APPENDIX A DETERMINATION OF PARAMETERS USED IN FLAC ANALYSES

A.1 Soil Parameters

A.1.1 Silty Sand with 20% Fines

The typical saturated unit weight value for this type of soil is 120 lb/ft^3 (based on Table A.1). This value is equivalent to density (ρ_{sat}) of 3.73 slug/ft^3, which was determined as follows:

$$\rho_{sat} = \frac{\gamma_{sat}}{g} = \frac{120 \frac{lb}{ft^3}}{32.185 \frac{ft}{\sec^2}} = 3.73 \frac{slug}{ft^3} \qquad \text{(A.1)}$$

(Note: slug is the unit used in FLAC, which is equivalent to lb-sec^2/ft)

Since FLAC analyses were configured for groundwater (**CONFIGgw**), the dry density of the soil should be used. FLAC will compute the saturated density of each element, using the known values of the density of water, the porosity, and the saturation. The dry unit weight of soil can be determined by the following equations:

$$G_s = \frac{\gamma_{sat}(1+e)}{\gamma_w} - e \qquad \text{(A.2)}$$

$$\gamma_d = \frac{G_s \gamma_w}{(1+e)} \qquad \text{(A.3)}$$

where:

γ_{sat} = the saturated unit weight of soil

γ_w = the unit weight of water

e = void ratio

G_s = the specific gravity of soil

γ_d = the dry unit weight of soil

Based on Table A.2, a value of void ratio (e) of 0.7 was selected. Based on the known values of γ_{sat} (=120 pcf), e (=0.7), and γ_w (=62.4 pcf), G_s = 2.57 was obtained by using equation (A.1). This value was used in equation (A.2) and γ_d = 94 pcf was obtained, which is equivalent to 2.93 slug/ft^3.

Based on the selected void ratio (e) of 0.7, the porosity of soil can be determined using equation (A.4) and n of 0.412 was obtained.

$$n = \frac{e}{1+e} \qquad \text{(A.4)}$$

Table A.3 shows the relationship between Standard Penetration Test N-values, $(N_1)_{60}$ versus friction angle (ϕ). Based on this relationship, the values of 10 blows/ft and 30° were used for $(N_1)_{60}$ and ϕ, respectively.

Tables A.4 and A.5 show the typical values of elastic modulus (E) and Poisson's ratio (ν) for various types of soil. Based on these tables, the values of 15 MPa (315,000 psf) and 0.3 were selected for E and ν, respectively.

The values of E and ν were then used to calculate the bulk modulus (K) and the shear modulus (G) using the following equations:

$$K = \frac{E}{3(1-2\nu)} \qquad \text{(A.5)}$$

$$G = \frac{E}{2(1+\nu)} \qquad \text{(A.6)}$$

By using equations (A.5) and (A.6) the following parameters were obtained:

K = 315,000 psf

G = 118,125 psf

Table A.6 shows the typical values of dilation angle (ψ). The dilation angle of 0° was selected in the FLAC analysis.

Based on Table A.7, permeability (k) of 10^{-4} cm/sec. ($3.28*10^{-6}$ ft/sec.) was selected. Equation (A.9) was used to determine the value of FLAC permeability, which result in the value of $5.26*10^{-8}$ ft^3-sec/slug.

$$FLAC\ \ permeability = \frac{k}{\gamma_w} \qquad \text{(A.7)}$$

A.1.2 Soft Clay

The typical saturated unit weight (γ_{sat}) value for this type of soil is 110 pcf (based on Table A.1), which is equivalent to density (ρ_{sat}) of 3.42 slug/ft^3. Based on Table A.2, a value of void ratio (e) of 1.1 was selected. By using equation (A.4), porosity (n) of 0.524 was obtained. Based on the known values of saturated unit weight (γ_{sat}) of 110 pcf, void ratio (e) of 1.1, and unit weight of water (γ_w) of 62.4 pcf, specific gravity (G_s) of 2.60 was obtained by using equation (A.2). This value was used in equation (A.3) and dry unit weight (γ_d) of 77 pcf was obtained, which is equivalent of 2.40 slug/ft^3.

Table A.8 shows the relationship between SPT (Standard Penetration Test) N-values versus consistency of clay soil. Based on this relationship, $(N_1)_{60}$ of 4 blows/ft was selected for soft clay.

Table A.9 shows the typical values of strength properties. Therefore, the values of 10 kPa (210 psf) and 17° were selected for cohesion (c) and friction angle (ϕ), respectively.

Based on Tables A.4 to A.6, the following values were selected for soft clay:

$$E = 5\ \text{MPa} = 105{,}000\ \text{psf},\ \nu = 0.414,\ \text{and}\ \psi = 0°$$

The above values were then used to calculate the bulk modulus (K) and the shear modulus (G) using equations (A.5) and (A.6). The following results were obtained:

$$K = 204{,}421\ \text{psf}$$

$$G = 37{,}118\ \text{psf}$$

Based on Table A.7, permeability (k) of 10^{-7} cm/sec. ($3.28*10^{-9}$ ft/sec.) was selected. Equation (A.7) results in the value of FLAC permeability of $5.26*10^{-11}$ ft^3-sec/slug.

A.1.3 Silt

Based on the Tables A.1 to A.6 and A.8 to A.9, the following values were selected and used in FLAC analysis:

$$\gamma_{sat} = 115 \text{ pcf} \Leftrightarrow \rho_{sat} = 3.57 \text{ slug/ft}^3$$

$$e = 0.9 \Leftrightarrow n = 0.474$$

$$\gamma_d = 85 \text{ pcf} \Leftrightarrow \rho_d = 2.65 \text{ slug/ft}^3$$

$$(N_1)_{60} = 8 \text{ blows/ft}$$

$$c = 3 \text{ kPa} = 63 \text{ psf}$$

$$\phi = 25° \Leftrightarrow \nu = 0.4$$

$$E = 10 \text{ MPa} = 210{,}000 \text{ psf}$$

$$\psi = 0°$$

The bulk modulus (K) and the shear modulus (G) were calculated using equations (A.5) and (A.6). The following results were obtained:

$$K = 261{,}268 \text{ psf}$$

$$G = 76{,}865 \text{ psf}$$

Based on Table A.7, permeability (k) of 10^{-6} cm/sec. ($3.28*10^{-8}$ ft/sec.) was selected. Equation (A.7) results in the value of FLAC permeability of $5.26*10^{-10}$ ft^3-sec/slug.

A.1.4 Determination of Parameters Used in Finn Model

As noted in Chapter 5, equations suggested by Byrne (1991) were used in the FLAC analyses. Based on the selected $(N_1)_{60}$ values the constant C_1 and C_2 can be computed.

$$C_1 = 8.7(N_1)_{60}^{-1.25} \qquad \text{(A.8)}$$

$$C_2 = \frac{0.4}{C_1} \qquad \text{(A.9)}$$

Therefore, for silty sand the following values were used:

$C_1 = 0.49$

$C_2 = 0.82$

For soft clay, the following values were used:

$C_1 = 1.54$

$C_2 = 0.26$

For silt, the following values were used:

$C_1 = 0.65$

$C_2 = 0.62$

A.2 Aggregate Pier Parameters

As noted previously in Chapter 5, an angle of friction (ϕ) of 50° was selected for the aggregate piers. Also selected the use of aggregate pier stiffness of 8 times stiffer than that of the surrounding soils. Therefore, the value of elastic modulus of 2,520,000 psf and 1,680,000 psf for the aggregate pier were used. These values are eight times stiffer than the elastic modulus of soil (315,000 psf and 210,000 psf for silty sand and silt, respectively).

Based on equation (5.6), the elastic modulus can be calculated. For silty sand, the elastic modulus of aggregate pier is:

$$E = \frac{(2,520,000 * 7.07 + 315,000 * 18.13)}{25.2} = 933,625 \; psf$$

By using equations (A.5) and (A.6) and Poisson's ratio (ν) of 0.2, the following values were obtained:

$$K = 501{,}299 \text{ psf}$$

$$G = 392{,}412 \text{ psf}$$

For silt,

$$E = \frac{(1{,}680{,}000 * 7.07 + 210{,}000 * 18.13)}{25.2} = 622{,}417 \ psf$$

and

$$K = 334{,}199 \text{ psf}$$

$$G = 261{,}608 \text{ psf}$$

Based on Table A.6, dilation angle of 0° was used.

The saturated unit weight of the aggregate pier is 147 pcf (ρ_{sat} = 4.57 slug/ft^3) and the dry unit weight is 136 pcf (ρ_d = 4.23 slug/ft^3). These values correspond to e = 0.25 (n = 0.2) and G_s = 2.69.

Based on Table A.7, permeability (k) of 10^{-1} cm/sec. ($3.28*10^{-3}$ ft/sec.) was selected, which corresponds to FLAC permeability of $5.26*10^{-5}$ ft^3-sec/slug.

A.3 Water Parameters

As noted previously, for uncoupled flow-mechanical approach, the flow calculation can be set in flow-only mode (**SET flow on, SET mech off**), and then in mechanical-only mode (**SET flow off, SET mech on**), to bring the model into equilibrium. For the latter, K_w is set to zero, while for the former, K_w should be adjusted to K_w^a by using the equation (4.29). Therefore, for silty sand,

$$K_w^a = \frac{0.412}{\dfrac{0.412}{4.2*10^7} + \dfrac{1}{315{,}000 + (4*118{,}125/3)}} = 193{,}662 \ psf$$

For soft clay,

$$K_w^a = \frac{0.524}{\dfrac{0.524}{4.2*10^7} + \dfrac{1}{204{,}421 + (4*37{,}118/3)}} = 132{,}582\ psf$$

For silt,

$$K_w^a = \frac{0.474}{\dfrac{0.474}{4.2*10^7} + \dfrac{1}{261{,}268 + (4*76{,}865/3)}} = 171{,}601\ psf$$

Once, the system is brought into equilibrium, bulk modulus of water (K_w) of 10^8 Pa (= $2.1 * 10^6$ psf) was used. The unit weight of water used in FLAC analysis is equal to $\gamma_w = 62.4$ pcf ($\rho_w = 1.94$ slug/ft^3).

For a coupled flow-mechanical problem (**SET flow on, SET mech on**), the value of K_w should be adjusted that the value of R_k is ≤ 20 by using equation (4.27). Since this case was analyzed only for silty sand soil, the value of R_k becomes

$$20 = \frac{K_w/0.412}{315{,}000 + (4*118{,}125/3)} \Leftrightarrow K_w = 3{,}995{,}730\ psf$$

Table A.1 Typical values of unit weights (after Coduto, 2001)

Soil type	**Above groundwater table (lb/ft^3)**	**Below groundwater table (lb/ft^3)**
GP – Poorly-graded gravel	110 – 130	125 – 140
GW – Well-graded gravel	110 – 140	125 – 150
GM – Silty gravel	100 – 130	125 – 140
GC – Clayey gravel	100 – 130	125 – 140
SP – Poorly-graded sand	95 – 125	120 – 135
SW – Well-graded sand	95 – 135	120 – 145
SM – Silty sand	80 – 135	110 – 140
SC – Clayey sand	85 – 130	110 – 135
ML – Low plasticity silt	75 – 110	80 – 130
MH – High plasticity silt	75 – 110	75 – 130
CL – Low plasticity clay	80 – 110	75 – 130
CH – High plasticity clay	80 – 110	70 – 125

Table A.2 Typical values of void ratio (after Das, 1994)

Soil type	Void ratio, e
Loose uniform sand	0.8
Dense uniform sand	0.45
Loose angular-grained silty sand	0.65
Dense angular-grained silty sand	0.4
Stiff clay	0.6
Soft clay	0.9 – 1.4
Loess	0.9
Soft organic clay	2.5 – 3.2
Glacial till	0.3

Table A.3 Estimation of friction angle of granular soils from SPT test results (after Peck, et. al., 1974)

$(N_1)_{60}$ (blows/ft)	Relative density	ϕ (°)
0 – 4	Very loose	< 28
4 – 10	Loose	28 – 30
10 – 30	Medium dense	30 – 36
30 – 50	Dense	36 – 41
> 50	Very dense	> 41

Table A.4 Values of elastic modulus and Poisson's ratio (after FLAC, 2000)

Soil type	**Dry density (kg/m^3)**	**Elastic modulus, E (MPa)**	**Poisson's ratio, ν**
Loose uniform sand	1470	10 – 26	0.2 – 0.4
Dense uniform sand	1840	34 – 69	0.3 – 0.45
Loose, angular-grained, silty sand	1630		
Dense, angular-grained, silty sand	1940		0.2 – 0.4
Stiff clay	1730	6 – 14	0.2 – 0.5
Soft clay	1170 – 1490	2 – 3	0.15 – 0.25
Loess	1380		
Soft organic clay	610 – 820		
Glacial till	2150		

Table A.5 Typical values of elastic modulus and Poisson's ratio (after Das, 1994)

Soil type	**Elastic modulus, E (psi)**	**Elastic modulus, E (kN/m^2)**	**Poisson's ratio**, ν
Loose sand	1500 – 4000	10,350 – 27,600	0.2 – 0.4
Medium sand			0.25 – 0.4
Dense sand	5000 – 10,000	34,500 – 69,000	0.3 – 0.45
Silty sand			0.2 – 0.4
Soft clay	250 – 500	1380 – 3450	0.15 – 0.25
Medium clay			0.2 – 0.5
Hard clay	850 – 2000	5865 – 13,800	

Table A.6 Typical values for dilation angle (after FLAC, 2000)

Soil type	Dilation angle, ψ (°)
Dense sand	15
Loose sand	< 10
Normally consolidated clay	0
Granulated and intact marble	12 – 20
Concrete	12

Table A.7 Typical values of permeability (after Duncan, 2001)

Soil type	**Permeability, k (cm/sec.)**
Coarse sand	$> 10^{-1}$
Fine sand	$10^{-3} – 10^{-1}$
Silty sand	$10^{-5} – 10^{-3}$
Silt	$10^{-7} – 10^{-5}$
Clay	$< 10^{-7}$

Table A.8 Typical values of $(N_1)_{60}$ for cohesive soil (after Das, 1994)

$(N_1)_{60}$ (blows/ft)	**Consistency**	**q_u (tsf)**
0 – 2	Very soft	0 – 0.25
2 – 4	Soft	0.25 – 0.5
4 – 8	Medium stiff	0.5 – 1.0
8 – 16	Stiff	1.0 – 2.0
16 – 32	Very stiff	2.0 – 4.0
> 32	Hard	> 4.0

(Note: q_u = unconfined compression strength)

Table A.9 Typical values of strength properties (after FLAC, 2000)

Soil type	**Cohesion, c (kPa)**	**ϕ'_{peak} (°)**	**$\phi'_{residual}$ (°)**
Low plasticity clay	6	24	20
Medium plasticity clay	8	20	10
High plasticity clay	10	17	6
Low plasticity silt	2	28	25
Medium to high plasticity silt	3	25	22