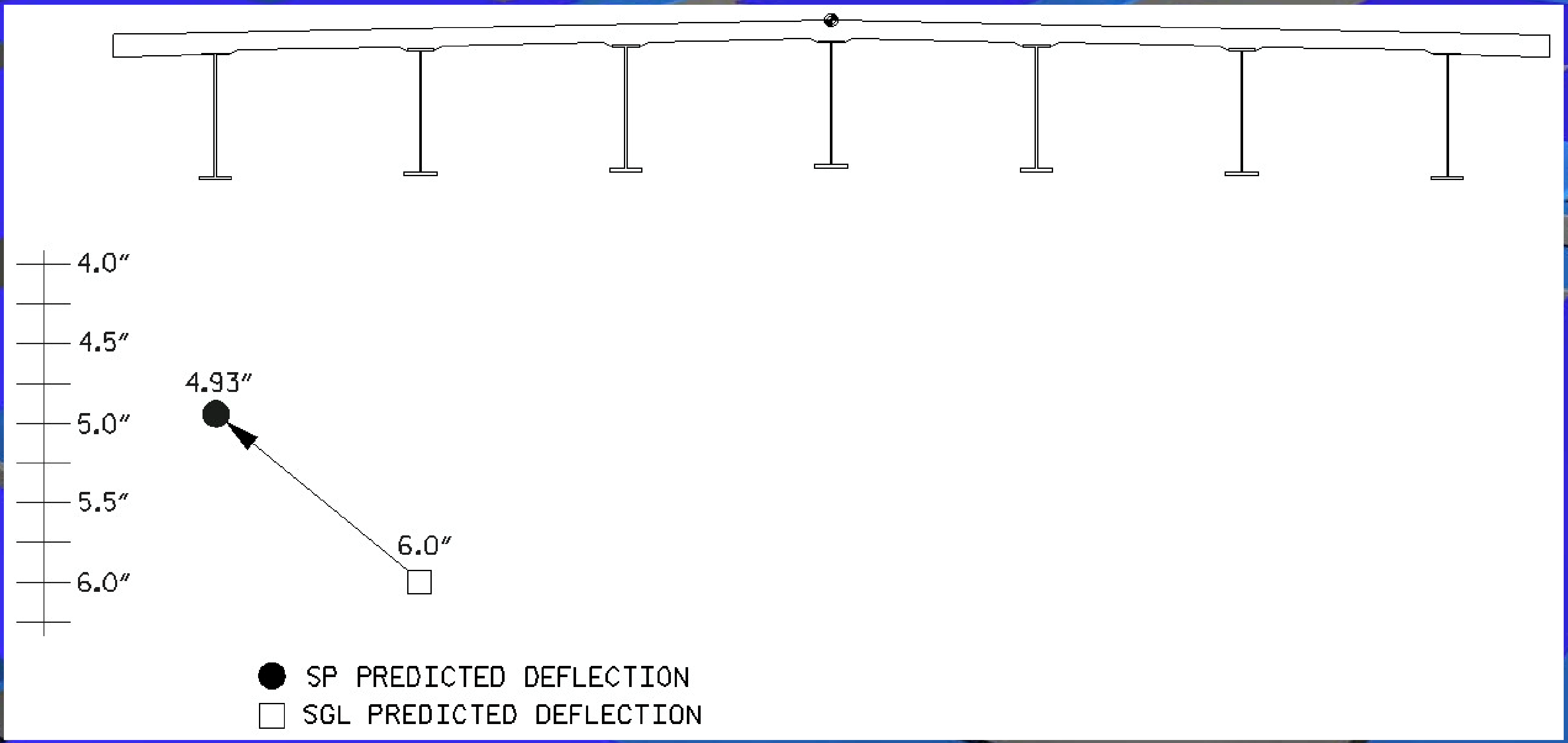
$\Phi = 0.0212$

$$\delta_{EXT} = [6'' - 0.0212(100-85)][1 - 0.1\tan(1.2(44))]$$

$$\delta_{EXT} = 4.93 \text{ in}$$

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios



# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

Step 4 - Calculate the predicted differential deflection between adjacent girders at each location along the span using the following equation:

$$D_{INT} = x[\alpha(S - 0.04)(1 + z) - 0.1\tan(1.2\theta)]$$

**$D_{INT}$ is a function of:**

**x -** SGL Predicted Span Location Deflection Ratio

**$\alpha$ -** Correction factor or multiplier variable

**z -** Correction factor or multiplier variable

**$\theta$ -** Skew Offset

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

$$D_{INT} = x[\alpha(S - 0.04)(1 + z) - 0.1\tan(1.2\theta)]$$

where: $x = (\delta_{SGL\_INT})/(\delta_{SGL\_M})$

where: $\delta_{SGL\_M}$ = SGL predicted girder deflection at midspan (in)

$\alpha = 3.0 - b(\theta)$

where: $b = -0.08$, if $(S \leq 0.05)$

$b = -0.08 + 8(S - 0.05)$, if $(0.05 < S \leq 0.08)$

$S$ = girder spacing-to-span ratio

$z = (10(S - 0.04) + 0.02)(2 - 0.02R)$

$\theta$ = skew offset (degrees) = $|\text{skew} - 90|$

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

$$D_{INT} = x[\alpha(S - 0.04)(1 + z) - 0.1\tan(1.2\theta)]$$

where: $x = (\delta_{SGL\_INT})/(\delta_{SGL\_M}) = (6")/(6") = 1$

$\alpha = 3.0 - b(\theta) = 3.0 - 0.024(44) = 1.94$

where: $b = -0.08 + 8(S - 0.05)$, if $(0.05 < S \leq 0.08)$

$= -0.08 + 8(0.063 - 0.05) = 0.024$

$S$ = girder spacing-to-span ratio = (7.75')/(123.83') = 0.063

$z = (10(S - 0.04) + 0.02)(2 - 0.02R)$

$z = (10(0.063 - 0.04) + 0.02)(2 - 0.02(85)) = 0.075$

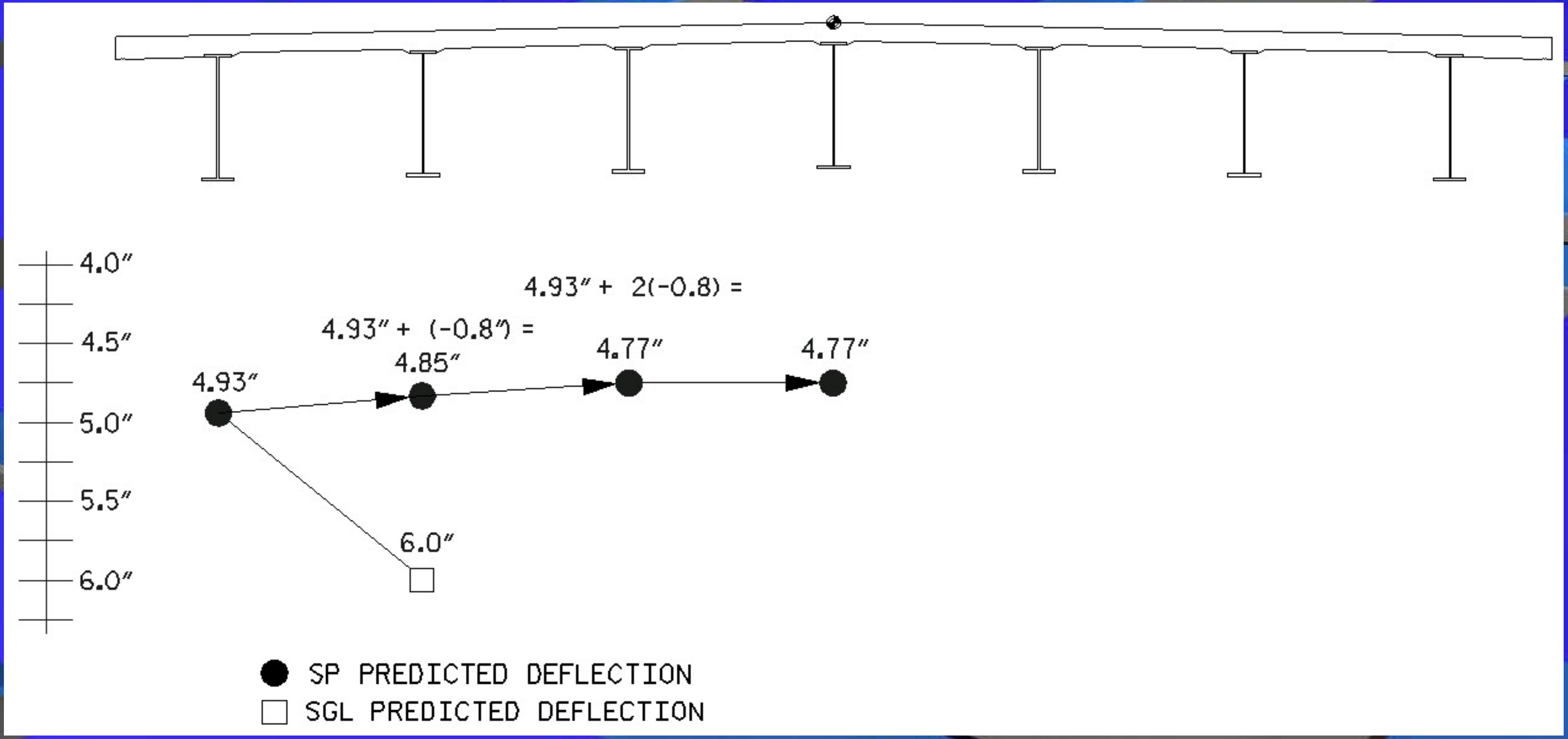
$\theta$ = skew offset (degrees) = $|46 - 90| = 44$

$$D_{INT} = 1[1.94(0.063 - 0.04)(1 + 0.075) - 0.1\tan(1.2(44))]$$
$$= -0.08 \text{ inches}$$

***** $D_{INT}$ only applies to 2 adjacent interior girders *****

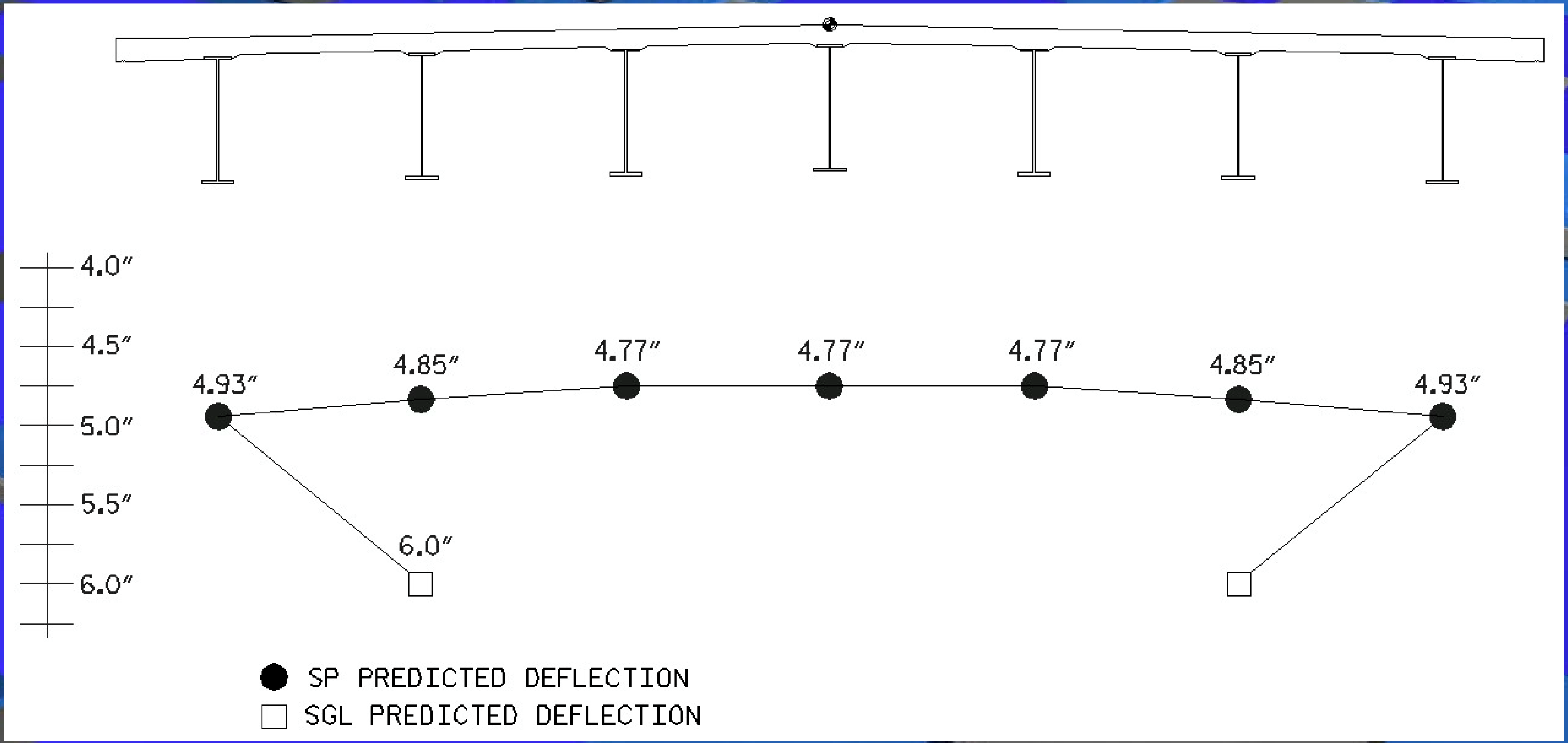
# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios



# SP Example

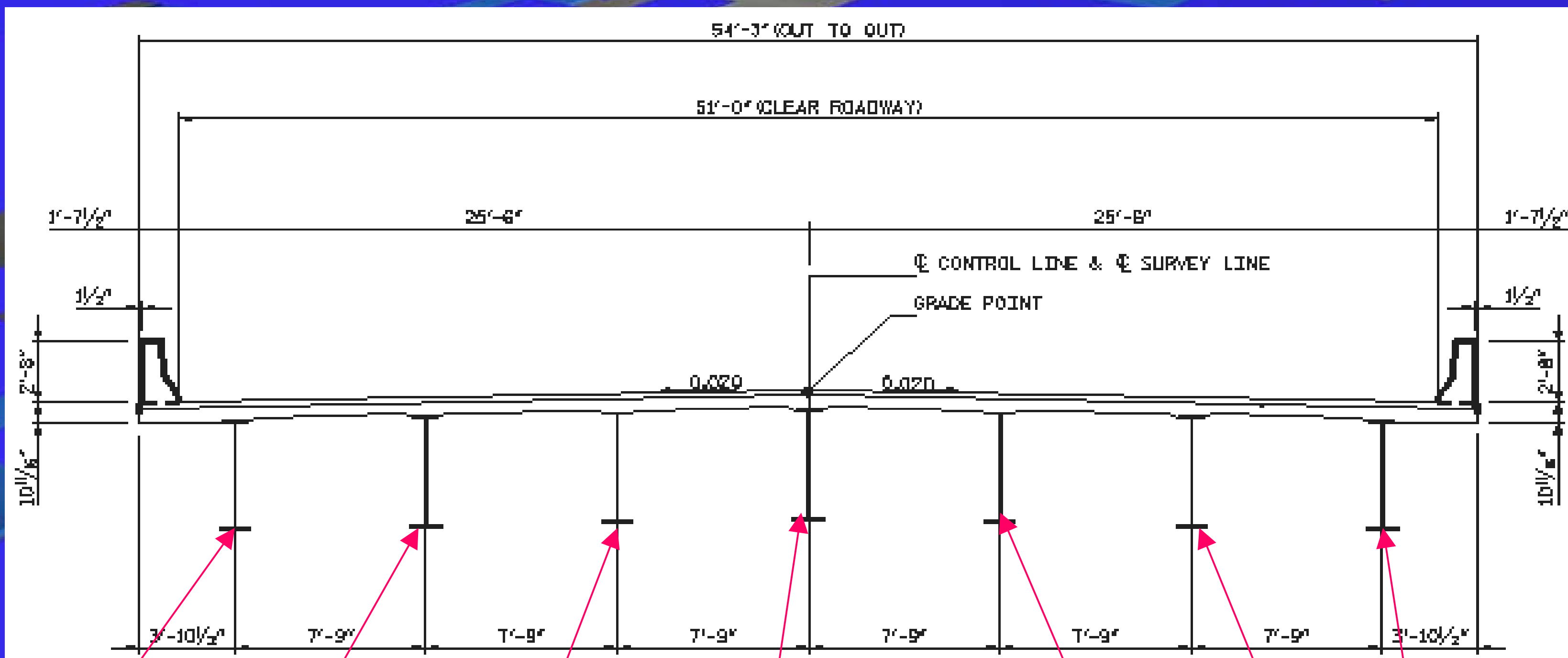
## Simple Span - Equal Exterior-to-Interior Girder Load Ratios



# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

MIDSPAN




$\delta_{EXT} = 4.93$ in

$\delta_{INT1} = \delta_{EXT} + D_{INT}$
$\delta_{INT1} = 4.93 + (-0.08)$
$\delta_{INT1} = 4.85$ in

$\delta_{INT2} = \delta_{EXT} + D_{INT}$
$\delta_{INT2} = 4.93 + 2(-0.08)$
$\delta_{INT2} = 4.77$ in

$\delta_{INT3} = 4.77$ in

$\delta_{INT4} = \delta_{EXT} + D_{INT}$
$\delta_{INT4} = 4.93 + 2(-0.08)$
$\delta_{INT4} = 4.77$ in

$\delta_{INT5} = \delta_{EXT} + D_{INT}$
$\delta_{INT5} = 4.93 + (-0.08)$
$\delta_{INT5} = 4.85$ in

$\delta_{EXT} = 4.93$ in

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

(For this example we will assume an interior deflection of 4.27" at 1/4 span)

$$\delta_{SGL\_INT} = 4.27''$$

$$\delta_{EXT} = [\delta_{SGL\_INT} - \Phi(100-R)][1 - 0.1\tan(1.2\theta)]$$

Previous solved:

$\Phi$ = 0.0212 R = 85% $\theta$ = 44 degrees

$$\delta_{EXT} = [4.27 - 0.0212(100-85)][1 - 0.1\tan(1.2(44))]$$

$$\delta_{EXT} = 3.43 \text{ in}$$

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

$$D_{INT} = x[\alpha(S - 0.04)(1 + z) - 0.1\tan(1.2\theta)]$$

where: $x = (\delta_{SGL\_INT})/(\delta_{SGL\_M}) = (4.27")/(6") = 0.712$

Previous solved:

$\alpha = 1.94$ $b = 0.024$ $S = 0.063$ $z = 0.075$ $\theta = 44$

$$D_{INT} = 0.712[1.94(0.063 - 0.04)(1 + 0.075) - 0.1\tan(1.2(44))]$$

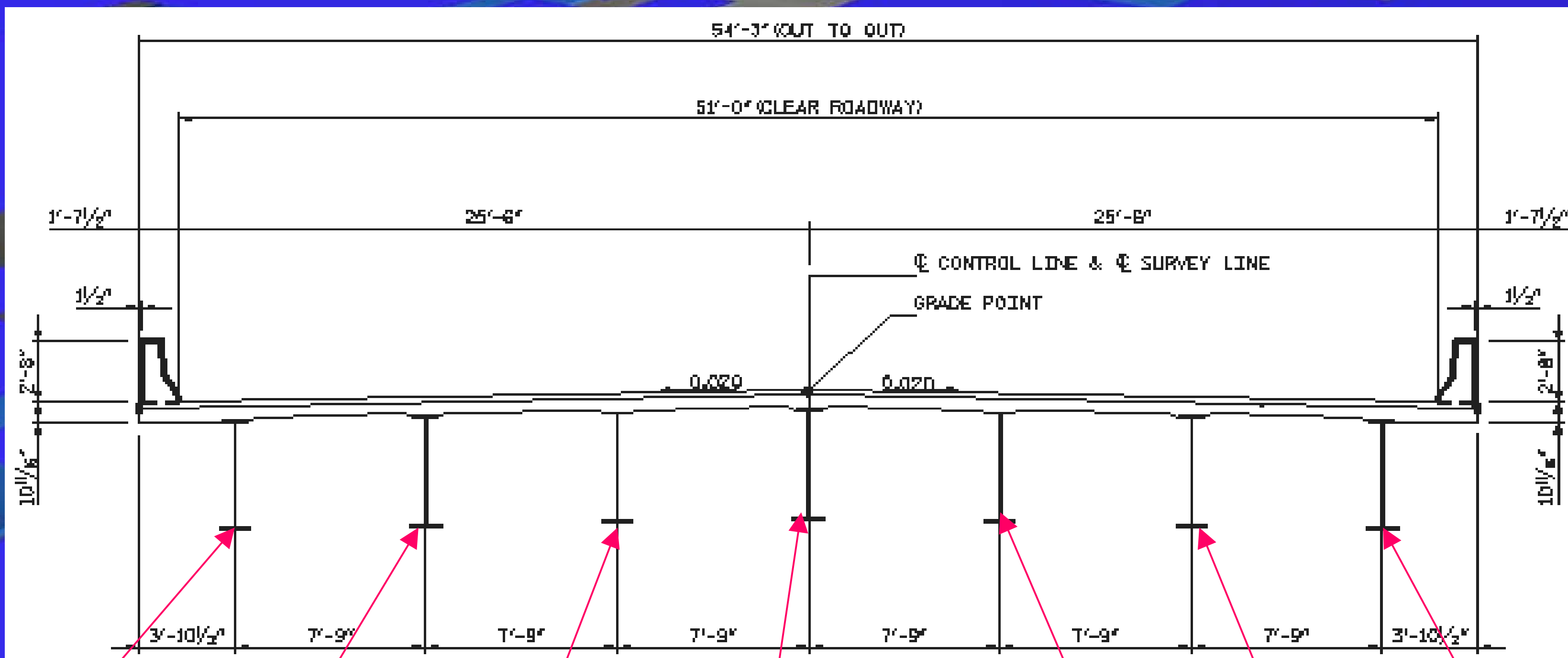
$$= -0.06 \text{ inches}$$

***** $D_{INT}$ only applies to 2 adjacent interior girders *****

# SP Example

## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

### 1/4 SPAN




$\delta_{EXT} = 3.43$ in

$\delta_{INT1} = \delta_{EXT} + D_{INT}$
$\delta_{INT1} = 3.43 + (-0.06)$
$\delta_{INT1} = 3.37$ in

$\delta_{INT2} = \delta_{EXT} - 2D_{INT}$
$\delta_{INT2} = 3.43 + 2(-0.06)$
$\delta_{INT2} = 3.31$ in

$\delta_{INT3} = 3.31$ in

$\delta_{INT4} = \delta_{EXT} - 2D_{INT}$
$\delta_{INT4} = 3.43 + 2(-0.06)$
$\delta_{INT4} = 3.31$ in

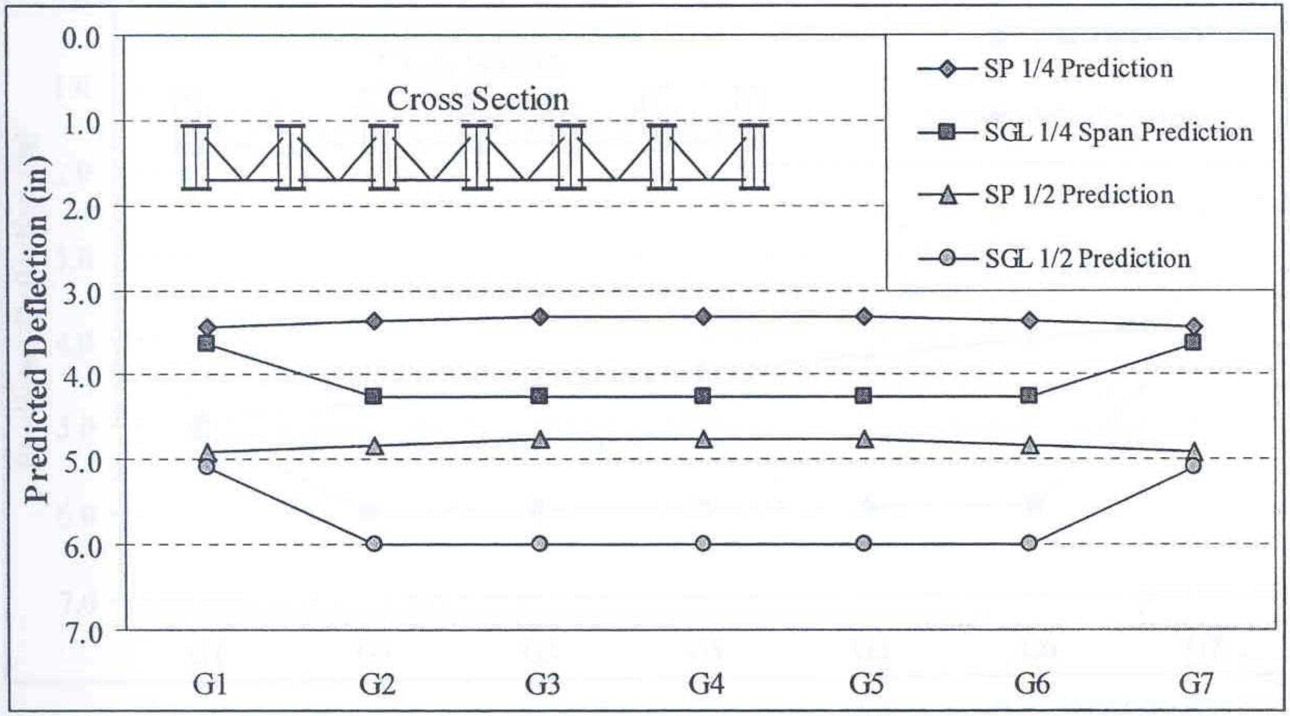
$\delta_{INT5} = \delta_{EXT} - D_{INT}$
$\delta_{INT5} = 3.43 + (-0.06)$
$\delta_{INT5} = 3.37$ in

$\delta_{EXT} = 3.43$ in

# SP Example

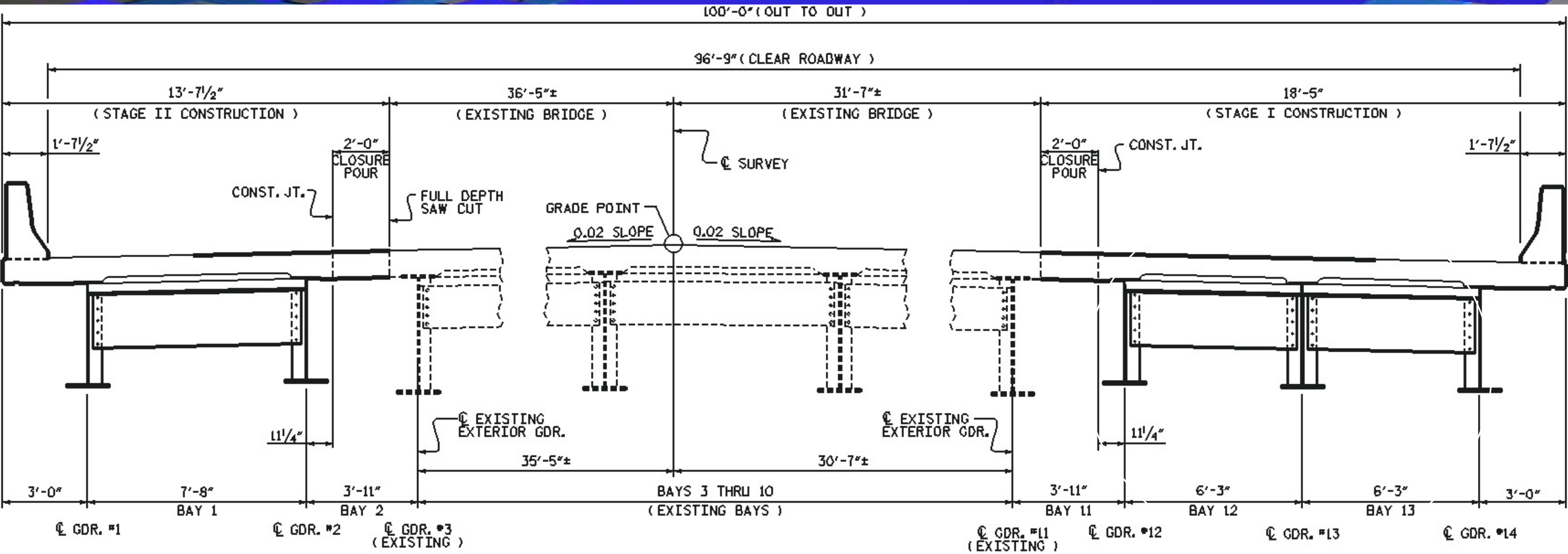
## Simple Span - Equal Exterior-to-Interior Girder Load Ratios

| Results (inches): | | G1 | G2 | G3 | G4 | G5 | G6 | G7 |
|---|---|---|---|---|---|---|---|---|
| SGL | ¼ Span | 3.63 | 4.27 | 4.27 | 4.27 | 4.27 | 4.27 | 4.27 |
| | ½ Span | 5.10 | 6.00 | 6.00 | 6.00 | 6.00 | 6.00 | 5.10 |
| Simplified Procedure | ¼ Span | 3.43 | 3.37 | 3.32 | 3.32 | 3.32 | 3.37 | 3.43 |
| | ½ Span | 4.93 | 4.85 | 4.77 | 4.77 | 4.77 | 4.85 | 4.93 |



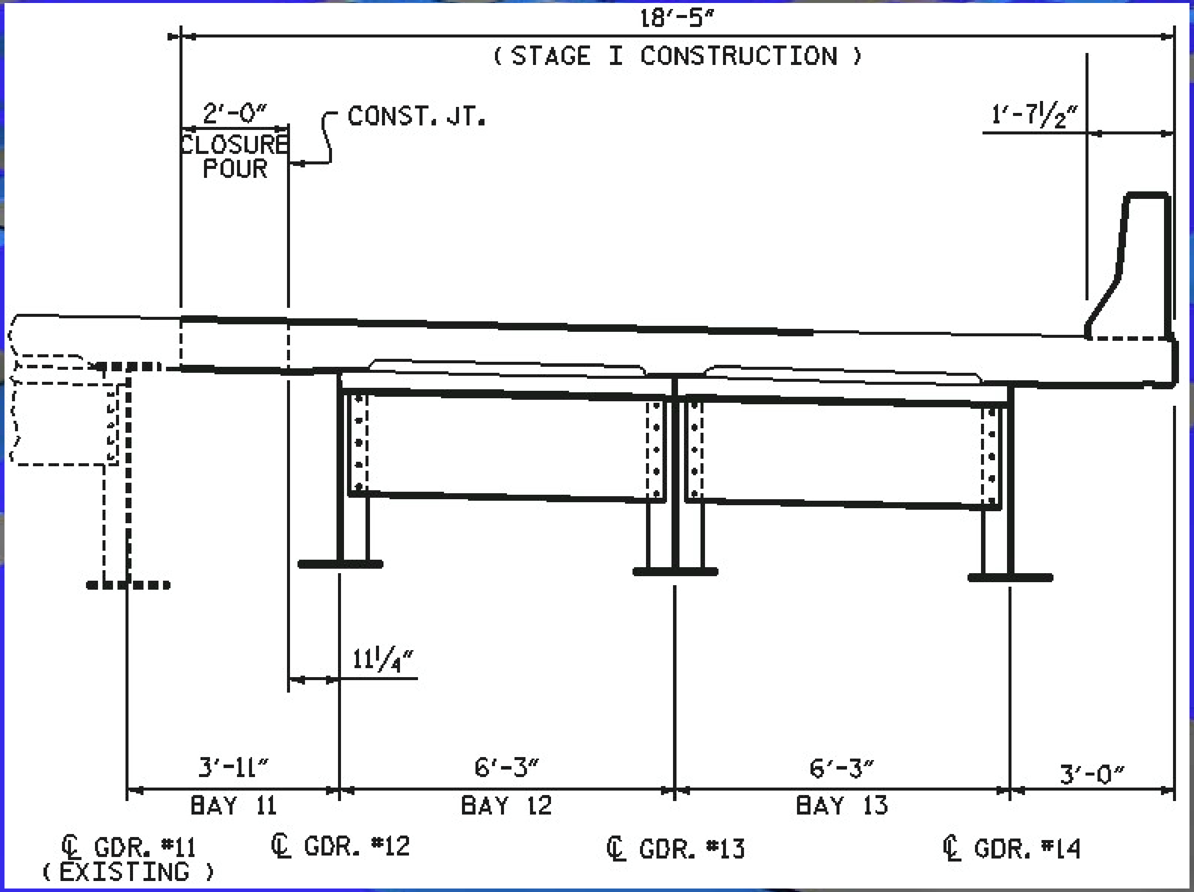
# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios



# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios




Number of Girders = 3
Skew Angle = 102 degrees
Girder Length = 106 ft

Interior girder load = 0.801 k/ft
Left Ext. girder load = 0.657 k/ft
Right Ext. girder load = 0.804 k/ft

# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios

### Step 1 - Calculate Load Ratio, expressed as a percentage

$$Rl = \frac{\text{Left Ext. girder load}}{\text{Interior girder load}} = \frac{9.588 \text{ k/ft}}{11.675 \text{ k/ft}} = 82.12\% \text{ (Low Ratio)}$$

$$Rr = \frac{\text{Right Ext. girder load}}{\text{Interior girder load}} = \frac{11.728 \text{ k/ft}}{11.675 \text{ k/ft}} = 100.45\% \text{ (High Ratio)}$$

Difference in Ratios = Rl - Rr

▲ = 82.12% - 100.45%

▲ = 18.33% ← Use ASP method

* If the difference in ratios (▲) were 10% or less you would need to use the SP method

# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios

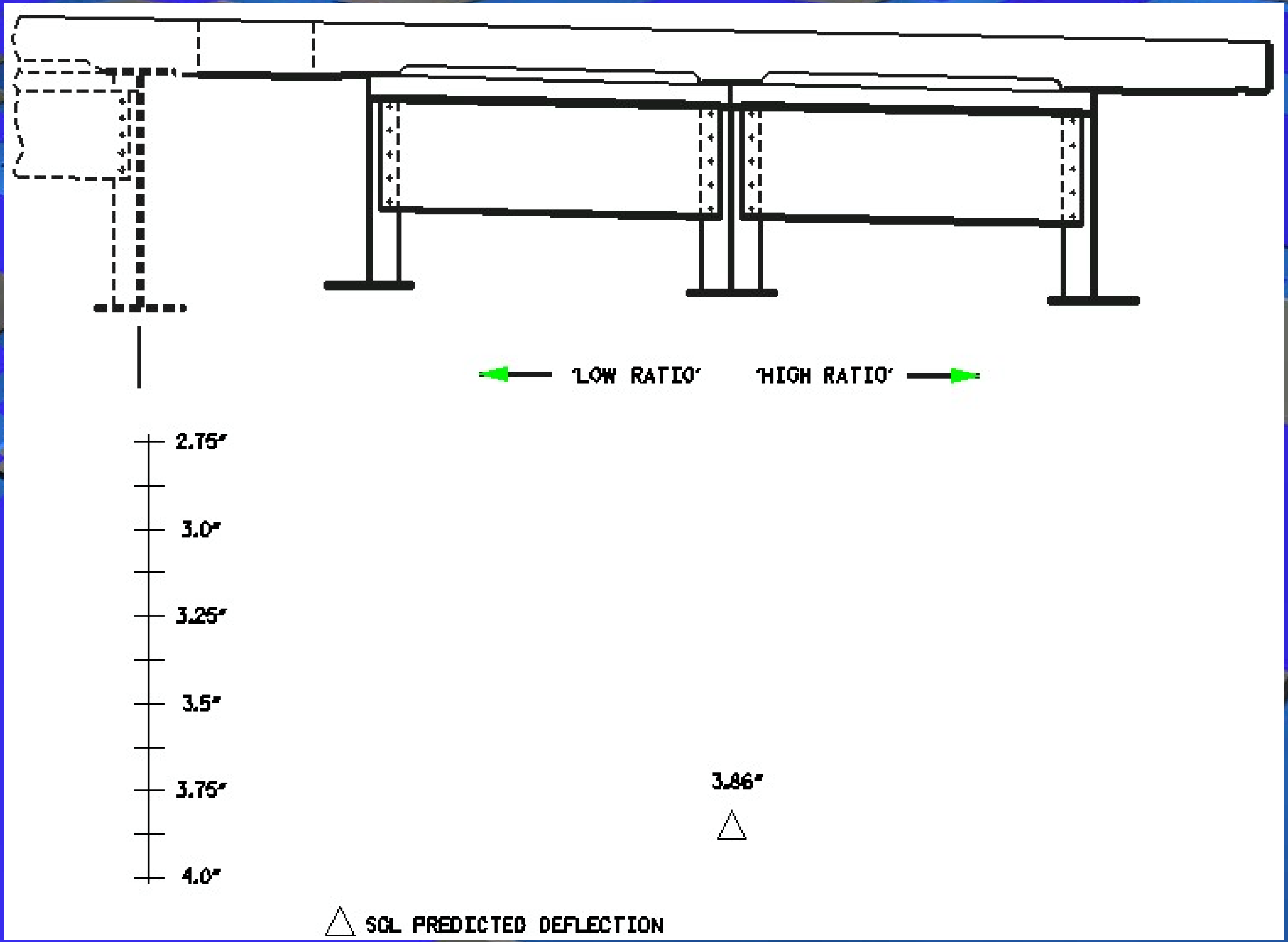
Step 2 - Retrieve interior girder SGL predictions for dead load deflection along the span, 1/10 or 1/20 points.

(For this example we will assume an interior girder deflection of 3.86”)

$$\delta_{SGL\_INT} = 3.86''$$

# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios



# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios

Step 3 - Calculate the predicted exterior girder deflections for both the high ratio and low ratio girders at each location along the span using the following equation:

$$\delta_{\text{EXT (high ratio)}} = [\delta_{\text{SGL\_INT}} - \Phi(100-R)][1 - 0.1\tan(1.2\theta)]$$

$$\delta_{\text{EXT (low ratio)}} = [\delta_{\text{SGL\_INT}} - \Phi(100-R)][1 - 0.1\tan(1.2\theta)]$$

# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios

$$\delta_{EXT\ (high\ ratio)} = [\delta_{SGL\_INT} - \Phi(100\text{-}R)][1 - 0.1\tan(1.2\theta)]$$

where: $\delta_{SGL\_INT}$ = interior girder SGL predicted deflection at locations along the span (in)

$\Phi = 0.03 - \alpha * \theta$

where: $\alpha = 0.0002$ , if $(g \leq 8.2)$

$\alpha = 0.0002 + 0.000305(g - 8.2)$ , if $(8.2 < g \leq 11.5)$

where: g = girder spacing (ft)

$\alpha = 0.0002$

$\Phi = 0.03 - \alpha * \theta = 0.03 - 0.0002*12 = 0.0276$

if $(g \leq 8.2)$

R = exterior-to-interior girder load ratio (%) = 82.12%

$\theta$ = skew offset (degrees) = |skew - 90| = |46 - 90| = 44

$$\delta_{EXT\ (high\ ratio)} = [3.86'' - 0.0276(100\text{-}82.12)][1 - 0.1\tan(1.2(12))]$$

$$\delta_{EXT\ (high\ ratio)} = 3.77 \text{ in}$$

# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios

$$\delta_{EXT\ (low\ ratio)} = [\delta_{SGL\_INT} - \Phi(100\text{-}R)][1 - 0.1\tan(1.2\theta)]$$

where: $\delta_{SGL\_INT}$ = interior girder SGL predicted deflection at locations along the span (in)

$\Phi = 0.03 - \alpha^*\theta$

where: $\alpha = 0.0002$ , if $(g \leq 8.2)$

$\alpha = 0.0002 + 0.000305(g - 8.2)$ , if $(8.2 < g \leq 11.5)$

where: g = girder spacing (ft)

$\alpha = 0.0002$

$\Phi = 0.03 - \alpha^*\theta = 0.03 - 0.0002^*12 = 0.0276$

if $(g \leq 8.2)$

R = exterior-to-interior girder load ratio (%) = 82.12%

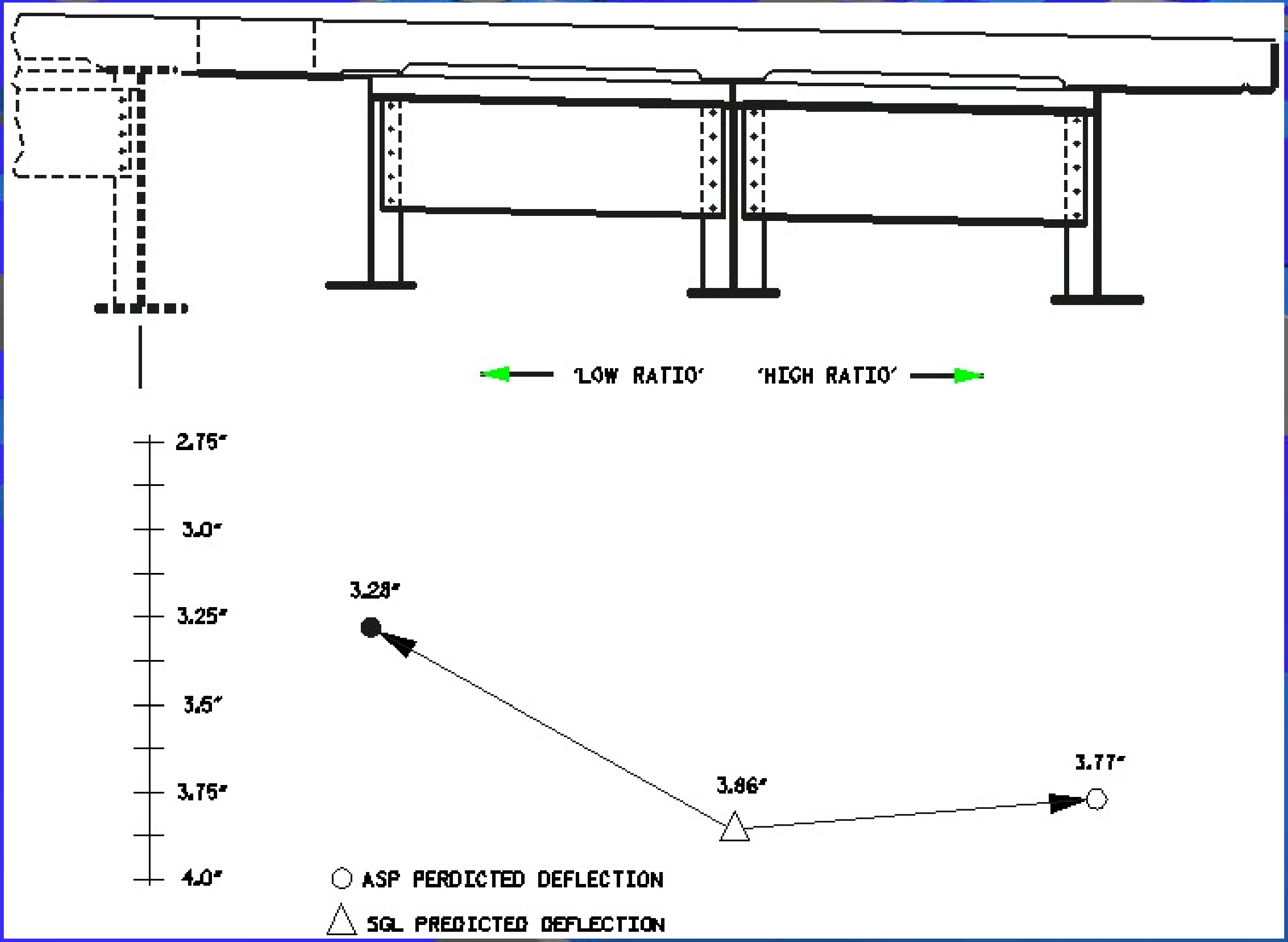
$\theta$ = skew offset (degrees) = |skew - 90| = |46 - 90| = 44

$$\delta_{EXT\ (low\ ratio)} = [3.86'' - 0.0276(100\text{-}82.12)][1 - 0.1\tan(1.2(12))]$$

$$\delta_{EXT\ (low\ ratio)} = 3.28\ \text{in}$$

# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios



# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios

Step 4 - Calculate the predicted differential deflection between the low ratio girder and the adjacent girder(s) at each location along the span using the following equation:

$$D_{INT} = x[\alpha(S - 0.04)(1 + z) - 0.1\tan(1.2\theta)]$$

# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios

$$D_{INT} = x[\alpha(S - 0.04)(1 + z) - 0.1\tan(1.2\theta)]$$

where: $x = (\delta_{SGL\_INT})/(\delta_{SGL\_M}) = (3.86")/(3.86") = 1$

$S$ = girder spacing-to-span ratio = $(6.25')/(106) = 0.059$

$b = -0.08 + 8(S-0.05) =$ when $(0.05 < S \leq 0.08)$

$b = -0.08 + 8(0.059-0.05) = -0.008$

$\alpha = 3.0 - b(\theta) = 3.0 - (-0.008(12)) = 3.096$

$z = (10(0.059 - 0.04) + 0.02)(2 - 0.02(82.12)) = 0.075$

$\theta$ = skew offset (degrees) = $|102 - 90| = 12$

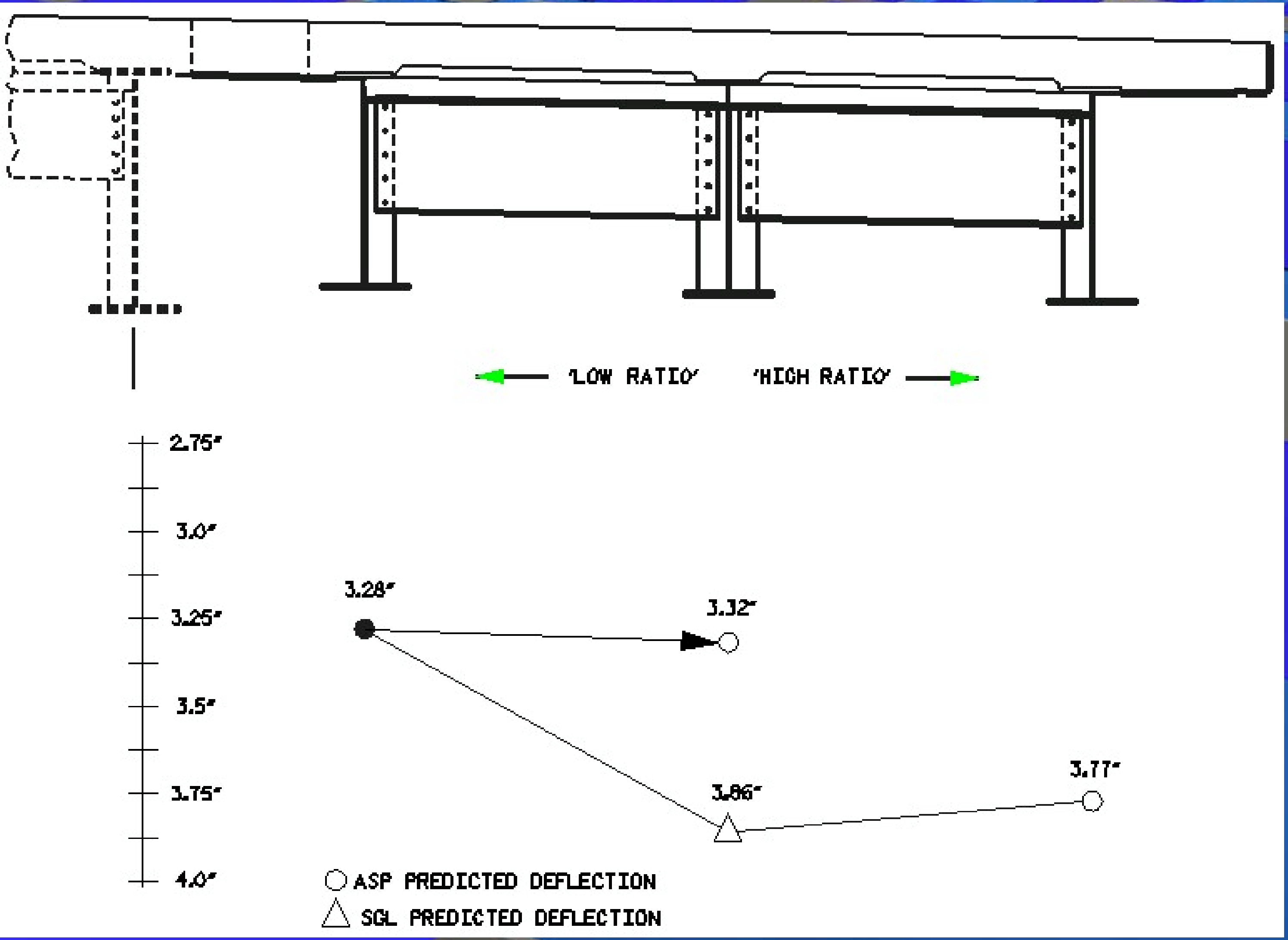
$$D_{INT} = 1[3.096(0.059 - 0.04)(1 + 0.075) - 0.1\tan(1.2(12))]$$
$$= 0.04 \text{ inches}$$

***** $D_{INT}$ only applies to 2 adjacent interior girders*****

$$\delta_{INT1} = \delta_{EXT} + D_{INT} = 3.28 + (0.04) = 3.32 \text{ in}$$

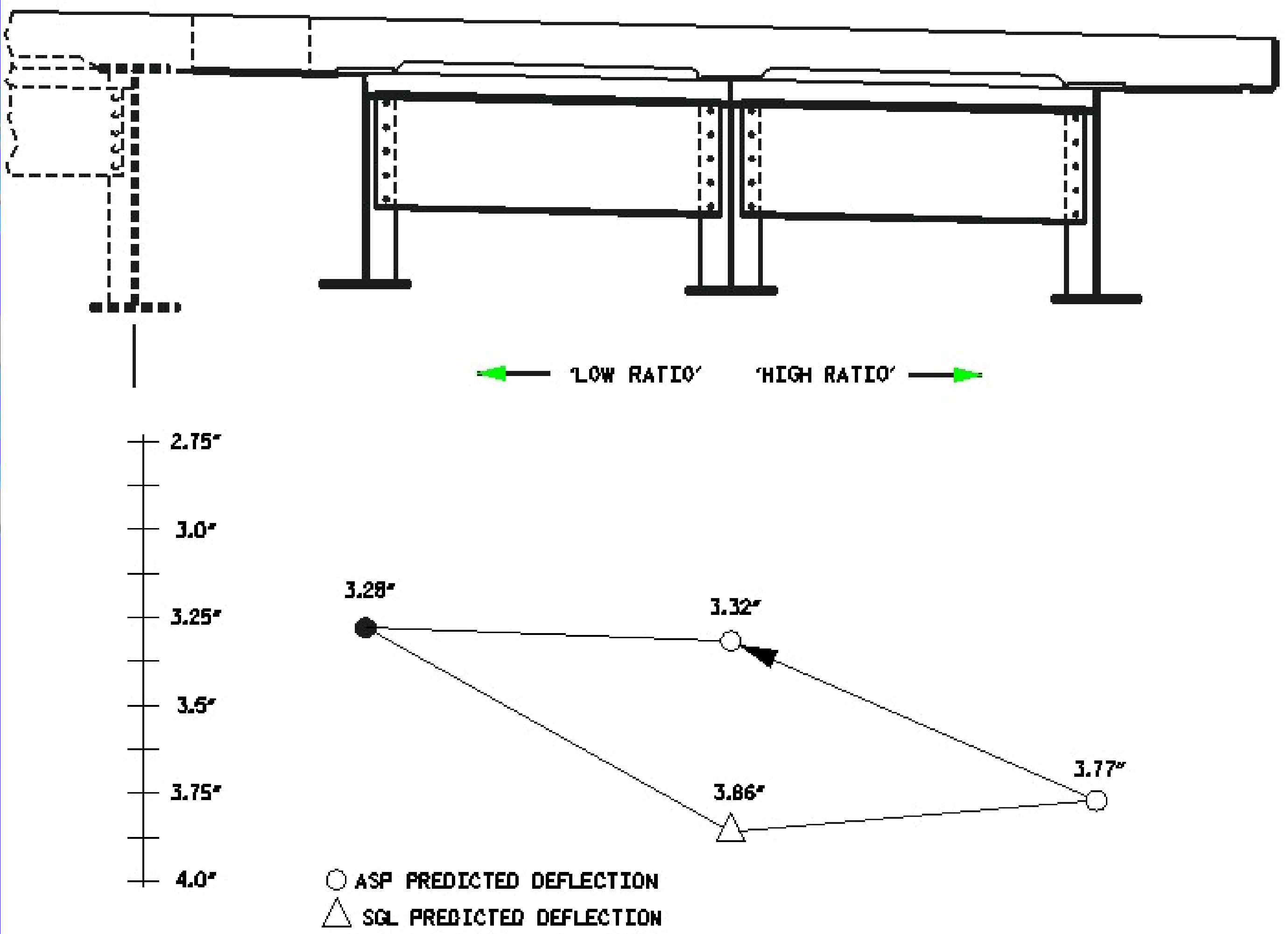
# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios



# ASP Example

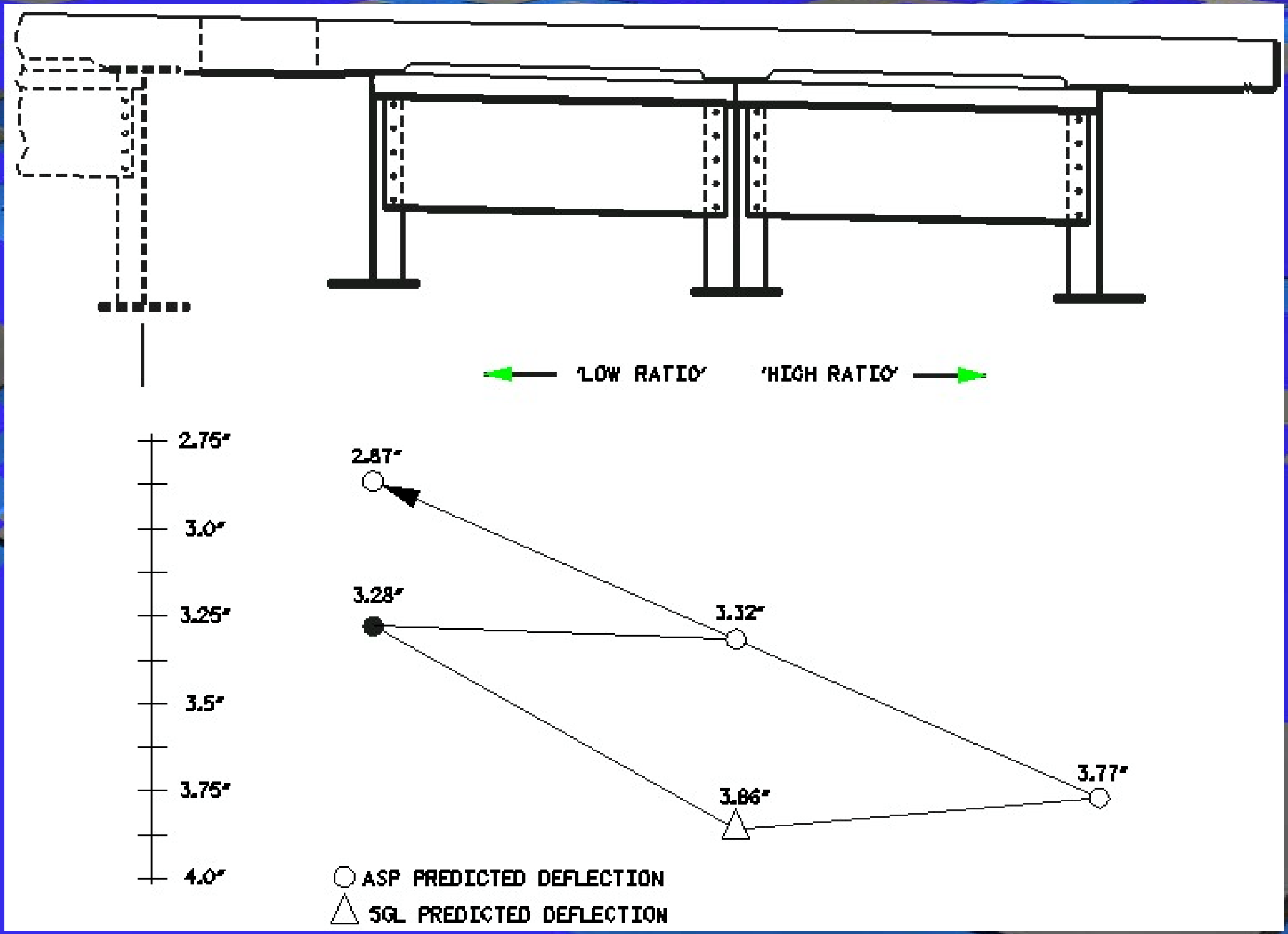
## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios




Find Slope between $\delta_{INT1}$ and $\delta_{EXT(high\ ratio)}$ = **(3.32 - 3.77) / 1 = -0.45**

# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios

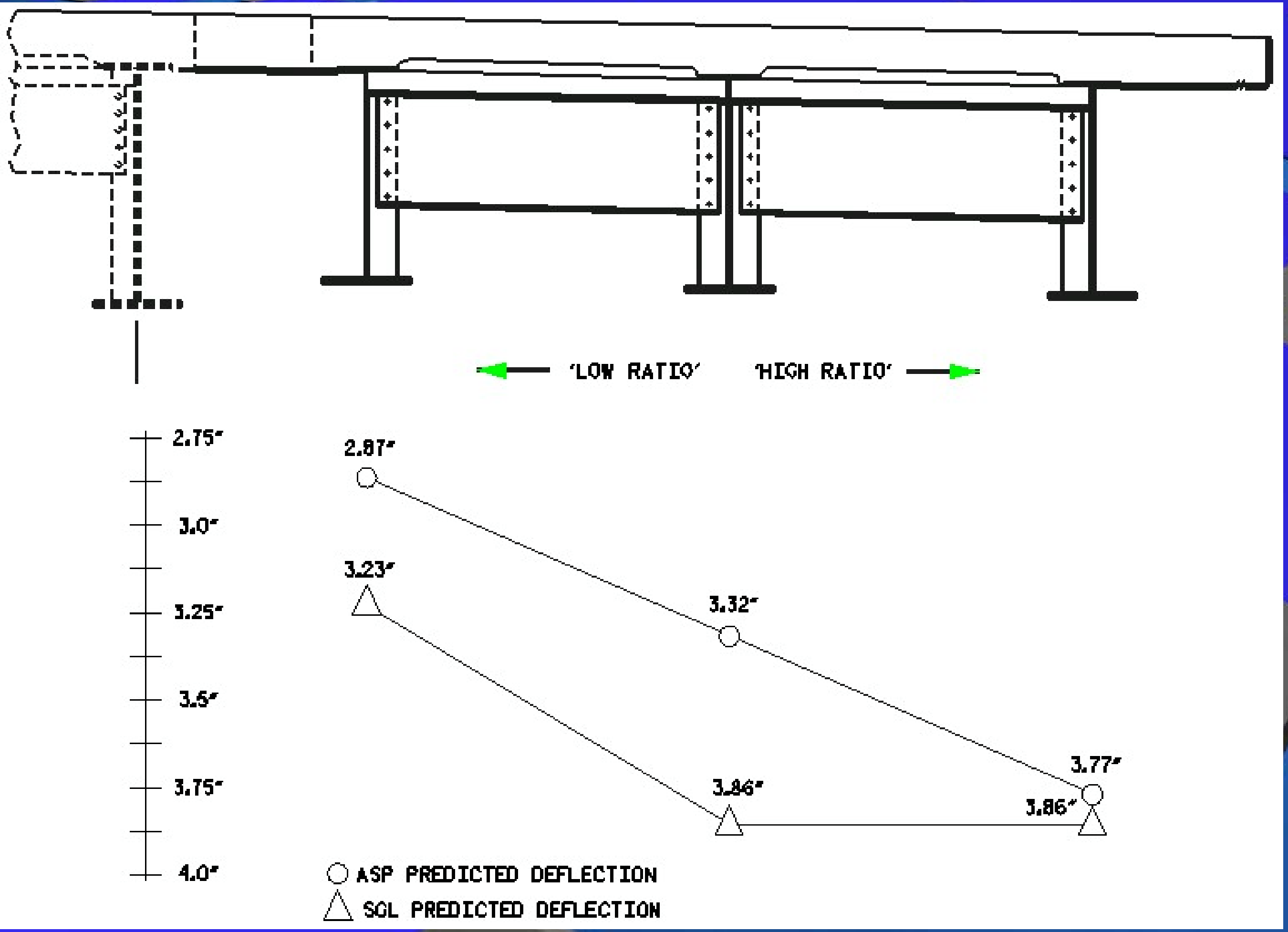



Extend Slope to $\delta_{EXT(low\ ratio)}$ = **(3.32 -0.45) = 2.87”**

# ASP Example

## Simple Span - Unequal Exterior-to-Interior Girder Load Ratios

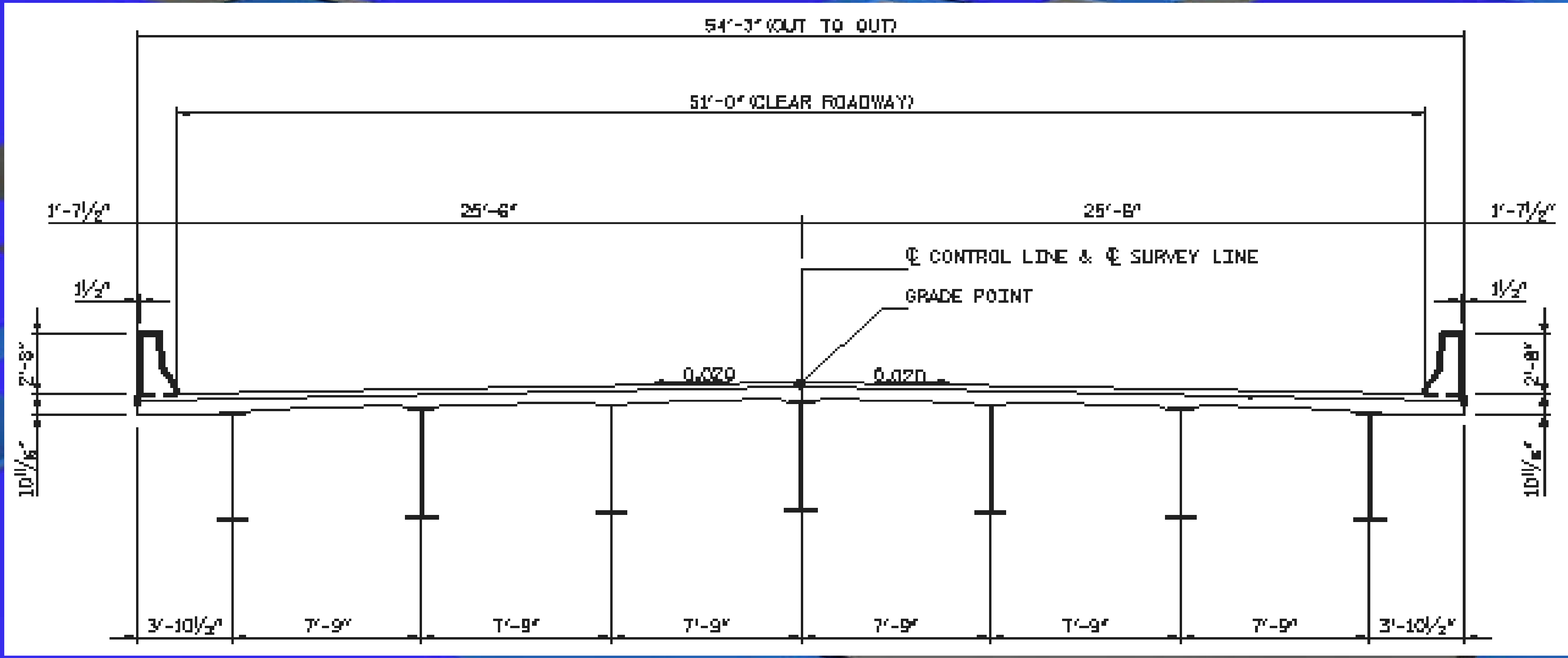
Comparison of the ASP and SGL Predicted Deflection



# SGLSL Example

## Continuous Span - Equal Exterior-to-Interior Girder Load Ratios

### Typical Section




Number of Girders = 7
Skew Angle = 46 degrees
Girder Length = 123.83 ft

Interior girder load = 2.0 k/ft
Left Ext. girder load = 1.7 k/ft
Right Ext. girder load = 1.7 k/ft

# SGLSL Example

## Continuous Span - Equal Exterior-to-Interior Girder Load Ratios

### Step 1 - Calculate Load Ratios

Rl = Left Ext. girder load / Interior girder load = 1.7 k/ft / 2.0 k/ft = 0.85%

Rr = Right Ext. girder load / Interior girder load = 1.7 k/ft / 2.0 k/ft = 0.85%

Difference in Ratios = Rl - Rr

▲ = 0.85 - 0.85

▲ = 0.0 ← O.K.

* If the difference in ratios exceeded 10% no alternative method is available

# SGLSL Example

## Continuous Span - Equal Exterior-to-Interior Girder Load Ratios

**Step 2 -** Retrieve Exterior girder SGL Predictions for dead load deflection along the span, 1/10 or 1/20 points.

(For this example we will assume an exterior girder deflection of 5.5” at midspan for both girders)

$$\delta_{SGL\_EXT} = 5.5''$$

**Step 3 -** Find the slope between the 2 exterior girders.

$$\frac{(\delta_{SGL\_EXT(L)} - \delta_{SGL\_EXT(R)})}{(\#\ Girders - 1)} = \frac{(5.5'' - 5.5'')}{(7-1)} = 0.0$$

# SGLSL Example

## Continuous Span - Equal Exterior-to-Interior Girder Load Ratios

### Step 4 - Apply Slope to Interior Girders

$\delta_{SGL\_EXT}$ = 5.5"

Slope = 0.0