APPENDIX K DESIGN EXAMPLES

GEOTECHNICAL DESIGN MANUAL

January 2022

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APPENDIX K

DESIGN EXAMPLES

K.1 INTRODUCTION

The purpose of this Appendix is to provide design examples to assist the GEOR with conducting sophisticated analysis. Typically this analysis requires direct interaction with other team members, such as the SEOR. It is not the intent of the Appendix to provide examples of analysis that is concerned to be part of normal procedures (i.e., foundation analysis, SSL analysis, settlement analysis, etc.). Currently there is one design example, the use of foundation elements to resist lateral movements induced within an embankment. In Section 14.8, unstable ground refers to slope.

K.2 FOUNDATION ELEMENTS IN UNSTABLE GROUND

This design example is for the analysis required to use bridge foundation elements to restrain the movement of bridge embankment located above unstable ground. Prior to applying this procedure, the GEOR should have determined the SSL potential and estimated the residual strength of the liquefied soil. In addition, the GEOR should have determined that the ground will be unstable during the EE I limit state check. This method shall not be used to mitigate unstable ground during the Strength or Service limit state checks.

This example describes the load Case 1 (restrained ground displacement (see Chapter 14)), which is observed when the displacing soil crust is limited to the dimensions of the approach embankment (i.e., the width of the embankment). Therefore, it is assumed that the foundation is sufficiently stiff to partially restrain the movement of the failure mass.

Note that LPile 2019.11.06 for Networks was used to conduct the lateral pile analysis and that Slide2 9.010 was used to conduct the slope stability analysis. The use of these software by SCDOT does not imply endorsement of the software, nor establishes a requirement that these software be used by the GECs.

K.2.1 Project description

This example evaluates the pile supported end bent for a three-span continuous flat slab bridge, with an overall length of 100 ft located in Florence County, South Carolina. The site has a peak ground acceleration (PGA) of 0.35g and the moment magnitude (Mw) is 7.36 (Safety Evaluation Earthquake, SEE). Loadings consists of a combined design dead load and live load of 140 kips per pile (Table K-1). The foundation support for the end bents will be provided by HP14x73 steel piles. Figure K-1 sketches the soil strata and proprieties for this project. The abutment has limited width, allowing the foundation to provide a restrictive force against the soil displacement. Thus, the procedure for Case 1 described in Chapter 14 is used.

The main goal of the procedure is to find the displacement demand of the foundation due to the crustal movement. This example illustrates the methodology using a single bent analysis, which

is sufficient for bridges with uniform foundations elements, and allows the demonstration of the "superpile" concept.

Loading Case	Service Limit (kips)	Strength Limit (kips)	Extreme Event I (kips)		
Axial – Compression (Fy)	98	140	60		
Lateral – Transverse (Fx)	0.3	0.5	40		
Lateral – Longitudinal (Fz)	1.3	2.2	39		

Table K-1, End Bent Design Pile Load Summary



Figure K-1, Soil Properties

The objective of the first three steps is to find the foundation resistive force (shear demand) of the "superpile" due to the soil displacement.

K.2.2 <u>Example Calculations</u>

K.2.2.1 Foundation Model

For most bridges with uniform foundation elements, a single bent analysis is sufficient. The single bent analysis together with the concept of "superpile" allows the use of a lateral pile analysis software such as LPile. The first step is capturing the properties of the bent foundation by an equivalent (single) "superpile".

A non-linear elastic model is recommended. To create a non-linear "superpile" it is necessary to scale the moment-stiffness curve of a single pile by the number of piles in the group. The following will illustrate the use of LPile to generate the moment-stiffness curve for an HP 14x73 pile.

I. Generate the Moment-Stiffness curve for the typical pile.

a. Using the Nonlinear EI Only Mode computational option (Figure K-2), create the Moment-Stiffness curve for a single pile (Figure K-7). Define the single pile section type, dimensions and material properties (Figure K-3 to K-5). Please note that all figures are screen captures from LPile.

Program Options and Settings			
Computational Options Conventional Analysis Mode LRFD Analysis Mode Nonlinear El Only Mode (Interaction diagram, input required) The options below are available for conventional and LRFD modes Use Modification Factors for p-y Curves (input required) Include Shearing Resistance at Pile Tip (input required) Include Moment Resistance at Pile Tip (input required)	Engineering Units of Input Data and Computations US Customary Units (inches, feet, and pounds) SI Units (millimeters, meters and kilonewtons) Loading Type and Number of Cycles of Loading Static Loading Cyclic Loading Number of Cycles of Loading 		
The options below are available only for conventional analysis mode Use Loading by Single Distributed Load Profile (input required) Use Separate Distributed Load Profiles for Each Load Case Use Loading by Single Soil Movement Profile (input required) Use Separate Soil Movement Profiles for Each Load Case Compute Pile-Head Stiffness Matrix Values (input required) Compute Push-over Analysis (input required) Compute Pile Buckling Analysis (input required) Options for Response of Layered Soils Use Layering Correction (Method of Georgiadis) Do not Compute Layering Correction if Layer Above is of Same Type	Analysis Control Options Number of Pile Increments Maximum Number of Iterations 500 Convergence Tolerance on Deflections (in) 1E-5 Deflection Iteration Limit at Pile Head (in) Data from Load Test Input Data from Load Test for Comp. to Computed Values		
Output Options Generate p-y Curves at User-Specified Depths (input required) Extend Printed p-y Curves up to Maximum Demanded Displacement Print Pile Response Every Text Viewer Options Use Internal Text Viewer (faster) Use External Viewing Brogram C:\windows\notepad.exe	Output Summary Tables Only Use Narrow Output Report Format	Browse	
Internet Update Notice Query Check Internet for Program Update on Program Startup		ОК	

Figure K-2, Computational Options – Single Pile

S	ection Type	Strong Axis AISC Section Dimension	s Steel Properties			
	о.: т					
	-Section Typ	e and Shape ection (Non-vielding)	Steel AISC Section Strong Avis			
		ection with Specified Moment Capacity	Steel AISC Section Weak Avis			
		lection with Specified Montent Capacity	Beund Breatrageed Caparate			
			Round Prestressed Concrete			
		oncrete Shaft (Bored Pile)				
	O Round Co	oncrete Shaft with Permanent Casing	O Square Prestressed Concrete			
	O Round SI	haft with Casing and Core/Insert	O Square Prestressed Concrete with Void			
	⊖ Steel Pip	e Section	Octagonal Prestressed Concrete			
	⊖ Steel H S	Section Strong Axis	Octagonal Prestressed Concrete with Void			
	⊖ Steel H S	Section Weak Axis	⊖ User Defined Non-linear Bending Section			
	Compute Equivalent Elastonlastic Moment Curvature (CALTBANS)					
	Note: Pro	ogram will use the Equivalent Elastopla:	stic curve for analysis if this option is checked			

Figure K-3, Section Type – Single Pile

Section Type Strong Axis AISC Section Dimensions			Steel Properties	teel Properties		
Elevation Dimensio	ons		Steel Strong Axis AIS Section Dimensions:	C Section Pile		
Elastic Section Prop	erties:		Section Diameter (in)	36		
Structural Shape	Select Shape		Casing Wall Thickness (in)	0		
Elastic Sect. Width (in)	At Top	At Botton	n Section Depth (in)	13.6		
No data required (in)	0	0	Corner Chamfer (in)	0		
Area (in^2)	21.4	0	Core Wall Thickness (in)	0		
Mom. of Inertia (in^4)	729	0	Flange Thickness (in)	0.505		
Plas. Mom. Cap. (in-lbs)	0	0	Web Thickness (in)	0.505		
Shear Capacity (Ibs)	0	0	Elastic Mod. (lbs/in^2)	0		
Select AISC Section	Section Type:	HP	Section Name: HP14X	73 ~		

Figure K-4, HP 14 x 73 Section Dimensions

Section Type Strong Axis AISC Section Dimensions	Steel Properties	
Steel Section, Casing, and	Core/Insert Material Proper	ties:
Yield Stress of AISC Section (Ib	s/in^2) 50000	
Elastic Modulus of AISC Sectio	n (Ibs/in^2) 29000000	
Yield Stress of Core (lbs/in^2)	36000	
Elastic Modulus of Core (Ibs/in^	2) 29000000	
Steel section, casing, and core/insert dimensions and	vall thicknesses are entered on the dim	ensions page

Figure K-5, HP 14 x 73 Steel Properties

b. Input the Axial Thrust loads (Figure K-6) for Interaction Diagram that includes the combination of dead and live loads.

Axial Thrust Loads for Interaction Diagram				
Type of Values	Settings Enter Maximum Values			
Axial Thrust Loads	O Enter Values Manually			
Edit Values				
Minimum Thrust Load (lbs) Maximum Thrust Load (lbs)	140000			

Figure K-6, Axial Thrust Loading

c. Run LPile to obtain the Moment-stiffness data from a single pile and scale up by the number of piles in the bent, n (Figure K-7a and b, respectively). For this example n = 12 piles.



The p-y curve for the cap/abutment-soil interaction is defined by a trilinear curve based on the ultimate crust load on the foundation elements, F_{ULT} , and the relative displacement required to achieve F_{ULT} , Δ_{MAX} . The trilinear curve is used as an input for the foundation model.

The efficiency factor is the average of the group reduction factors for each row in the pile group. For this methodology, the reduction factor for each row in the pile group is computed according with Chapter 16. For single row pile bents, which are the vast majority of the bridges in South Carolina, the group reduction factor is 1.0.

II. An example of the input required and the results of the development of the Force-Displacement Curve are provided. The numerical values assigned to the variables are assumed. Figure K-8 depicts the Idealized Pile-Cap Force-Displacement Curve.

Geometry:

n =	12	
в=	14.0 in ≈ 1.17 ft	B = Pile Diameter
c/c =	86.0 in	c/c = Pile Separation Center to Center
T =	3.0 ft	T = Pile cap thickness
W _T =	83.7 ft	W_T = Transverse Pile Cap Width
W ∟ =	3.0 ft	W _L = Longitudinal Pile Cap Width
D =	2.8 ft	D = Depth from Ground Surface to Top Cap

Crust data:

Select soil behavior

Sand-Like or c - φ soils

γ =	110.0 pcf 330.0 psf	γ = Effective Unit Weight
c =	0.0 psf	c = Undrained Shear Strength
φ = δ =	32° 10.7°	φ = Friction Angle 20 < $φ$ < 40 δ = Pile Cap-Soil Crust Interface Friction
		Angle

с'	= 0.0 psf		c' = Cohesion Intercep	t
Z₅ Ħ	= 10.0 ft = 7.4 ft		$Z_c = Crust Thickness$ $\overline{H} = Average Pile Dept$	th in the Crust
L _c α	= 4.2 ft = 0.5		L_c = Length of Pile Ext α = Adhesion Factor	ending Through Crust
Determinat	tion of F _{ULT}			
Case A:	K _a =	0.307	K _a = Crust materials ac coefficient	ctive earth pressure
Case A: Cen Grou	Select loca ter to center up reduction	ation of piles pile spacing factor (GRF)	Row 3 and higher 6 B 1	(GDM Chapter 16)
	P _{ULT} =	17083 lb/ft	P _{∪L⊺} = Ultimate lateral	resisting force per unit
	F _{PILES-A} =	867732 lbs	length F _{PILES-A} = Ultimate resi length above liquefied	stance of individual pile zone
	K _{p,log-spiral} =	4.16	K _p = Crust materials pa	assive earth pressure
	K _{w,CASE A} =	1.41	K_W = Adjustment facto	r for wedge shaped failure
	F _{PASSIVE-A} =	487018 lbs	F _{PASSIVE} = Passive force	ce from compression of soil undation
	F _{SIDES-A} =	1119 lbs	F _{SIDES} = Friction or adh side of foundation	nesion of soil moving along
	F _{ULT-A} =	1355869 lbs		
Case B:				
	K _{p,Rankine} =	3.25	K _p = Crust materials pa	assive earth pressure
	K _{w,CASE B} =	1.32	K _W = Adjustment facto	or for wedge shaped failure
	F _{PASSIVE-B} =	354866 lbs	F _{PASSIVE} = Passive for on up-slope face of fo	ce from compression of soil oundation
	F _{SIDES-B} =	2697 lbs	F _{SIDES} = Friction or ad side of foundation	hesion of soil moving along
	F _{ULT-B} =	357564 lbs		
F _{ULT-A}	>	F _{ULT-B}	Case B controls!	
Determinat	ion of Δ_{MAX}			

f_{depth} = 0.01 f_{depth} = factor to account the effect of crust thickness with respect to the pile cap thickness

 Δ_{MAX} = 2.0 in

Table K-2, Data Point for Idealized Force-Displacement Behavior of Pile Cap

F _{∪LT} [lbs]	p _{∪∟⊤} [lbs/in]	Δ _{MAX} [in]		
0	0	0.00		
178782	4966	0.51		
357564	9932	2.03		
357564	9932	4.07		



Figure K-8, Idealized Force-Displacement Behavior of Pile Cap.

In addition to the definition of the non-linear "superpile" and the p-y curve for the cap/abutmentsoil interaction, define the rotational stiffness of the pile in the transverse direction, if applicable. For this case study and most bridges, a single row of piles does not provide an arm, therefore, x_i will be equal to zero and the rotational stiffness may be neglected.

III. Create the foundation model on LPile. Figure K-9 shows computational options on LPile for the foundation model. The pile head is modeled free to rotate and move laterally. Select in Lpile the pile-head loading conditions for shear and moment.

Program Options and Settings					
Computational Options Conventional Analysis Mode CRFD Analysis Mode Nonlinear El Only Mode (Interaction diagram, input required) The options below are available for conventional and LRFD modes Use Modification Factors for p-y Curves (input required) Include Shearing Resistance at Pile Tip (input required) Include Moment Resistance at Pile Tip (input required)	Engineering Units of Input Data and Computations				
The options below are available only for conventional analysis mode Use Loading by Single Distributed Load Profile (input required) Use Separate Distributed Load Profiles for Each Load Case Use Loading by Single Soil Movement Profile (input required) Use Separate Soil Movement Profiles for Each Load Case Compute Pile-Head Stiffness Matrix Values (input required) Compute Push-over Analysis (input required) Options for Response of Layered Soils Use Layering Correction (Method of Georgiadis) Do not Compute Layering Correction if Layer Above is of Same Type	Analysis Control Options Number of Pile Increments Maximum Number of Iterations Convergence Tolerance on Deflections (in) Deflection Iteration Limit at Pile Head (in) Data from Load Test Input Data from Load Test for Comp. to Comp	100 500 1E-5 100			
Output Options Generate p-y Curves at User-Specified Depths (input required) Extend Printed p-y Curves up to Maximum Demanded Displacement Print Pile Response Every Node(s)	Output Summary Tables Only				
Text Viewer Options O Use Internal Text Viewer (faster) Use External Viewing Program C:\windows\notepad.exe		Browse			
Internet Update Notice Query		ОК			

Figure K-9, Computational Options - "Superpile"

Define the non-linearity of the "superpile" selecting the "User Defined non-linear Bending Section" in the section type options (Figure K-10).

Section Type	Nonlinear El Pile Dimensions No	nlinear El
-Section Typ	e and Shape	
O Elastic S	ection (Non-yielding)	O Steel AISC Section Strong Axis
⊖Elastic S	ection with Specified Moment Capaci	ty O Steel AISC Section Weak Axis
ORectangu	Ilar Concrete Section	O Round Prestressed Concrete
O Round Co	oncrete Shaft (Bored Pile)	O Round Prestressed Concrete with Void
O Round Co	oncrete Shaft with Permanent Casing	○ Square Prestressed Concrete
O Round SI	haft with Casing and Core/Insert	◯ Square Prestressed Concrete with Void
⊖ Steel Pip	e Section	Octagonal Prestressed Concrete
⊖ Steel H S	Section Strong Axis	Octagonal Prestressed Concrete with Void
⊖ Steel H S	Section Weak Axis	User Defined Non-linear Bending Section

Figure K-10, Selection of Section Type - "Superpile"

Elevation Dimensio	ns	Elastic Pile (non-yielding) Section Dimensions:			
Length of Section (ft)	63.2		Section Diameter (in)	14	
Elastic Section Prope	erties:		Casing Wall Thickness (in)	0	
Structural Shape	Select Shape ~		Section Width (in)	0	
	At Top	At Bottom	Section Depth (in)	0	
Elastic Sect. Width (in)	0	0		0	
No data required (in)	0	0	Comer Chamfer (In)	U	
Area (in^2)	0	0	Core Void Diameter (in)	0	
, aou (in 2)	·		Core Wall Thickness (in)	0	
Mom. of Inertia (in^4)	0	0	Flange Thickness (in)	0	
Plas. Mom. Cap. (in-lbs)	0	0	Web Thickness (in)	0	
Shear Capacity (lbs)	0	0	Elastic Mod (lbs/in^2)	0	

Figure K-11, "Superpile" dimensions and length

Copy data from moment-stiffness curve for the equivalent "superpile" and paste it in nonlinear EI-vs-Moment Data. Figure K-12 shows the step by step to input moment-stiffness curve for the foundation model.







250,000,000,000

200 000 000 000

150,000,000,000

100.000.000.000

-sql

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Vonlir

(c) Paste the data points

Figure K-12, "Superpile" Scaled Moment-Stiffness Curve Input

Input the soil layer properties. Use the option to input a user-defined p-y curve to model the crust (Figure K-13). Use the p-y curve for idealized force-displacement behavior generated previously.

	Select p-y Curve Type	Vertical Depth Below Pile Head Vertical Depth Below Pile Head for Top of Soil Layer (ft) of Bottom of Soil Layer (ft)		Press Button to Enter					
	from Drop-down List			Soil Properties					
1	User Input p-y Curves 1	0	3	1: User Input p-y Curves 2 🥝					
2 User Input p-y Curves 3 Soft Clay (Matlock)		3	7.23	2: User Input p-y Curves					
		7.23	13.56	3: Soft Clay					
4	Sand (Reese) 🗸 🗸	13.56	19.11	4: Sand (Reese, et al.)					
5 Sand (Reese) \checkmark		19.11	34.93	5: Sand (Reese, et al.)					
6	Sand (Reese) 🗸 🗸	I(Reese) 34.93 100		6: Sand (Reese, et al.)					
Add Row Insert Row Delete Row All positive depth coordinates are defined as vertical distances below the pile-head. If the pile-head is embedded below the ground surface, the top layer must extend from the ground surface (defined by a negative vertical depth) to some point below the pile head. Select the p-y soil type using the drop-down list in the left table column.									

(a) Select User Input p-y curves for the cap and the soil above the liquefiable layer and click on soil properties

	E	ffective Unit	U	ser-Input p-y Curves		_
	W	/eight, (lbs/ft^3	3)			
	1 11	U	_	1: p-y Curve fo	Layer (Show
	2 1	10		2: p-y Curve fo	r Layer	
	oad-trans /alues of	fer values betw Effective Unit V stress in layers	Ween the Weight states	are used to compute this layer.	vertical	
) Se p-y	elect Curve fo	p-y curv	ve f	or layer to	nput	the da
ce, p, (lbs/	8,000 6,000		/			
Soil Resistance	4,000 2,000 0		1	2	3	4
Soil Resistance	4,000 2,000 0 - 0		1 Lat	2 eral Deflection, y, (Soil Resistance, p	3 (lbs/in)	4
Soil Resistance	4,000 2,000 0 0 0 0 0) I Deflection, y,	1 Lat	2 eral Deflection, y, (Soil Resistance, p	3 in) (lbs/in)	4
Soil Resistant	4,000 2,000 0 0 0 0 0 0 0 0	l Deflection, y,	1 Lat	2 eral Deflection, y, (Soil Resistance, p 0	in) (lbs/in)	4
Soil Resistant 5 2 3	4,000 2,000 0 0 0 0 0 0 0 0 0 0 0 0 0 0	I Deflection, y,	1 Lat	2 eral Deflection, y, (Soil Resistance, p 0 4966	3 in) , (lbs/in)	4
Point 2 2 3 4	4,000 2,000 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	Deflection, y,	1 Lat	2 eral Deflection, y, f Soil Resistance, p 0 4966 9932	3 in)	4

Figure K-13, User-defined P-y curve for crust modeling

The liquefied sand could be modeled using the residual strength model or as a soft clay. In this example, the liquefied layer was modeled as a soft clay equating the cohesive strength equal to the residual strength of liquefied sand (Figure K-14). In addition, the strain factor is taken equal to 0.05 as recommended in the LPile Technical Manual.

a	Soil	Layers							
[Select p-y Curve Type	Vertical Depth Below Pile Head Vertical Depth Below Pile Head P		Press Button to Enter				
		from Drop-down List	of Top of Soil Layer (ft)	of Bottom of Soil Layer (ft)	Soil Properties				
	1	User Input p-y Curves 🗸 🗸 🗸	0	3	1: User Input p-y Curves				
	2 User Input p-y Curves ~ 3 Soft Clay (Matlock) 1		3	7.23	2: User Input p-y Curves				
			7.23	13.56	3: Soft Clay 2				
	4	Sand (Reese)	13.56	19.11	4: Sand (Reese, et al.)				
	5	Sand (Reese) 🗸 🗸	19.11	34.93	5: Sand (Reese, et al.)				
	6	Sand (Reese) 🗸 🗸	34.93 100		6: Sand (Reese, et al.)				
Add Row Insert Row Delete Row All positive depth coordinates are defined as vertical distances below the pile-head. If the pile-head is embedded below the ground surface, the top layer must extend from the ground surface (defined by a negative vertical depth) to some point below the pile head. Select the p-y soil type using the drop-down list in the left table column.									

(a) Select soft clay as p-y curve type, click on soil properties

(b) Input the corresponding data for the liquefiable layer

Figure K-14, Liquefied Soil Layer Modeled as Soft Clay

The corresponding "p" in the p-y curves for a single group pile must be scaled by a factor equal to the number of piles multiplied by the group efficiency factor. Modify the p-value of the curve using the option to modify the p-y factors under the data tab (Figure K-15).

Data Computation Graphics Tools Window Help	ſ		tion Factors for n-v Cunves			
Project Information		any modification Pactors for p-y curves				
Program Options and Settings		Depth Point	Distance from Pile Head	(ft)	p-Multiplier	y-Multiplier
Structural Dimensions and Pile Material Properties		1	0		1	1
Pile Batter and Ground Slope Angles		2	3		1	1
Soil Layering and Soil Property Data		3	7.23		1	1
Modification Factors for p-y Curves		4	7.23		12	1
Shear-Resistance Curve at Pile Tip	· · · ·	5	13.56		12	1
Moment-Resistance Curve at Pile Tip		6	60		12	1
Shift Pile Elevation in Soil Profile		7	100		12	1
Pile Head Loading and Options				_		
Distributed Lateral Loading		Add Row	Insert Row Delete Row	_		
Lateral Soil Movements	Enter p-y modification factors from the ground surface to the tip of the pile. Usual practice is to enter a value of 1.0 for all v-multipliers and to					
<u> </u>		enter values l	ess than or equal to 1.0 for the p-mult	ipliers.		

Figure K-15, p-value Modification to Create "Superpile"

The group reduction and efficiency factor are equal to 1.0. Multiply p-value by a factor equal to 12 corresponding to the number of piles in the cap. Do not account for group effects in the liquefied layer.

K.2.2.2 Bridge Longitudinal Resistance

The next step is to determine if the bridge can provide any lateral resistance to the movement of the abutments. This type of analysis is typically performed by the SEOR with input from the

GEOR. The restraining force from the bridge superstructure depends on the structural configuration, the characteristics of the embankment soils, as well as the capacity of the adjacent opposite abutments. The restraining force that develops at the abutment must be transferred to the intermediate bents and the opposite abutment. If superstructure restraint is considered in the lateral spreading analysis, it is recommended that a global structural model is used. This type of modeling is not anticipated being performed on typical SCDOT projects. For this example, it is assumed that there is not longitudinal resistance from bridge deck.

K.2.2.3 Foundation Model Displacement Analysis

A displacement analysis of the foundation model should be performed next. Impose a series of increasing soil displacement profiles on the foundation model (Figure K-16). For each displacement increment, determine the shear force on the foundation at the center of the liquefiable layer. Define this as the foundation resistive force corresponding to a given crustal displacement, R.



The soil displacement is incremented every 2.5 in up to 20 in. For each point read the shear force in the "superpile" at the middle of the liquefiable layer and record it. To compensate the effect of the change of the sliding mass, use the running average of the shear force. A summary of the "superpile" analysis is presented in Table K-3 and plotted in Figure K-17.

Data point	d [in]	R [kips]	R _{running avg} [kips]
1	2.5	357.99	358.0
2	5	578.42	468.2
3	7.5	608.69	515.0
4	10	613.9	539.8
5	12.5	617.37	555.3
6	15	619.51	566.0
7	17.5	621.28	573.9
8	20	622.82	580.0

Table K-3, Crustal Displacement Data Points and Foundation Resistive Force



Figure K-17, Foundation resistive force given a crustal displacement

K.2.2.4 Bridge Embankment Slope Stability and Deformation Analyses

This example uses the stability model in Slide to determine the foundation resisting forces at the center of the liquefied layer for a series of horizontal accelerations.

Run the slope stability analysis for the EE I with a peak ground acceleration equal to 0.35g to identify the location of the failure surface (Figure K-18). The failure surface needs to pass through the middle of the liquefied layer. A non-circular surface option and block search for this analysis is recommended (Figure K-20). Longitudinally, the failure surface is limited to four times the embankment thickness.



Figure K-18, EE I Slope Stability Analysis

The following figures depict the options selected for the creation of the slope model. Select the Spencer option as the methodology of analysis, required per Chapter 17 and the seismic option to compute a yielding coeffcient with a target factor of safety equal to one (Figure K-19). Notice that the parameter "Ky" in Slide to refers to the yield coefficient (called k_c in Chapter 14) and not the yield acceleration (k_y) as defined in the Chapter 13.



Surface Options				?	×
Surface Type:	O Circular Non-Circular	r			
Search Method:	Block Search	~	~	<u>O</u> pti	ons
Surface Type Options Convex Surfaces Or Optimize Surfaces	l y Settings				
Weak Layer Handling:	Always snap to highest layer				\sim
👕 Filter Defau	ılts	ОК		Car	ncel

Figure K-20, Surface Option Selection

Place an additional vertex in the middle of liquefied layer directly below the cap to place the restraining force (point force) representative of the resistive force provided by the "superpile" (Figure K-21). Use the option to add a polyline under the block search option to place the failure surface in accordance with the vertical and horizontal limits considerations (Figure K-22). Create the block failure surface to pass slightly under this point of force application. If the point force is placed on the failure surface, the model does not take into account the force acting against the displacement of the crust. For this example, the failure surface is placed two inches below the application point of the resistive force.



Figure K-21, Additional Vertex Location



Figure K-22, Block Search Location Option

The height of the embankment in the longitudinal direction, H, is measured from the top of the roadway to the top of slope. For this case H = 19.2 ft, 4^{*} H = 76.8 ft. The lateral constrain is placed at 63 ft behind the top of the roadway, which is less than 4H (Figure K-23).



Figure K-23, Block Failure Surface Limits

The next step is to apply a constant force at the middle of the liquefied layer, representing the resistive force provided by the foundation, and find the corresponding yield coefficient, k_c , for a target factor of safety equal to 1. With the resultant yielding coefficient, calculate the corresponding displacement using Bray and Travasarou (2007) for the Newmark rigid sliding block case (Equation K-1).

Equation K-1
$$d = Exp \left[-0.22 - 2.83ln(k_c) - 0.333 (ln(k_c))^2 + 0.566ln(k_c)ln(PGA) + 3.04ln(PGA) - 0.244 (ln(PGA))^2 + 0.278(M_w - 7) \right]$$

The first point of the curve is where the constant force equals to zero (Figure K-24):



Figure K-24, Yield Coefficient at a Resistive Force Equal to zero

Next, apply a series of constant forces at the middle of the liquefied layer and determine the corresponding yield coefficient to generate the points for the curve (Figure K-25):



Figure K-25, Constant Force Application to Determine Yield Coefficient

Prior creating the curve, make an adjustment for non-rectangular embankment shape multiplying the force by the tributary width of the sliding mass, W_T (Figure K-31)



Figure K-26, Non-rectangular embankment adjustment

Table K-4 shows the applied resistive force and the resultant yield coefficient, k_c . Plot the total resistive force provided for the embankment vs. the crust displacement calculated with Equation K-1 (Figure K-27).

R _{dist} [lbs/ft]	kc	d [cm]	R [kips]	d [in]
0	0.00655	184.6	0	72.7
100	0.00783	180.2	10.1	70.9
1000	0.01376	145.3	101.2	57.2
2000	0.02584	88.9	202.4	35.0
3000	0.05438	35.4	303.6	13.9
4000	0.06646	25.9	404.8	10.2
5000	0.07535	21.1	506.0	8.3
6000	0.08418	17.4	607.2	6.8
7000	0.09299	14.5	708.4	5.7
8000	0.10194	12.2	809.6	4.8
9000	0.16818	4.3	910.8	1.7
10000	0.16818	4.3	1012.0	1.7

 Table K-4, Resistive Force Anticipated Crustal Displacement



Figure K-27, Resistive Force vs Anticipated Crustal Displacement

K.2.2.5 Target Displacement Determination

Combine the results from Subsections K.2.1.3 and K.2.1.4 to determine the target displacement. Plot the displacement compatibility curve with these data (Figure K-28). Use the running average for the foundation resistive force given a crustal displacement and the expected crustal displacement for a given resistive force. The displacement corresponding to the intersection of these two curves represents the expected displacement demand on the foundation (Figure K-29).



Figure K-28, Determination of compatible displacements



Figure K-29, Expected crustal displacement given a constant resistive force

K.2.2.6 Calculate Foundation Demands

The adequacy of the pile (structural) capacity is generally performed by the SEOR. The SEOR evaluates the performance of the foundation checking the displacement, shear and moment demand for an imposed soil displacement found in Subsection K.2.2.1. The methodology assumes that the unstable soil will occur during strong shaking and the inertial loading of the foundation must be considered in tandem with kinematic loading (Equation K-2). However, for the case of freestanding abutment it is recommended to ignore the inertial forces since the backwall is generally designed as a weak fuse. A soil profile with a maximum displacement equal to 8.1 inches is imposed on the foundation model in tandem with the inertial loads (Figure K-30).

Equation K-2

```
100% kinematic \pm 50% inertial \rightarrow (peak pile cap displacement, moment or shear)
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Figure K-30, Profile of Displacement, Moment and Shear (HP14x73 piles)

The moment demand is 4,775.3 kip-in at a depth of 13.25 ft from the surface. The capacity of the HP14x73 is 4,361 kip-in, which indicates the formation of a plastic hinge. Plastic hinging is allowed by the SDOT Seismic Design Specifications with the permission from the Regional Production Group (RPG), in consultation with the Geotechnical and Structural Design Support Engineer. Alternatively, the piles size could be increased to avoid the formation of plastic hinges. For this example, when the pile size was increased to HP14x89, the target displacement was 11% smaller (Figure K-31) and there were not plastic hinges forming due to the imposed displacement (Figure K-32). The HP14x89 has a moment demand of 5,939 kip-in and a capacity of 6,599 kip-in.



Figure K-31, Expected crustal displacement for HP14x89 piles



Figure K-32, Profile of Displacement, Moment and Shear (HP14x89 piles)

K.3 REFERENCES

Arduino, P., McGann, C. R., and Ghofrani, A., (2017), "Design Procedure for Bridge Foundations Subjected to Liquefaction-Induced Lateral Spreading", Washington State Department of Transportation, Office of Research & Library Services.

Ashford, S. A., Boulanger, R. W., and Brandenberg, S. J., (2011), "Recommended Design Practice for Pile Foundations in Laterally Spreading Ground", Pacific Engineering Research Center, PEER Report 2011/04.

Caltrans (2017 A), "Memo to Designers 20-15: Lateral Spreading Analysis Fort New and Existing Bridges", California Department of Transportation (Caltrans) <u>https://dot.ca.gov/programs/engineering-services/manuals/memo-to-designers</u> (last visit: 09/17/2021)

Caltrans (2017 B), "Memo to Designers 20-15: Lateral Spreading Analysis Fort New and Existing Bridges, Attachment 1", California Department of Transportation (Caltrans) <u>https://dot.ca.gov/programs/engineering-services/manuals/memo-to-designers</u> (last visit: 09/17/2021)