APPENDIX J
Slide Curve Median Wall FLAC Model

Memorandum

To: File
From: Suren Balendra, Ethan Dawson
Date: December 3, 2010
Subject: FLAC analysis of reinforcement forces in inverted MSE wall

This memo describes numerical simulations, performed with the program FLAC, to estimate reinforcing strip forces for a proposed non-standard, inverted MSE wall design. The inverted MSE wall does not have the usual rectangular shape, but instead is narrower at the base than at the top. This unusual configuration is designed to reduce the amount of excavation required of the rock slope against which the wall is placed.

Before proceeding with the analysis of the inverted wall, a calibration or validation analysis was performed for a well documented case history of an MSE wall with similar reinforcing, fill soil, facing system and height. The purpose of this verification analysis was to confirm that the selected modeling procedure and material properties could adequately capture the mechanical behavior of the MSE wall system. Results of this check analysis were discussed with WSDOT personnel before proceeding with analysis of the inverted wall.

Minnow Creek MSE Wall Case History

The verification exercise was performed for a case history of a 16.9 m high, steel strip MSE retaining wall which formed part of a bridge abutment. A comprehensive field study of the performance of this wall was funded by the Indiana Department of Transportation (INDOT) and is documented in papers by Runser (1999) and Runser et al. (2001).

The Minnow Creek wall consists of reinforced concrete facing panels, ribbed steel reinforcing strips, and freely draining backfill soil. A cross section of the wall is shown in Figure 1. The instrumented section of the wall has 22 layers of reinforcement with a vertical spacing of 0.75 m. Horizontal spacing ranged from 0.34 m at the bottom of the wall to 1.05 m at the top. Reinforcing strips were 50 mm wide and 4 mm thick. Most of the reinforcement strips had a length of 11.9 m (0.7H), but the lower 5 strips were lengthened to 15.5 m due to concerns about the bearing capacity of the foundation soils. The wall was designed using the coherent gravity method as defined by AASHTO 1996 Standard Specifications.

Instrumentation of the wall included strain gages on selected reinforcing strips to measure the distribution of strip tension in the reinforced mass including tensions at the connections to the facing panels. Three inclinometers were installed, one behind the facing and two within the reinforced section to measure lateral deformations during and after construction. In addition, pneumatic earth pressure cells were installed in and around the reinforced soil mass to measure vertical and lateral soil pressures. The instrumentation layout and distributions of measured reinforcement forces are shown in Figure 2.

FLAC Numerical Analysis of Minnow Creek MSE Wall Case History

Numerical analyses were performed with the computer code FLAC, Version 6.0 (Itasca, 2008), a two-dimensional explicit finite difference program for geotechnical engineering and rock mechanics computations. FLAC offers a wide range of capabilities to solve complex problems in geomechanics, including nonlinear static and dynamic stress-strain analysis of soil continua, soil-structure interaction, and groundwater flow.

The numerical mesh used for the analyses, shown in Figures 3, consists of approximately 7000 solid elements, and 900 cable and beam elements. Each reinforcing strip level is modeled with 40 to 50 cable elements. Fill and foundation soils were modeled with a linear-elastic/perfectly plastic Mohr-Coulomb constitutive model. In this model, the soil shear strength is defined in terms of a friction angle and cohesion. For stress states below the shear strength, the behavior of the model is linear elastic. For stresses at the shear strength, the model behavior is perfectly plastic.

The reinforcing strips were modeled with elastic-plastic cable elements that interact with the soil mesh through non-linear springs similar to the t-z springs used in pile analyses. These springs account for the forces produced by relative displacement between the cables and surrounding soil. For this analysis, a simple bi-linear force-displacement curve was used for the t-z springs. The springs have an initial elastic stiffness and an ultimate pull-out force, both of which were estimated from pullout tests reported by Runser (2001). In the plane-strain FLAC model, axial stiffness and t-z spring properties are scaled to account for the horizontal spacing of the reinforcing strips.

The concrete block wall facing is modeled with beam elements, with a plastic moment capacity assigned to limit the maximum bending moment within the wall. These beam elements are connected directly to the soil mesh nodes. The facing beams are also connected directly to the reinforcing strip cable elements. Soil and structural properties used in the FLAC analysis, listed in Tables 1, 2 and 3 were, for the most part, taken directly from the paper of Runser et al, (2001).

The analysis was performed by modeling the construction process of the wall, step by step. After each 0.75 m thick layer of fill was placed, the model was solved for equilibrium. Next, cable elements for the reinforcing layer were installed, and another layer of fill was placed. At each construction step, soil elastic properties were updated as a function of the mean effective stress, using Equation (1) below:

(1) $$G = K\left(\sigma_m\right)^{0.5}$$

where σ_m is the mean effective stress and K is a constant. The fill wedge directly in front of the toe was installed after the 8th reinforcing layer was placed, when the wall was at approximately one third of its final height.

Computed wall deflections after construction are shown in Figure 4, where they are compared to the measured deflections of the Minnow Creek wall. Computed tensile forces in selected reinforcing strips are shown in Figure 5, along with the measured tensile forces, and forces computed with AASHTO (1996) and ASSHTO (1999). The FLAC results are in reasonably close agreement with the measured tensile forces.

Wall 8 FLAC Numerical Analysis

Using the same methodology described in the previous section, FLAC numerical analyses were performed to estimate reinforcing-strip tensile forces for the proposed Wall 8 design at WB Sta. 1399+00. Two configurations were modeled: First a standard rectangular wall and second, a non-standard, inverted MSE wall which is narrower at the base (0.4H) than at the top (1H). This unusual configuration was designed to reduce the amount of excavation required of the rock slope against which the wall is placed.

The FLAC numerical meshes for the two analyses are shown in Figures 6 and 7. Soil properties used in the analysis are listed in Table 4. Reinforcing strip properties and facing properties are the same as those used for the Minnow Creek wall analysis described above (Table 2 and 3).

Computed horizontal-deflection contours (Figure 8) show that the maximum computed wall deflection is 0.6 inches for both cases. Computed tensile forces in selected reinforcing strips, along with forces computed with AASHTO Simplified Method (2010), are shown in Figure 9 for the rectangular wall, and in Figure 10 for the inverted wall. Figure 11 shows profiles of maximum computed tensile force in each reinforcing layer, along with values computed with the AASHTO Simplified Method and the Coherent Gravity Method. Figure 12 shows the same profiles for the seismic (i.e. pseudostatic) case, in which a constant horizontal acceleration of one half the PGA is applied (the design PGA = 0.35 g, and k_h = 0.175 g).

Conclusion

The FLAC-analysis results above demonstrate that the computed maximum reinforcement forces (Figures 11 and 12) of Wall 8 with a rectangular wall configuration are essentially identical to those of an inverted wall configuration. The results also indicate that design of the wall using the coherent gravity method should result in reinforcement that is adequate to resist the forces predicted by the FLAC model.

Note that AASHTO (2010) doesn't have specific guidance for calculating the eccentricity, e, for an inverted wall, which is needed for the coherent gravity method. For the profiles shown in Figures 11 and 12, the eccentricity was calculated using a method described in Principles of Foundation Engineering (Das, 2004) for a stepped wall. It is clear that the method used to calculate e has a significant influence on the calculated reinforcement forces. The possibility exists that a vendor could calculate e using a method that results in calculated reinforcement forces smaller than those predicted by FLAC. In this case, it is possible the reinforcement could be under designed.

REFERENCES

AASHTO, 2010, "AASHTO LRFD Bridge Design Specifications", 5th Edition, American Association of State Highway and Transportation Officials, Washington, DC, USA.

AASHTO, 1999, "Standard Specifications for Highway Bridges", 16th Edition, 1999 Interim Revisions, American Association of State Highway and Transportation Officials, Washington, DC, USA.

AASHTO, 1996, "Standard Specifications for Highway Bridges", 16th Edition, American Association of State Highway and Transportation Officials, Washington, DC, USA.

Das, B.M., 2004, "Principles of Foundation Engineering, 5th Edition", Brooks/Cole, a division of Thomson Learning, Inc.

Fast Lagrangian Analysis of Continua (FLAC), 2008, Itasca Consulting Group, Version 6.0, Minneapolis, Minnesota, USA.

Runser, D.J., 1999, "Instrumentation and Experimental Evaluation of a 17 m Tall Reinforced Earth Retaining Wall", M.S. Thesis, School of Civil Engineering, Purdue University, West Lafayette, Indiana, USA, 289 p.

Runser, D.J., Fox, P.J., and Bourdeau, P.L., 2001, "Field Performance of a 17 m-High Reinforced Soil Retaining Wall", Geosynthetics International, Vol. 8, No. 5, pp. 367-391.

TABLES

Table 1. Soil Properties Used in FLAC Analysis of Minnow Creek Wall

Material	Friction Angle (deg)	Cohesion (kPa)	Dilation Angle (deg)	Unit weight (kN/m3)	Poisson's Ratio	G (Pa)[1]
Retained Soil	35.3	0	5.5	20.84	0.35	$7.3e4*\sigma'_m{}^{1/2} \geq 2.7e7$
Reinforced Soil/Front Back Fill	38	0	8	21.80	0.35	$7.3e4*\sigma'_m{}^{1/2} \geq 2.7e7$
Top Foundation Soil	32	10	2	19.00	0.35	$9.4e4*\sigma'_m{}^{1/2} \geq 1.7e7$
Foundation Soil	38	10	8	21.00	0.35	$1.5e5*\sigma'_m{}^{1/2} \geq 2.3e8$

[1]where σ'_m is the mean effective stress in Pa

Table 2. Steel Reinforcing Strip Properties

Properties	Value (SI Units)	Value (Imperial Units)
Area	$2e^{-4}$ m^2	0.002153 ft^2
Perimeter	0.108 m	0.354 ft
Elastic Modulus	200e9 Pa	4.18e9 lb/ft^2
Tensile Yield Strength	$1.07e^5$ N	$2.4e^4$ lb
Compressive Yield Strength	$1.07e^5$ N	2.4e4 lb
Soil-Reinforcement Adhesion	0 N/m	0 lb/ft
Soil-Reinforcement Friction	38^o	38^o
Soil-Reinforcement Stiffness	$5e^6$ N/m/m	$1e^5$ lb/ft/ft

Table 3. Wall Facing Properties

Properties	Value (SI Units)	Value (Imperial Units)
Area	0.14 m^2/m	0.459 ft^2/ft
Elastic Modulus	2.5e10 Pa	5.22e8 psf
Plastic Bending Moment	700N-m	516 lb-ft
Moment of Inertia	$2.3e^{-4}$ m^4	$8.02e^{-3}$ ft^4
Density	23.55 kN/m^3	4.66 $slugs/ft^3$

Table 4. Soil Properties Used in FLAC Analysis of Wall 8

Material	Friction Angle (deg)	Cohesion (ksf)	Dilation Angle (deg)	Unit weight (pcf)	Poisson's Ratio	G (psf)[1]
Retained Soil	38	0	8	138	0.35	$1.05e4*\sigma'_m{}^{1/2} \geq 5.6e5$
Reinforced Soil/Front Back Fill	38	0	8	138	0.35	$1.05e4*\sigma'_m{}^{1/2} \geq 5.6e5$
Foundation Rock	52	8	12	150	0.25	1.80E+07
Foundation Soil	40	10	8	135	0.35	$2.1e4*\sigma'_m{}^{1/2} \geq 4.8e6$

[1]where σ'_m is the mean effective stress in psf

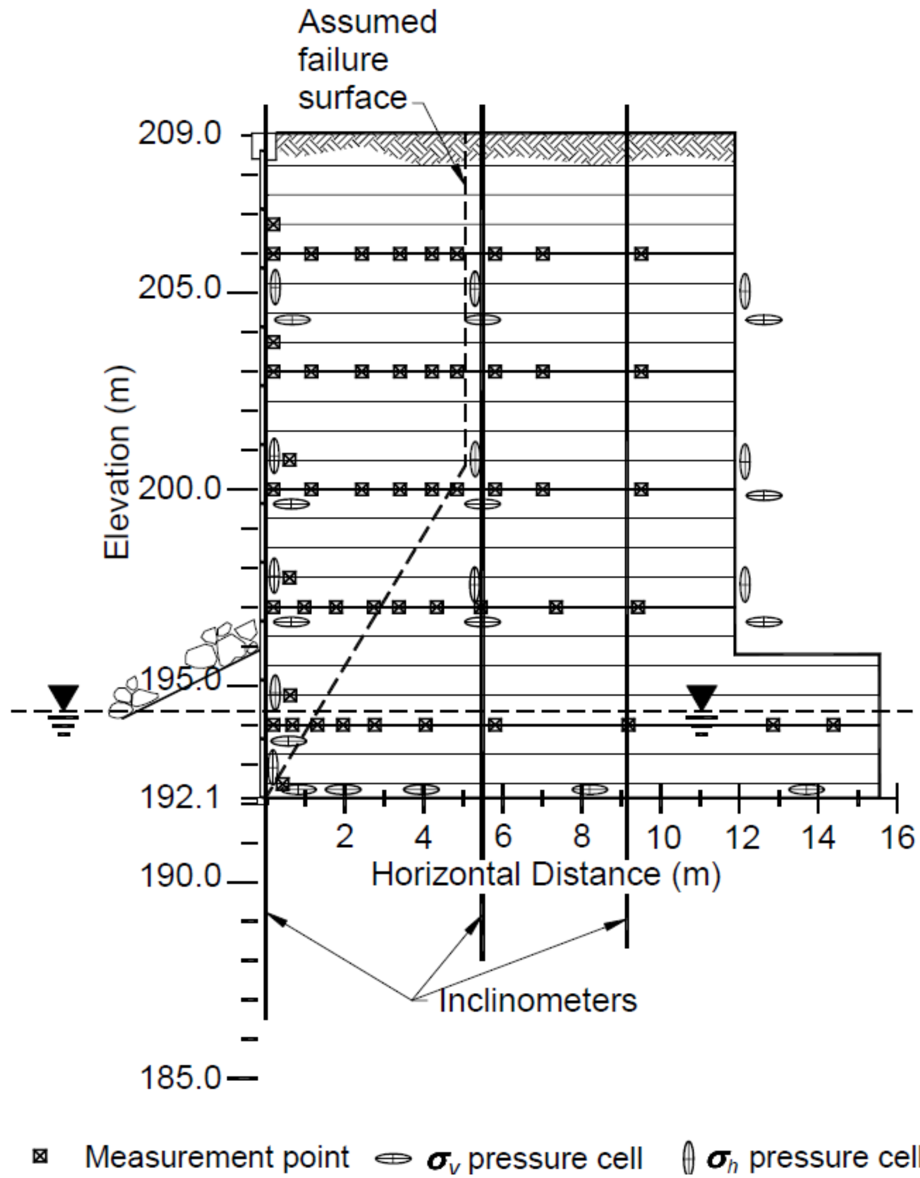


Figure 1. Cross section of Minnow Creek MSE wall. (Runser et al., 2001)

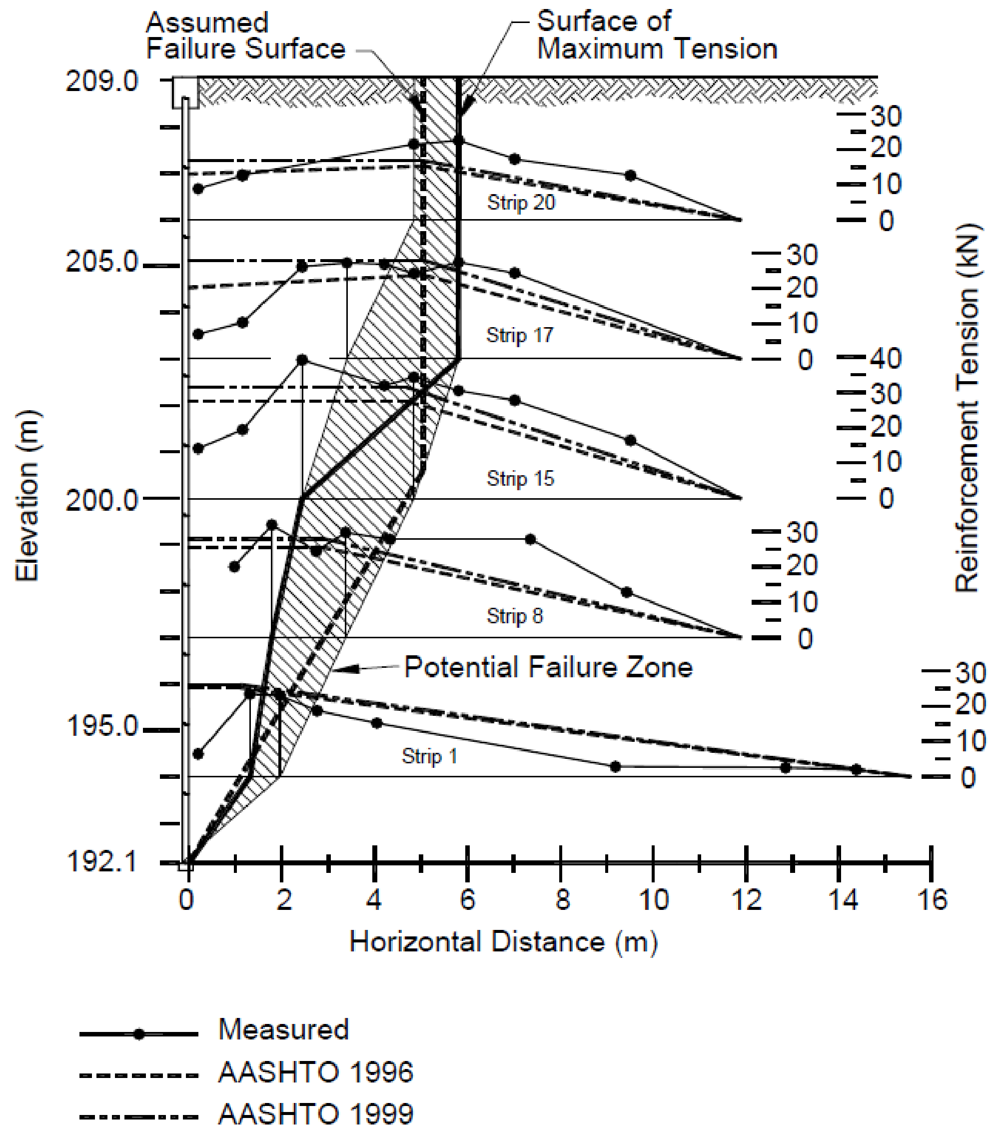


Figure 2. Measured distribution of tension in reinforcement, Minnow Creek MSE wall. (Runser et al., 2001)

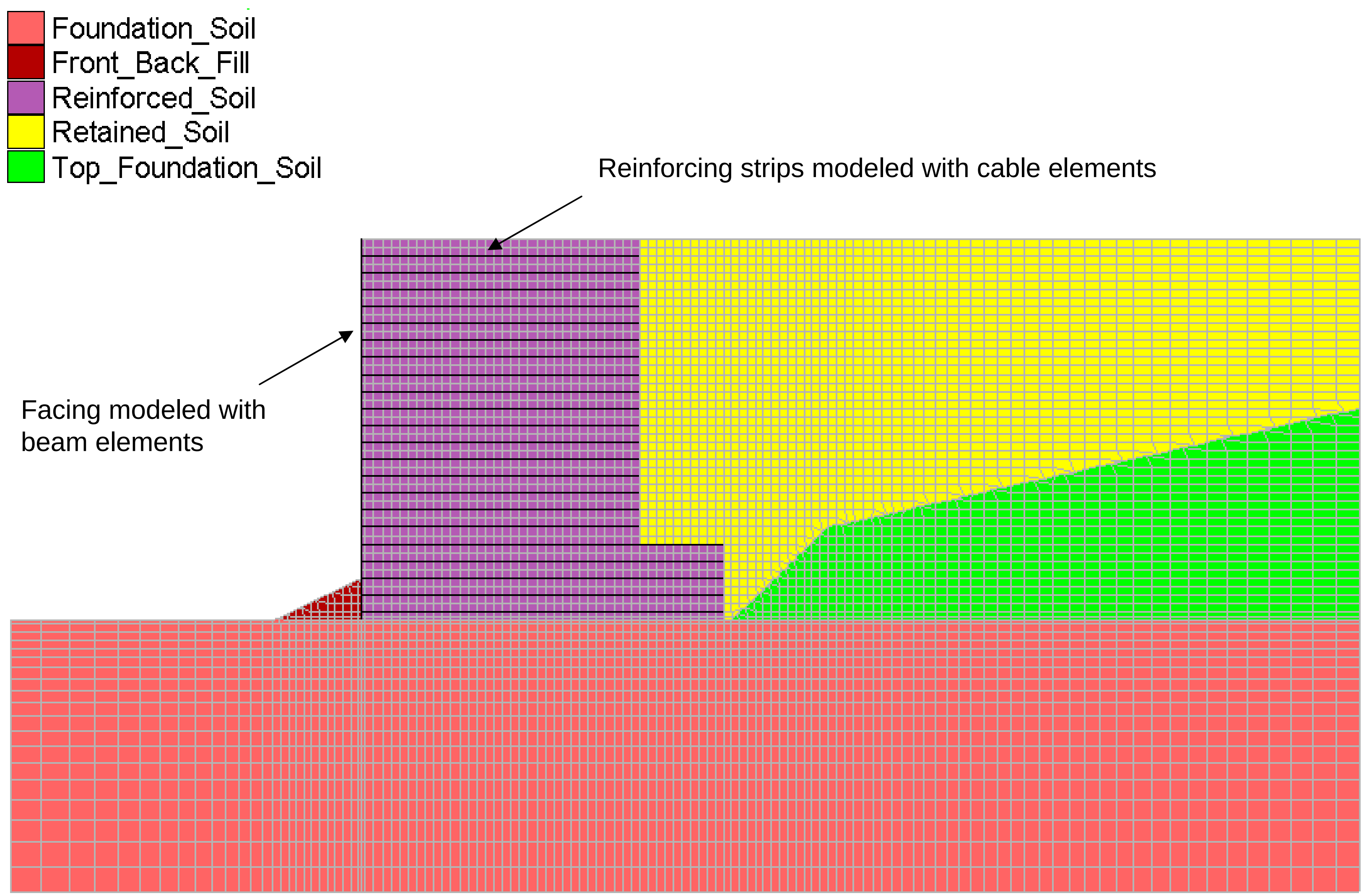


Figure 3. FLAC numerical mesh for Minnow Creek MSE wall.

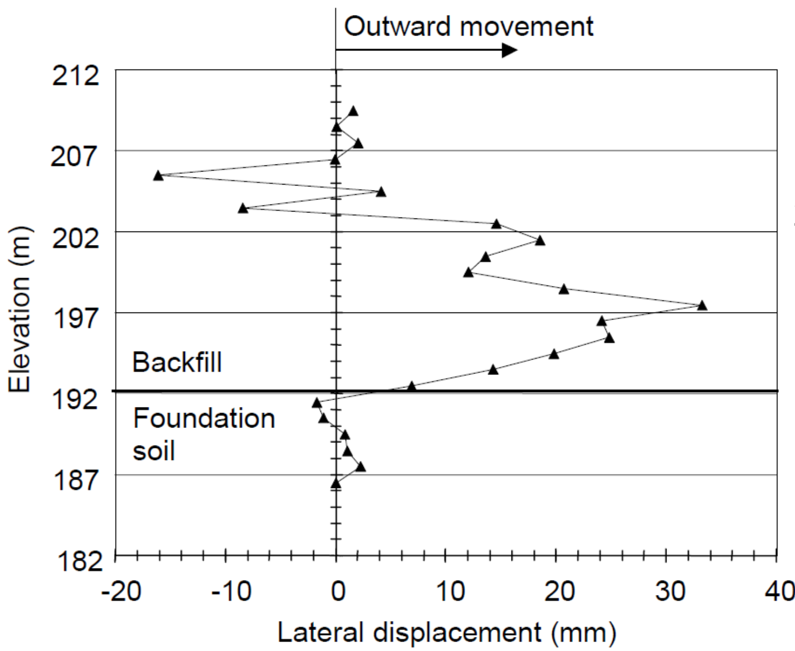
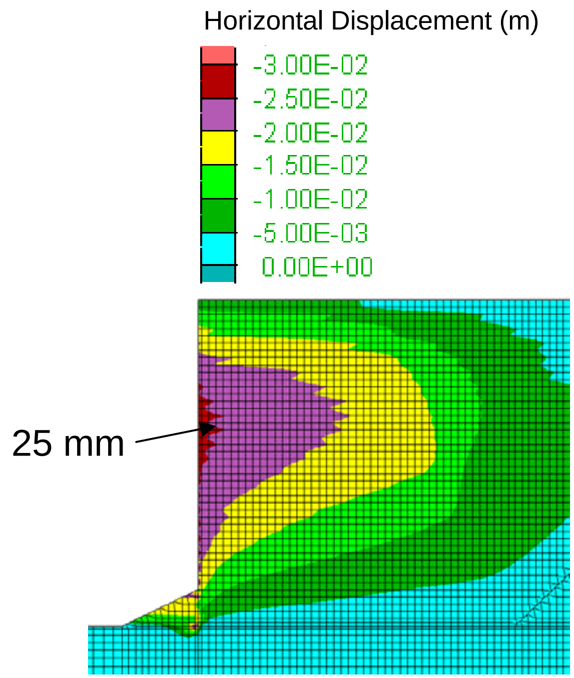


Figure 17. Displacement of facing panels as recorded by inclinometer I1.



Contours of Horizontal Displacement, FLAC Analysis

Figure 4. Measured and computed wall deflections for Minnow Creek MSE wall.

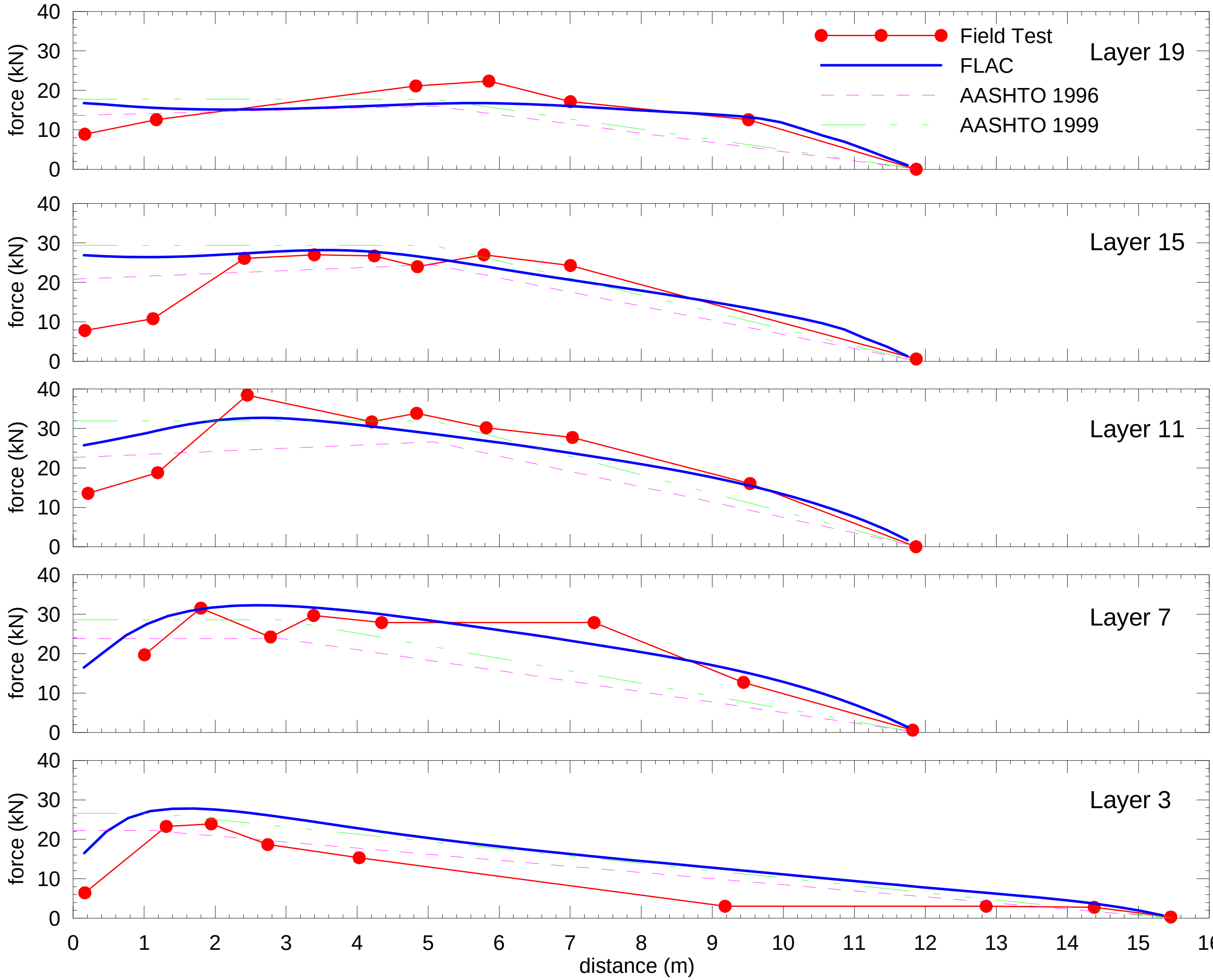


Figure 5. Computed and measured tensile force in reinforcement, Minnow Creek MSE wall.

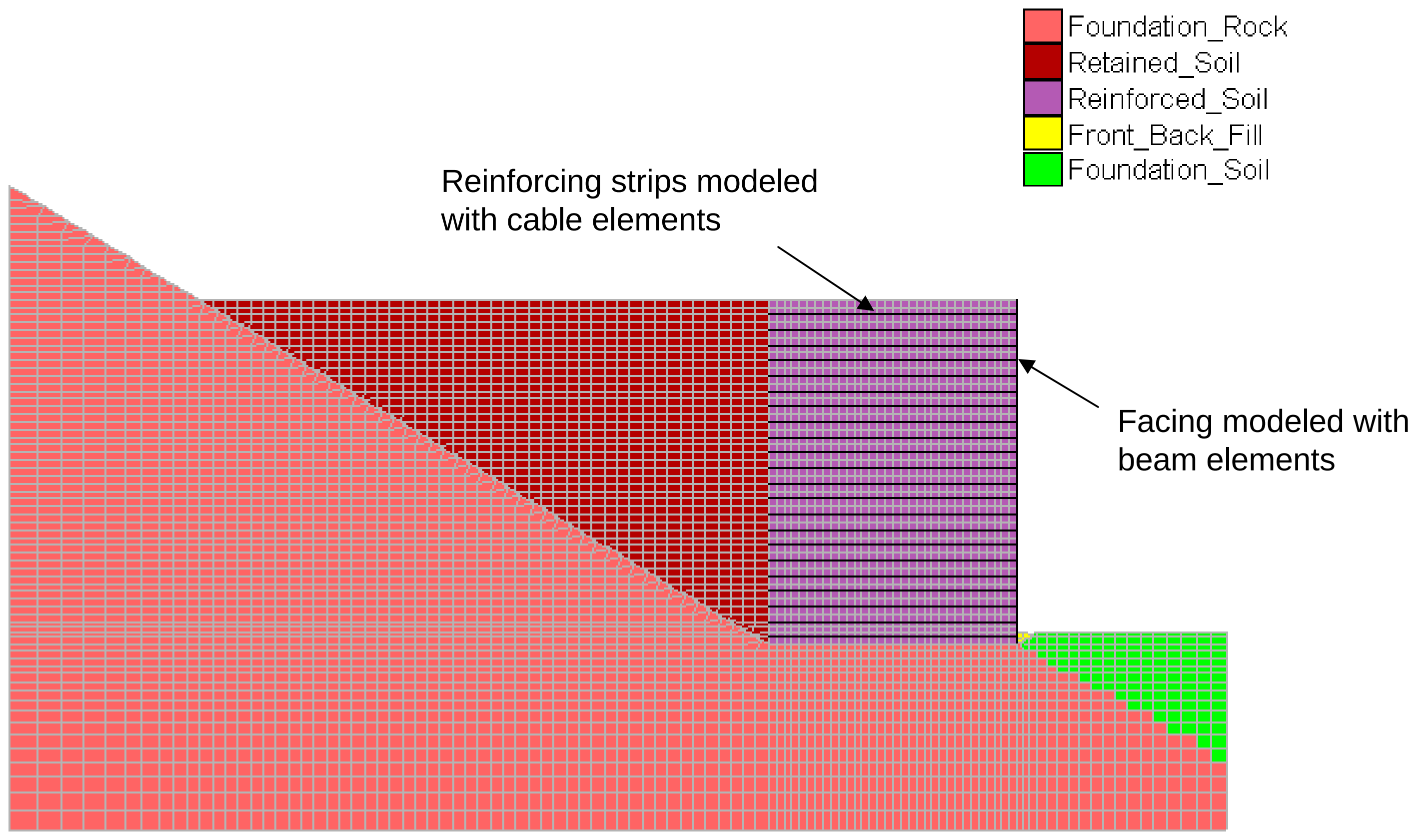


Figure 6. FLAC numerical mesh for Wall 8, rectangular wall.

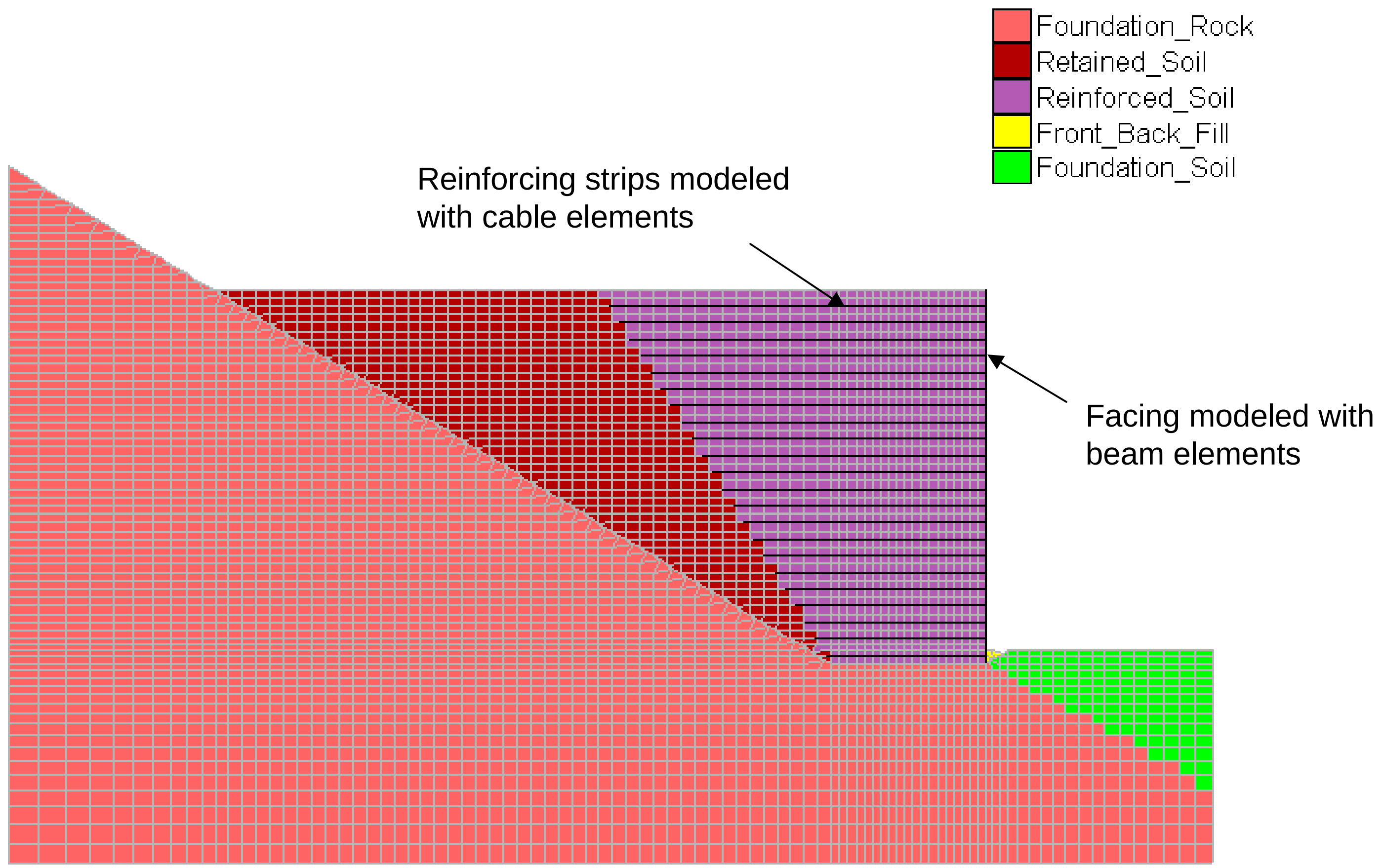


Figure 7. FLAC numerical mesh for Wall 8, inverted wall.

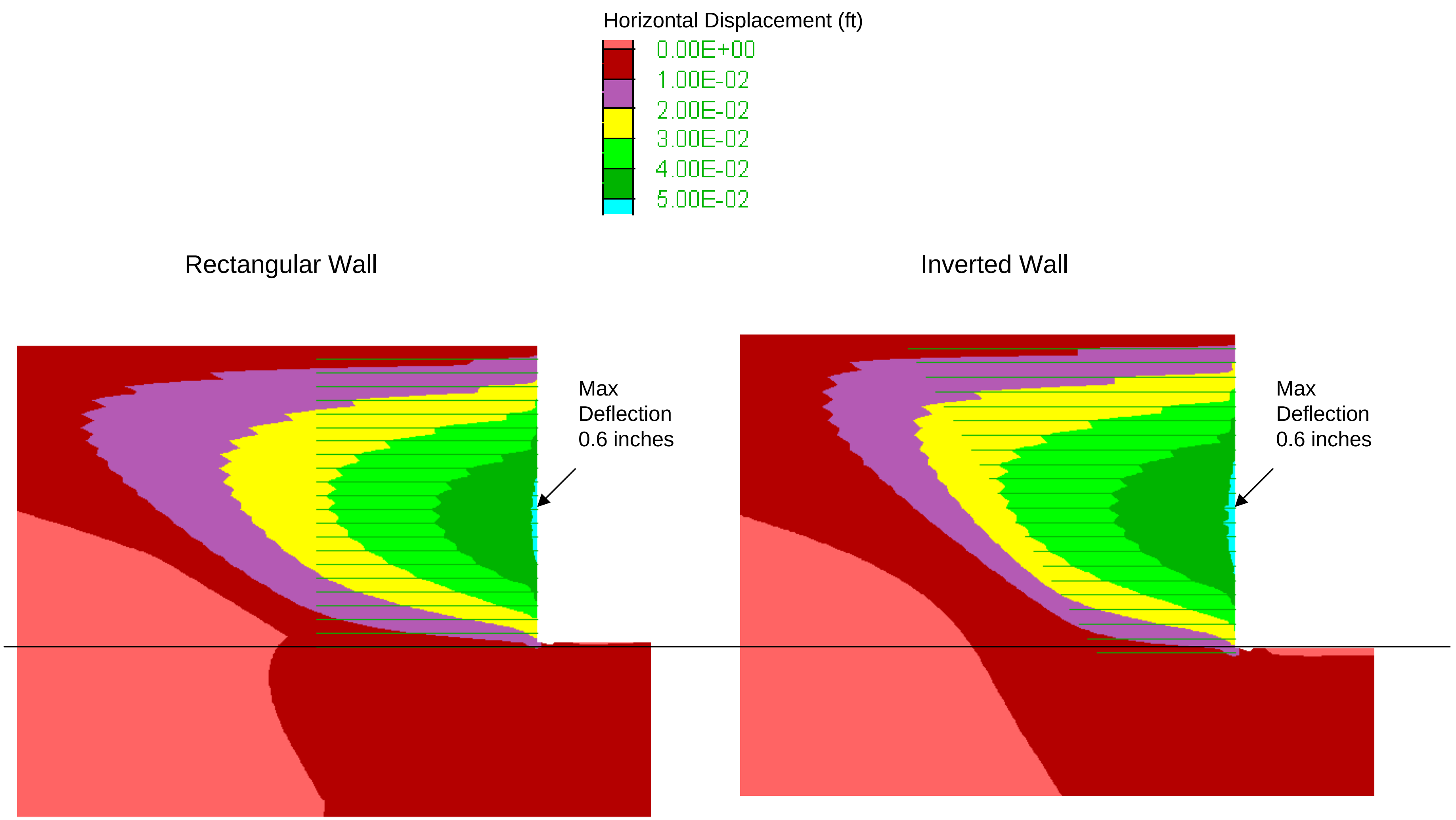


Figure 8. Computed horizontal displacement contours, rectangular and inverted Wall 8

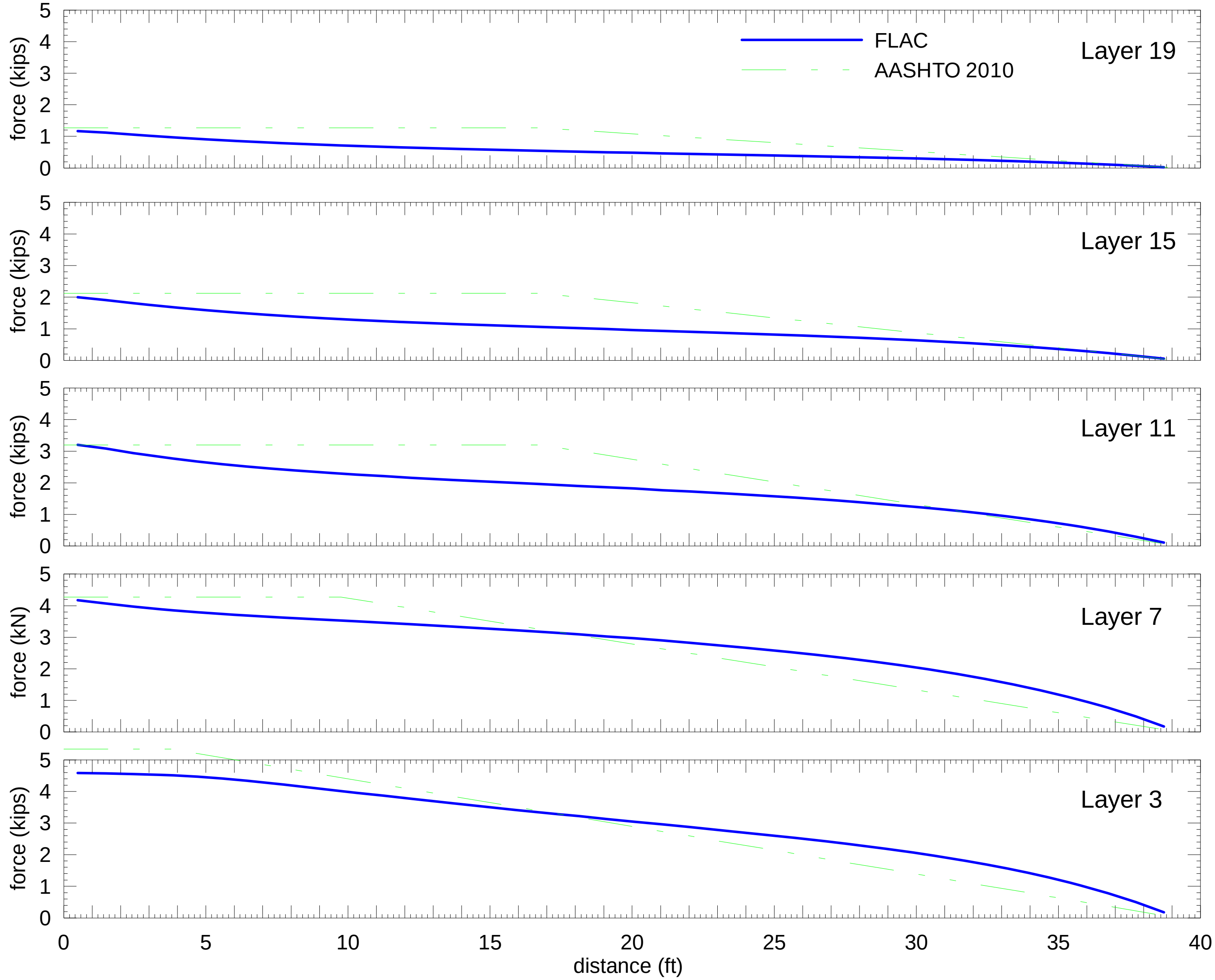


Figure 9. Computed tensile force in reinforcement, Wall 8, rectangular wall.

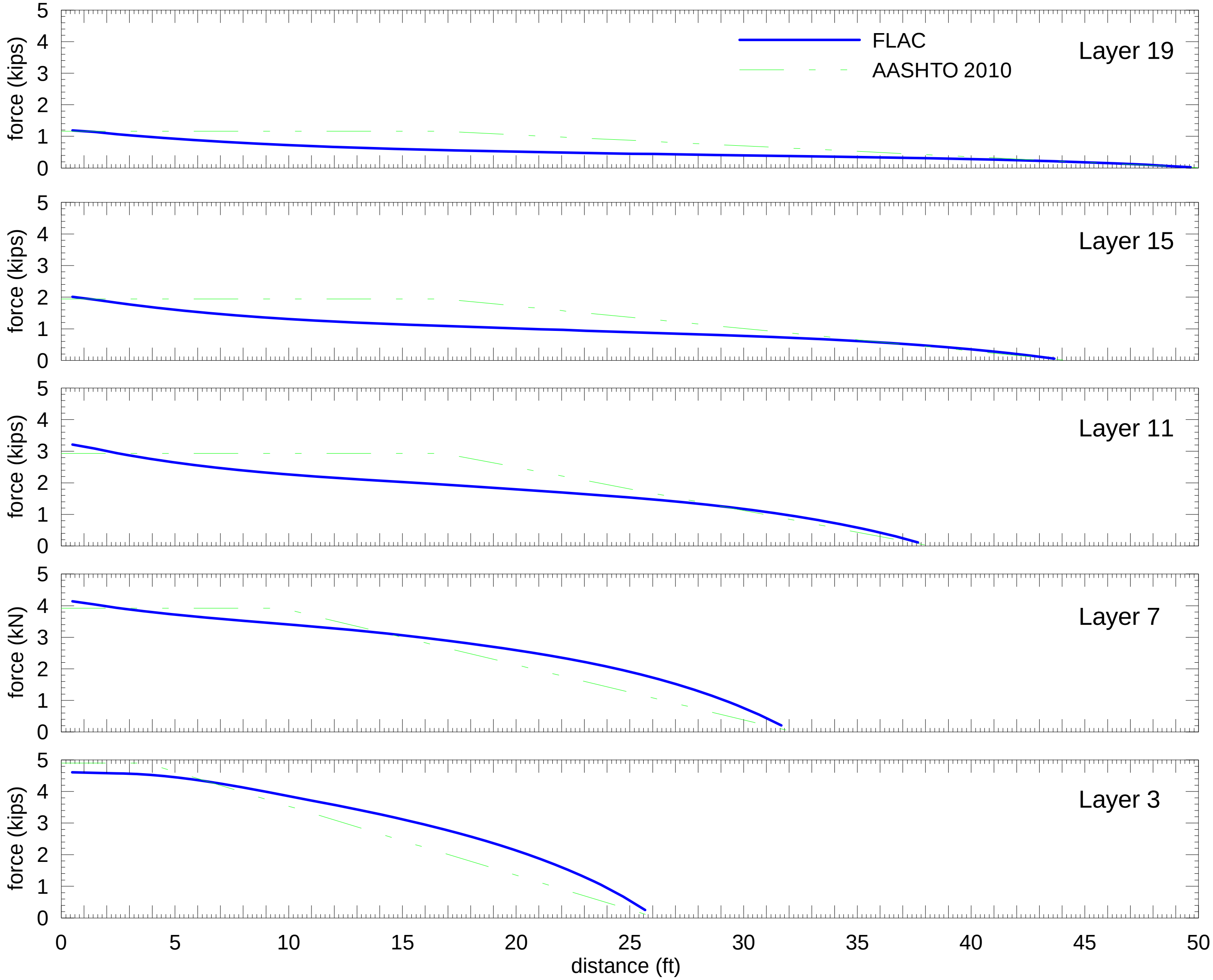


Figure 10. Computed tensile force in reinforcement, Wall 8, inverted wall.

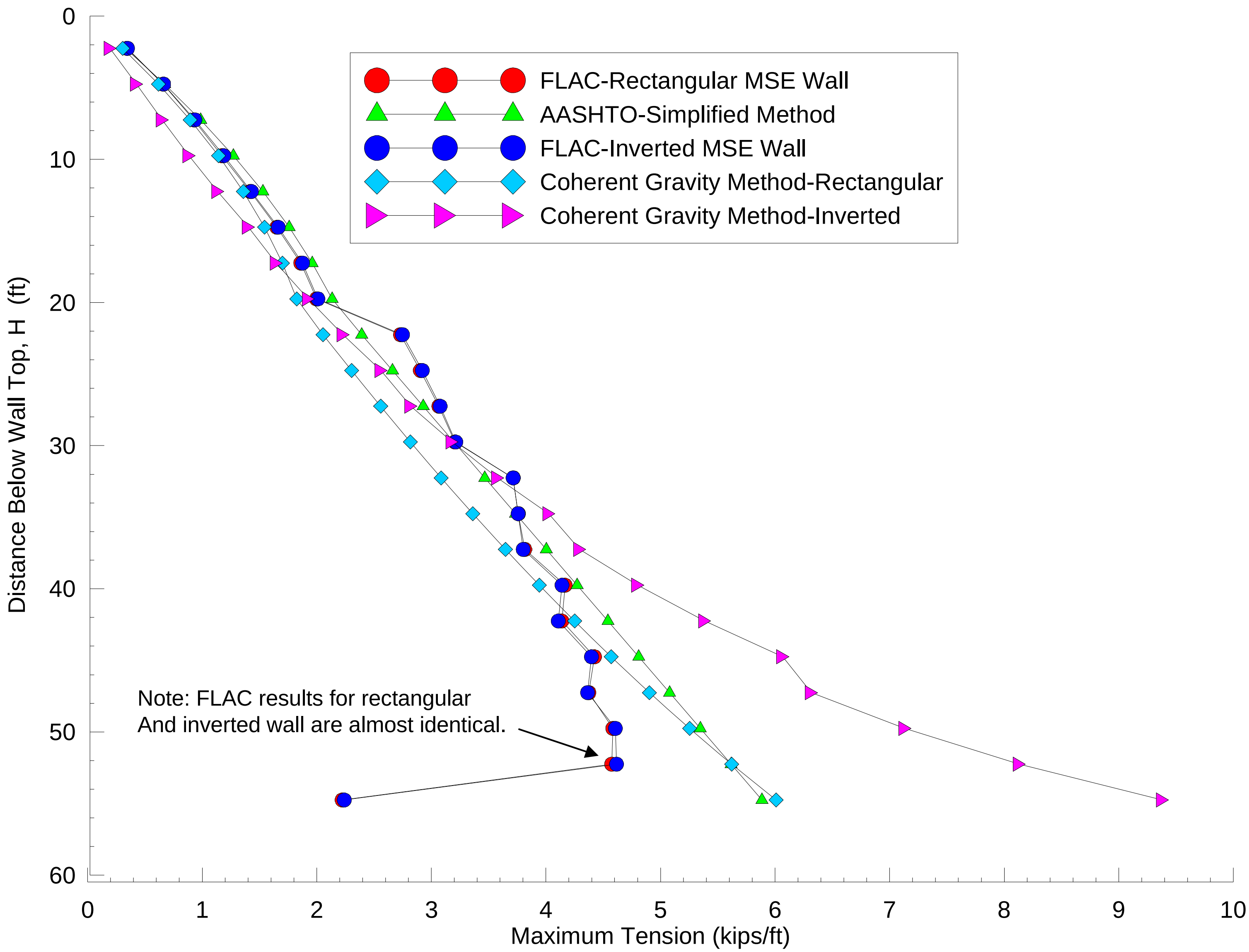


Figure 11. Maximum computed and tensile force in reinforcement layers compared to various design methods, Wall 8

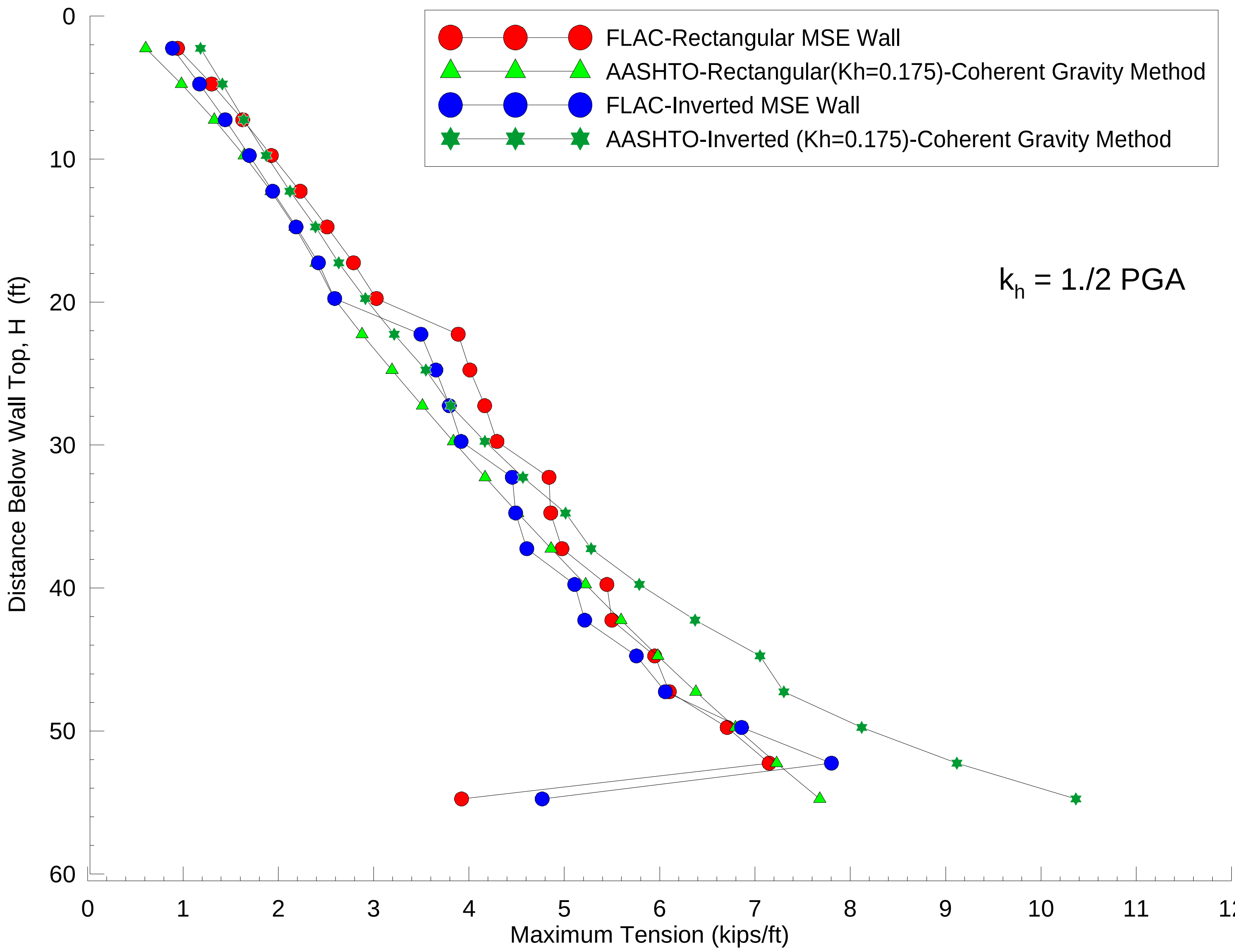


Figure 12. Seismic Analysis: Maximum computed and tensile force in reinforcement layers, Wall 8