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TRANSPORTATION RESEARCH BOARD

Predicting Deformations of Geosynthetic Reinforced Soil for Bridge Support

Monday, September 17, 2018
1:00-2:30 PM ET

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RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Purpose

Discuss design equations for predicting the maximum lateral deformation and settlement of geosynthetic reinforced soil (GRS) under various configurations and service loads.

Learning Objectives

At the end of this webinar, you will be able to:

- Apply design tools to deformation analysis of GRS bridge support systems
- Evaluate service limit state performance of bridge supports

Predicting Deformations of Geosynthetic Reinforced Soil for Bridge Support

Moderator: Jennifer Nicks, PhD, PE
Chair, AFS70 (Geosynthetics)

Co-Sponsors: AFS10 (Transportation Earthworks)
AFS70 (Geosynthetics)

September 17, 2018

Background

- In 2014, the Federal Highway Administration (FHWA) issued a contract for a research project titled "*Service Limit State Design and Analysis of Engineered Fills for Bridge Support*"
- Motivation for the study was the limited methods available to accurately estimate deformations of abutments and foundations built using engineered fills.
- In this evaluation, engineered fills were defined as compacted granular fill with and without layered reinforced soil systems.

Objectives

Develop practice-ready design tools to evaluate immediate and secondary settlement and lateral deformation of engineered fills used for bridge support.

Determine the stress distribution as a function of depth transferred by the engineered fill to native foundation soils.

Limitations of the Study & Future Research Needs

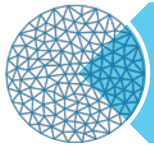
- Does not support metallically stabilized earth abutments
- Rigid facing elements were not evaluated
- Deformation equations were prepared assuming static load (no live load or thermal load)

Tasks

Literature review and data search

Synthesis and Evaluation of The Service Limit State of Engineered Fills for Bridge Support (FHWA-HRT-15-080

Development of the research plan



Parametric study

Design analysis and recommendations

$$\frac{1}{\sigma\sqrt{2\pi}}$$

Final Report and Recommendations
(not yet published)

Research Team

- Principal Investigator:
  - Dr. Ming Xiao *(Penn State University)*
- Co-Principal Investigator:
  - Dr. Tong Qiu *(Penn State University)*
- Research Assistant:
  - Dr. Mahsa Khosrojerdi *(formerly Penn State University)*
- Consultant:
  - Jim Withiam *(D'Appolonia Engineering Division of Group Technology, Inc.)*

Predicting Deformations of Geosynthetic Reinforced Soil for Bridge Support

TRB Webinar
September 2018

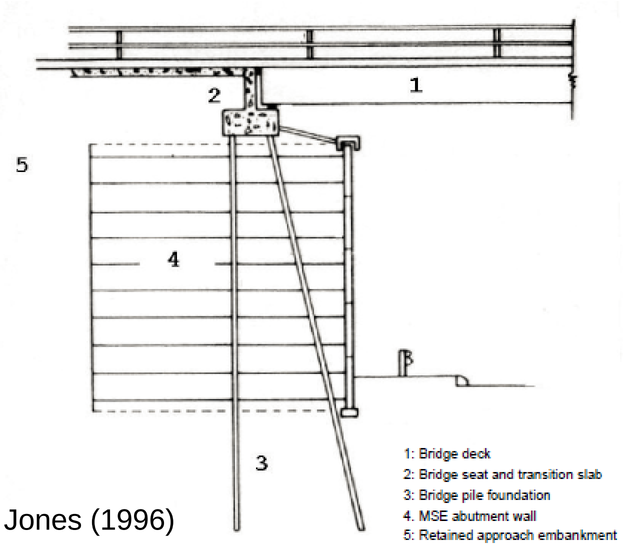
Presented by:
Ming Xiao, PhD, PE - *Pennsylvania State University*
Tong Qiu , PhD, PE - *Pennsylvania State University*
Mahsa Khosrojerdi, PhD - *Pennsylvania State University*

Moderated by:
Jennifer Nicks , PhD, PE- *U.S. Department of Transportation*

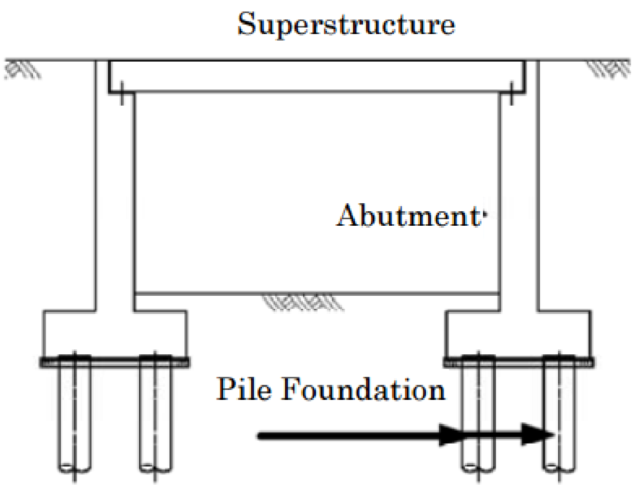
Outline

- Introduction
- Available Methods to Predict GRS abutment Deformations
- Numerical Model Development and Validation
- Prediction Tools for GRS Abutment Deformation
- Prediction Tools for RSF deformation
- Conclusions

Conventional Bridge Foundation Systems

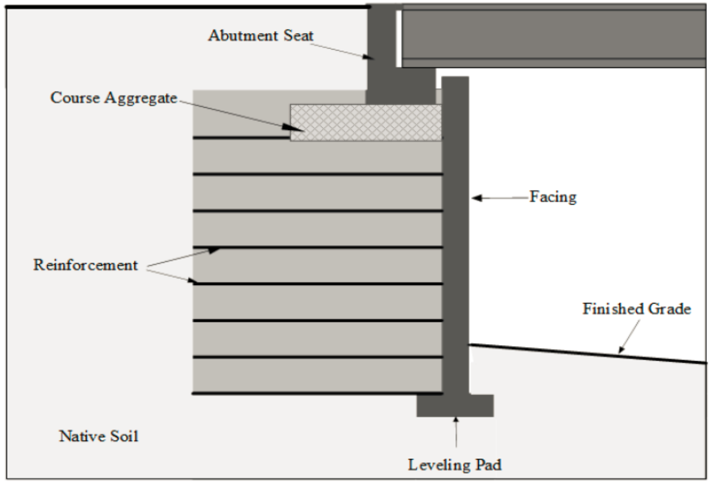


Jones (1996)

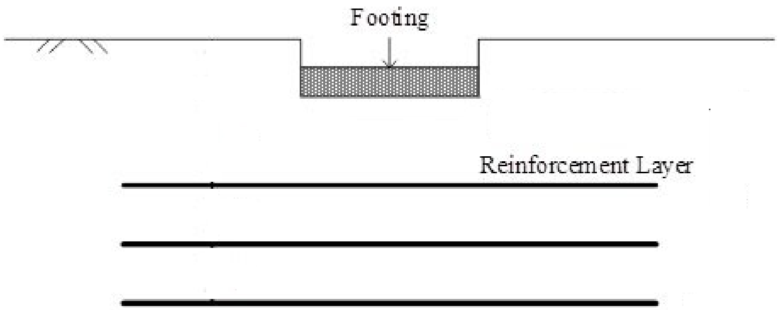


Nishida et al. (2012)

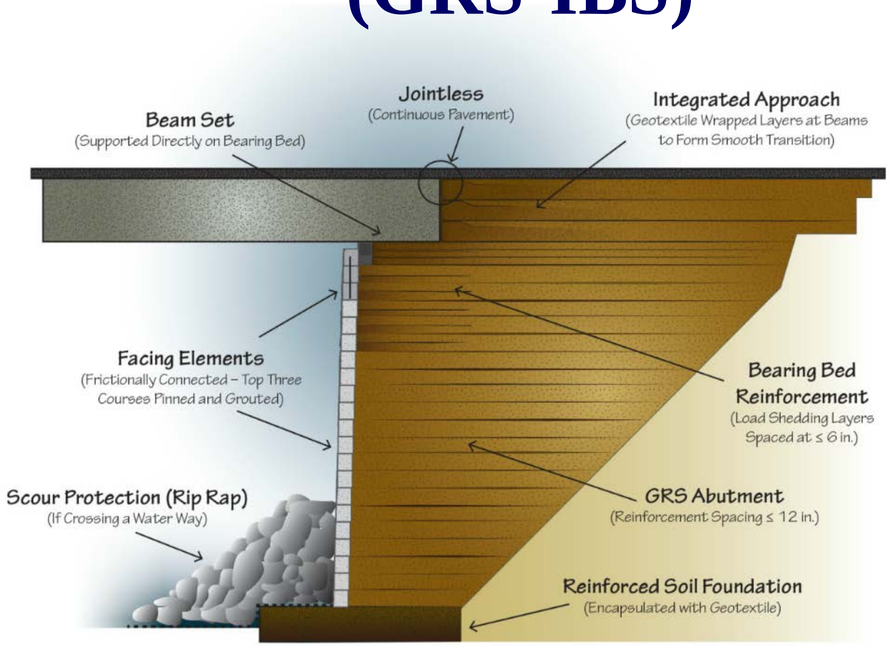
Engineered Fills Used for Bridge Support



Recreated after Anderson and Brabant (2010)



Geosynthetic Reinforced Soil Integrated Bridge System (GRS-IBS)



https://www.ipwea.org

Geotextile

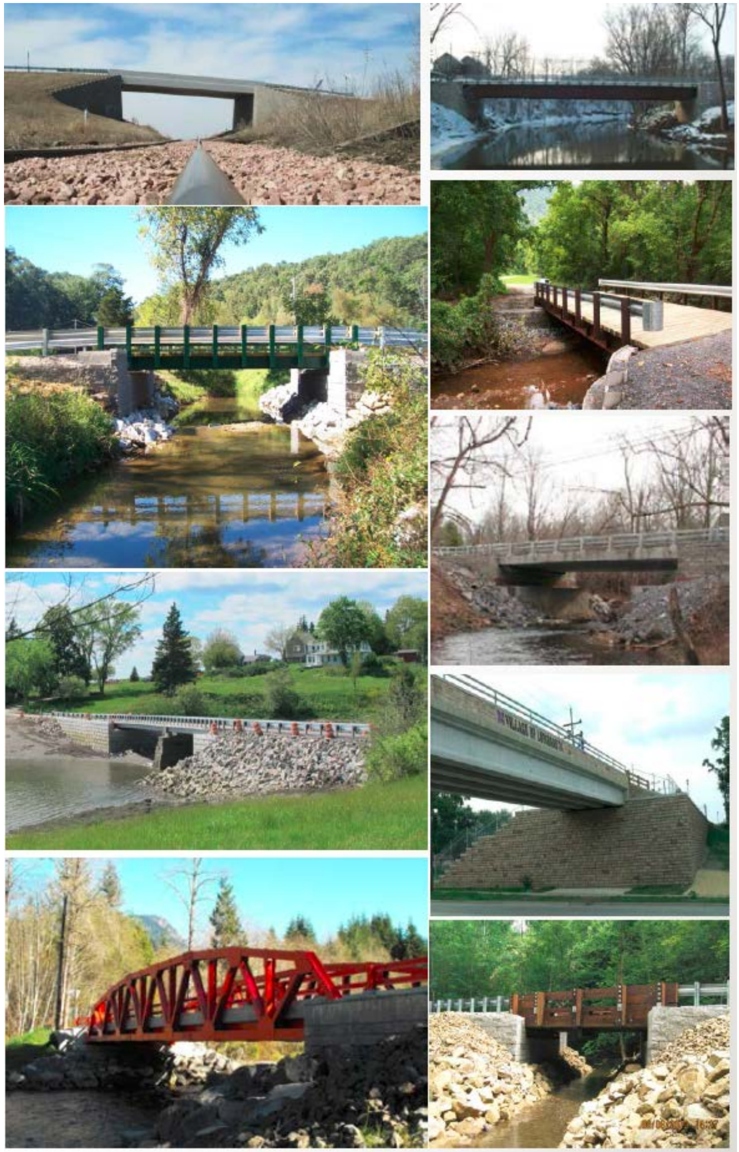
https://www.fhwa.dot.gov

Geogrid

https://www.fhwa.dot.gov

Advantages

- ✓ Simple and rapid construction
- ✓ Lower costs
- ✓ Readily available material and equipment
- ✓ Constructability in any weather condition
- ✓ Easier maintenance
- ✓ Environmental friendly



https://www.fhwa.dot.gov/

Limit States

A condition beyond which the structure no longer fulfills the relevant design criteria.

- **Ultimate Limit State (ULS)**

  Set of unacceptable conditions related to safety/danger, e.g., collapse.

- **Service Limit State (SLS)**

  Set of unacceptable conditions related to performance, e.g., excessive settlement or tilt.

Predicting Lateral Deformations of GRS Abutments

FHWA Method (Christopher et al. 1990)**:**

$$\delta_R = 11.81\left(\frac{L}{H}\right)^4 - 42.25\left(\frac{L}{H}\right)^3 + 57.16\left(\frac{L}{H}\right)^2 - 35.45\left(\frac{L}{H}\right) + 9.471$$

Geoservices Method (Giroud 1989)**:**

$$\delta_h = \frac{\varepsilon_d L}{2}$$

CTI Method (Wu 1994)**:**

$$\delta_h = \varepsilon_d\left(\frac{H}{1.25}\right)$$

Jewell-Milligan Method (Jewell and Milligan, 1989)**:**

$$\Delta_h = \left(\frac{1}{2}\right)\left(\frac{P_{\mathrm{rm}}}{K_{\mathrm{reinf}}}\right)(H - z_i)\left[\tan\left(45^\circ - \frac{\psi}{2}\right) + \tan(90^\circ - \phi_{ds})\right]$$

Wu Method (Wu et al. 2013)**:**

$$\Delta_i = 0.5\left(\frac{K_h(\gamma_s z_i + q)S_v - \gamma_b b S_v \tan\delta(1 + \tan\delta\tan\beta)}{K_{\mathrm{reinf}}}\right)(H - z_i)\left[\tan\left(45^\circ - \frac{\psi}{2}\right) + \tan(90^\circ - \phi_{ds})\right]$$

Adams Method (Adams et al. 2002)**:**

$$D_L = \frac{2b_{q,vol}D_v}{H}$$

Predicting Maximum Settlement of GRS Abutments

Adams Method (Adams et al. 2011)**:**

$$\rho = \frac{3qb'}{4\pi E_{GRS}}\left[\frac{1}{2}\left(1+\frac{a+\frac{b'}{2}}{\frac{b'}{2}}\right)\ln\left(\frac{H^2+\left(a+\frac{b'}{2}\right)^2}{\left(\frac{b'}{2}\right)^2}\right)+\frac{1}{2}\left(1-\frac{a+\frac{b'}{2}}{\frac{b'}{2}}\right)\ln\left(\frac{H^2+a^2}{\left(\frac{b'}{2}\right)^2}\right)+\frac{H}{a}\tan^{-1}\left(\frac{a+b'}{H}\right)+\frac{H}{a}\tan^{-1}\left(\frac{-b'}{H}\right)\right]$$

ρ = Vertical displacement of GRS abutment

E_{GRS} = Young's modulus of the GRS composite

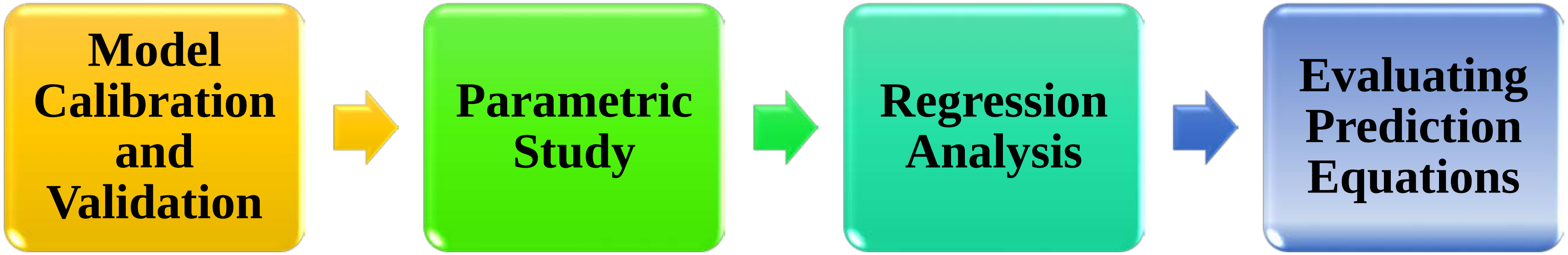
q = Applied pressure

a = Setback distance between the face of the wall and the applied load

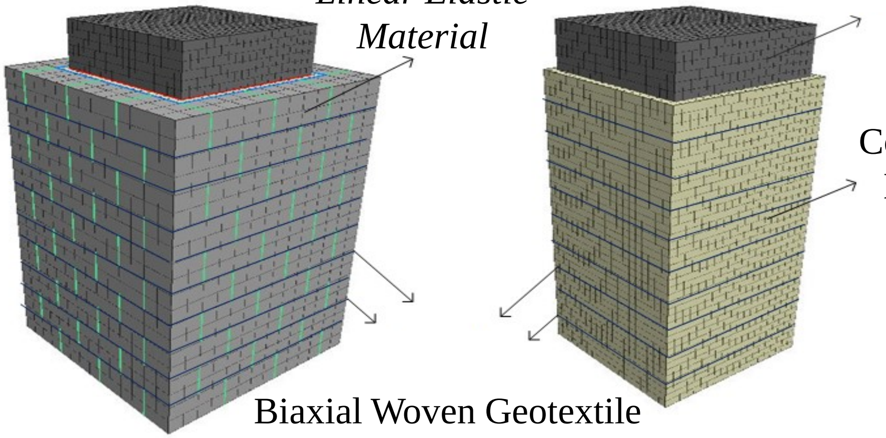
b' = Width of facing block

H = Height of abutment

General Approach for Developing Prediction Tool



Numerical Modeling Using FLAC^{3D} Software



Soil Constitutive Models

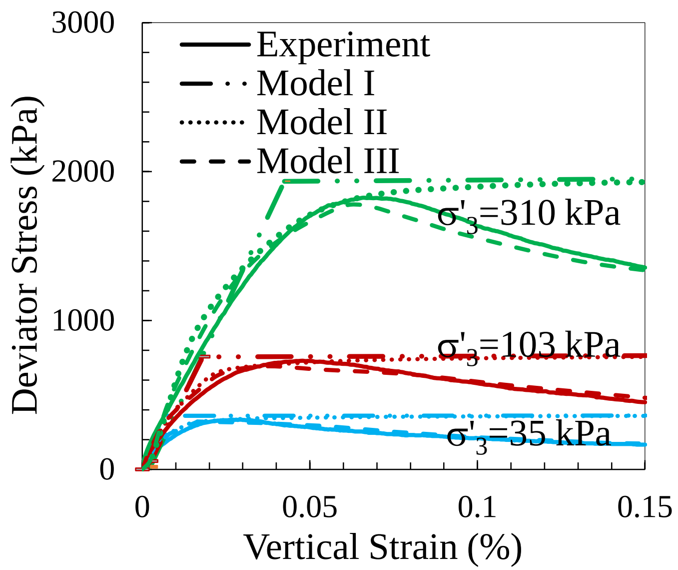
1. The elastic-perfectly plastic Mohr-Coulomb model

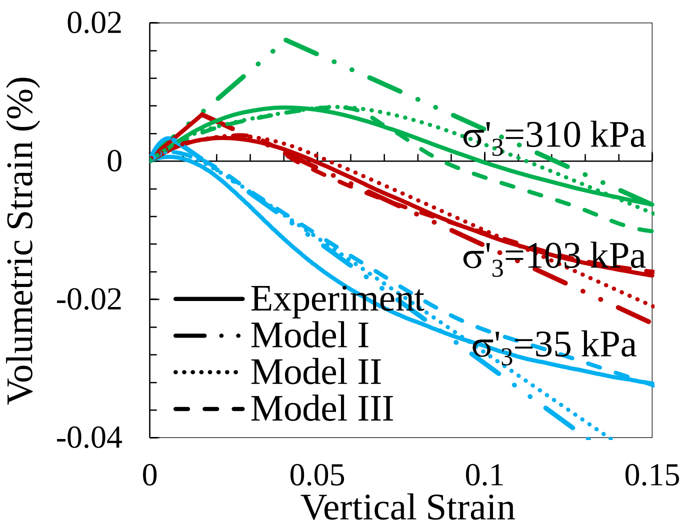
2. The Plastic Hardening model

3. The Plastic Hardening model combined with strain-softening behavior

Model Calibration

- Nicks el al. (2013) Experiment

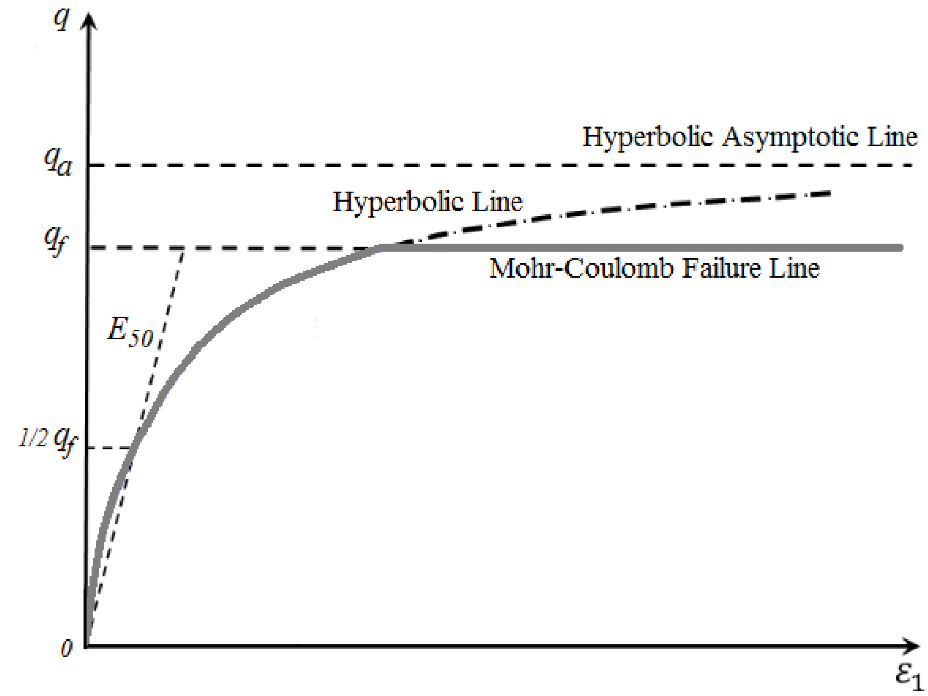




Model Parameters	**Model I**	**Model II**	**Model III**
Mohr-Coulomb Model			
E	50 MPa	N/A	N/A
ν	0.3	0.3	0.3
ϕ	48°	48°	48°
Ψ	7°	7°	7°
c	27.6 kPa	27.6 kPa	27.6 kPa
Plastic Hardening Model			
E_{50}^{ref}	N/A	50 MPa	50 MPa
P^{ref}	N/A	100	100
m	N/A	0.5	0.5
R_f	N/A	0.8	0.8
Strain Softening Model			
Residual friction angel	N/A	N/A	38°
Residual dilation angel	N/A	N/A	0°
Residual cohesion	N/A	N/A	1.3 kPa

Soil Constitutive Model: Plastic Hardening Model

$$E_{50} = E_{50}^{ref}\left(\frac{c\cot\phi - \sigma'_3}{c\cot\phi + p^{ref}}\right)^m$$



Shear yield function is defined as:

$$f_s = \frac{2}{E_i}\frac{q q_a}{q_a - q} - \frac{q}{2E_{50}} - \gamma^p = 0$$

m: Power coefficient for stress level dependency of stiffness

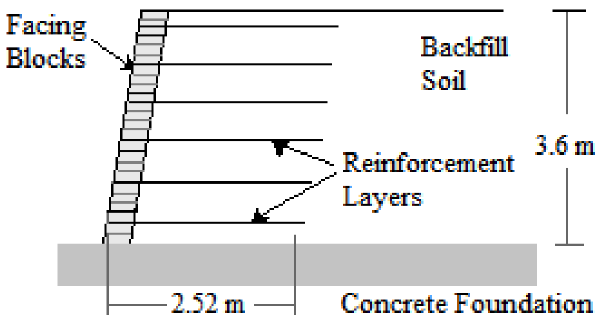
σ'_3: Minor principal stress

E_{50}^{ref}: Secant stiffness in standard drained triaxial test

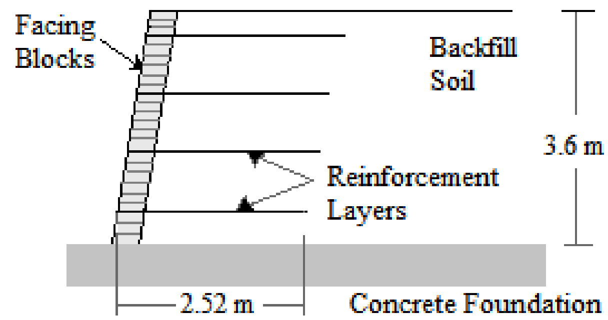
R_f: Failure ratio, q_f is the ultimate deviatory stress, and q_a is: $q_a = \dfrac{q_f}{R_f}$

Model Validation

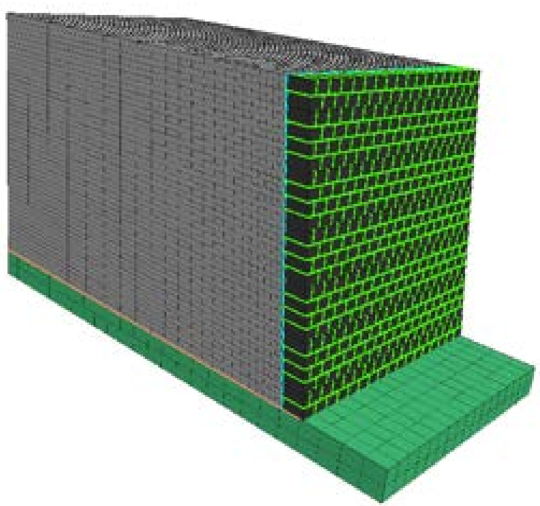
➢ **Full-Scale GRS Wall Test by Bathurst et al. (2000)**



Walls 1 and 2



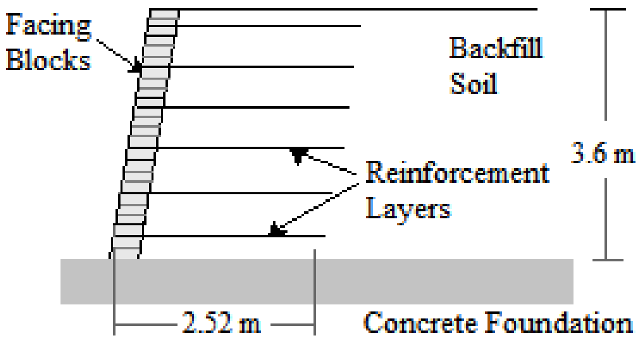
Wall 3



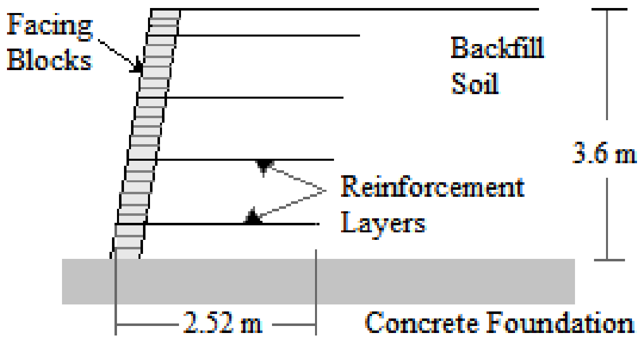
Model Parameters	
Plastic Hardening Model Parameters	
E_{50}^{ref} (MPa)	110
m (dimensionless)	0.5
R_f (dimensionless)	0.75
P^{ref} (kPa)	100
(dimensionless)	0.3
Block-Block Interface Properties	
Friction angle (°)	57
Normal stiffness (kN/m/m)	1000×10^3
Shear stiffness (kN/m/m)	50×10^3
Soil-Block Interface Properties	
Friction angle (°)	44
Normal stiffness (kN/m/m)	100×10^3

Model Validation

- **Full-Scale GRS Wall Test by Bathurst et al. (2000)**



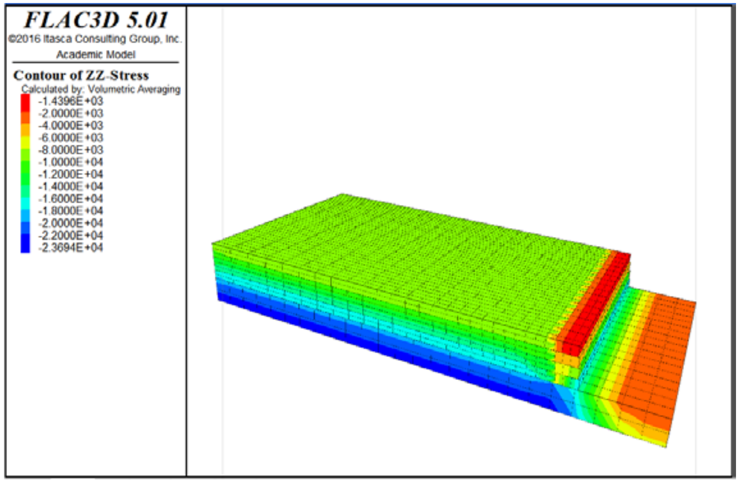
Walls 1 and 2

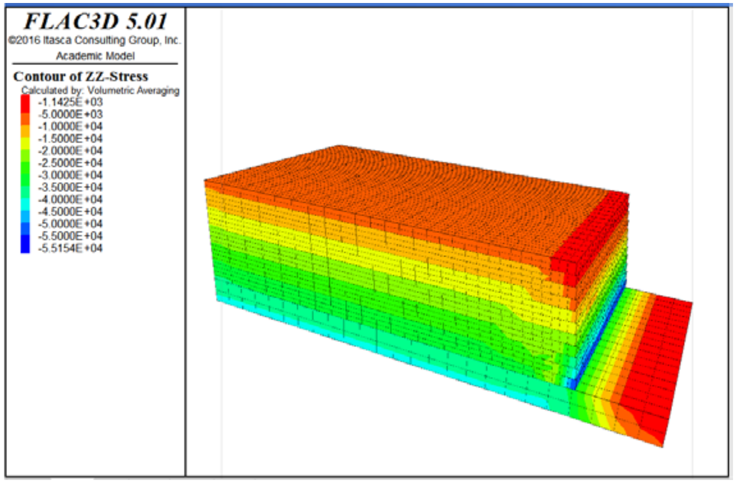


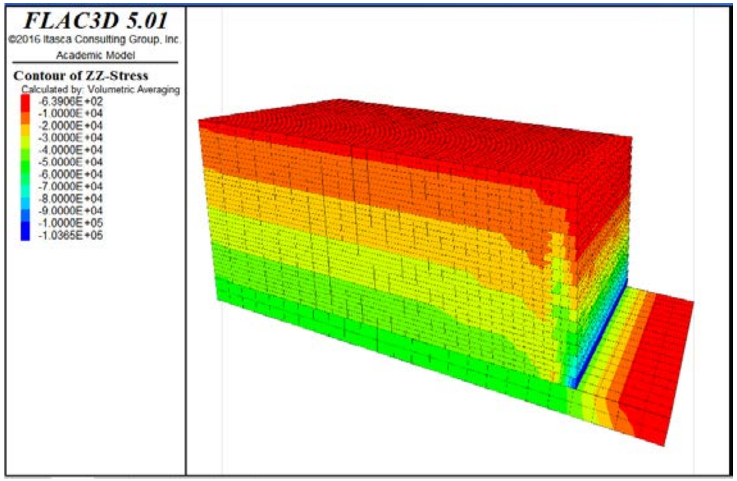
Wall 3

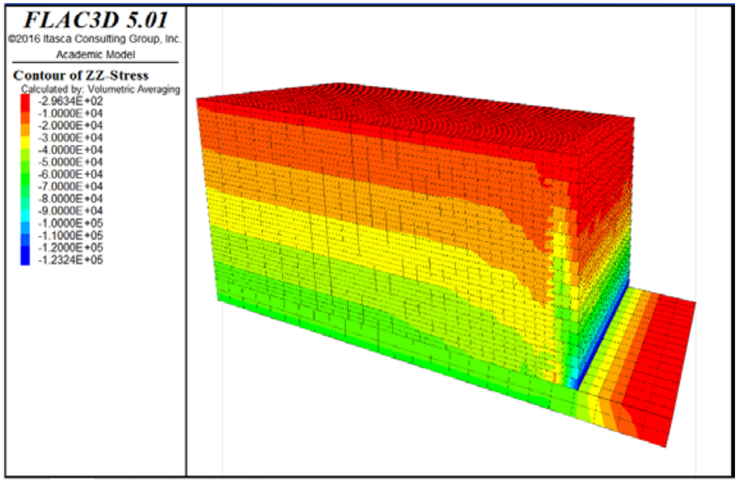
Geogrid Properties	Walls 1 and 3	Wall 2
Reinforcement type	PP	PP
Aperture dimensions (mm)	25×33	25×69
Ultimate strength (kN/m)	14	7
Initial stiffness (kN/m)	115	56.5

Multi-stage Construction Process in Numerical Model

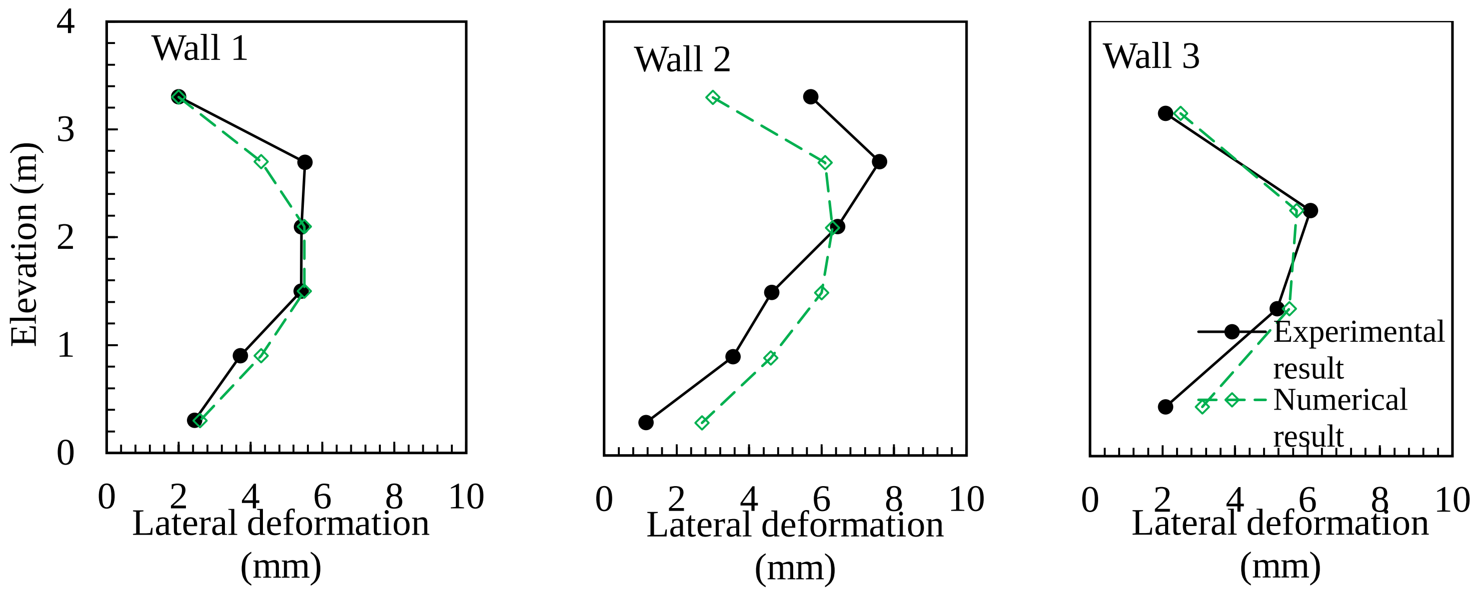




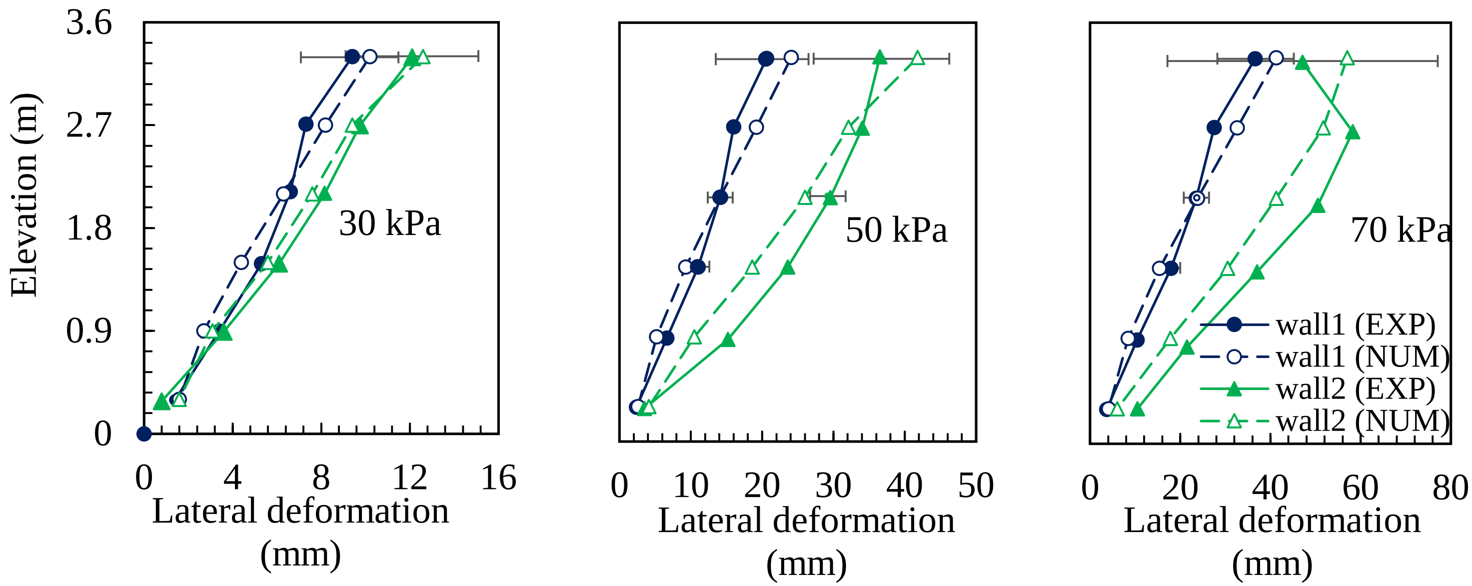




Lateral deformation of GRS walls at the end of construction without surcharge

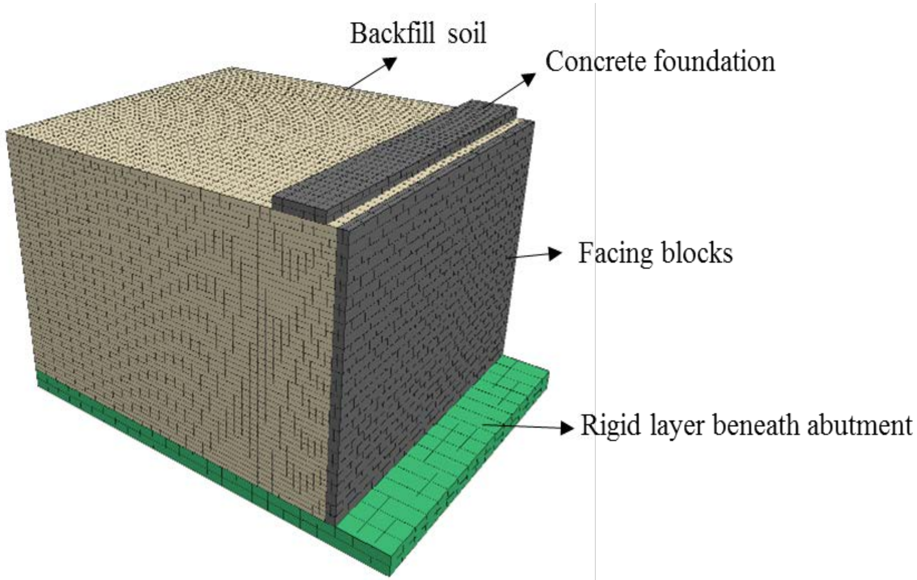


Lateral deformation of GRS walls under surcharge loads



Parametric Study

Parameters (unit)		Values
Backfill properties	Friction angle, ϕ (°)	40, 45, 46, 48, 50, 55
Reinforcement properties	Reinforcement spacing, S_v (m)	0.2, 0.4, 0.6, 0.8
	Reinforcement length, L_R	0.4 , 0.5 , 0.7 , (*H* is height of abutment)
	Reinforcement stiffness, *J* (kN/m)	500, 1000, 1500, 2000, 2500
Abutment geometry	Abutment height, *H* (m)	3, 4, 5, 6, 9
	Facing batter, β (°)	0, 2, 4, 8
	Concrete footing width, *B* (m)	0.5, 0.7, 1, 1.5, 2, 3
Surcharge load (kPa)		50, 100, 200, 400



Parameters	Benchmark Values
Friction angle	48°
Reinforcement length	2.5 m
Reinforcement stiffness	2000 kN/m
Reinforcement spacing	0.2 m
Abutment height	5 m
Facing batter	2°

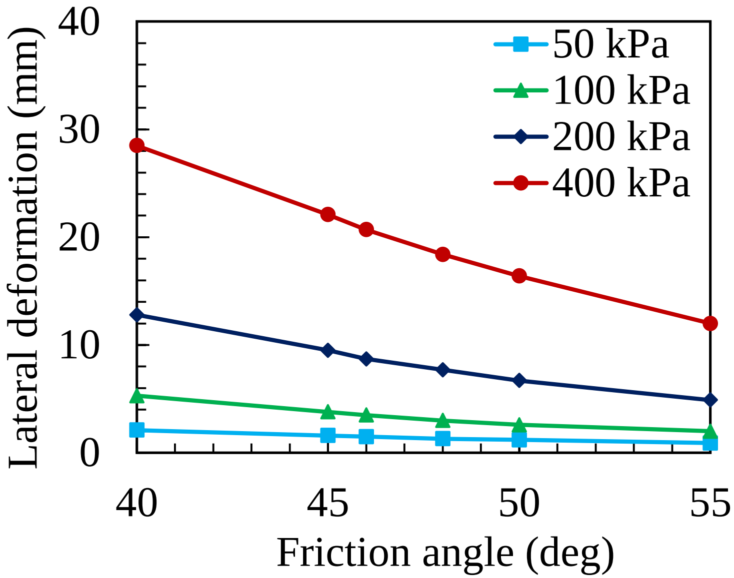
Parametric Study

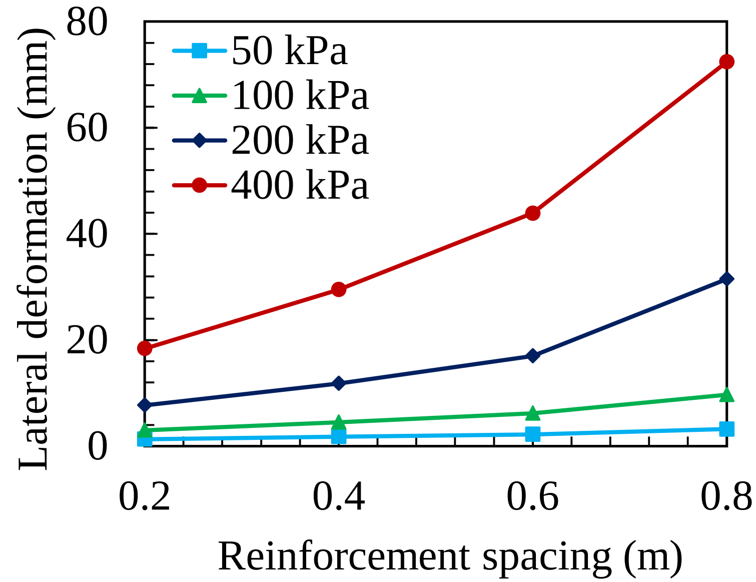
Parametric study was conducted in two phases:

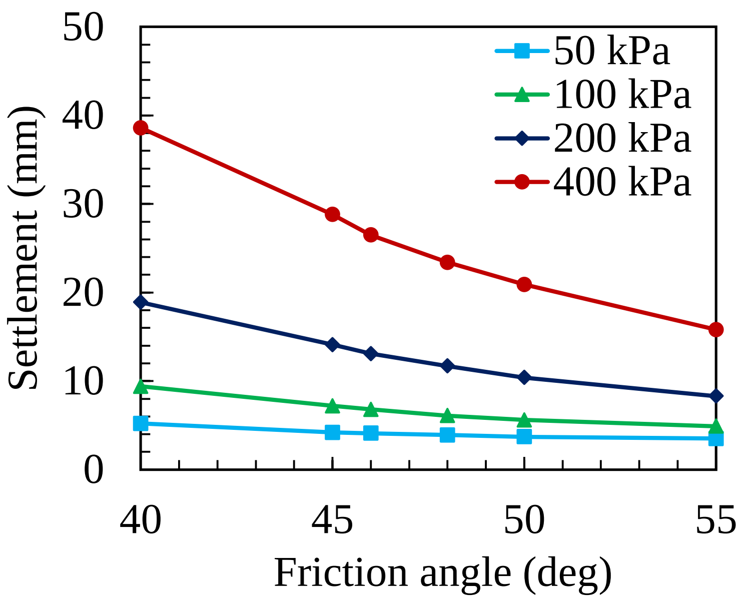
Phase 1: One of the parameters was changed.
Objective: To obtain an initial understanding of the deformation variation with one parameter when other parameters are fixed.
A total of 172 simulations were conducted in Phase 1.

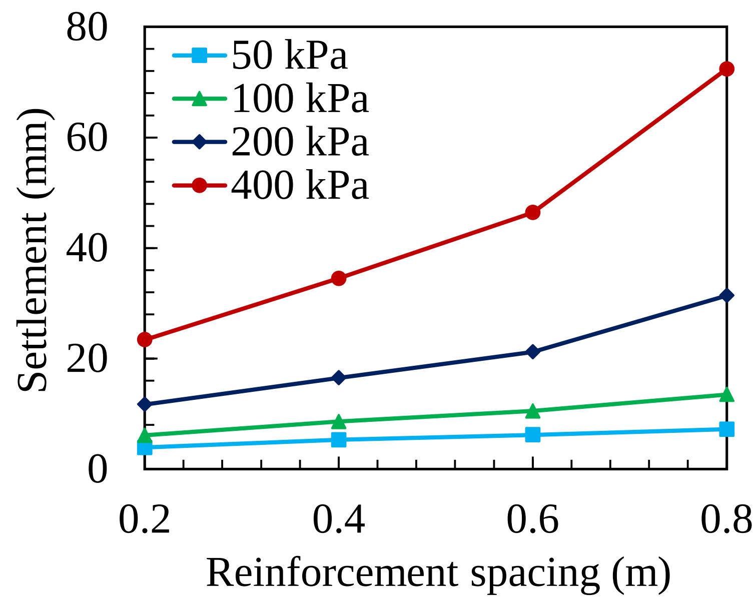
Phase 2: Parameters were varied simultaneously.
Objective: To quantify the dependency between the parameters and their mutual effects on deformation.
A total of 184 simulations were conducted in Phase 2.

Phase 1 of Parametric Study









Regression Analysis

$$\Delta_{GRS} = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 + a_5 x_5 + a_6 x_6 + a_7 x_7 + a_8 x_8$$

In this equation, Δ_{GRS} is the maximum lateral deformation or settlement of GRS abutment, a_i are constant coefficients, x_i represent functions of input parameters which could have any format (i = 0 to 8).

The best prediction model:

✓ Least root mean square error, RMSE value;

✓ Highest coefficient of determination, R^2 value;

✓ Correct polarity for each a_i coefficient.

First Try for Regression Model

$$\Delta_{GRS} = a_0 + a_1 q^* + a_2 \phi^* + a_3 S_v^* + a_4 J^* + a_5 \beta^* + a_6 H^* + a_7 L_R^* + a_8 B^*$$

- q^*, ϕ^*, S_v^*, J^*, β^*, H^*, L_R^* and B^* are defining as q/q_0, ϕ/ϕ_0, S_v/S_{v0}, J/J_0, β/β_0, H/H_0, L_R/L_{R0} and B/B_0, respectively.

- In this study $q_0 = 200$ kPa, $S_{v0} = 0.2$ m, $J_0 = 500$ kN/m, $\phi_0 = 45°$, $\beta_0 = 90°$, $H_0 = 5$ m, $L_{R0} = 2.5$ m and $B_0 = 1$ m.

- q should be in the unit of kPa, ϕ and β should be in degree, J in kN/m, and S_v , H, L_R, and B should be in the unit of m, then Δ_{GRS} result would be in m.

First Try for Regression Model

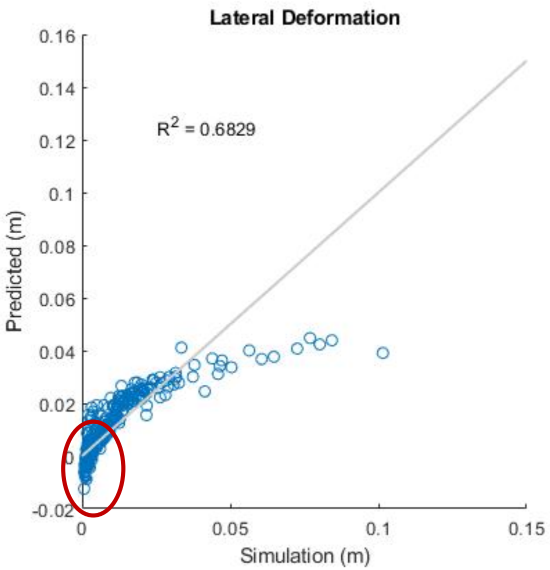
$$\Delta_{GRS} = a_0 + a_1 q^* + a_2 \phi^* + a_3 S_v^* + a_4 J^* + a_5\,\beta^* + a_6 H^* + a_7 L_R^* + a_8 B^*$$

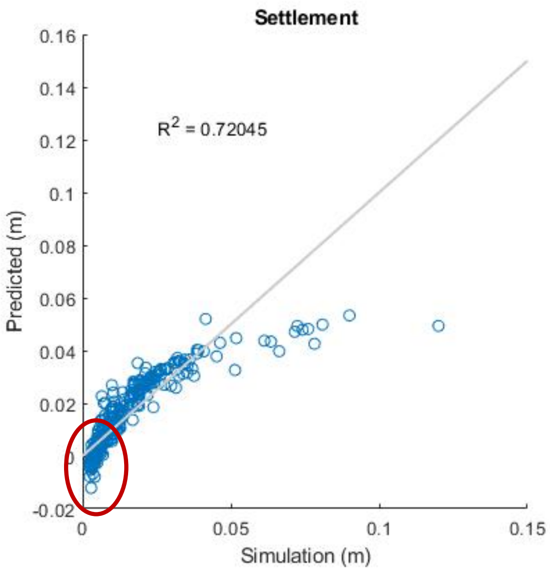
Model should have the least RMSE value and the closest R^2 value to one!

Prediction Eq.	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	R^2	RMSE
Lateral deformation	0.019	7e-5	-7e-4	-5e-6	0.03	-9e-4	0.001	-8e-4	0.008	0.68	0.008
Settlement	0.038	8e-5	-1e-3	-5e-6	0.03	-9e-4	0.002	-7e-4	0.009	0.72	0.009

The signs of a_3 and a_4 are not logical!

Model Predicts negative deformation values!

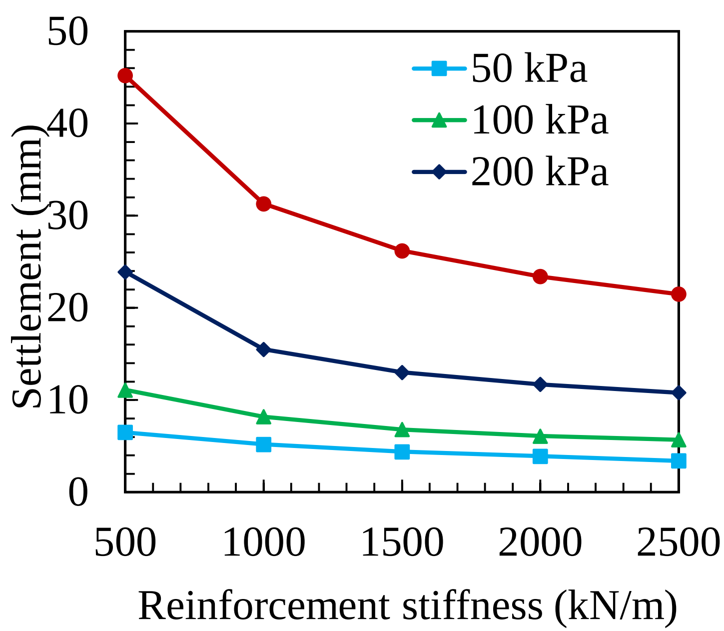


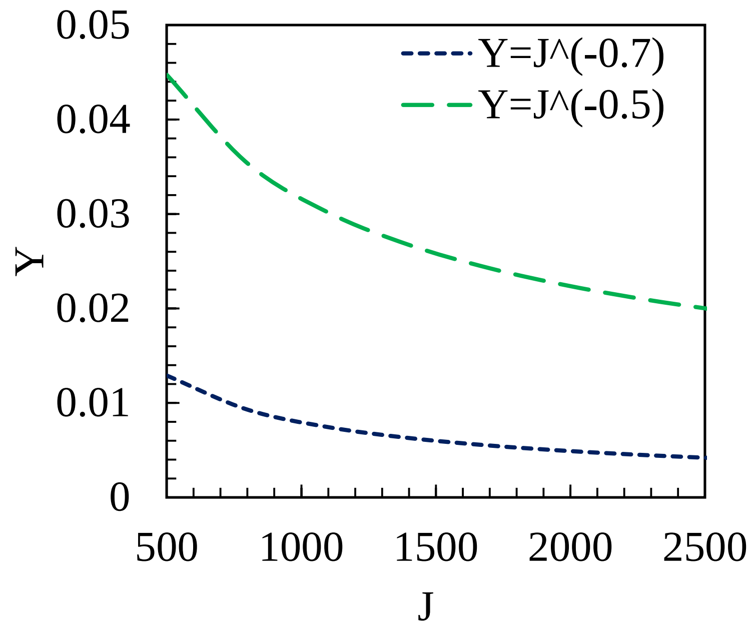


Developing Prediction Equation

The effects of individual variables on the deformation of GRS abutment, investigated through Phase 1, were studied to find functions for input parameters (x_i).

- **Reinforcement Stiffness:**





→ Instead of using $x_4=J^*$ in the first equation, it can be replaced by

$$x_4=J^{*a}$$

Tries for Nonlinear Regression Prediction Model

$$\Delta_{GRS}= a_0 + a_1 q^* + a_2 \tan(90+\phi) + a_3 S_v^* + a_4 J^* + a_6(1-\beta^*) + a_7 H^* + a_8 L_R^* + a_9 B^{*a10}$$ ✗

$$\Delta_{GRS}= a_0 + a_1 \frac{S_v^*}{J^{*a2}}\left(a_3 q^* + a_4 \tan(90+\phi) + a_5(1-\beta^*) + a_6 H^* + a_7 L_R^* + a_8 B^{*a9}\right)$$ ✗

$$\Delta_{GRS}= a_0 + a_1 q \frac{S_v^*}{J^{*a2}} \times B^{*a3}\left(a_4 \tan(90+\phi) + a_5(1-\beta^*) + a_6 H^* + a_7 L_R^*\right)$$ ✗

$$\Delta_{GRS}= a_0 + a_1 q^{*a2} \times tan^2(90+\phi) \times \frac{S_v^*}{J^{*a3}} \times B^{*a4}\left(a_5(1-\beta^*) + a_6 H^* + a_7 L_R^*\right)$$ ✗

$$\Delta_{GRS}= a_0 + a_1 q^{*a2} \times tan^2(90+\phi) \times \frac{S_v^*}{J^{*a3}} \times B^{*a4}\left(a_5(1-\beta^*) + a_6 H^* + a_7 \left(\frac{L_R^*}{H^*}\right)^2\right)$$ ✗

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$$L_{GRS} = 0.056 \times q^{*1.32} \times tan^2(90+\phi) \times \frac{S_v^*}{J^{*0.17}} \times B^{*1.11}\left(-1.53 + 1.69(1-\beta^*) + 0.105 H^* - 0.0125 L_R^{*2}\right)$$

$$S_{GRS} = 0.005 + 0.006 \times q^{*1.42} \times tan^2(90+\phi) \times \frac{S_v^*}{J^{*0.49}} \times B^{*1.26}\left(-23.3 + 26.7(1-\beta^*) + 0.025 H^* - 0.2 L_R^*\right)$$

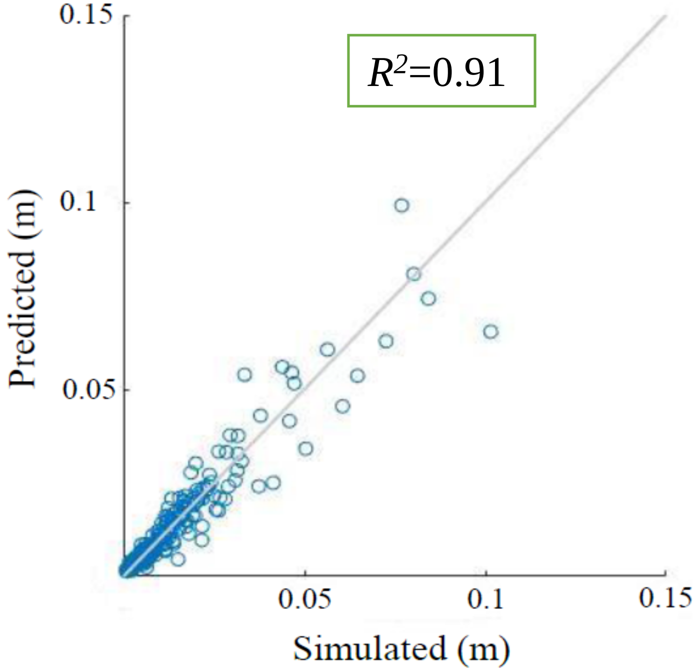
✓

Prediction Models

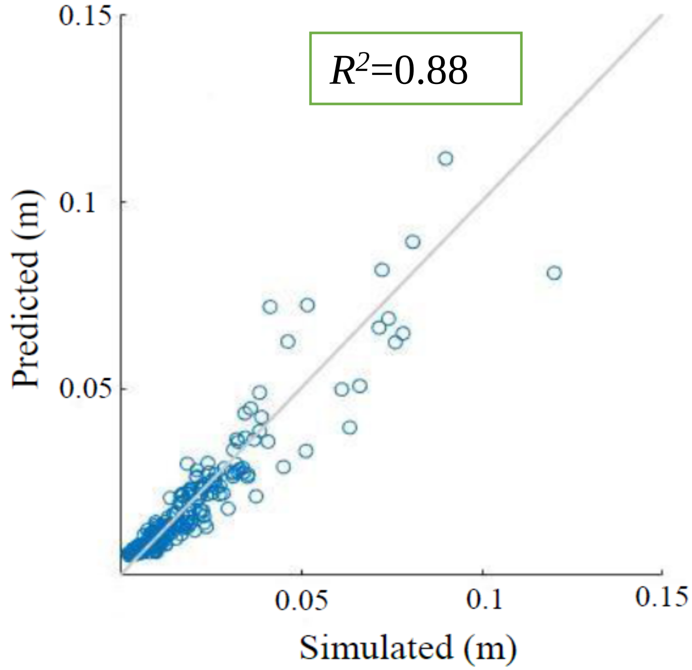
$$L_{GRS} = 0.056 \times q^{*1.32} \times tan^2(90+\phi) \times \frac{S_v^*}{J^{*0.17}} \times B^{*1.11}\left(-1.53 + 1.69(1-\beta^*) + 0.105H^* - 0.0125{L_R^*}^2\right)$$

$$S_{GRS} = 0.005 + 0.006 \times q^{*1.42} \times tan^2(90+\phi) \times \frac{S_v^*}{J^{*0.49}} \times B^{*1.26}\left(-23.3 + 26.7(1-\beta^*) + 0.025H^* - 0.2L_R^*\right)$$

Lateral Deformation



Settlement



Evaluation of Prediction Equation of Settlement of GRS Abutment

Set No.	Reference	ϕ (°)	J (kN/m)	Sv (m)	B (m)	β (°)	H (m)	L_R (m)
1	Helwany et al. (2007)	34.8	800	0.2	0.9	0	4.65	3.15
2	Helwany et al. (2007)	34.8	380	0.2	0.9	0	4.65	3.15
3	Hatami and Bathurst (2005)	40	115	0.6	6.0	8	3.6	2.5
4	Hatami and Bathurst (2005)	40	56.5	0.6	6.0	8	3.6	2.5
5	Gotteland et al. (1997)	30	340	0.6	1.0	8	4.35	2.4

Set No.	Load (kPa)	Actual value (mm)	**This study**		**FHWA Method**	
			Δ (mm)	Error (%)	Δ (mm)	Error (%)
1	100	15	16	6.7	6.7	-55.3
	200	33	32	-3.0	13.5	-59.1
	300	55	54	-1.8	20.2	-63.3
	400	75	79	5.3	27.0	-64.0
	500	97	105	8.2	33.7	-65.3
2	100	23	20	-13.0	6.7	-70.9
	200	57	44	-22.8	13.5	-76.3
	300	100	74	-26.0	20.2	-79.8
	400	155	110	-29.0	27.0	-82.6
5	123	33	32	-3.0	8.4	-74.5

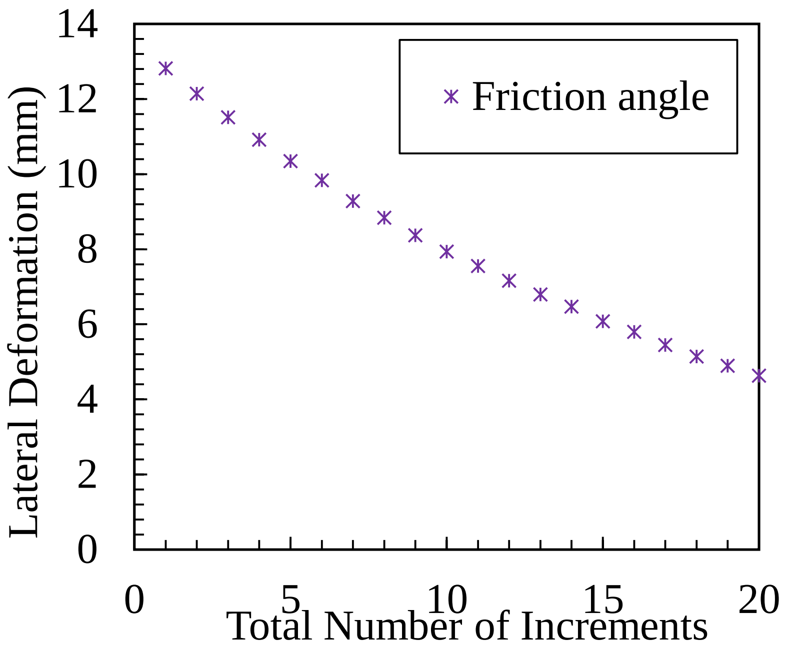
Evaluation of Prediction Equation of Lateral Deformation

Set No	Load (kPa)	Actual value (mm)	This study		FHWA method		Geoservice method		CTI method		Jewell-Milligan method		Wu method		Adams method	
			Δ (mm)	Error (%)	Δ (mm)	Error (%)	Δ (mm)	Error (%)	Δ (mm)	Error (%)	Δ (mm)	Error (%)	Δ (mm)	Error (%)	Δ (mm)	Error (%)
1	307	24	40	40.0	307	1179.2	-	-	-	-	-	-	-	-	16	-33.3
	475	57	71	19.7	465	715.8	-	-	-	-	-	-	-	-	42	-26.3
2	214	36	28	-28.6	244	577.8	-	-	-	-	-	-	-	-	27	-25.0
	317	61	48	-27.1	331	442.6	-	-	-	-	-	-	-	-	45	-26.2
	414	115	68	-69.1	413	259.1	-	-	-	-	-	-	-	-	69	-40.0
3	30	9	13	30.8	68	655.6	-	-	-	-	31	242.2	7.3	-18.9	-	-
	50	21	26	19.2	81	285.7	-	-	-	-	38	79.0	17	-19.0	-	-
	70	37	40	7.5	93	151.4	-	-	-	-	44	20.0	31	-16.2	-	-
4	30	12	15	20.0	68	466.7	-	-	-	-	62	413.3	15	25.0	-	-
	50	37	30	-23.3	81	118.9	-	-	-	-	75	103.2	34	-8.1	-	-
	70	58	47	-23.4	93	60.3	-	-	-	-	89	53.1	61	5.2	-	-
5	190	83	46	-80.4	264	218.1	111	33.7	180	116.9	-	-	-	-	-	-

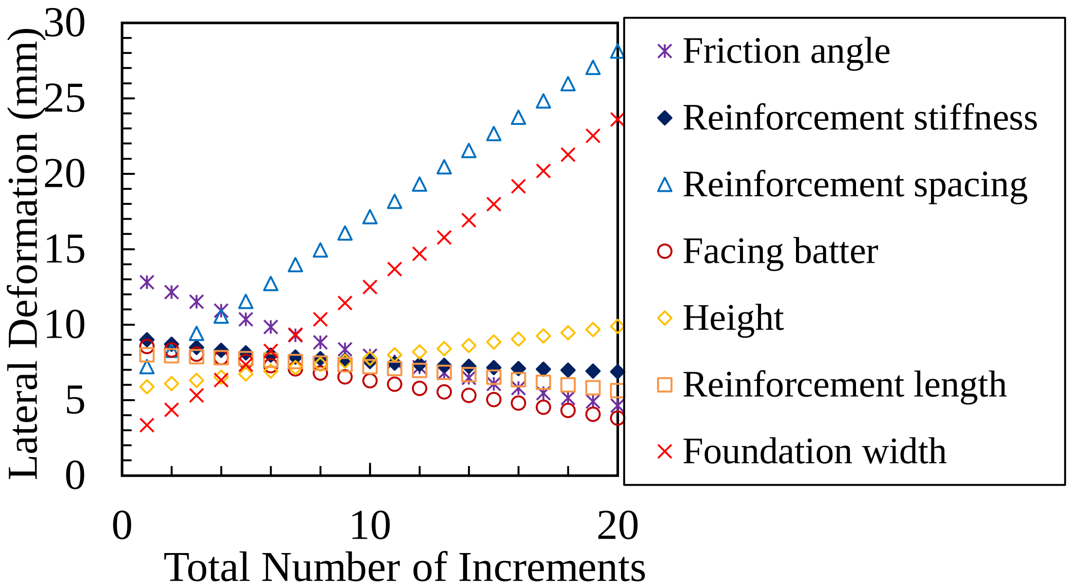
Incremental Sensitivity Analysis

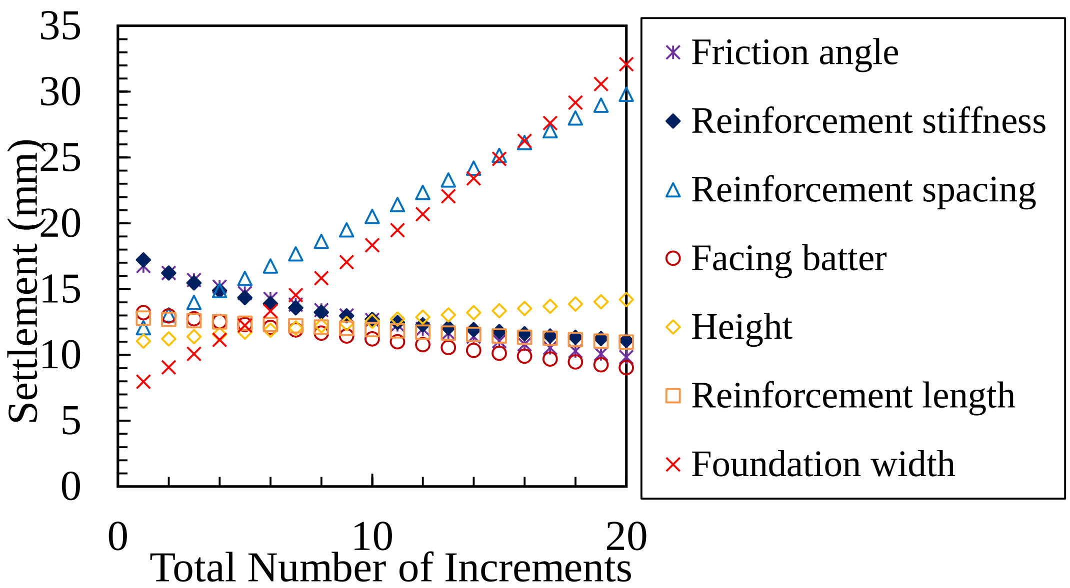
$$SR = \frac{\frac{y_{i+1}(x) - y_i(x)}{y_i(x)}}{\frac{x_{i+1}(x) - x_i(x)}{x_i(x)}}$$

where $y_{i+1}(x)$ = equation output in step i+1 due to variable x; $y_i(x)$ = equation output in step i due to variable x; $x_{i+1}(x)$ = value of variable x in step i+1; and $x_i(x)$= value of variable x in step i.



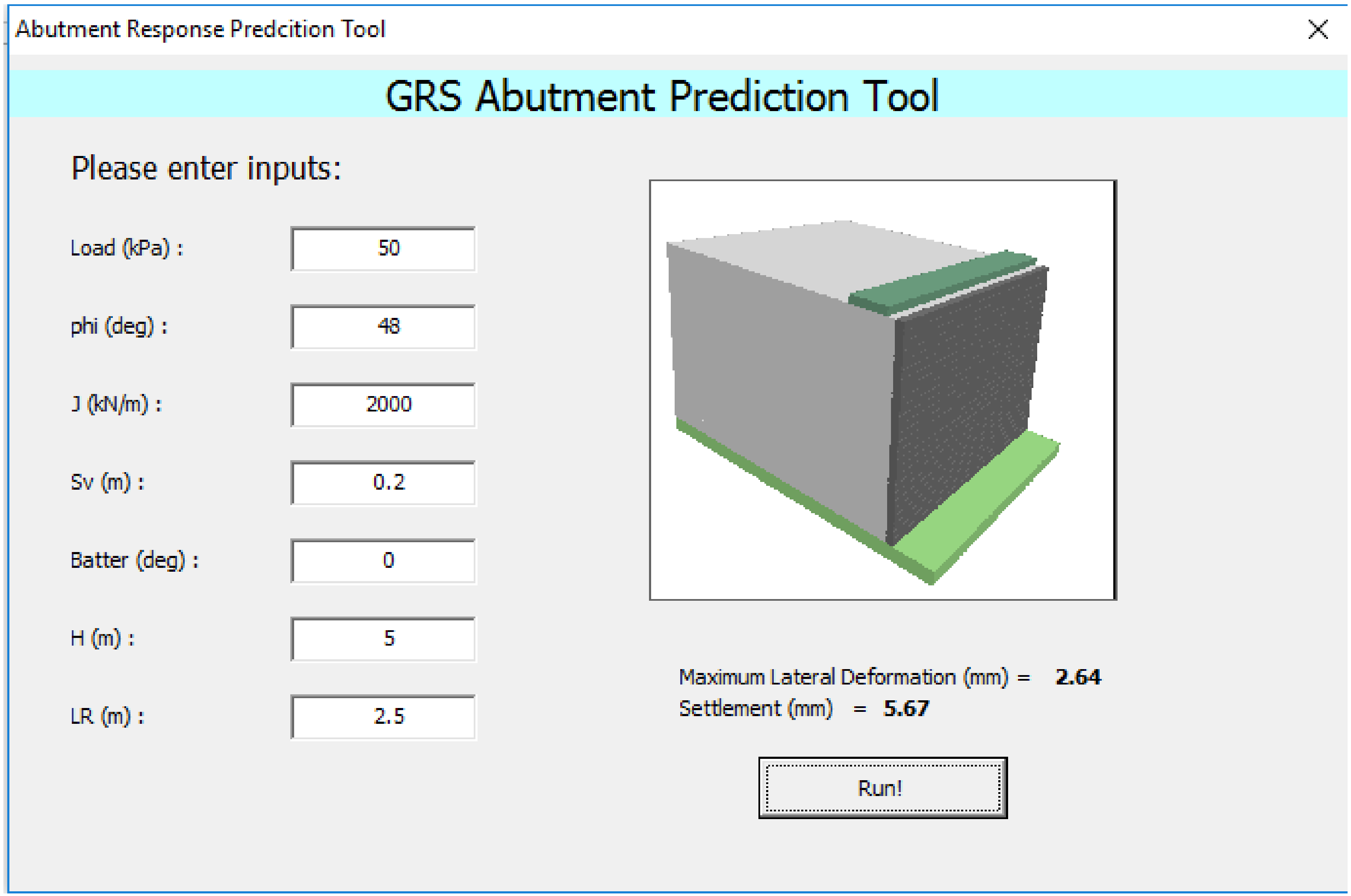
Incremental Sensitivity Analysis





Parameters	SR	
	Lateral Deformation	Settlement
Friction angle	-3.26	-1.71
Reinforcement spacing	1.00	0.69
Footing width	0.90	1.20
Abutment height	0.50	0.25
Facing batter	-0.45	-0.20
Reinforcement length	-0.33	-0.13
Reinforcement stiffness	-0.16	-0.25

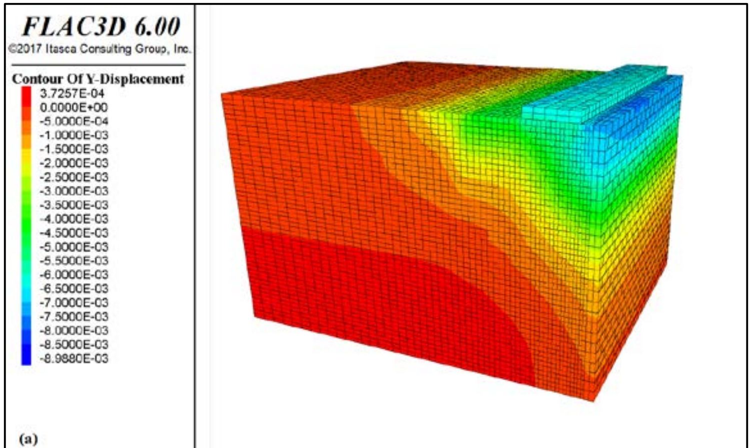
Tool Development



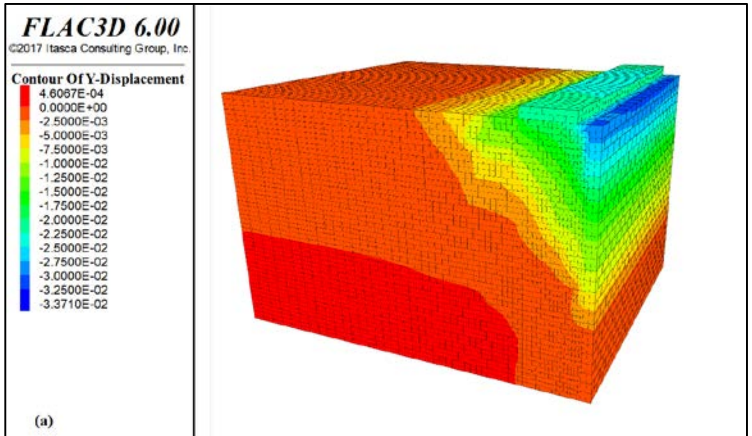
Deformations and Vertical Stress Distribution under 200 kPa Applied Pressure

Reinforcement spacing = 0.2 m

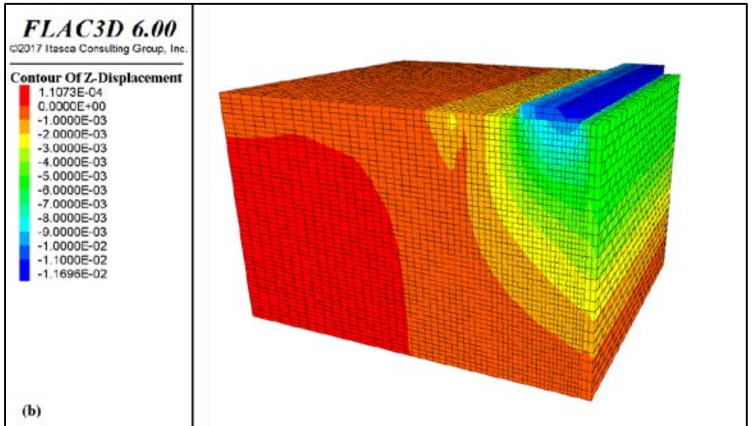
Reinforcement spacing = 0.8 m



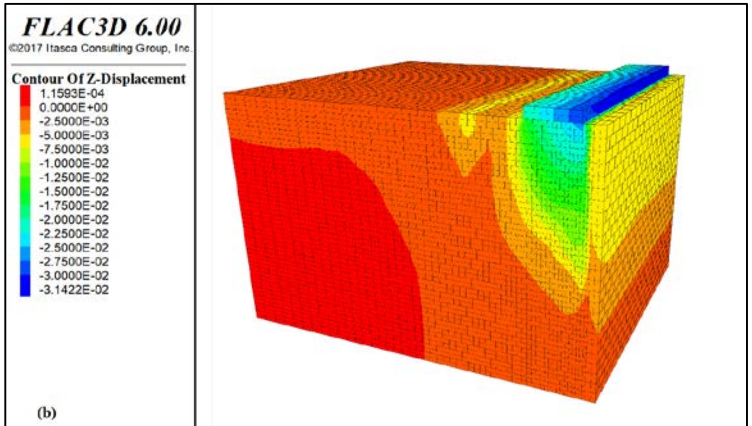
Max. Lateral Deformation= 9 mm



Max. Lateral Deformation= 34 mm



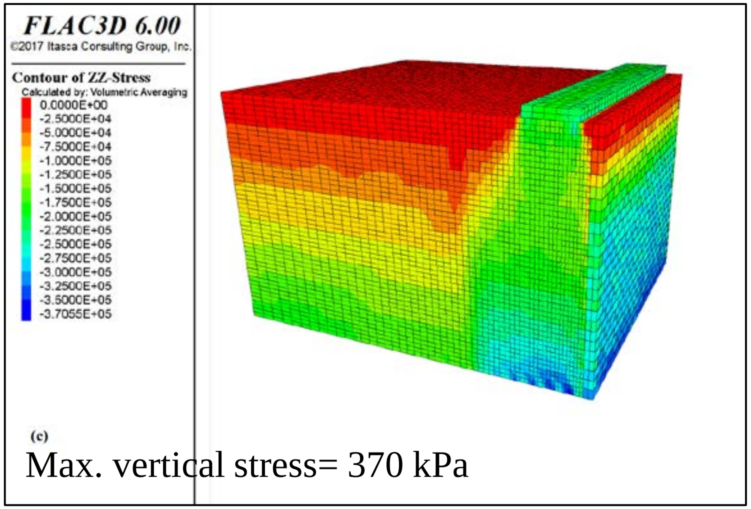
Max. Settlement=12 mm

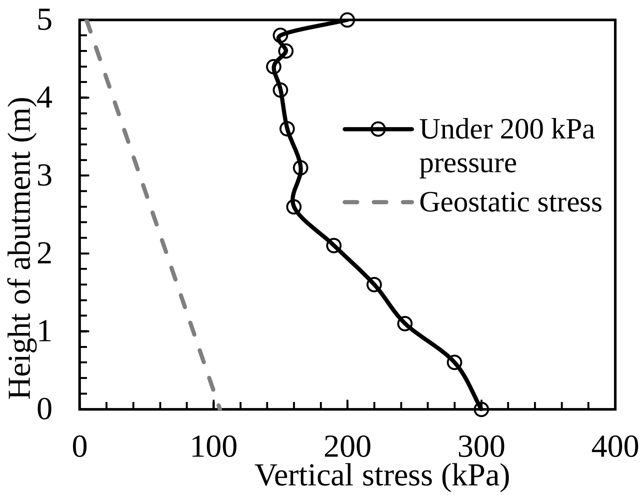


Max. Settlement=31mm

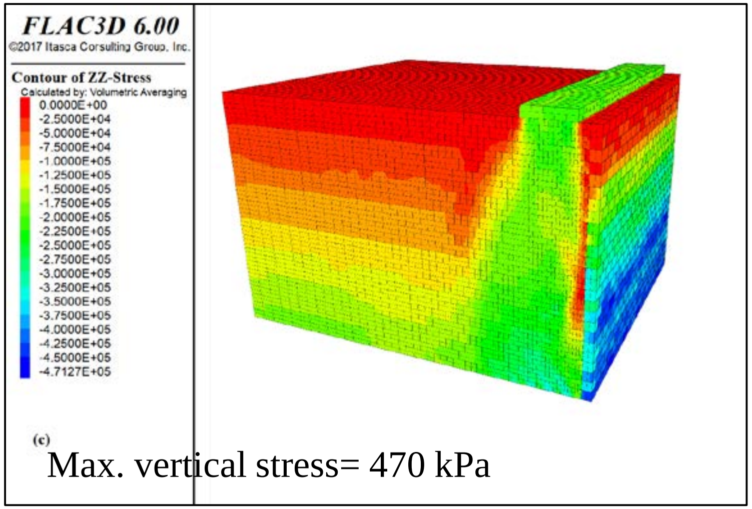
Deformations and Vertical Stress Distribution under 200 kPa applied pressure

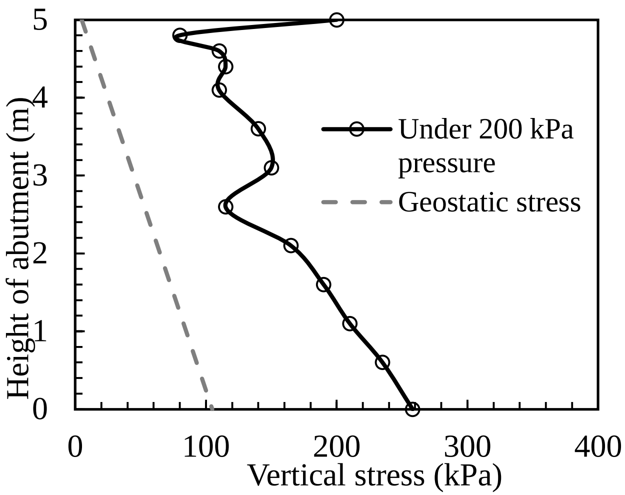
Reinforcement spacing = 0.2 m



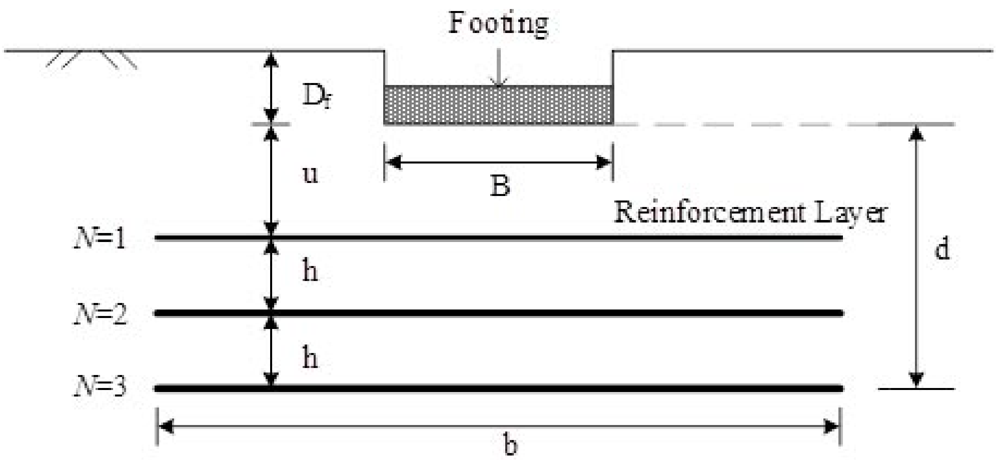


Reinforcement spacing = 0.8 m





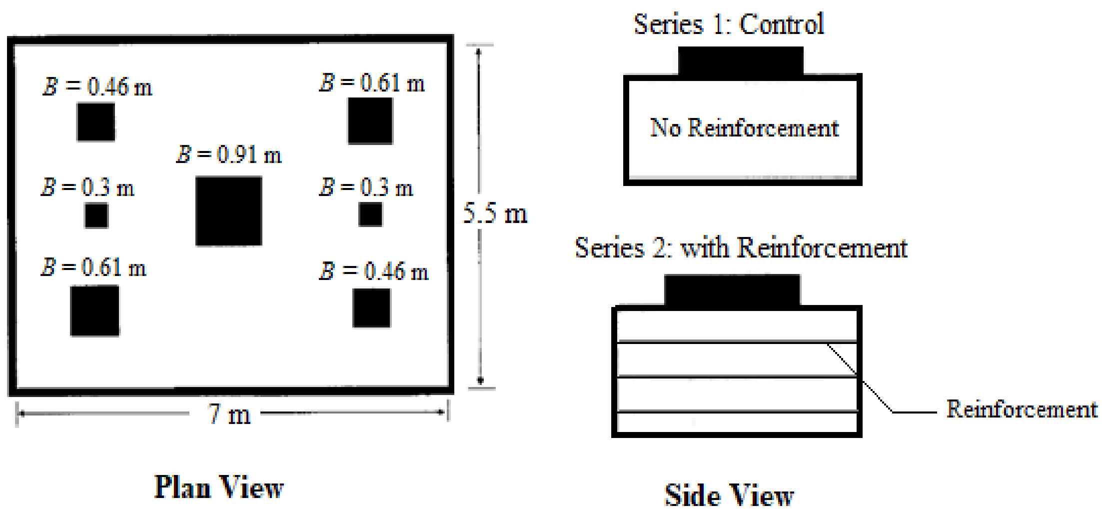
Reinforced Soil Foundation (RSF)



Methods to predict the settlement of footings placed on unreinforced granular soil:

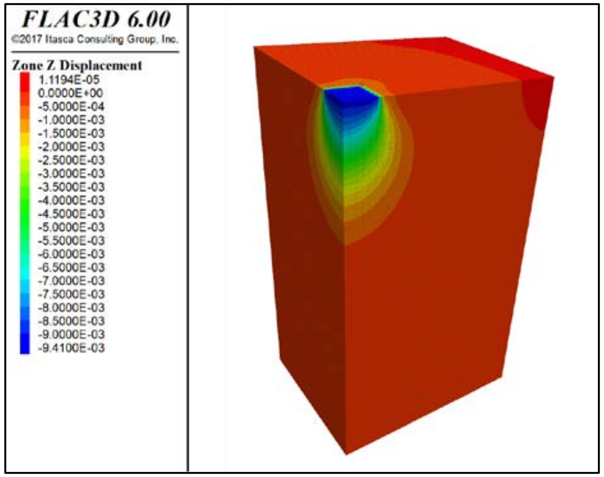
- Modified Schmertmann
- Hough
- Peck and Bazaraa
- Burland and Burbidge
- D’Appolonia

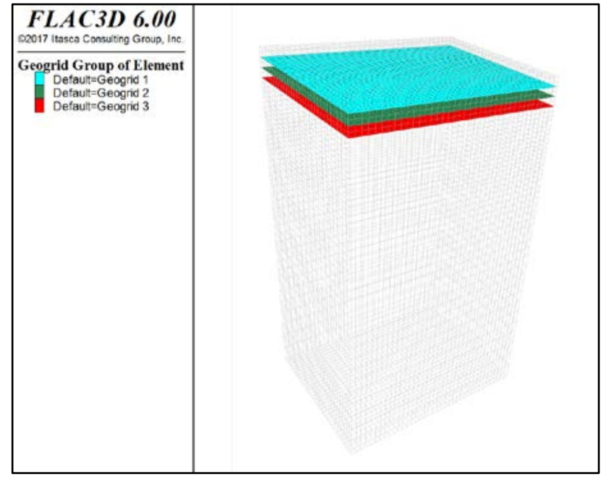
Model Validation - Adams and Collin (1997) Experiments

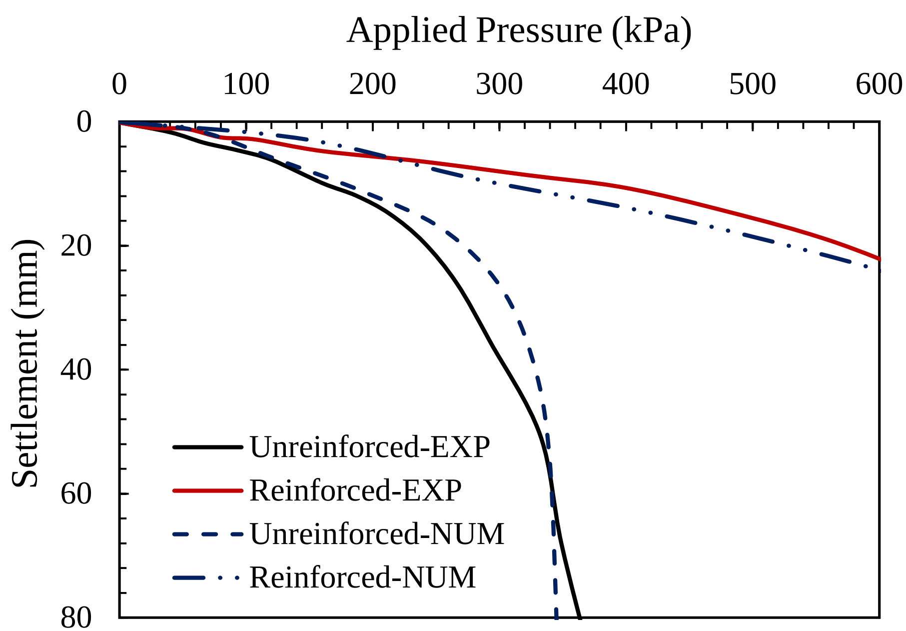


Type	Biaxial geogrid
Ultimate strength	34 kN/m
Tensile strength in machine direction at 5% strain	20 kN/m
Tensile strength in cross machine direction at 5% strain	25 kN/m
Vertical spacing of reinforcement	0.15 m
Embedment depth of top geogrid layer	0.15 m
Apparatus size	25 mm × 30 mm

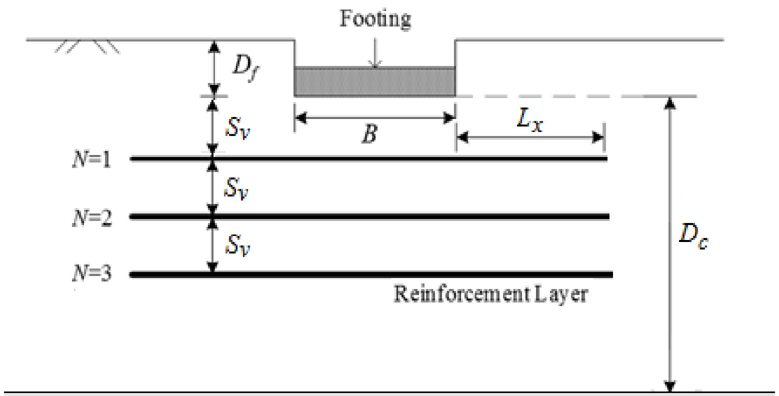
Model Validation







Parametric Study



Parametric study was conducted in two phases:

Phase 1: One of parameters changes; a total of 135 simulations was conducted in Phase 1.

Phase 2: Parameters are varied simultaneously; a total of 175 simulations was conducted in Phase 2.

Parameters (unit)		Values
Backfill properties	Friction angle, ϕ (deg)	30, 35, **40**, 45, 50
	Cohesion, c (kPa)	0, **1**, 5, 10
Reinforcement properties	Reinforcement spacing, S_v (m)	0.2, **0.3**, 0.4
	Number of reinforcement layers, N	2, **3**, 4,5
	Reinforcement length extended beyond foundation, L_X (m)	**0.25*B***, 0.5B, 0.75B, B
	Compacted depth, D_c (m)	0.9, **1.2**, 1.5. 1.8
	Reinforcement stiffness, J (kN/m)	500, **1000**, 2000, 3000
Foundation dimension	Width of foundation, B (m)	**1**, 2, 3
	Length of foundation, L (m)	1B, **2*B***, 3B, 7B, 10B
Service load (kPa)		50, 100, 200, 400, 600

Tries for Nonlinear Regression Prediction Model

$$S_{RSF} = a_0 + a_1 q + a_2 \tan(90+\phi) + a_3 c + a_4 J + a_5 S_v + a_6 D_c + a_7 B + a_8 L + a_9 L_X + a_{10} N$$ ✗

$$S_{RSF} = a_0 \times q^{a_1} \times \left(a_2 \tan(90+\phi) + a_3 c + a_4 J + a_5 S_v + a_6 D_c + a_7 B + a_8 L + a_9 L_X + a_{10} N\right)$$ ✗

$$S_{RSF} = a_0 \times q^{a_1} \times \tan(90+\phi) \times \left(a_2 c + a_3 J + a_4 S_v + a_5 D_c + a_6 B + a_7 L + a_8 L_X + a_9 N\right)$$ ✗

$$S_{RSF} = a_0 \times q^{a_1} \times \tan^2(90+\phi) \times \left(a_2 c + a_3 J + a_4 S_v + a_5 D_c + a_6 B + a_7 L + a_8 L_X + a_9 N\right)$$ ✗

$$S_{RSF} = a_0 \times q^{a_1} \times \tan^2(90+\phi) \times \left(a_2 + a_3 c + a_4 \left(S_v / J\right) + a_5 D_c + a_6 B + a_7 L + N^{a8}\right)$$ ✗

$$S_{RSF} = a_0 \times q^{a_1} \times \tan^2(90+\phi) \times \left(B / L^{a_2}\right) \times N^{a_3} \left(a_4 + a_5 c + a_6 \left(S_v / J\right) + a_7 D_c + a_8 B + a_9 L_x\right)$$ ✗

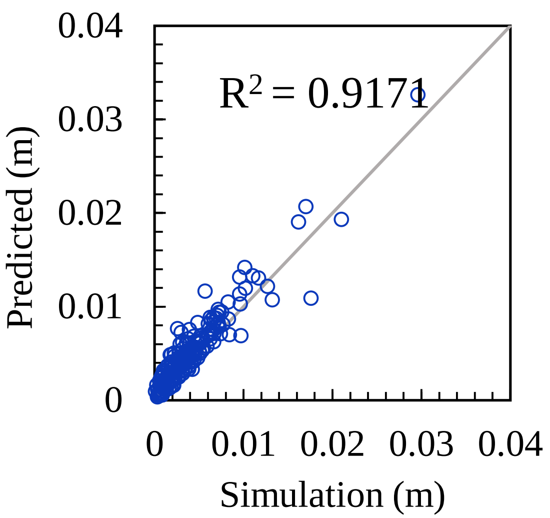
$$S_{RSF} = 1.3 \times 10^{-3} \times q^{*1.17} \times cot^2\phi \times N^{-0.05} \times (-0.07 -$$

✓

Equation for Predicting Settlement of RSF

$$S_{RSF} = 1.3 \times 10^{-3} \times q^{*1.17} \times cot^2\phi \times N^{-0.05} \times (-0.07 - 6.5 \times 10^{-5} c^* + 67.9(S_v^*/J^*) +$$

- ✓ q^*, c^*, J^*, S_v^*, D_c^*, B^*, L^*, and L_x^* are defined as q/q_0, c/c_0, J/J_0, Sv/S_{v0}, D_c/D_{c0}, B/B_0, L/L_0, and L_X/L_{X0} respectively.
- ✓ q and c should be in the unit of kPa, ϕ in degree, J in kN/m, and S_v, D_c, B, L and L_X in the unit of m, then S_{RSF} result would be in m.
- ✓ In this study q_0 = 100 kPa, c_0 = 1 kPa, J_0 = 100 kN/m, S_{v0} = 0.1 m, D_{c0} = 1 m, B_0 = 1 m, L_0 = 1 m and L_{X0} = 1 m.



Evaluation of RSF Settlement Prediction Equation

Reference	Set No.	ϕ (°)	c (kPa)	J (kN/m)	Sv (m)	D_c (m)	B (m)	L (m)	N
Adams and Collin (1997)	1	36	1	450	0.15	5.55	0.91	0.91	3
Chen and Abu-Farsakh (2011)	2	25	13	370	0.607	4.86	1.822	1.822	4
Abu-Farsakh et al. (2013)	3	46	1	365	0.051	0.75	0.152	0.152	3

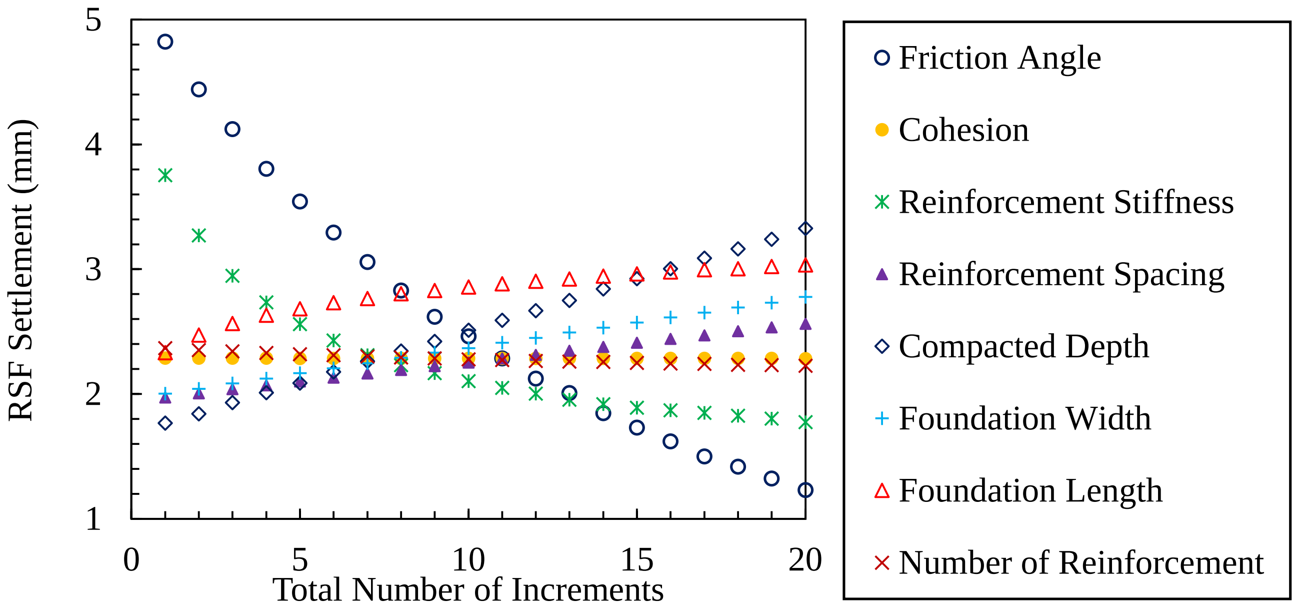
B = 0.91 m

B = 1.822 m

B = 0.152 m

Set No.	Load (kPa)	Actual Settlement (mm)	Predicted Settlement (mm)	Error (%)
1	100	2.94	2.45	-17
	200	5.87	5.50	-6
	300	8.12	8.83	9
	400	11.06	12.36	12
	500	15.72	16.04	2
	600	22.46	19.84	-12
2	100	11.89	12.49	5
	200	25.79	28.07	9
	300	40.79	45.07	10
	400	60.72	63.06	4
	500	83.95	81.84	-3
	600	109.19	101.26	-7
3	100	0.36	0.19	-47
	200	0.73	0.43	-41
	300	1.2	0.69	-43
	400	1.51	0.97	-36
	500	1.83	1.26	-31
	600	2.24	1.55	-31

Incremental Sensitivity Analysis



Parameters	SR
Friction angle	-2.7
Reinforcement spacing	0.52
Compacted depth	0.39
Reinforcement stiffness	-0.34
Width of foundation	0.32
Length of foundation	0.10
Number of reinforcement	-0.05
Cohesion	-0.01

Conclusions

- The Plastic Hardening model can accurately predict the behavior of soil in simulation of GRS abutments and RSF under service loads.
- This study suggests these equations for calculating the maximum lateral deformation and settlement of GRS abutment and maximum settlement of RSF under service loads:

$$L_{GRS} = 0.056 \times q^{*1.32} \times tan^2(90+\phi) \times \frac{S_v^*}{J^{*0.17}} \times B^{*1.11}\left(-1.53 + 1.69(1-\beta^*) + 0.105H^* - 0.0125{L_R^*}^2\right)$$

$$S_{GRS} = 0.005 + 0.006 \times q^{*1.42} \times tan^2(90+\phi) \times \frac{S_v^*}{J^{*0.49}} \times B^{*1.26}(-23.3 + 26.7(1-\beta^*) + 0.025H^* - 0.2L_R^*)$$

$$S_{RSF} = 1.3 \times 10^{-3} \times \; q^{*1.17} \times cot^2\phi \times N^{-0.05} \times (-0.07 - 6.5 \times 10^{-5}c^* + 67.9(S_v^*/J^*) + 0.15D_c^* + 0.06B^* +$$

Conclusions

- Results of sensitivity analysis for suggested equations indicated that:
  - ✓ In GRS abutment lateral deformation equation, **soil friction angle** and **reinforcement spacing** have the highest effect;
  - ✓ In GRS abutment settlement equation, **soil friction angle** and **foundation width** have the highest effect;
  - ✓ In RSF settlement equation, **soil friction angle** and **reinforcement spacing** have the highest effect.

Today's Speakers

- Jennifer Nicks, *Federal Highway Administration*, jennifer.nicks@dot.gov
- Ming Xiao, *Penn State University*, mxiao@engr.psu.edu
- Tong Qiu, *Penn State University*, tqiu@engr.psu.edu
- Mahsa Khosrojerdi, *Arup*, mahsa.khosrojerdi@arup.com

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