Contents

Abstract .................................................................................................................. ii

1 Introduction ..................................................................................................... 1
  1.1 Background .............................................................................................. 1
  1.2 Interface Behavior in SSI Analyses ............................................................ 3
    1.2.1 The North Lock Wall at McAlpine Locks ............................................. 3
    1.2.2 Limitations of existing interface models ............................................. 7
  1.3 Project Scope ............................................................................................ 11
    1.3.1 Interface testing .................................................................................. 11
    1.3.2 Extended hyperbolic model for interfaces .......................................... 13
    1.3.3 Implementation of the model in SOILSTRUCT-ALPHA ..................... 14
    1.3.4 Lock wall simulation .......................................................................... 14
  1.4 Report Organization .................................................................................. 15

2 Literature Review .......................................................................................... 16
  2.1 Interface Testing ...................................................................................... 16
    2.1.1 Direct Shear Box (DSB) devices ....................................................... 17
    2.1.2 Direct Simple Shear (DSS) devices .................................................... 18
    2.1.3 Other devices .................................................................................... 19
    2.1.4 Summary of previous findings on interface testing and interface behavior ............................................................................ 21
    2.1.5 The Large Direct Shear Box (LDSB) ............................................... 22
  2.2 Interface Modeling ................................................................................... 23
    2.2.1 Interface elements ............................................................................. 23
    2.2.2 Interface constitutive models .............................................................. 26
    2.2.3 The hyperbolic model ....................................................................... 27
  2.3 SSI Analyses of Retaining Walls .......................................................... 31
    2.3.1 Review of previous work ................................................................... 31
    2.3.2 Simplified procedure for calculating the downdrag force ................... 33
  2.4 Summary .................................................................................................. 42

3 Laboratory Testing ........................................................................................ 45
  3.1 Soil Properties ....................................................................................... 46
    3.1.1 Triaxial testing ................................................................................ 48
    3.1.2 Consolidation testing ........................................................................ 49
    3.1.3 Hyperbolic parameters .................................................................... 49
  3.2 Concrete Specimen ................................................................................ 50
    3.2.1 Materials ......................................................................................... 52
    3.2.2 Preparation of the specimen .............................................................. 52
    3.2.3 Surface texture ................................................................................ 55
  3.3 Interface Testing Procedures .................................................................. 60
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.1</td>
<td>The soil box</td>
<td>60</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Preparation of the interface</td>
<td>60</td>
</tr>
<tr>
<td>3.3.3</td>
<td>The Large Direct Shear Box (LDSB)</td>
<td>62</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Test setup</td>
<td>64</td>
</tr>
<tr>
<td>3.3.5</td>
<td>Data reduction</td>
<td>64</td>
</tr>
<tr>
<td>3.4</td>
<td>Interface Testing Program</td>
<td>64</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Testing parameters</td>
<td>65</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Types of interface tests</td>
<td>65</td>
</tr>
<tr>
<td>3.5</td>
<td>Results of Interface Tests</td>
<td>69</td>
</tr>
<tr>
<td>3.5.1</td>
<td>Interface response to initial loading</td>
<td>69</td>
</tr>
<tr>
<td>3.5.2</td>
<td>Interface response to staged shear</td>
<td>70</td>
</tr>
<tr>
<td>3.5.3</td>
<td>Interface response to unloading-reloading</td>
<td>71</td>
</tr>
<tr>
<td>3.5.4</td>
<td>Interface response to multidirectional stress paths</td>
<td>72</td>
</tr>
<tr>
<td>3.6</td>
<td>Summary</td>
<td>72</td>
</tr>
<tr>
<td>4</td>
<td>Extended Hyperbolic Model</td>
<td>75</td>
</tr>
<tr>
<td>4.1</td>
<td>Experimental Observations of Interface Response</td>
<td>76</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Normalization of interface test data</td>
<td>76</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Development of yield surfaces during interface shear</td>
<td>80</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Loading regions</td>
<td>89</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Interface response at yield</td>
<td>92</td>
</tr>
<tr>
<td>4.1.5</td>
<td>Interface response during unloading-reloading</td>
<td>96</td>
</tr>
<tr>
<td>4.1.6</td>
<td>Interface response during transition loading</td>
<td>97</td>
</tr>
<tr>
<td>4.2</td>
<td>Formulation of the Extended Hyperbolic Model</td>
<td>100</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Hypothesis of interface response at yield</td>
<td>101</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Mathematical formulation</td>
<td>104</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Formulation of the extended hyperbolic model for interfaces at yield</td>
<td>108</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Behavior of the model</td>
<td>109</td>
</tr>
<tr>
<td>4.3</td>
<td>Formulation of the Extended Hyperbolic Model for Unloading-Reloading</td>
<td>114</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Version I</td>
<td>115</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Version II</td>
<td>117</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Version III</td>
<td>121</td>
</tr>
<tr>
<td>4.4</td>
<td>Determination of the Model Parameter Values</td>
<td>125</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Determination of parameter values for interfaces at yield</td>
<td>126</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Determination of interface parameter values for unloading-reloading</td>
<td>134</td>
</tr>
<tr>
<td>4.5</td>
<td>Evaluation of the Extended Hyperbolic Model</td>
<td>143</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Accuracy of the model of yield-inducing shear</td>
<td>144</td>
</tr>
<tr>
<td>4.5.2</td>
<td>Accuracy of the model for unloading-reloading</td>
<td>149</td>
</tr>
<tr>
<td>4.5.3</td>
<td>Accuracy of the model for staged shear</td>
<td>154</td>
</tr>
<tr>
<td>4.5.4</td>
<td>Accuracy of the model for shearing along complex stress paths</td>
<td>156</td>
</tr>
<tr>
<td>4.6</td>
<td>Implementation of the Extended Hyperbolic Model</td>
<td>172</td>
</tr>
<tr>
<td>4.6.1</td>
<td>Incremental analyses</td>
<td>172</td>
</tr>
<tr>
<td>4.6.2</td>
<td>Identification of type of loading</td>
<td>173</td>
</tr>
<tr>
<td>4.6.3</td>
<td>Implementation of the formulation for yield-inducing shear</td>
<td>173</td>
</tr>
<tr>
<td>4.6.4</td>
<td>Implementation of Version I</td>
<td>176</td>
</tr>
<tr>
<td>4.6.5</td>
<td>Implementation of Version II</td>
<td>176</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>4.6.6 Implementation of Version III</td>
<td>179</td>
<td></td>
</tr>
<tr>
<td>4.6.7 Implementation of the extended hyperbolic model in SOILSTRUCT-ALPHA</td>
<td>182</td>
<td></td>
</tr>
<tr>
<td>4.7 Summary and Conclusions</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>5 Lock Wall Simulation</td>
<td>186</td>
<td></td>
</tr>
<tr>
<td>5.1 The IRW Facility</td>
<td>187</td>
<td></td>
</tr>
<tr>
<td>5.1.1 Components of the IRW</td>
<td>187</td>
<td></td>
</tr>
<tr>
<td>5.1.2 Preparations for the test</td>
<td>191</td>
<td></td>
</tr>
<tr>
<td>5.2 Testing Procedures</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>5.2.1 Stage 1, Backfilling</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>5.2.2 Stage 2, Surcharge</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td>5.2.3 Stage 3, Inundation</td>
<td>196</td>
<td></td>
</tr>
<tr>
<td>5.3 Test Results</td>
<td>196</td>
<td></td>
</tr>
<tr>
<td>5.3.1 Results from stage 1</td>
<td>196</td>
<td></td>
</tr>
<tr>
<td>5.3.2 Results from stage 2</td>
<td>198</td>
<td></td>
</tr>
<tr>
<td>5.3.3 Results from stage 3</td>
<td>199</td>
<td></td>
</tr>
<tr>
<td>5.4 Discussion of Test Results</td>
<td>201</td>
<td></td>
</tr>
<tr>
<td>5.4.1 Response of the wall-backfill system to backfilling</td>
<td>201</td>
<td></td>
</tr>
<tr>
<td>5.4.2 Response of the wall-backfill system to surcharge</td>
<td>204</td>
<td></td>
</tr>
<tr>
<td>5.4.3 Response of the wall-backfill system to inundation</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>5.4.4 Special considerations for finite element analyses of the IRW</td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>5.5 Finite Element Analysis Procedures</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>5.5.1 Summary of features of SOILSTRUCT-ALPHA</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>5.5.2 Finite element mesh</td>
<td>214</td>
<td></td>
</tr>
<tr>
<td>5.5.3 Tentative soil properties</td>
<td>216</td>
<td></td>
</tr>
<tr>
<td>5.5.4 Near-field interface properties</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>5.6 Calibration Analyses</td>
<td>221</td>
<td></td>
</tr>
<tr>
<td>5.6.1 Analysis of backfilling</td>
<td>221</td>
<td></td>
</tr>
<tr>
<td>5.6.2 Analysis of surcharge application and removal</td>
<td>222</td>
<td></td>
</tr>
<tr>
<td>5.7 Analysis of Backfill Inundation</td>
<td>227</td>
<td></td>
</tr>
<tr>
<td>5.8 Summary and Conclusions</td>
<td>227</td>
<td></td>
</tr>
<tr>
<td>6 Summary and Conclusions</td>
<td>231</td>
<td></td>
</tr>
<tr>
<td>6.1 Summary of Activities</td>
<td>232</td>
<td></td>
</tr>
<tr>
<td>6.1.1 Literature review</td>
<td>232</td>
<td></td>
</tr>
<tr>
<td>6.1.2 Laboratory testing</td>
<td>233</td>
<td></td>
</tr>
<tr>
<td>6.1.3 Extended hyperbolic model</td>
<td>235</td>
<td></td>
</tr>
<tr>
<td>6.1.4 Lock wall simulation</td>
<td>238</td>
<td></td>
</tr>
<tr>
<td>6.2 Recommendations for Future Work</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>References</td>
<td>241</td>
<td></td>
</tr>
</tbody>
</table>

Appendix A: Results of Triaxial and Consolidation Tests

A.1 Triaxial Tests

A.2 Consolidation Testing
List of Figures

Figure 1-1. Typical section, north wall of new RCC McAlpine Lock (adapted from Ebeling and Wahl 1997) .................................................. 4

Figure 1-2. Simplified illustration of the mechanism of downdrag and shear reversal in a typical lock wall ............................................. 6

Figure 1-3. Types of loading expected on the interface between a lock wall and the backfill ................................................................. 8

Figure 1-4. Two models for interface shear stress-displacement response under unloading (adapted from Ebeling and Wahl 1997) .......... 10

Figure 1-5. Laboratory stress paths to study the response of a wall-backfill interface ........................................................................ 12

Figure 2-1. Distortion of the sand mass during interface tests in the DSB and DSS devices ........................................................................ 19

Figure 2-2. Goodman, Taylor, and Brekke (1968) zero thickness interface element and corresponding element stiffness matrix ....... 24

Figure 2-3. Application of the Clough and Duncan (1971) interface hyperbolic model to a typical set of test data ............................ 28

Figure 2-4. Vertical and effective horizontal earth pressure forces on vertical plane extending from through the backfill from the heel of the monolith (adapted from ETL 1110-2-352 (HQUSACE 1994)) ................................................................. 34

Figure 2-5. Rock-founded retaining wall definition sketches (adapted from Filz, Duncan, and Ebeling 1997) ............................................. 36

Figure 2-6. Value of $K_{c,sol,ref}$ recommended for design (adapted from Filz, Duncan, and Ebeling 1997) .................................................. 39

Figure 2-7. Value of $K_{c,q,ref}$ recommended for design (adapted from Filz, Duncan, and Ebeling 1997) .................................................. 40

Figure 2-8. Values of the correction factors $C_\theta$, $C_N$, and $C_s$ (adapted
from Filz, Duncan, and Ebeling 1997) ............................................. 41

Figure 2-9. Values of the correction factor \( C_{\text{w}} \) recommended for design
(adapted form EM 1110-2-2100 (HQUSACE, in preparation)) ...... 43

Figure 3-1. Grain size distribution of the soils used for interface testing .......... 47

Figure 3-2. Microscopic view of the sands used for interface testing ............... 48

Figure 3-3. Hyperbolic parameter values for Density sand
and Light Castle sand and comparison to values
reported by Duncan et al. (1980) for similar soils ............................ 51

Figure 3-4. Preparation of the concrete specimen ........................................... 53

Figure 3-5. Grain size distribution of aggregates used for the preparation
of the concrete specimen .................................................................. 54

Figure 3-6. Surface texture of representative retaining walls ....................... 57

Figure 3-7. Preparation of sand-to-concrete interface and setup for testing ...... 61

Figure 3-8. View of the LDSB ready for soil-to-concrete interface testing ....... 63

Figure 3-9. Types of laboratory interface shear tests performed .................... 68

Figure 4-1. Degradation of the tangent shear stiffness during initial
loading of the dense-density-sand-to-concrete interface ................... 78

Figure 4-2. Diagram of normalized interface shear stiffness
for the dense-Density-sand-to-concrete interface ............................... 79

Figure 4-3. Unload-reload Test T203_15 on the dense-Density-sand-to-concrete Degradation................................................................. 81

Figure 4-4. Staged shear Test T105_40 on for the dense-Density-sand-to-concrete interface ................................................................. 83

Figure 4-5. Diagram of normalized interface shear stiffness
for unload-reload Test T203_15 .......................................................... 85

Figure 4-6. Diagram of normalized interface shear stiffness
for staged shear Test T105_40 .................................................................. 87

Figure 4-7. Evolution of yield surfaces during interface shear ....................... 88

Figure 4-8. Loading regions for Versions I and II of the extended
hyperbolic model ............................................................................ 90
Figure 4-9. Comparison between the normalized stiffness diagrams for Tests T203_15 and T10540 ........................................................ 91

Figure 4-10. Loading regions for Version III of the extended hyperbolic model ............................................................................................... 93

Figure 4-11. Multidirectional stress path test T205_5 on the dense-Density-Sand-to-concrete interface ................................................... 94

Figure 4-12. Multidirectional stress path Test T206_5 on the dense-Density-Sand-to-concrete interface ................................................... 98

Figure 4-13. Interface response to a set of hypothetical initial loading tests ...... 102

Figure 4-14. Type of interface response assumed in the extended hyperbolic formulation ........................................................................... 103

Figure 4-15. Determination of the interface stiffness along an inclined stress path .......................................................................................... 105

Figure 4-16. Interface response at yield for inclined stress paths in the extended hyperbolic model ................................................................. 110

Figure 4-17. Interface response assumed in Version I for unloading-reloading ......................................................................................... 116

Figure 4-18. Interface response assumed in Version II for unloading-reloading .............................................................................................. 118

Figure 4-19. Normalized interface response during transition loading assumed in Version III ................................................................. 122

Figure 4-20. Adjustment of the value of stiffness number $n_j$ of the dense-Density-sand-to-concrete interface using normalized data from initial loading tests ................................................................. 128

Figure 4-21. Normalized hyperbolic diagrams for different values of the stiffness number $K_f$ and failure ratio $R_j$ ............................................. 130

Figure 4-22. Adjustment of the value of stiffness number $K_f$ for the dense-Density-Sand-to-concrete interface ........................................... 131

Figure 4-23. Proposed approximation for the estimation of the stiffness number for unloading-reloading $K_{urj}$ ................................................. 136

Figure 4-24. Proposed approximation for the estimation of the scaling factor $\alpha$ ......................................................................................... 139
Figure 4-25. Comparison between the extended hyperbolic model and data from initial loading tests on the dense-Density-Sand-to-concrete interface .............................................................. 145

Figure 4-26. Comparison between the extended hyperbolic model and data from initial loading tests on the medium-dense-Density-sand-to-concrete interface ............................................................... 146

Figure 4-27. Comparison between the extended hyperbolic model and data from initial loading tests on the dense-Light-Castle-Sand-to-concrete interface .............................................................. 147

Figure 4-28. Comparison between the extended hyperbolic model and data from multidirectional stress path Test T205_5 performed on the dense-Density-Sand-to-concrete interface .......... 148

Figure 4-29. Application of the extended hyperbolic model for unload-reload stress paths contained in Quadrant I of the $\tau-\sigma_n$ plane ............................................................................. 150

Figure 4-30. Comparison between the extended hyperbolic model and data from Test T201_5 performed on the dense-Density-Sand-to-concrete interface .............................................................. 151

Figure 4-31. Comparison between the extended hyperbolic model and data from Test T202_5 performed on the dense-Density-sand-to-concrete interface .............................................................. 152

Figure 4-32. Comparison between the extended hyperbolic model and data from Test T203_15 performed on the dense-Density-sand-to-concrete interface .............................................................. 153

Figure 4-33. Application of the extended hyperbolic model for staged shear stress paths ............................................................................. 155

Figure 4-34. Comparison between the extended hyperbolic model and data from Test T105_40 performed on the dense-Density-sand-to-concrete interface .............................................................. 157

Figure 4-35. Comparison between the extended hyperbolic model and data from Test T106_15 performed on the dense-Density-sand-to-concrete interface .............................................................. 159

Figure 4-36. Comparison between the extended hyperbolic model and data from multidirectional stress path Test T204_5 performed on the dense-Density-Sand-to-concrete interface .......... 161

Figure 4-37. Comparison between the extended hyperbolic model
and data from multidirectional stress path Test T206_5 performed on the dense-Density-Sand-to-concrete interface .......... 164

Figure 4-38.Comparison between the extended hyperbolic model and data from multidirectional stress path Test T305_10 performed on the medium-dense-Density-sand-to-concrete interface.......................................................................................... 167

Figure 4-39.Comparison between the extended hyperbolic model and data from multidirectional stress path Test T405_10 performed on the dense-Light-Castle-Sand-to-concrete interface... 170

Figure 4-40.Procedure for the determination of the type of loading applied to an interface element during the i\textsuperscript{th} load step................... 174

Figure 4-41.Flowchart for the determination of the tangent shear stiffness of an interface element at yield during the i\textsuperscript{th} load step .... 175

Figure 4-42.Flowchart for the determination of the tangent shear stiffness of an interface element during the i\textsuperscript{th} load step, using Version I of the extended hyperbolic model ....................... 177

Figure 4-43.Flowchart for the determination of the tangent shear stiffness of an interface element during the i\textsuperscript{th} load step, using Version II of the extended hyperbolic model.......................... 178

Figure 4-44. Flowchart for the determination of the tangent shear stiffness of an interface element during the i\textsuperscript{th} load step, using Version III of the extended hyperbolic model....................... 180

Figure 5-1. The IRW test facility (after Sehn 1990).......................................... 188

Figure 5-2. Cross-section of the IRW................................................................. 189

Figure 5-3. IRW panels (after Sehn 1990) ........................................................ 190

Figure 5-4. Stages of the lock wall simulation performed in the IRW test facility.......................................................... 194

Figure 5-5. View of the IRW at different stages of the lock wall simulation .... 195

Figure 5-6. Evolution of the lateral earth pressure coefficient $K_h$ during backfilling in the IRW.......................................................... 202

Figure 5-7. Lateral pressure distribution at the end of backfilling................. 203

Figure 5-8. Evolution of the vertical shear force coefficient $K_v$ during backfilling in the IRW.......................................................... 204
Figure 5-9. Vertical shear force coefficient for surcharge $K_{v,q}$ in the IRW........ 205
Figure 5-10. Values of the correction factor $C_{wt}$ during inundation
of the backfill in the IRW ................................................................. 206
Figure 5-11. Finite element mesh used for the analyses.............................. 215
Figure 5-12. Adjustment of stress-dependent backfill property for finite
element analyses of the IRW .......................................................... 218
Figure 5-13. Results of calibration analyses of backfilling and comparison
to IRW test data.............................................................................. 223
Figure 5-14. Results of calibration analyses of surcharge and comparison
to IRW test data.............................................................................. 226
Figure 5-15. Results of finite element analyses of inundation and comparison
to IRW test data.............................................................................. 228
Figure A-1. Results of CD triaxial tests on medium-dense Density sand
Figure A-2. Results of CD triaxial tests on dense Density sand
Figure A-3. Results of CD triaxial tests on medium dense Light Castle sand
Figure A-4. Results of CD triaxial tests on dense Light Castle sand
Figure A-5. Results of consolidation tests on medium dense Density sand
Figure A-6. Results of consolidation tests on dense Density sand
Figure A-7. Results of consolidation tests on medium dense Light Castle sand
Figure A-8. Results of consolidation tests on dense Light Castle sand
Figure A-9. Relationship between hydrocompression strain and relative
density for Light Castle sand
Figure B-1. Transformed stress-strain plots from triaxial test data
on medium-dense Density sand and determination of hyperbolic
parameter values
Figure B-2. Determination of hyperbolic parameters $K$ and $n$
for medium-dense Density sand
Figure B-3. Determination of hyperbolic parameters $K_b$ and $m$
for medium-dense Density sand
Figure B-4. Hyperbolic model for medium-dense Density sand and
comparison to CD triaxial test data

Figure B-5. Transformed stress-strain plots from triaxial test data on dense Density sand and determination of hyperbolic parameter values

Figure B-6. Determination of hyperbolic parameters $K$ and $n$ for dense Density Sand

Figure B-7. Determination of hyperbolic parameters $K_b$ and $m$ for dense Density Sand

Figure B-8. Hyperbolic model for dense Density Sand and comparison to CD triaxial test data

Figure B-9. Transformed stress-strain plots from triaxial test data on medium-dense Light Castle Sand and determination of hyperbolic parameter values

Figure B-10. Determination of hyperbolic parameters $K$ and $n$ for medium-dense Light Castle sand

Figure B-11. Determination of hyperbolic parameters $K_b$ and $m$ for medium-dense Light Castle sand

Figure B-12. Hyperbolic model for medium-dense Light Castle sand and comparison to CD triaxial test data

Figure B-13. Transformed stress-strain plots from triaxial test data on dense Light Castle Sand and determination of hyperbolic parameter values

Figure B-14. Determination of hyperbolic parameters $K$ and $n$ for dense Light Castle sand

Figure B-15. Determination of hyperbolic parameters $K_b$ and $m$ for dense Light Castle sand

Figure B-16. Hyperbolic model for dense Light Castle sand and comparison to CD triaxial test data

Figure B-17. Example determination of axial and volumetric strain values at 70 and 95 percent of strength. Data from CD triaxial tests on dense Light Castle Sand

Figure B-18. Determination of the normalized values of $E_i$ and $B$ for each of the CD triaxial tests performed on dense Light Castle sand (adapted from Duncan et al. 1980)
Figure B-19. Determination of hyperbolic parameters $K$ and $n$
from the $E_i / p_a$ values determined in column (15)
of Figure B18

Figure B-20. Determination of hyperbolic parameters $K_b$ and $m$
from the $B/p_a$ values determined in column (16)
of Figure B18

Figure C-1. Results of initial loading tests on dense-Density-sand-to-concrete interface

Figure C-2. Peak and residual shear strength envelopes for initial
on dense-Density-sand-to-concrete interface

Figure C-3. Results of initial loading tests on medium-dense-Density-sand-to-concrete interface

Figure C-4. Peak and residual shear strength envelopes for initial
on medium-dense-Density-sand-to-concrete interface

Figure C-5. Results of initial loading tests on dense-Light-Castle-sand-to-concrete interface

Figure C-6. Peak and residual shear strength envelopes for initial
on dense-Light-sand-to-concrete interface

Figure C-7. Staged shear test on dense-Density-sand-to-concrete interface,
Specimen S105. Data on shear reversals are omitted

Figure C-8. Staged test on dense-Density-sand-to-concrete interface,
Specimen S106. Data on shear reversals are omitted

Figure C-9. Staged tests on dense-Density-sand-to-concrete interface,
Specimen S101

Figure C-10. Staged tests on dense-Density-sand-to-concrete interface,
Specimen S102

Figure C-11. Staged tests on dense-Density-sand-to-concrete interface,
Specimen S103

Figure C-12. Unload-reload test on dense-Density-sand-to-concrete interface,
$\sigma_n = 33$ kPa, Specimen S201

Figure C-13. Unload-reload test on dense-Density-sand-to-concrete interface,
$\sigma_n = 33$ kPa, Specimen S202

Figure C-14. Unload-reload test on dense-Density-sand-to-concrete interface,
Figure C-15. Cycle of shear reversals on dense-Density-sand-to-concrete interface, $\sigma_n = 15$ kPa, Specimen S101

Figure C-16. Cycle of shear reversals on dense-Density-sand-to-concrete interface, $\sigma_n = 33$ kPa, Specimen S102

Figure C-17. Cycle of shear reversals on dense-Density-sand-to-concrete interface, $\sigma_n = 102$ kPa, Specimen S103

Figure C-18. Cycle of shear reversals on dense-Density-sand-to-concrete interface, $\sigma_n = 274$ kPa, Specimen S104

Figure C-19. Shear reversal on medium-dense-Density-sand-to-concrete interface, $\sigma_n = 35$ kPa, Specimen S302

Figure C-20. Cycle of shear reversals on medium-dense-Density-sand-to-concrete interface, $\sigma_n = 104$ kPa, Specimen S303

Figure C-21. Cycle of shear reversals on medium-dense-Density-sand-to-concrete interface, $\sigma_n = 276$ kPa, Specimen S304

Figure C-22. Cycle of shear reversals on dense-Light-Castle-sand-to-concrete interface, $\sigma_n = 15$ kPa, Specimen S401

Figure C-23. Cycle of shear reversals on dense-Light-Castle-sand-to-concrete interface, $\sigma_n = 35$ kPa, Specimen S402

Figure C-24. Cycle of shear reversals on dense-Light-Castle-sand-to-concrete interface, $\sigma_n = 104$ kPa, Specimen S403

Figure C-25. Cycle of shear reversals on dense-Light-Castle-sand-to-concrete interface, $\sigma_n = 276$ kPa, Specimen S404

Figure C-26. Multidirectional stress path Test T204_5 on dense-Density-sand-to-concrete interface

Figure C-27. Multidirectional stress path Test T205_5 on dense-Density-sand-to-concrete interface

Figure C-28. Multidirectional stress path Test T206_5 on dense-Density-sand-to-concrete interface

Figure C-29. Multidirectional stress path Test T305_10 on dense-Density-sand-to-concrete interface

Figure C-30. Multidirectional stress path Test T405_10 on dense-Density-
sand-to-concrete interface

Figure D-1. Transformed plots for initial loading tests on dense-Density-sand-to-concrete interface

Figure D-2. Determination of hyperbolic parameters $K_i$ and $n_i$
for dense-Density-sand-to-concrete interface

Figure D-3. Comparison between the hyperbolic model and data
from initial loading tests on dense-Density-sand-to-concrete interface

Figure D-4. Transformed plots for initial loading tests on medium-dense-Density-sand-to-concrete interface

Figure D-5. Determination of hyperbolic parameters $K_i$ and $n_i$
for medium-dense-Density-sand-to-concrete interface

Figure D-6. Comparison between the hyperbolic model and data
from initial loading tests on medium-dense-Density-sand-to-concrete interface

Figure D-7. Transformed plots for initial loading tests on dense-Light-Castle-sand-to-concrete interface

Figure D-8. Determination of hyperbolic parameters $K_i$ and $n_i$
for dense-Light-Castle-sand-to-concrete interface

Figure D-9. Comparison between the hyperbolic model and data from initial loading tests on dense-Light-Castle-sand-to-concrete interface

Figure D-10. Example determination of interface displacements
at 70 and 95 percent of strength. Data from interface tests on dense Light Castle sand

Figure D-11. Determination of the normalized valued of $K_{ni}$ for each of the initial loading tests performed on the dense-Light-Castle-sand-to-concrete interface

Figure D-12. Determination of hyperbolic parameters $K_i$ and $n_i$ from the $K_{ni} / \gamma_e$ values determined in column (12) of Figure D-11
List of Tables

Table 1-1 Summary of Results from SSI Analyses for the North Lock at McAlpine Locks (adapted from Ebeling and Wahl, 1997) .......... 5

Table 1-2. Comparison of Results of SSI Analysis at Section A-A for Two Different Models of Interface Response to Unloading (adapted from Ebeling and Wahl, 1997) ....................... 9

Table 2-1. Previous Work on Direct Shear Testing of Sand-to-Concrete and Sand-to-Steel Interfaces ............................................................. 18

Table 2-2. Previous Work on Direct Simple Shear Testing to Sand-to-Concrete and Sand-to-Steel Interfaces ............................ 20

Table 3-1. Characteristics of the Soils Used for Interface Testing ......................... 46

Table 3-2. Summary of Results of CD Triaxial Tests ...................................... 49

Table 3-3. Hyperbolic Parameter Values of Soils Used for Interface Testing .... 50

Table 3-4. Mixing Proportions of Concrete ....................................................... 55

Table 3-5. Physical Properties of the Concrete Mix ........................................... 55
Table 4-16. Summary of Parameter Values for Unloading-Reloading of the Medium Dense Density Sand against Concrete Interface...... 143

Table 4-17. Summary of Parameter Values for Unloading-Reloading of the Dense Light Castle Sand against Concrete Interface............ 143

Table 5-1. Features of the Data Acquisition System for the Lock Wall Simulation................................................................. 192

Table 5-2. Summary of the Force Measurements during Stage 1 of the IRW Test (Backfilling)....................................................... 197

Table 5-3. Data From Gloetzl Pressure Cells at the End of Stage 1 (Backfilling) ........................................................................ 198

Table 5-4. Summary of the Results of Stage 2 of the IRW (Surcharge) ....... 199

Table 5-5. Summary of the Results of Stage 3 of the IRW (Inundation) ....... 200

Table 5-6. Summary of Soil Properties Required in SOILSTRUCT-ALPHA Analyses ................................................................. 213

Table 5-7. Summary of Property Values for Structural Materials in the IRW Analyses.................................................................. 214

Table 5-8. Tentative Property Values for the Light Castle Sand Backfill ...... 216

Table 5-9. Property Values of the Wall-Backfill Interface used for the Finite Element Analyses of the IRW ................................. 221

Table 5-10. Backfill Property Values Determined from Calibration Analyses of Stage 1 of the IRW Test........................................ 222

Table 5-11. Backfill Property Values Determined from Calibration Analyses of Stage 2 of the IRW Test........................................ 225

Table B-1. Determination of Bulk Modulus for Medium Dense Density Sand ..............................................................................B5

Table B-2. Determination of Bulk Modulus for Dense Density Sand. .........B5

Table B-3. Determination of Bulk Modulus for Medium-Dense Light Castle Sand........................................................................B5

Table B-4. Determination of Bulk Modulus for Dense Light Castle Sand ......B6

Table C-1. Organization of the Figures in Appendix C..........................C1
Table E-1. Summary of State Parameters at Selected Points along in Multidirectional stress path T405_10 ......................................................E2

Table E-2. Summary of Hyperbolic Parameter Values for the Dense-Light-Castle-Sand-against-Concrete Interface .......................................E2

Table E-3. Summary of Parameter Values for Unloading-Reloading of the Dense-Light-Castle-Sand-against-Concrete Interface ..........E4