10.15 FOUNDATION MODELING FOR SUPERSTRUCTURE ANALYSIS (NON-SEISMIC)

10.15.1 GENERAL

For superstructure analysis, designers need to assign supports at the column base. For bridges supported on pile extensions or Type I shafts, the shaft or pile extension is replaced with an equivalent column with conventional fixed support. This simplified modeling facilitates superstructure analysis and eliminates the need for soil-structure interaction analysis when using software such as CTBridge. This document provides guidance for structural modeling of the columns for superstructure analysis.

Underestimating the length of the equivalent column may reduce superstructure internal forces/moment and results in under-designing the superstructure. Overestimating the length of the equivalent column may lead to underestimating column internal forces/moments.

10.15.2 NOTATION

D = Diameter of the column (ft)

D_M = Deflection at column top under bending moment (in.)

D_V = Deflection at column top under shear force (in.)

E = Modulus of elasticity of column (ksf)

I = Moment of inertia of column (ft^4)

M = Approximate unfactored bending moment from dead load, additional dead load, and live load (added together) at the top of the column (kip-ft)

M_D = Moment at column top caused by applied predefined displacement (kip-ft)

M_R = Moment at column top caused by applied predefined rotation (kip-ft)

R_M = Rotation at column top under bending moment (radian)

R_V = Rotation at column top under shear force (radian)

V = Approximate unfactored shear from dead load, additional dead load, and live load (added together) at the top of the column (kip)

V_D = Shear at column top caused by applied predefined displacement (kip)

V_R = Shear at column top caused by applied predefined rotation (kip)

10.15.3 MODELING ASSUMPTIONS

The following recommendations have been developed to simplify superstructure non-seismic analysis and design for certain types of foundations. Designers may decide to conduct refined analysis for more accurate results following procedures illustrated in 10.15.4 and 10.15.5.

1) For columns in multi-column bents supported on shallow foundations, a pin connection may be assumed at the middle of the thickness of the spread footing, as shown in Figure 10.15.3-1 (a).
2) For columns supported on pile groups, the fixed-end connection at the base of the column may be assumed at the middle of the thickness of the pile cap, as shown in Figure 10.15.3-1 (b).

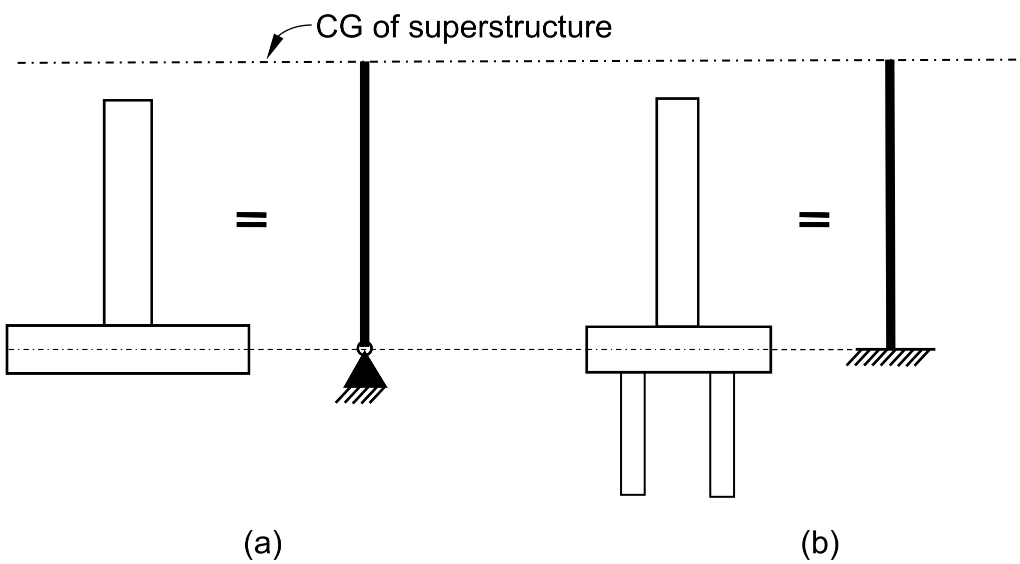


Figure 10.15.3-1 – Structural Modeling of (a) Shallow Foundations and (b) Pile Groups (Superstructure is not shown)

3) For columns supported on Type II shafts, defined per Caltrans' Seismic Design Criteria (SDC), or uncased columns supported on a single cast-in-steel-shell (CISS) pile, or cast-in-drilled-hole (CIDH) pile with a permanent casing, the fixed-end connection may be assumed at a depth of *D* below the column-to-shaft connection, as shown in Figure 10.15.3-2. For Type II shafts with a pin connection, the pin support may be assumed at the base of the column.

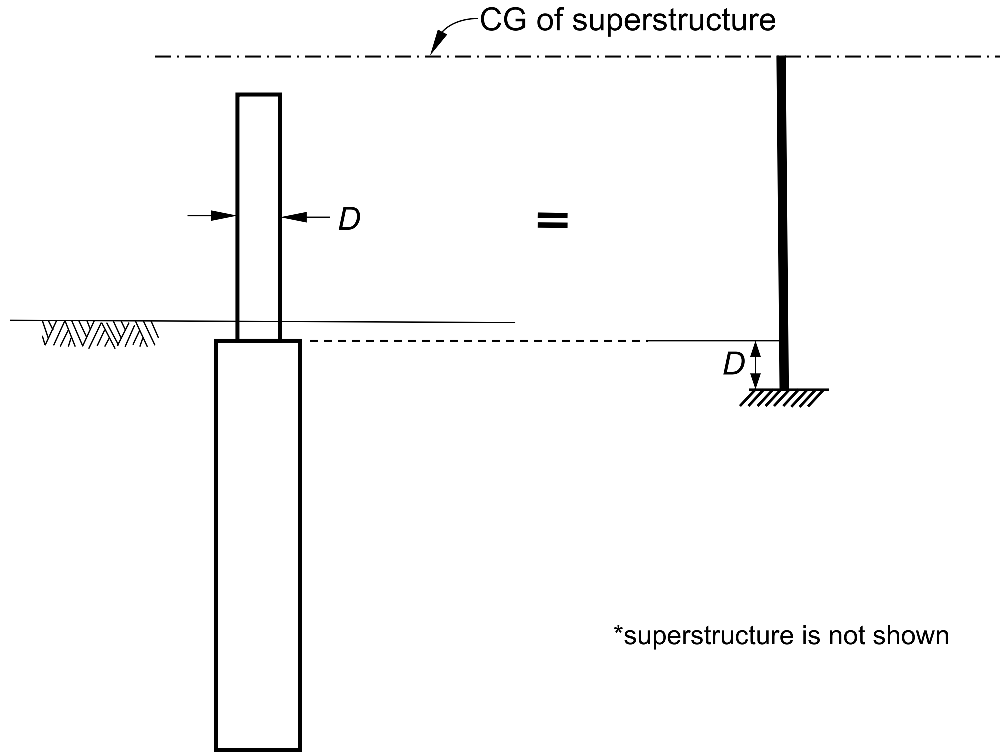


Figure 10.15.3-2 – Structural Modeling of Type II Shafts

4) For Type I shafts and pile extensions in stiff soils meeting the Class S1 soil classification, defined per SDC soil classification, designers may assume a fixed-end connection below finished grade (FG) elevation at a depth of 2*D* and 3*D* for clay and sand, respectively. For bridges in waterways, this depth is considered below the scour depth calculated based on the strength limit state scour combination shown in Table 3.7.5-1 of the California Amendments to AASHTO-CA LRFD BDS.

For Type I shafts and pile extensions in soft soil meeting the Class S2 soil classification defined in the SDC, lateral analysis is needed to determine the point of fixed support. Such analysis is shown in 10.15.4. Alternatively, the designer may run LPILE to determine lateral and rotational stiffnesses of the pile at the finished grade (FG) and include them as linear soil springs in the superstructure analysis software such as CTBridge, as shown in 10.15.5. The application of the two methods and comparison of results for a typical bridge are shown in 10.15.6.

10.15.4 – METHOD OF EQUIVALENT COLUMN LENGTH

In this method, a fixed support is added at the base of the column with an equivalent length to provide the stiffness comparable to the real foundation system. Equations have been developed for the analysis of a single column bent in the transverse direction in

10.15.4.1. The method has then been generalized for longitudinal analysis of the bridge as well as transverse analysis of multicolumn bents in 10.15.4.2.

10.15.4.1 Transverse Analysis of Single Column Bents

The steps to find the equivalent column length to an arbitrary fixed-end support for transverse direction analysis of pile extensions and Type I shafts used in single column bents are as follows:

1) Develop the LPILE model with soil information provided by the geotechnical designer. Include the column in the model.
2) Apply V and M as two separate load cases and record the deflection and rotation at the top of the column for each case, as shown in Table 10.15.4.1-1.

Table 10.15.4.1-1 Column Deflection and Rotation under Shear and Moment

Applied Load (Shear/Moment)	Deflection (top of column)	Rotation (top of column)
V	D_V	R_V
M	D_M	R_M

3) Use the following equations to estimate the equivalent column length needed for superstructure analysis:

$$L_{DV} = \left|\frac{3D_V EI}{V}\right|^{\frac{1}{3}} \qquad (10.15.4.1\text{-}1)$$

$$L_{DM} = \left|\frac{2D_M EI}{M}\right|^{\frac{1}{2}} \qquad (10.15.4.1\text{-}2)$$

$$L_{RV} = \left|\frac{2R_V EI}{V}\right|^{\frac{1}{2}} \qquad (10.15.4.1\text{-}3)$$

$$L_{RM} = \left|\frac{R_M EI}{M}\right| \qquad (10.15.4.1\text{-}4)$$

4) The average of the four calculated lengths (L_{avg}) can be used to define the equivalent column length.

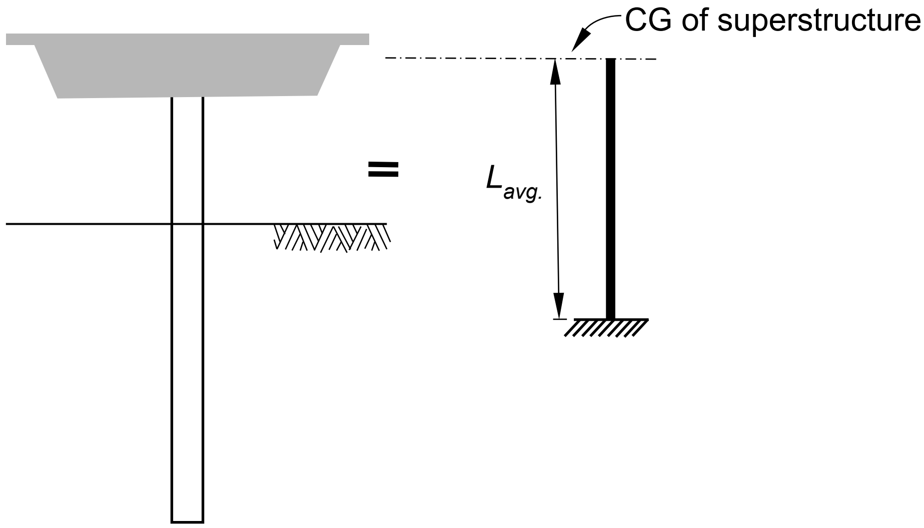


Figure 10.15.4.1-1 Arbitrary Fixed-End Support

10.15.4.2 Longitudinal Analysis of the Bridge and Transverse Analysis of Multicolumn Bents

For analysis in the longitudinal direction of the bridge or for transverse analysis of multi-column bents supported on pile extension or Type I shafts, the designer may consider a pile fixed at the top. The column should be included in the model as part of the pile but without surrounding soil. In this case, the designer may run LPILE for the following two cases:

1) The zero rotation and predefined displacement (Δ_p) are applied at the top of the column to find the corresponding moment and shear at the top of the column (M_D, V_D) as shown in Table 10.15.4.2-1.
2) The zero displacement and predefined rotation (θ_P in radian) at the top of the column to find the corresponding moment and shear at the top of the column (M_R, V_R) as shown in Table 10.15.4.2-1.
   Note: Considering the nonlinearity of the soil springs, it is recommended to select predefined displacement and rotation such that the resulting maximum moment and shear at the top of the column are within 10% of the values calculated from superstructure analysis. This may need an initial iteration using LPILE.

Table 10.15.4.2-1 Column Moment and Shear caused by Applied Predefined Displacement or Rotation

Applied predefined displacement/rotation	Moment (top of column)	Shear (top of column)
Displacement	M_D	V_D
Rotation	M_R	V_R

3) Calculate equivalent fixed-end column lengths from the following equations:

$$L_{VD} = \left| \frac{12EI\Delta_p}{V_D} \right|^{\frac{1}{3}} \quad (10.15.4.2\text{-}1)$$

$$L_{MD} = \left| \frac{6EI\Delta_p}{M_D} \right|^{\frac{1}{2}} \quad (10.15.4.2\text{-}2)$$

$$L_{VR} = \left| \frac{6EI\theta_p}{V_R} \right|^{\frac{1}{2}} \quad (10.15.4.2\text{-}3)$$

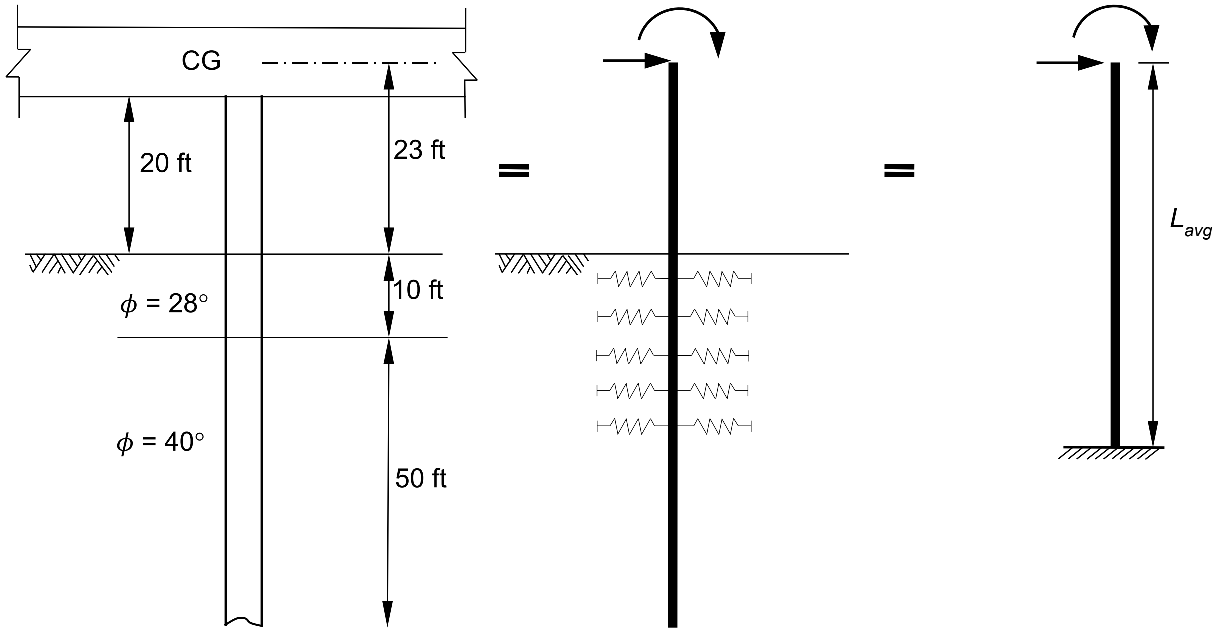
$$L_{MR} = \left| \frac{4EI\theta_p}{M_R} \right| \quad (10.15.4.2\text{-}4)$$

4) Calculate the average length of the equivalent column and use it for superstructure analysis.

10.15.5 FOUNDATION SOIL SPRINGS

For superstructure analysis under non-seismic loads, the effects of a foundation system can be modeled by a 6 x 6 linear stiffness matrix attached to the base of the column. In general, the diagonal elements of the stiffness matrix are the most effective components, and the non-diagonal elements can be disregarded to simplify the process.

10.15.6 ANALYSIS EXAMPLE



Assume a 5′-6″ Type I shaft with a gross moment of inertia of I = 44.9 ft^4 and f'_c = 4000 psi supports a box girder superstructure as shown in Figure 10.15.6-1. The length of the column and the shaft are 20 ft and 60 ft, respectively. The distance between the top of the column and the Center of Gravity (CG) of the superstructure is 3 ft. The soil includes a top 10-ft layer of loose sand with ϕ = 28° and γ = 130 pcf, over dense sand with ϕ = 40° and γ = 130 pcf .

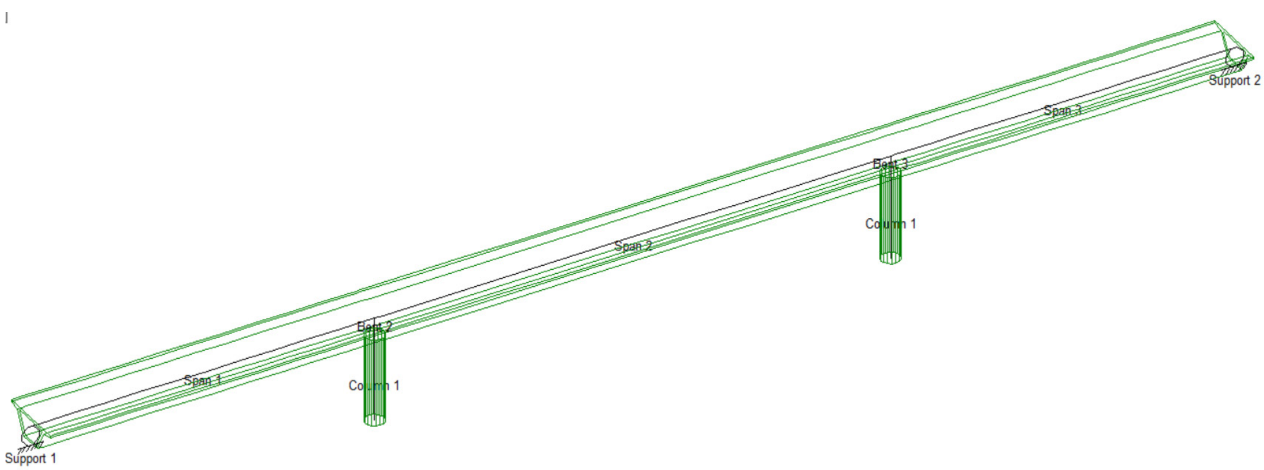


Figure 10.15.6-1 Analysis of Example Bridge Using Equivalent Column Length Method

The total shear and moment of unfactored loads (dead load, additional dead load, and live load) calculated at the top of the column (CTBridge output) are estimated as 253 kips, and 3514 kip-ft, respectively.

10.15.6.1 Equivalent Column Length

Upon an iterative process using LPILE the predefined displacement and rotation were assumed as 1 in. and 0.002 radian, respectively.

The LPILE results for moment and shear at the top of the column (CG of the superstructure) when predefined displacement and rotation are applied separately are shown in Table 10.15.6.1-1.

Table 10.15.6.1-1 – Pile Moment and Shear at the top of the column for Example Bridge

Load Case No.	Applied Displacement (in.)	Applied Rotation (Radian)	Bending Moment (kip-ft)	Shear Force (kips)
1	1	0	5275	238 (close to 253)
2	0	0.002	3766 (close to 3514)	130

Assuming E = 3600 ksi, then EI = 2.33x10^7 kip-ft^2. The equivalent column lengths are calculated as:

$$L_{VD} = \left|\frac{12EI\Delta_p}{V_D}\right|^{\frac{1}{3}} = \left(\frac{(12)(2.33\text{ x }10^7)\left(\frac{1}{12}\right)}{238}\right)^{\frac{1}{3}} = 46.1\text{ ft}$$

$$L_{MD} = \left|\frac{6EI\Delta_p}{M_D}\right|^{\frac{1}{2}} = \left(\frac{(6)(2.33\text{ x }10^7)\left(\frac{1}{12}\right)}{5275}\right)^{\frac{1}{2}} = 47.0\text{ ft}$$

$$L_{VR} = \left|\frac{6EI\theta_p}{V_R}\right|^{\frac{1}{2}} = \left(\frac{(6)(2.33\text{ x }10^7)(0.002)}{130}\right)^{\frac{1}{2}} = 46.4\text{ ft}$$

$$L_{MR} = \left|\frac{4EI\theta_p}{M_R}\right| = \frac{(4)(2.33\text{ x }10^7)(0.002)}{3766} = 49.5\text{ ft}$$

Therefore, the length to equivalent fixed support is calculated as the average of calculated column lengths, that is 47.3 ft.

10.15.6.2 – Foundation Soil Springs

The stiffness matrix for the pile used below the FG was generated by LPILE as shown in Figure 10.15.6.2-1.

K[2,2] V/y lb/in.	K[3,2] M/y in-lb/in.
2030947.	239245065.
2030947.	239245065.
2030947.	239245065.

K[2,3] V/rot. lb/rad	K[3,3] M/rot. in-lb/rad
239245065.	4.15916E+10
239245065.	4.15916E+10
239245065.	4.15916E+10

Figure 10.15.6.2-1 Stiffness Matrix (from LPILE)

The general form of the stiffness matrix after unit conversion and rounding is written as:

$$K = \begin{bmatrix} 24400 \text{ kips/ft} & 239200 \text{ kips/ft} \\ 239000 \text{ kip-ft/ft} & 3466000 \text{ kip-ft/rad} \end{bmatrix}$$

The diagonal members of the stiffness matrix can be added to the CTBridge, as shown in Figure 10.15.6.2-2. The effect of non-diagonal members may be disregarded. The axial stiffness shown for member 1,1 (2,000,000 kips/ft) is arbitrary and has been selected as a large number to represent a high axial stiffness of the pile. The effect of this number on the analysis is negligible.

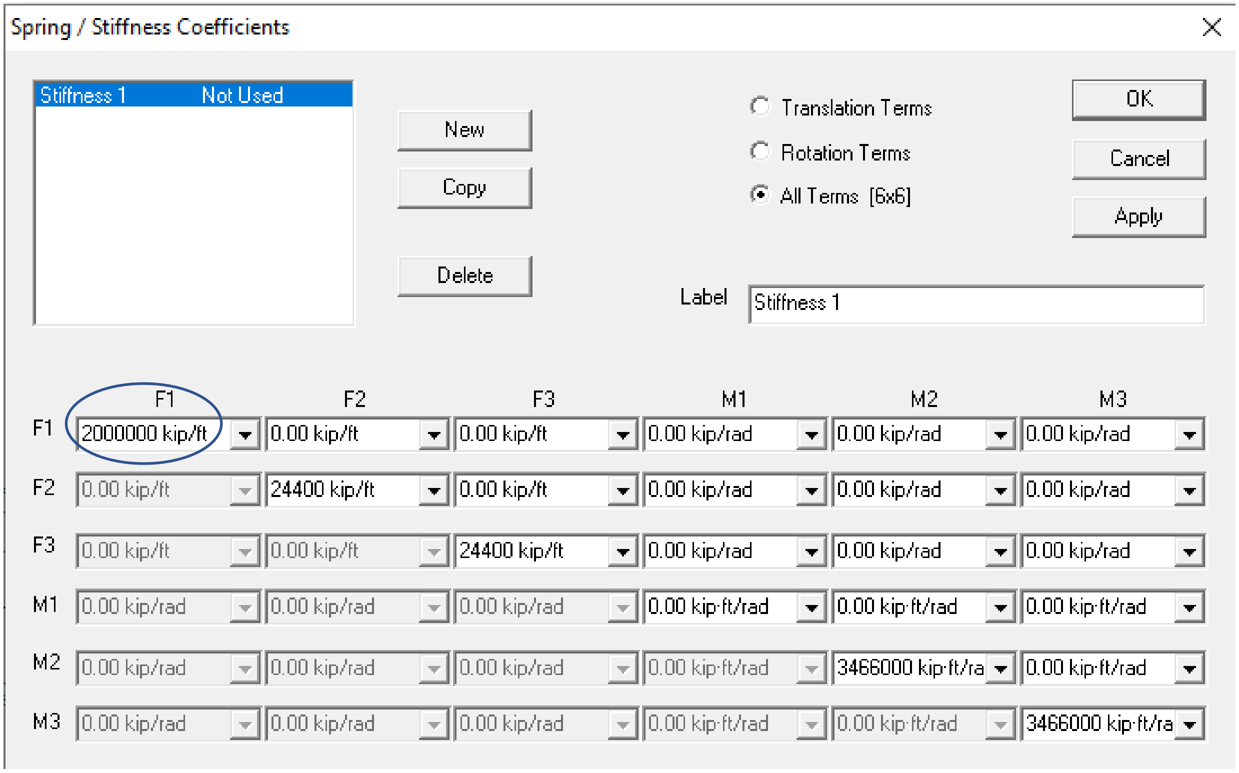


Figure 10.15.6.2-2 Adding Stiffness Matrix in CTBridge

10.15.6.3 – Comparison of Results

Typical analysis results for two methods consisting of added soil springs vs. use of equivalent column length are shown in Figures 10.15.6.3-1 to 10.15.6.3-3. Results have been compared for dead load, additional dead load, and live load (design truck). The top and bottom tables in these figures show results of adding a linear soil spring stiffness matrix at the column base vs. using an equivalent column fixed at the base, respectively.

Dead Load - Unfactored Span Forces - Final

Span 1

Location ft	AX kip	VY kip	VZ kip	TX kip·ft	MY kip·ft	MZ kip·ft
2.50	0.0	143.7	-0.0	0.0	-0.0	359.4
10.00	0.0	110.3	-0.0	0.0	-0.0	1312.0
20.00	0.0	65.7	-0.0	0.0	-0.0	2192.2
30.00	0.0	21.1	-0.0	0.0	-0.0	2626.5
40.00	0.0	-23.4	-0.0	0.0	-0.0	2615.1
50.00	0.0	-68.0	-0.0	0.0	-0.0	2157.9
60.00	0.0	-112.6	-0.0	0.0	-0.0	1254.8
70.00	0.0	-157.2	-0.0	0.0	-0.0	-94.1
80.00	0.0	-201.8	-0.0	0.0	-0.0	-1888.7
90.00	0.0	-246.3	-0.0	0.0	-0.0	-4129.2
98.50	0.0	-284.2	-0.0	0.0	-0.0	-6384.1

Span 1

Location ft	AX kip	VY kip	VZ kip	TX kip·ft	MY kip·ft	MZ kip·ft
2.50	0.0	142.3	-0.0	0.0	-0.0	355.8
10.00	0.0	108.9	-0.0	0.0	-0.0	1297.8
20.00	0.0	64.3	-0.0	0.0	-0.0	2163.7
30.00	0.0	19.7	-0.0	0.0	-0.0	2583.8
40.00	0.0	-24.9	-0.0	0.0	-0.0	2558.1
50.00	0.0	-69.4	-0.0	0.0	-0.0	2086.6
60.00	0.0	-114.0	-0.0	0.0	-0.0	1169.3
70.00	0.0	-158.6	-0.0	0.0	-0.0	-193.8
80.00	0.0	-203.2	-0.0	0.0	-0.0	-2002.7
90.00	0.0	-247.8	-0.0	0.0	-0.0	-4257.4
98.50	0.0	-285.7	-0.0	0.0	-0.0	-6524.4

Figure 10.15.6.3-1 Comparison of Results for Dead Load

Additional Dead Load - Unfactored Span Forces

Span 1

Location ft	AX kip	VY kip	VZ kip	TX kip·ft	MY kip·ft	MZ kip·ft
2.50	0.0	63.8	-0.0	0.0	-0.0	165.7
10.00	0.0	48.9	-0.0	0.0	-0.0	588.4
20.00	0.0	29.1	-0.0	0.0	-0.0	978.8
30.00	0.0	9.3	-0.0	0.0	-0.0	1171.2
40.00	0.0	-10.5	-0.0	0.0	-0.0	1165.7
50.00	0.0	-30.2	-0.0	0.0	-0.0	962.2
60.00	0.0	-50.0	-0.0	0.0	-0.0	560.7
70.00	0.0	-69.8	-0.0	0.0	-0.0	-38.8
80.00	0.0	-89.6	-0.0	0.0	-0.0	-836.2
90.00	0.0	-109.4	-0.0	0.0	-0.0	-1831.6
98.50	0.0	-126.3	-0.0	0.0	-0.0	-2833.3

Span 1

Location ft	AX kip	VY kip	VZ kip	TX kip·ft	MY kip·ft	MZ kip·ft
2.50	0.0	62.8	-0.0	0.0	-0.0	163.2
10.00	0.0	48.0	-0.0	0.0	-0.0	578.6
20.00	0.0	28.2	-0.0	0.0	-0.0	959.3
30.00	0.0	8.4	-0.0	0.0	-0.0	1142.0
40.00	0.0	-11.4	-0.0	0.0	-0.0	1126.8
50.00	0.0	-31.2	-0.0	0.0	-0.0	913.5
60.00	0.0	-51.0	-0.0	0.0	-0.0	502.3
70.00	0.0	-70.8	-0.0	0.0	-0.0	-106.9
80.00	0.0	-90.6	-0.0	0.0	-0.0	-914.0
90.00	0.0	-110.4	-0.0	0.0	-0.0	-1919.1
98.50	0.0	-127.2	-0.0	0.0	-0.0	-2929.1

Figure 10.15.6-3.2 Comparison of Results for Additional Dead Load

Live Load - Controlling Unfactored Span Forces

LRFD Design Vehicle - Span 1

Dynamic Load Allowance (Included) = 1.3300

Location ft	# Lanes	MZ+ kip·ft	assoc VY kip	# Lanes	# Lanes	MZ- kip·ft	assoc VY kip	# Lanes
2.50	1.500	398.32	94.53	1.500	1.500	-47.72	-19.09	1.500
10.00	1.500	1427.32	74.39	1.500	1.500	-190.89	-19.09	1.500
20.00	1.500	2400.89	46.75	1.500	1.500	-381.78	-19.09	1.500
30.00	1.500	2955.15	11.85	1.500	1.500	-572.67	-19.09	1.500
40.00	1.500	3156.88	-14.42	1.500	1.500	-763.56	-19.09	1.500
50.00	1.500	3040.75	-72.93	1.500	1.500	-954.45	-19.09	1.500
60.00	1.500	2620.31	-97.86	1.500	1.500	-1145.34	-19.09	1.500
70.00	1.500	1905.18	-121.25	1.500	1.500	-1381.05	-19.73	1.500
80.00	1.500	994.83	-129.05	1.500	1.500	-1606.18	-32.13	1.500
90.00	1.500	354.79	-54.28	1.500	1.500	-2534.43	-124.37	1.500
98.50	1.500	41.07	0.16	1.500	1.500	-3720.65	-151.61	1.500

Live Load - Controlling Unfactored Span Forces

LRFD Design Vehicle - Span 1

Dynamic Load Allowance (Included) = 1.3300

Location ft	# Lanes	MZ+ kip·ft	assoc VY kip	# Lanes	# Lanes	MZ- kip·ft	assoc VY kip	# Lanes
2.50	1.500	400.77	95.51	1.500	1.500	-53.77	-21.51	1.500
10.00	1.500	1438.96	75.56	1.500	1.500	-215.09	-21.51	1.500
20.00	1.500	2428.50	48.14	1.500	1.500	-430.19	-21.51	1.500
30.00	1.500	2999.56	13.33	1.500	1.500	-645.28	-21.51	1.500
40.00	1.500	3221.62	-12.80	1.500	1.500	-860.38	-21.51	1.500
50.00	1.500	3121.91	-71.31	1.500	1.500	-1075.47	-21.51	1.500
60.00	1.500	2721.40	-96.18	1.500	1.500	-1290.57	-21.51	1.500
70.00	1.500	2021.22	-119.59	1.500	1.500	-1579.48	-22.56	1.500
80.00	1.500	1103.89	-130.58	1.500	1.500	-1821.22	-32.20	1.500
90.00	1.500	408.23	-102.53	1.500	1.500	-2621.43	-124.27	1.500
98.50	1.500	68.99	0.33	1.500	1.500	-3804.90	-152.36	1.500

Figure 10.15.6.3-3 Comparison of Results for Live Load (Design Truck)

10.15.7 SUMMARY

As shown in the Analysis Example of 10.15.6, the results of using the methods of equivalent column length and soil springs are close and both methods provide reasonable accuracy. However, considering the simplicity and higher accuracy when analyzing superstructure for different types of loads, the use of foundation soil springs is recommended.

10.15.8 REFERENCES

1. AASHTO. (2017), *AASHTO LRFD Bridge Design Specifications*, 8th Edition, American Association of State Highway and Transportation Officials, Washington DC.

5) Caltrans. (2019), *California Amendments to AASHTO LRFD Bridge Design Specifications*, 8th Edition, California Department of Transportation, Sacramento, CA.

6) Caltrans. (2019), *Seismic Design Criteria (SDC), Version 2.0*, California Department of Transportation, Sacramento, CA.