

Appendix H

Details of the Dynamic Numerical Analyses

Part of: The Use of Waste Rock Inclusions to Control the Effects
of Liquefaction in Tailings Impoundments

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This appendix presents the results of numerical modeling of the conceptual impoundment subjected to evaluation earthquakes E1, E2, E4, and E5, as well as additional figures from the numerical analyses. The additional figures are provided in “pdf” format on the enclosed CD-ROM disk.

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Conceptual Tailings Impoundment without Waste Rock Inclusions
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- | | |
|---|-------------------------------------|
| 1 | FLAC Model |
| 2 | Static vertical effective stress. |
| 3 | Static horizontal effective stress. |
| 4 | Hydrostatic porewater pressure. |

Earthquake E2 ($M_w=6.75$)
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- | | |
|----|---|
| 5 | Horizontal acceleration input to bottom of model. |
| 6 | Horizontal acceleration calculated on top of bedrock. |
| 7 | Horizontal acceleration calculated on top of glacial till. |
| 8 | Horizontal acceleration calculated on crest of dike. |
| 9 | Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1. |
| 10 | Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2. |
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- 18 Horizontal displacement at the end of shaking.
19 Vertical displacement at the end of shaking.

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- 20 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
21 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
22 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
23 Displacement of the crest of the dike.
24 Vertical effective stress at the end of the post-shaking analysis.
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26 Porewater pressure at the end of the post-shaking analysis.
27 Horizontal displacement at the end of the post-shaking analysis.
28 Vertical displacement at the end of the post-shaking analysis.

Earthquake E4 ($M_w=7.25$)

- 29 Horizontal acceleration input to bottom of model.
30 Horizontal acceleration calculated on top of bedrock.
31 Horizontal acceleration calculated on top of glacial till.
32 Horizontal acceleration calculated on crest of dike.
33 Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
34 Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
35 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
36 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
37 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
38 Displacement of the crest of the dike during shaking.
39 Vertical effective stress at the end of shaking.
40 Horizontal effective stress at the end of shaking.
41 Porewater pressure at the end of shaking.
42 Horizontal displacement at the end of shaking.
43 Vertical displacement at the end of shaking.

Post-shaking (Earthquake E4)

- 44 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
45 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
46 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
47 Displacement of the crest of the dike.
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50 Porewater pressure at the end of the post-shaking analysis.
51 Horizontal displacement at the end of the post-shaking analysis.

52 Vertical displacement at the end of the post-shaking analysis.

Conceptual Tailings Impoundment without Waste Rock Inclusions
Variation of degree of consolidation of impounded tailings.
Variation of $(N_1)_{60}$ of impounded tailings.

$(N_1)_{60} = 2.5$ - Earthquake E4 (Mw=7.25)

53	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
54	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
55	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
56	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
57	Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
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59	Vertical effective stress at the end of shaking.
60	Horizontal effective stress at the end of shaking.
61	Porewater pressure at the end of shaking.
62	Horizontal displacement at the end of shaking.
63	Vertical displacement at the end of shaking.

$(N_1)_{60} = 4.5$ - Earthquake E5 (Mw=7.5)

64	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
65	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
66	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
67	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
68	Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
69	Displacement of the crest of the dike during shaking.
70	Vertical effective stress at the end of shaking.
71	Horizontal effective stress at the end of shaking.
72	Porewater pressure at the end of shaking.
73	Horizontal displacement at the end of shaking.
74	Vertical displacement at the end of shaking.

$(N_1)_{60} = 7.5$ - Earthquake E5 (Mw=7.5)

- 75 Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
- 76 Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 77 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
- 78 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 79 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
- 80 Displacement of the crest of the dike during shaking.
- 81 Vertical effective stress at the end of shaking.
- 82 Horizontal effective stress at the end of shaking.
- 83 Porewater pressure at the end of shaking.
- 84 Horizontal displacement at the end of shaking.
- 85 Vertical displacement at the end of shaking.

$(N_1)_{60} = 11$ - Earthquake E5 (Mw=7.5)

- 86 Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
- 87 Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 88 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
- 89 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 90 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
- 91 Displacement of the crest of the dike during shaking.
- 92 Vertical effective stress at the end of shaking.
- 93 Horizontal effective stress at the end of shaking.
- 94 Porewater pressure at the end of shaking.
- 95 Horizontal displacement at the end of shaking.
- 96 Vertical displacement at the end of shaking.

Conceptual Tailings Impoundment without Waste Rock Inclusions
Compaction of tailings used to construct the dike.
Variation of (N₁)₆₀ of impounded tailings.

(N₁)₆₀ = 22 - Earthquake E5 (M_w=7.5)

97	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
98	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
99	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
100	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
101	Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
102	Displacement of the crest of the dike during shaking.
103	Vertical effective stress at the end of shaking.
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105	Porewater pressure at the end of shaking.
106	Horizontal displacement at the end of shaking.
107	Vertical displacement at the end of shaking.

Conceptual Tailings Impoundment with Waste Rock Inclusions

108	FLAC Model
109	Static vertical effective stress.
110	Static horizontal effective stress.
111	Hydrostatic porewater pressure.

Earthquake E2 (M_w=6.75)

112	Horizontal acceleration input to bottom of model.
113	Horizontal acceleration calculated on top of bedrock.
114	Horizontal acceleration calculated on top of glacial till.
115	Horizontal acceleration calculated on crest of dike.
116	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
117	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
118	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
119	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
120	Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
121	Displacement of the crest of the dike during shaking.
122	Vertical effective stress at the end of shaking.
123	Horizontal effective stress at the end of shaking.
124	Porewater pressure at the end of shaking.
125	Horizontal displacement at the end of shaking.
126	Vertical displacement at the end of shaking.

Post-shaking (Earthquake E2)

- 127 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
- 128 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 129 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 130 Displacement of the crest of the dike.
- 131 Vertical effective stress at the end of the post-shaking analysis.
- 132 Horizontal effective stress at the end of the post-shaking analysis.
- 133 Porewater pressure at the end of the post-shaking analysis.
- 134 Horizontal displacement at the end of the post-shaking analysis.
- 135 Vertical displacement at the end of the post-shaking analysis.

Earthquake E4 ($M_w=7.25$)

- 136 Horizontal acceleration input to bottom of model.
- 137 Horizontal acceleration calculated on top of bedrock.
- 138 Horizontal acceleration calculated on top of glacial till.
- 139 Horizontal acceleration calculated on crest of dike.
- 140 Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
- 141 Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 142 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
- 143 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 144 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 145 Displacement of the crest of the dike during shaking.
- 146 Vertical effective stress at the end of shaking.
- 147 Horizontal effective stress at the end of shaking.
- 148 Porewater pressure at the end of shaking.
- 149 Horizontal displacement at the end of shaking.
- 150 Vertical displacement at the end of shaking.

Post-shaking (Earthquake E4)

- 151 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
- 152 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 153 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
- 154 Displacement of the crest of the dike.
- 155 Vertical effective stress at the end of the post-shaking analysis.
- 156 Horizontal effective stress at the end of the post-shaking analysis.
- 157 Porewater pressure at the end of the post-shaking analysis.
- 158 Horizontal displacement at the end of the post-shaking analysis.
- 159 Vertical displacement at the end of the post-shaking analysis.

Conceptual Tailings Impoundment with Waste Rock Inclusions
Hydraulic conductivity of the waste rock inclusions.
Variation of (N1)60 of impounded tailings.

$k_{WR}=1 \times 10^{-4}$ m/s - Earthquake E1 ($M_w=6.5$)

160	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
161	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
162	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
163	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
164	Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
165	Displacement of the crest of the dike during shaking.
166	Vertical effective stress at the end of shaking.
167	Horizontal effective stress at the end of shaking.
168	Porewater pressure at the end of shaking.
169	Horizontal displacement at the end of shaking.
170	Vertical displacement at the end of shaking.

$k_{WR}=1 \times 10^{-4}$ m/s - Earthquake E3 ($M_w=7$)

171	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
172	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
173	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
174	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
175	Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
176	Displacement of the crest of the dike during shaking.
177	Vertical effective stress at the end of shaking.
178	Horizontal effective stress at the end of shaking.
179	Porewater pressure at the end of shaking.
180	Horizontal displacement at the end of shaking.
181	Vertical displacement at the end of shaking.

$k_{WR}=1 \times 10^{-4}$ m/s - Earthquake E5 ($M_w=7.5$)

182	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
183	Cyclic stress ratio, CSR, at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
184	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
185	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
186	Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
187	Displacement of the crest of the dike during shaking.
188	Vertical effective stress at the end of shaking.
189	Horizontal effective stress at the end of shaking.
190	Porewater pressure at the end of shaking.
191	Horizontal displacement at the end of shaking.
192	Vertical displacement at the end of shaking.

Conceptual Tailings Impoundment with Waste Rock Inclusions
Configuration of the waste rock inclusions.
Variation of (N1)60 of impounded tailings.

Case A: 5 Inclusions, 8-m-wide, 20-m spacing (center-to-center).

193	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
194	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
195	Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
196	Displacement of the crest of the dike during shaking.
197	Vertical effective stress at the end of shaking.
198	Horizontal effective stress at the end of shaking.
199	Porewater pressure at the end of shaking.
200	Horizontal displacement at the end of shaking.
201	Vertical displacement at the end of shaking.

Case B: 5 Inclusions, 4-m-wide, 20-m spacing (center-to-center).

202	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
203	Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
204	Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
205	Displacement of the crest of the dike during shaking.
206	Vertical effective stress at the end of shaking.
207	Horizontal effective stress at the end of shaking.
208	Porewater pressure at the end of shaking.
209	Horizontal displacement at the end of shaking.
210	Vertical displacement at the end of shaking.

Case C: 2 Inclusions, 8-m-wide, 20-m spacing (center-to-center).

- 211 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
212 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
213 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
214 Displacement of the crest of the dike during shaking.
215 Vertical effective stress at the end of shaking.
216 Horizontal effective stress at the end of shaking.
217 Porewater pressure at the end of shaking.
218 Horizontal displacement at the end of shaking.
219 Vertical displacement at the end of shaking.

Case D: 3 Inclusions, 6-m-wide, 20-m spacing (center-to-center).

- 220 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
221 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
222 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
223 Displacement of the crest of the dike during shaking.
224 Vertical effective stress at the end of shaking.
225 Horizontal effective stress at the end of shaking.
226 Porewater pressure at the end of shaking.
227 Horizontal displacement at the end of shaking.
228 Vertical displacement at the end of shaking.

Case E: 5 Inclusions, 8-m-wide, 24-m spacing (center-to-center).

- 229 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
230 Excess porewater pressure ratio, r_u , at 0.275H, 0.475H, 0.675H, and 0.875H at P2.
231 Porewater pressure development, at 0.275H, 0.475H, 0.675H, and 0.875H at P1.
232 Displacement of the crest of the dike during shaking.
233 Vertical effective stress at the end of shaking.
234 Horizontal effective stress at the end of shaking.
235 Porewater pressure at the end of shaking.
236 Horizontal displacement at the end of shaking.
237 Vertical displacement at the end of shaking.

H1. ANALYSES OF THE CONCEPTUAL IMPOUNDMENT - EARTHQUAKE E1 ($M_w=6.5$)

The models of the conventional and reinforced conceptual impoundments were analyzed using Earthquake E1 which simulated a moment magnitude 6.5 event with a PGA of 0.229g (on hard rock) and a duration of 25 seconds.. The results are summarized in this section. The static conditions are presented in Sections 6.4.4.1 and 6.4.4.2 for the conventional and reinforced models, respectively.

H1.1 Dynamic Analysis – Conventional Impoundment

The PGA values and amplification factors calculated by FLAC at various points in the model are presented on Table H1-1. The horizontal accelerations underwent moderate amplification between the top of bedrock and the top of glacial till, severe damping within the tailings and high amplification at the crest of the dike.

Table H1-1 – Calculated amplification factors
– conventional impoundment, Earthquake E1 ($M_w=6.5$).

Location	Peak Horizontal Ground Acceleration, PGA (g)	Amplification Factor (F_a)
Top of bedrock	0.249	-
Top of glacial till	0.315	1.265
Surface of Impoundment at P1	0.095	0.382
Surface of Impoundment at P2	0.100	0.402
Crest of dike	0.664	2.667

The excess porewater pressures ratios, r_u , developed in the tailings at locations P1 and P2 are plotted on Figure H1-1. The r_u values increased rapidly at the onset of shaking and varied between 0.75 and 1.0 by the 10th second. At the end of shaking ($t=25.0$ s), the r_u

values ranged from 0.68 to 0.99. There was evidence of drainage at 0.875H, near the surface of the impoundment.

Figure H1-2 shows the horizontal and vertical displacement of the crest of the dike during shaking. The displacement was essentially complete by the 4th second of shaking after which only minimal movement occurred. At the end of shaking the crest had been displaced 0.75 m downstream and 0.45 m downwards.

The vertical effective stresses at the end of shaking are shown on Figure H1-3. The low stresses (0 to 50 kPa) within most of the impoundment are indicative of very high excess porewater pressure development. However, the stresses in the bottom of the tailings and in the tailings underlying the downstream slope of the dike vary from 100 to 250 kPa, indicating that the excess porewater pressure generation in these areas was limited.

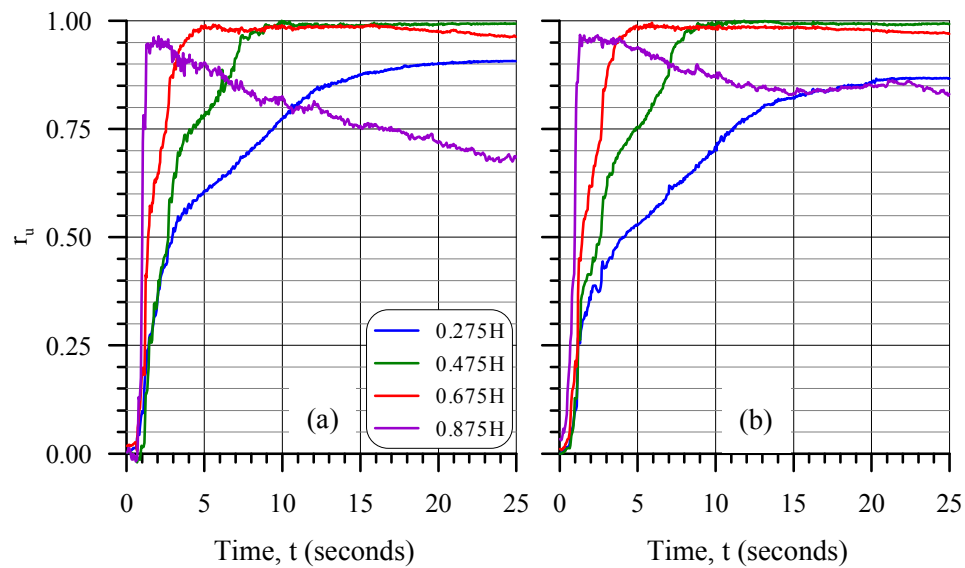


Figure H1-1 – Excess porewater pressure ratio, r_u , developed in the tailings at P1 (a) and at P2 (b) in the conventional impoundment – Earthquake E1 ($M_w=6.5$).

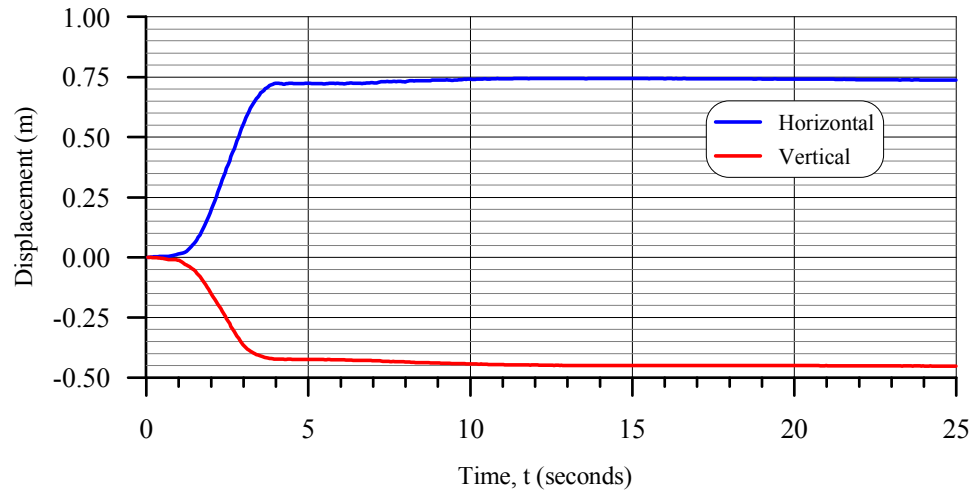


Figure H1-2 – Displacement of the crest of the dike during shaking – conventional impoundment, Earthquake E1 ($M_w=6.5$).

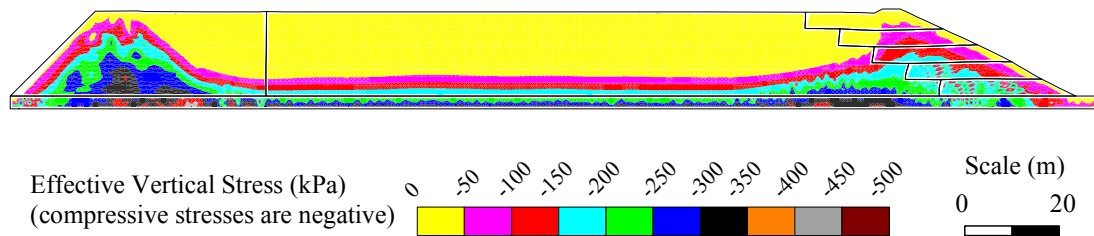


Figure H1-3 – Vertical effective stress at the end of shaking – conventional impoundment, Earthquake E1 ($M_w=6.5$).

Contours of the horizontal displacement of the impoundment at the end of shaking are shown on Figure H1-4. Displacements were concentrated in the area of the dike and a maximum displacement of about 1.0 m occurred in the center of the downstream slope and was directed downstream.

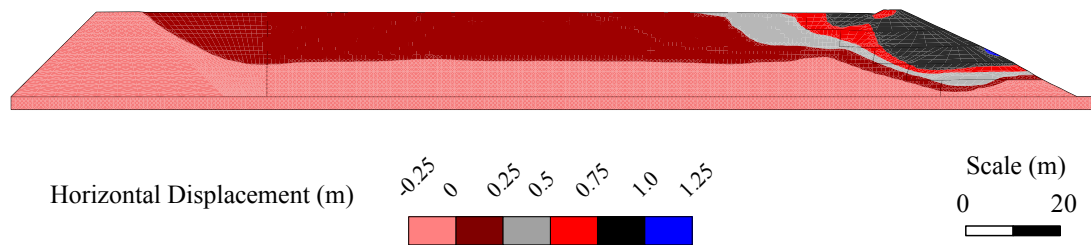


Figure H1-4 – Horizontal displacement at the end of shaking – conventional impoundment, Earthquake E1 ($M_w=6.5$).

H1.2 Post-shaking Analysis – Conventional Impoundment

The excess porewater pressure ratio development in the tailings at locations P1 and P2 during the dynamic and post-shaking phases analyses are displayed on Figure H1-5. At both locations there was a rapid decrease in the porewater pressures following the dynamic loading. At P1 the decrease in the porewater pressures was followed by a gradual decline to relatively constant r_u values indicative of steady state flow by the end of the analysis ($t=200$ s). At P2 the decrease was followed by a period of sudden increases and gradual decreases and the porewater pressures were not yet stable by the 200th second (the end of the post-shaking phase). The sudden changes in the r_u values at P2 are attributed to non-uniformity in the excess porewater pressures generated within the tailings and to the heterogeneity and anisotropy assigned to the hydraulic conductivity of the tailings.

Porewater pressures within the impoundment at $t=200$ s were comparable to the hydrostatic conditions prior to shaking. Thus, the non-zero r_u values at the end of the analyses are attributed to stress redistribution within the tailings.

The horizontal and vertical displacements of the crest of the dike during the dynamic and post-shaking phases are shown on Figure H1-6. During the post-shaking analysis, there was a very slight decrease in the downstream horizontal displacement and no significant vertical displacement of the crest.

The vertical effective stresses in the model at the end of the post-shaking analysis are contoured on Figure H1-7. Generally, the vertical effective stresses at the end of the analysis were similar to those resulting from the static analysis, except for stress concentrations on the upstream side of the starter dike as high as 350 kPa, which were as much as 200 kPa higher than those resulting from the static analysis, and lower stresses in the tailings immediately upstream of the starter dike. There was a redistribution of stresses from the tailings to the starter dike as a result of the earthquake loading.

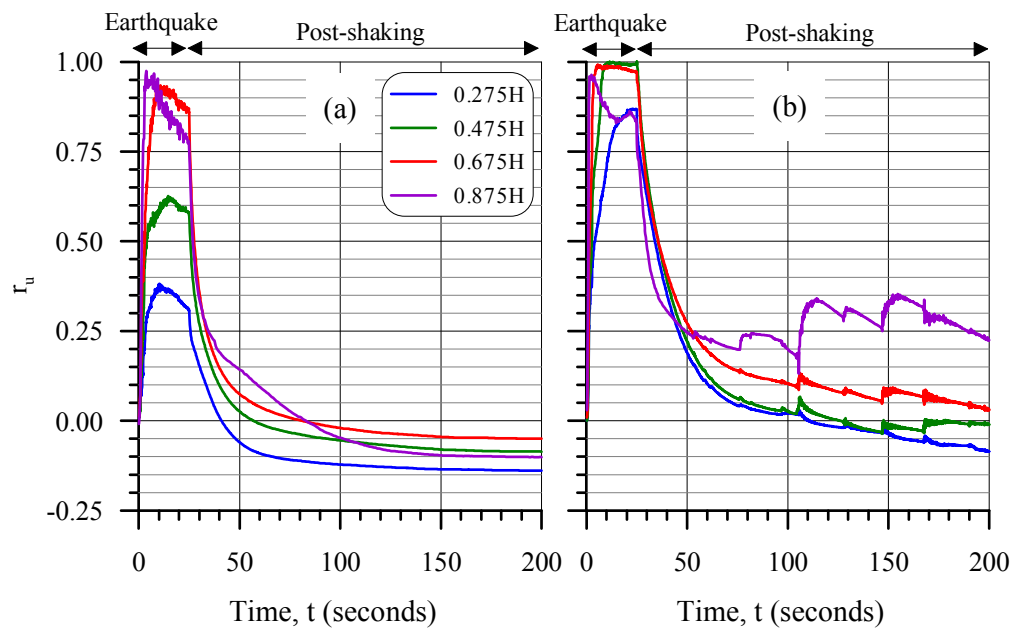


Figure H1-5 – Post-shaking dissipation of porewater pressure at locations P1 (a) and P2 (b) - conventional impoundment, Earthquake E1 ($M_w=6.5$).

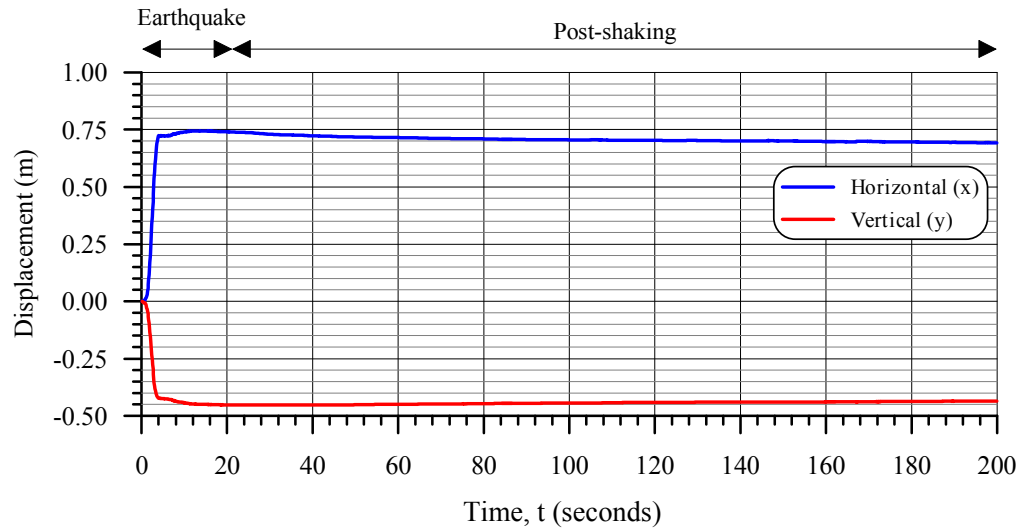


Figure H1-6 – Post-shaking displacements of the crest of the dike – conventional impoundment, Earthquake E1 ($M_w=6.5$).

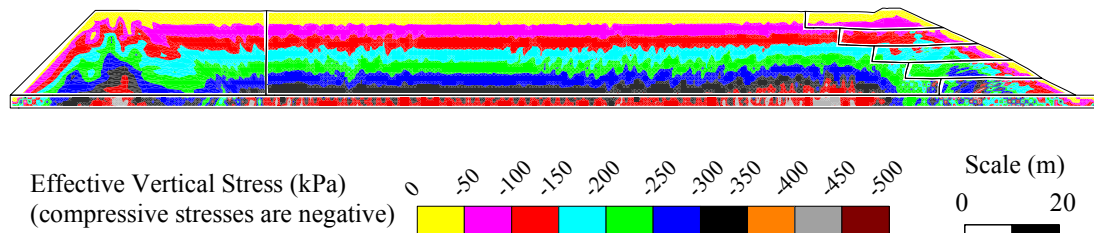


Figure H1-7 – Vertical effective stresses at the end of the post-shaking analysis – conventional impoundment, Earthquake E1 ($M_w=6.5$).

Contours of the horizontal displacement of the impoundment at the end of the post-shaking analysis are shown on Figure H1-8. Comparing this figure to the contours of the horizontal displacement at the end of shaking (Figure H1-4) shows that there was no significant displacement within the impoundment during the post-shaking analysis, except for about 0.25 of outwards bulging of the center of the downstream slope.

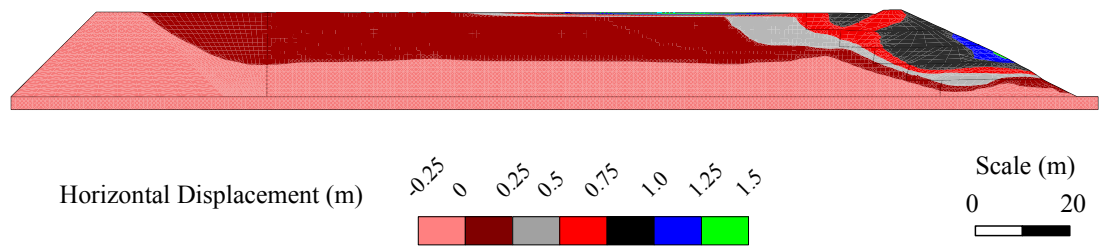


Figure H1-8 – Post-shaking horizontal displacement
– conventional impoundment, Earthquake E1 ($M_w=6.5$).

H1.3 Dynamic Analysis – Reinforced Impoundment

The site response of the reinforced impoundment was inferred from the PGA values extracted from FLAC. These are provided on Table H1-2 along with the calculated amplification factors, F_a , and indicate very high amplification of the horizontal accelerations within the 2-m-thick layer of glacial till between bedrock and the bottom of the tailings, moderately high damping within the tailings at location P1, no significant amplification or damping on the waste rock inclusion at P2, and high amplification at the crest of the dike.

Table H1-2 – Calculated amplification factors
– reinforced impoundment, Earthquake E1 ($M_w=6.5$).

Location	Peak Horizontal Ground Acceleration, PGA (g)	Amplification Factor (F_a)
Top of bedrock	0.255	-
Top of glacial till	0.486	1.906
Surface of Impoundment at P1	0.116	0.455
Surface of Impoundment at P2	0.250	0.957
Crest of dike	0.545	2.137

The variation in the excess porewater pressures at P1 and P2 are shown on Figure H1-9 using the excess porewater pressure ratio, r_u . The excess porewater responses at these two locations were quite different as described below.

In the tailings at P1, the excess porewater pressures increased fairly rapidly at the start of shaking, leveled off, and then decreased slowly until the end of shaking. The maximum value of r_u varied with depth, a maximum of 0.38 occurred at 0.275H and a maximum of

0.97 occurred at 0.875H. By the end of shaking, the r_u values varied from 0.3 at 0.275H to 0.87 at 0.675H. The decrease in the excess porewater pressures in the latter 15 seconds of shaking are attributed to drainage at the surface.

At location P2 (the center of a waste rock inclusion), the r_u values varied between -0.9 and 0.8, as shown on Figure H1-9. The variation is attributed to both changes in the porewater pressure and stress redistribution within the inclusion.

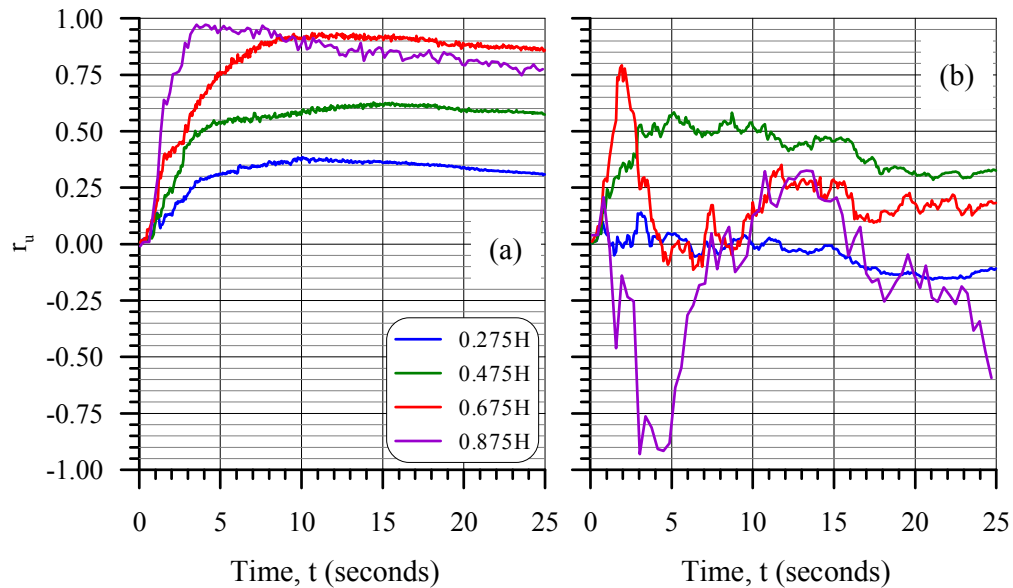


Figure H1-9 – Excess porewater pressure ratio, r_u , developed in at P1 (a) and P2 (b) in the reinforced impoundment – Earthquake E1 ($M_w=6.5$).

The vertical and horizontal displacements of the crest of the dike during shaking are presented on Figure H1-10. During the first 11 seconds of shaking, the crest moved downstream and downwards at nearly constant rates. After this period, the crest moved slightly upstream at a very low rate and the downwards movement continued at a very low rate. By the end of shaking the crest of the dike had displaced 0.045 m downstream and 0.058 m downwards.

Figure H1-11 presents contours of the vertical effective stresses within the reinforced impoundment at the end of shaking. Comparing these stresses to the static vertical effective stresses prior to shaking leads to the following observations:

- a) The vertical effective stresses in the upper two-thirds of the retained tailings and in the upper half of the waste rock inclusions were greatly reduced during shaking;
- b) Generally, the vertical effective stresses at the bottom of the retained tailings decreased by about 50 kPa during shaking; and
- c) The vertical effective stresses in the tailings underlying the dam and the lower zones of the waste rock inclusions increased by 50 to 100 kPa during shaking.

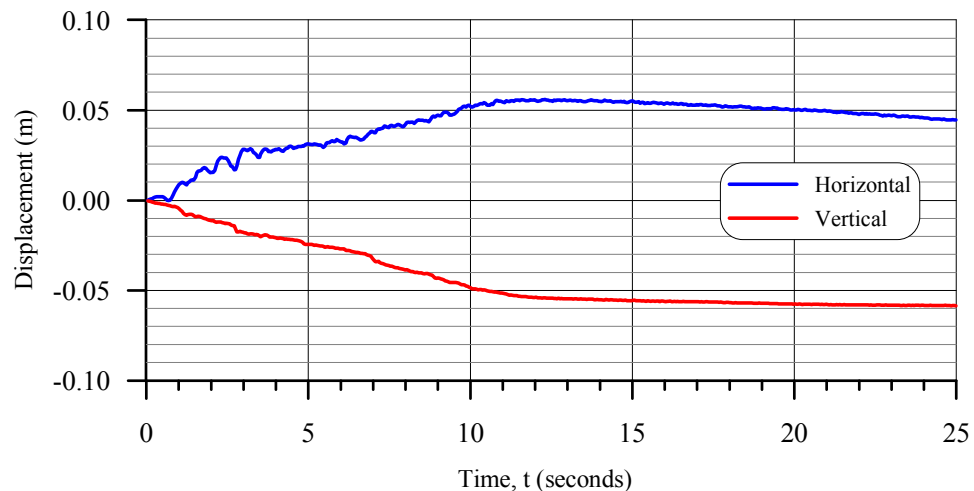


Figure H1-10 – Displacement of the crest of the dike during shaking – reinforced impoundment, Earthquake E1 ($M_w=6.5$).

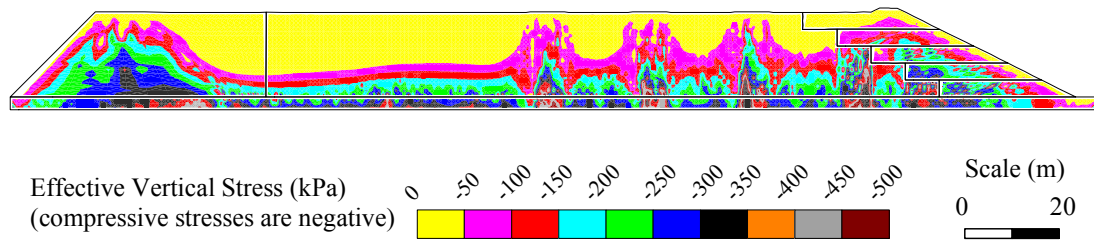


Figure H1-11 – Vertical effective stress at the end of shaking – reinforced impoundment, Earthquake E1 ($M_w=6.5$).

As shown on Figure H1-12, the displacements in the reinforced impoundment at the end of shaking were as great as 0.25 m and were concentrated in the upper portion of the dike and the adjacent area of the impoundment.

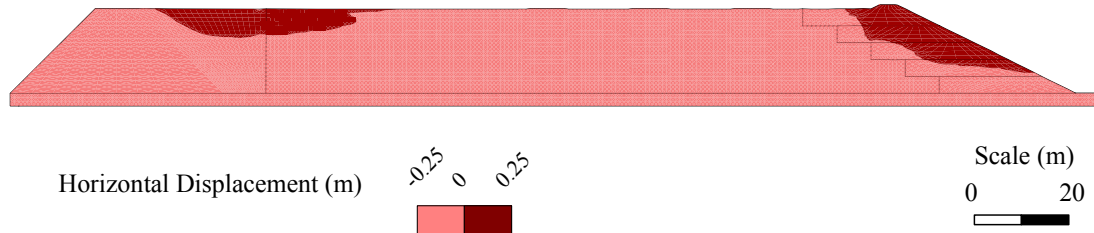


Figure H1-12 – Horizontal displacement at the end of shaking – reinforced impoundment, Earthquake E1 ($M_w=6.5$).

H1.4 Post-shaking Analysis – Reinforced Impoundment

The r_u development within the impoundment at locations P1 and P2 after shaking are presented on Figure H1-13. At P1, in the tailings, the excess porewater pressures dissipated rapidly after the end of shaking and were relatively stable by the 100th second. The stability of the r_u values at the end of the post-shaking analysis is indicative of steady state flow conditions. The r_u values at P1 at the end of the analysis varied from -0.05 to -

0.15. These negative values indicate that the vertical effective stresses at P1 were 5 to 15% lower than those calculated during the static analysis.

Location P2 coincided with the center of a waste rock inclusion. At this location, the r_u values indicate that there was a rapid, moderate increase in the excess porewater pressure after shaking, which was followed by a period of dissipation and then stabilization of the vertical effective stresses.

By the end of the analysis ($t=200$ s), porewater pressures had returned to hydrostatic conditions.

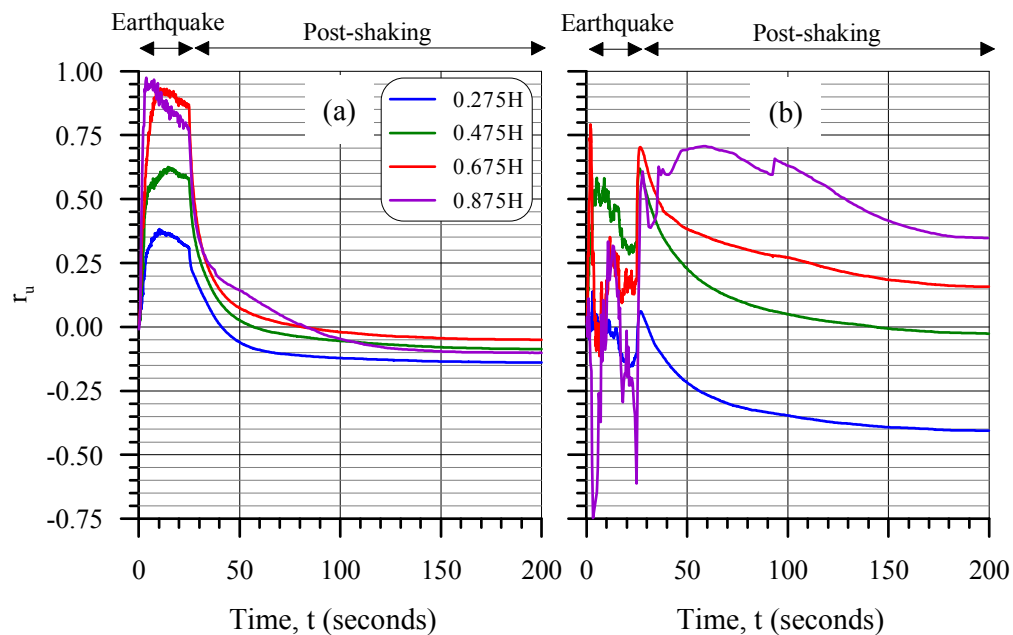


Figure H1-13 – Post-shaking dissipation of porewater pressure at locations P1 (a) and P2 (b) – reinforced impoundment, Earthquake E1 ($M_w=6.5$).

The vertical effective stresses at the end of the post-shaking analysis are plotted on Figure H1-14. In general, the stresses returned to the levels from the static analysis of the

impoundment, except that the stress transfer evident in the static analysis is less pronounced, particularly in the vicinity of the waste rock inclusions.

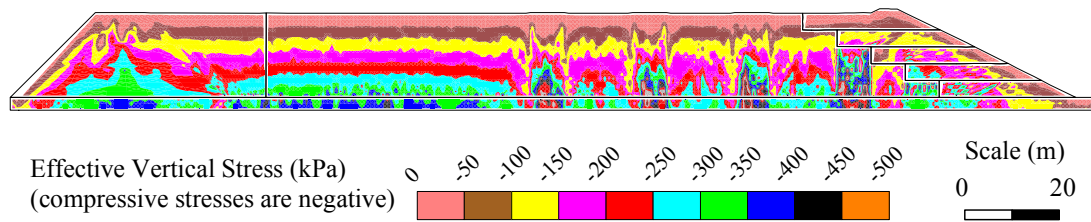


Figure H1-14 – Vertical effective stresses at the end of the post-shaking analysis – reinforced impoundment, Earthquake E1 ($M_w=6.5$).

Following shaking, the crest of the dike moved about 0.1 m upstream and there was no vertical movement. Otherwise, post-shaking deformation of the impoundment was limited to less than 0.25 m of outward bulging of the center of the downstream slope of the dike.

H2. ANALYSES OF THE CONCEPTUAL IMPOUNDMENTS - EARTHQUAKE E2 ($M_w=6.75$)

This section presents a very brief summary of the results of the dynamic and post-shaking analyses of the conventional and reinforced impoundments with respect to the Earthquake E2 ground motion. Additional details are provided in Appendix H.

H2.1 The Conventional Impoundment

During shaking, the development of the excess porewater pressure ratio, r_u , in the tailings at P1 and P2 indicated rapid increases in excess porewater pressures at the onset of shaking leading to values approaching 1.0, except near the surface, where drainage was evident (see Figure H2-1).

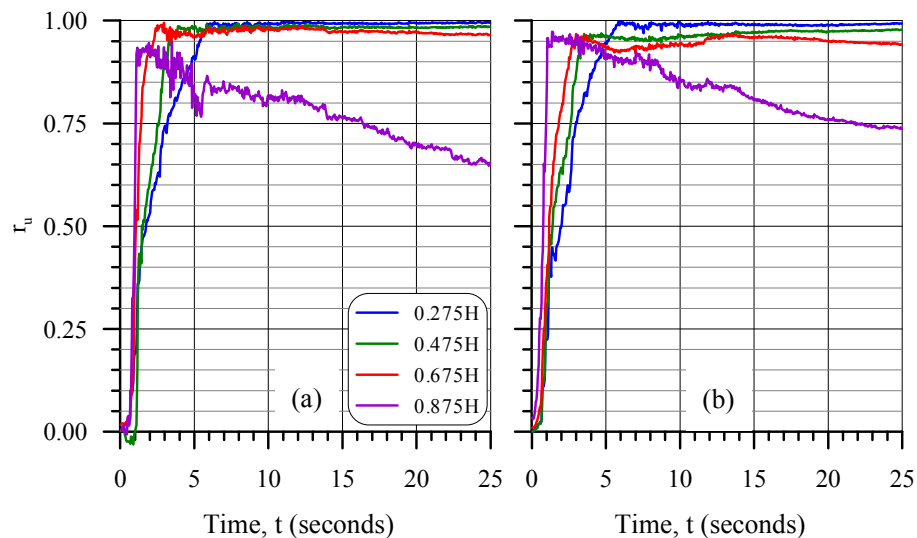


Figure H2-1 – Excess porewater pressure ratio, r_u , at P1 (a) and P2 (b)
- conventional impoundment, Earthquake E2 ($M_w=6.75$).

At the end of shaking, the respective horizontal and vertical displacements of the crest of the dike were 1.26m (downstream) and 0.55 m (downwards).

At the end of shaking, the vertical effective stresses within the retained tailings were very low (less than 50 kPa). Vertical effective stresses in the tailings below the dike and comprising the dike were not significantly lower than prior to shaking.

The dissipation of excess porewater pressures at P1 and P2 following shaking is shown on Figure H2-2. By the end of the post-shaking analysis, steady state flow conditions were approached. At P1, the r_u values at $t=200$ s varied from -0.33 at 0.875H to 0.1 at 0.275H, indicating that there was an increase in the vertical effective stresses in the upper portion of the tailings and a decrease in the vertical effective stresses in the lower portion. At P2, the r_u values at $t=200$ s varied from 0.1 to 0.15 and are indicative of moderately low increases in vertical effective stresses within the tailings.

By the end of the post-shaking analysis ($t=200$ s), porewater pressures within the impoundment returned to the hydrostatic conditions that existing prior to shaking.

There was no appreciable horizontal or vertical movement of the crest following shaking.

The vertical effective stresses within the impoundment at the end of the post-shaking analysis are plotted on Figure H2-3. In comparing these stresses to those prior to shaking, it is observed that the vertical effective stresses after the dissipation of excess porewater pressures were very similar to those from before shaking, varying from 0 at the surface to about 350 kPa at the bottom of the tailings.

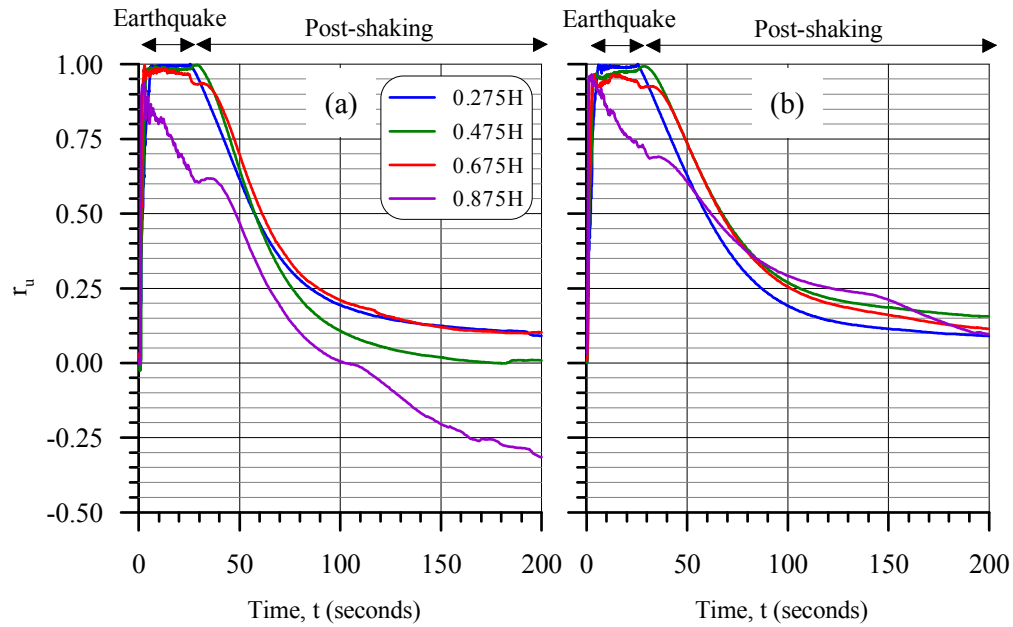


Figure H2-2 – Post-shaking dissipation of porewater pressure at locations P1 (a) and P2 (b) – conventional impoundment, Earthquake E2 ($M_w=6.75$).

Horizontal displacements of the impoundment at the end of the post-shaking analysis are shown on Figure H2-4. The displacements were focused in the areas of the dike and a maximum horizontal displacement of about 1.75 m (downstream) occurred on the downstream slope, just above the starter dike.

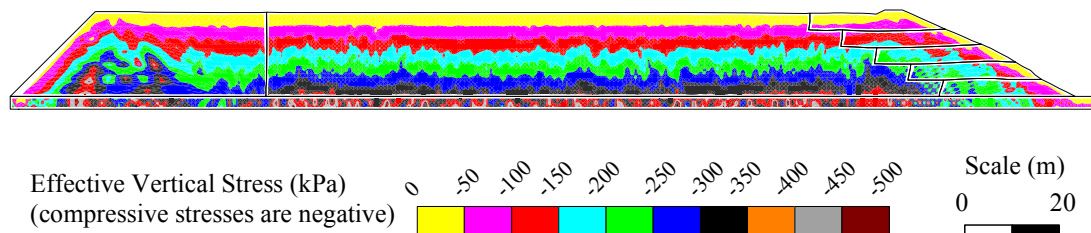


Figure H2-3 – Vertical effective stress at the end of the post-shaking analysis – conventional impoundment, Earthquake E2 ($M_w=6.75$).

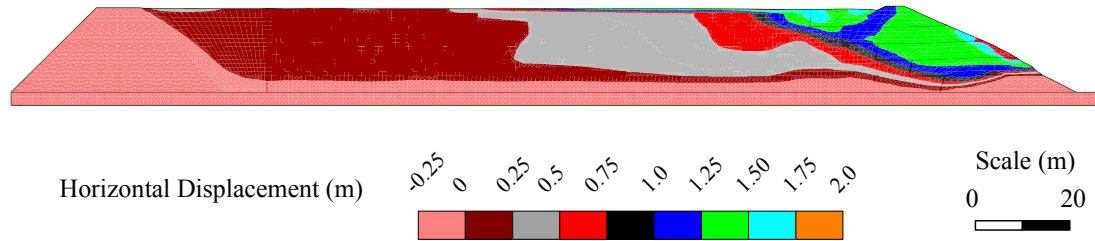


Figure H2-4 – Post-shaking horizontal displacement
– conventional impoundment, Earthquake E2 ($M_w=6.75$).

H2.2 The Reinforced Impoundment

The r_u values developed at P1 and P2 during shaking are plotted on Figure H2-5. In the tailings at P1, the r_u values increased rapidly and reached 0.9 or greater within 3 to 10 seconds. After the 10th second, the r_u values declined at a relatively low rate and varied from 0.7 to 0.94 by the end of shaking ($t=25$ s). At P2 (a waste rock inclusion), the r_u response varied significantly with depth, but was characterized by an upwards trend, except at 0.275H where the r_u value declined rapidly at the start of shaking, to less than -1.0 and remained below this level for the remainder of shaking.

The respective horizontal and vertical displacements of the crest at the end of shaking were 0.06 m downstream and 0.07 m downwards.

At $t=25$ s, vertical effective stresses ranged between 0 and 50 kPa in the upper 2/3 of the tailings between the waste rock inclusions and in the upper 3/4 of the tailings upstream of the waste rock inclusions.

The post-shaking development of r_u values at P1 and P2 in the impoundment are shown on Figure H2-6. Hydrostatic conditions were restored to the impoundment by the end of the post-shaking analysis ($t=200$ s). In the tailings (P1), the dissipation of excess porewater pressures was quite rapid and r_u values at $t=200$ s varied between -0.25 and

0.05. In the waste rock inclusion (P2), shaking was followed by an increase in r_u values and then a gradual decline, with r_u values at $t=200$ s between 0.1 and 0.25.

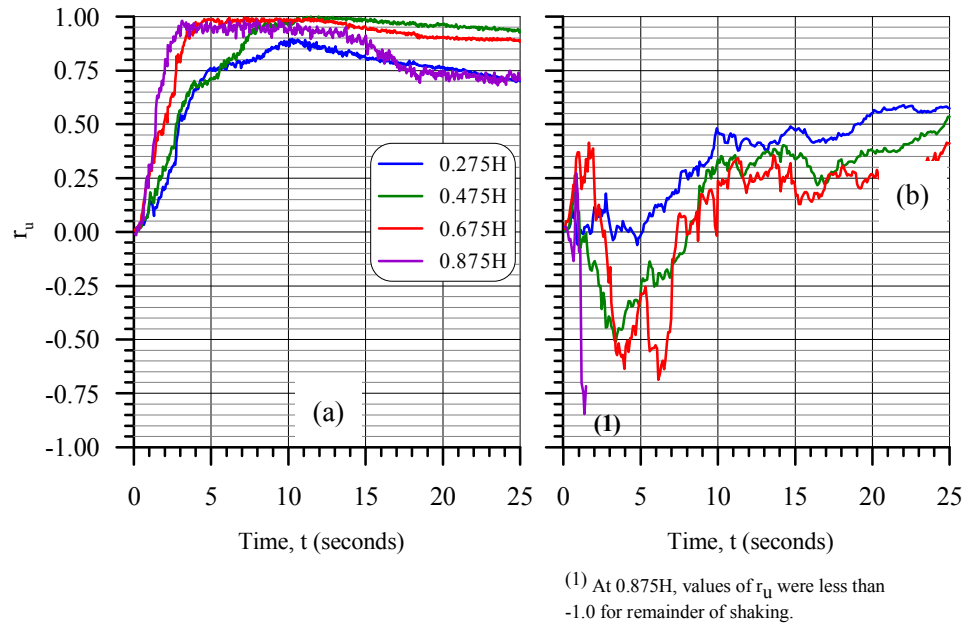


Figure H2-5 – Excess porewater pressure ratio, r_u , developed at P1 (a) and P2 (b) – reinforced impoundment, Earthquake E2 ($M_w=6.75$).

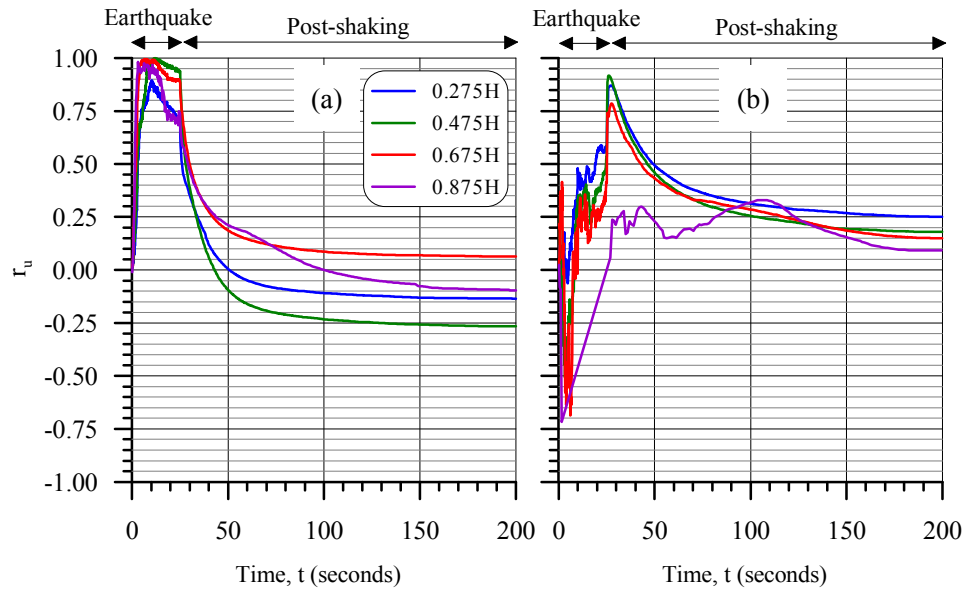


Figure H2-6 – Post-shaking dissipation of excess porewater pressure at P1 (a) and P2 (b)
– reinforced impoundment, Earthquake E2 ($M_w=6.75$).

Post-shaking displacement of the crest of the dike was minor and consisted of 0.02 m of upstream movement with no vertical component (see Figure H2-7).

The vertical effective stresses in the impoundment at $t=200$ s are shown on Figure H2-8. Generally, the stresses returned to their static levels, except for a reduction in the stress transfer between the waste rock inclusions and tailings.

The horizontal displacements at the end of the post-shaking analysis were typically less than 0.5 m (downstream) and a maximum displacement of less than 0.75 m occurred on the downstream slope, just above the starter dike (Figure H2-9).

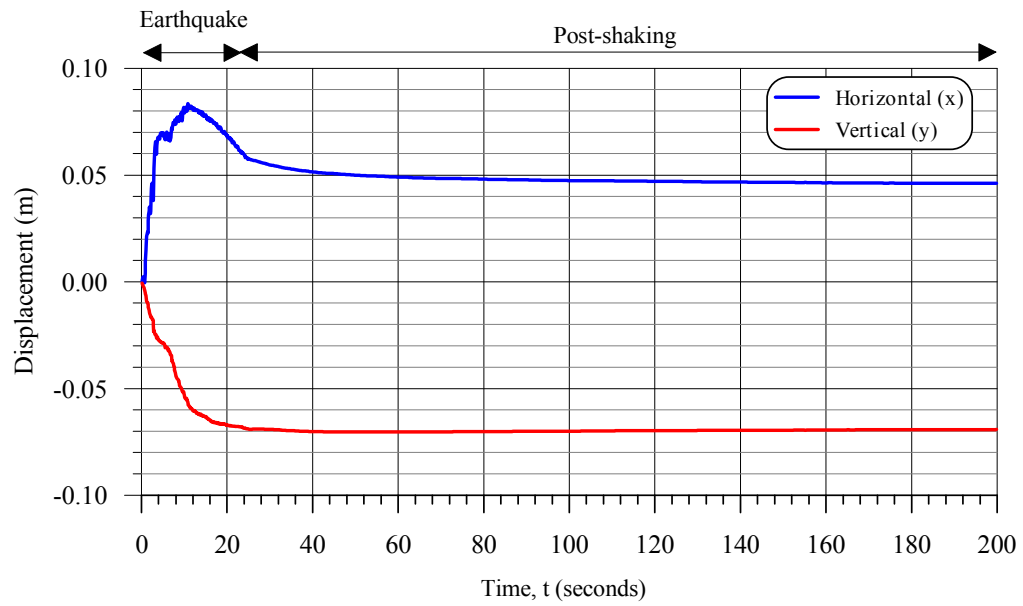


Figure H2-7 – Post-shaking displacement of the crest of the dike – reinforced impoundment, Earthquake E2 ($M_w=6.75$).

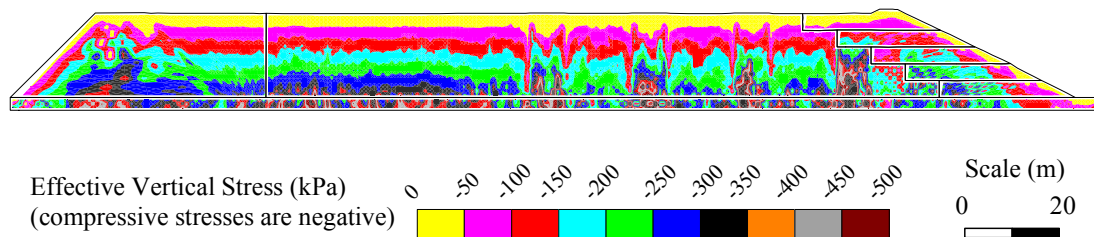


Figure H2-8 – Vertical effective stresses at the end of the post-shaking analysis – reinforced impoundment, Earthquake E2 ($M_w=6.75$).

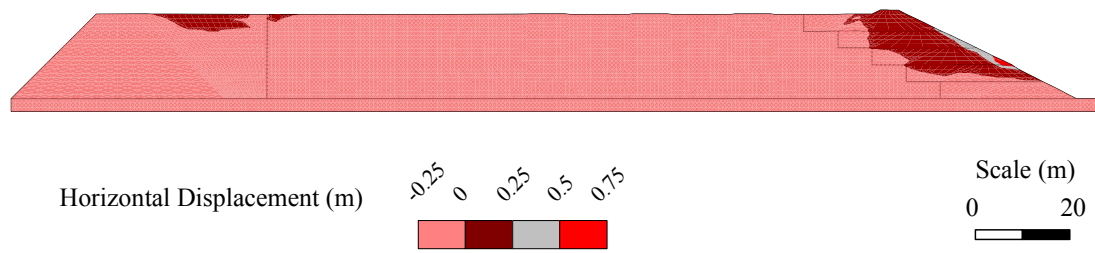


Figure H2-9 – Post-shaking horizontal displacement – reinforced impoundment,
Earthquake E2 ($M_w=6.75$).

H3. ANALYSES OF THE CONCEPTUAL IMPOUNDMENTS - EARTHQUAKE E4 ($M_w=7.25$)

The effect of the Earthquake E4 loading on the conventional and reinforced impoundments was simulated and the results are briefly summarized in this section.

H3.1 The Conventional Impoundment

The excess porewater pressure ratios, r_u , developed in the tailings at P1 and P2 during shaking are graphed on Figure H3-1. At both P1 and P2, the development of excess porewater pressures was very rapid. Values of r_u over 0.95 was attained at P1 by $t=10$ s. At 0.475H, 0.675H and 0.875H the r_u values remained above 0.95 for the remainder of shaking. However, at 0.275H the value of r_u varied during shaking and was 0.68 at $t=37.5$ s (the end of shaking). At P2, the excess porewater pressure development resulted in r_u values of 0.5 to 1.0 by the 2nd second of shaking. After the 2nd second, the development of excess porewater pressures at this location was fairly variable and resulted in values ranging from 0.71 to 0.96 at the end of shaking.

By the end of shaking, the crest of the dike moved 3.6 m downstream and 0.6 m downwards.

Within the retained tailings, the vertical effective stresses at the end of shaking were 0 to 50 kPa. Recall that prior to shaking they ranged from 0 to 350 kPa.

The dissipation of excess porewater pressures in the tailings at P1 and P2 following shaking is represented on Figure H3-2. The dissipation of excess porewater pressures was relatively rapid and conditions approached steady state flow by the end of the analysis ($t=200$ seconds). The r_u values at the end of the analysis ranged between -0.27 and 0.09 at P1 and 0.03 and 0.08 at P2, indicating that there was some stress transfer or redistribution within the impoundment during and/or after shaking.

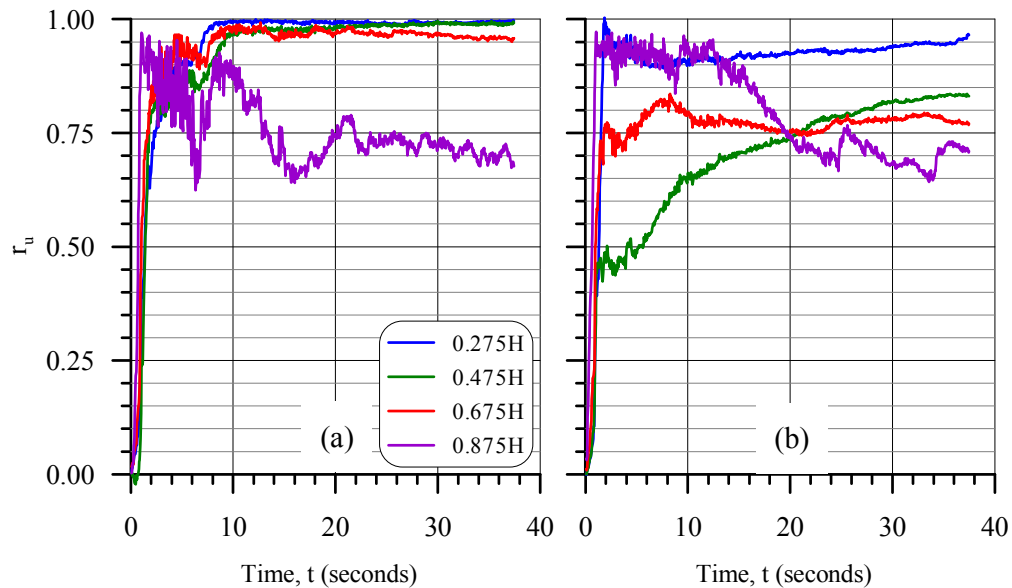


Figure H3-1 – Excess porewater pressure ratio, r_u , developed at P1 (a) and P2 (b)
– conventional impoundment, Earthquake E4 ($M_w=7.25$).

The horizontal and vertical displacements recorded on the crest of the dike during the shaking and post-shaking analyses are plotted on Figure H3-3. There was no appreciable displacement of the crest during the post-shaking analysis.

Figure H3-4 presents contours of the horizontal effective stress within the impoundment at $t=200$ s. The stresses were in general agreement with those prior to shaking, except for minor variations attributed to stress redistribution.

The horizontal displacements at the end of the post-shaking analysis are plotted on Figure H3-5 and show downstream displacements varying from about 5 m on the downstream slope to near 0 about 100 m upstream of the crest of the dike.

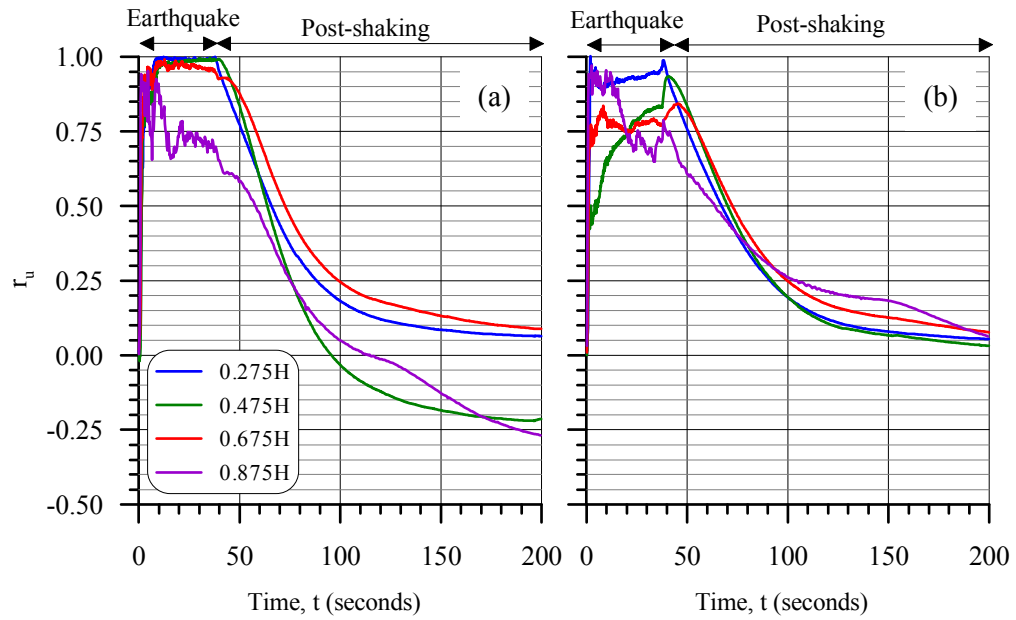


Figure H3-2 – Post-shaking dissipation of excess porewater pressure at P1 (a) and P2 (b)
– conventional impoundment, Earthquake E4 ($M_w=7.25$).

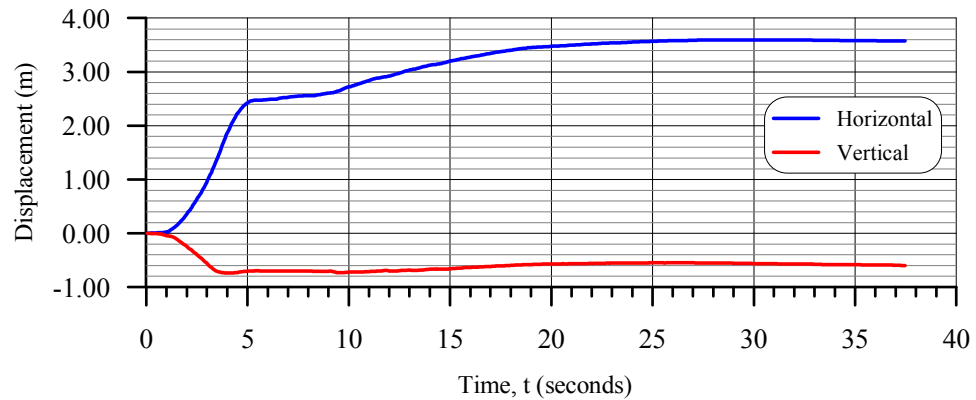


Figure H3-3 – Post-shaking displacement of the crest of the dike
– conventional impoundment, Earthquake E4 ($M_w=7.25$).

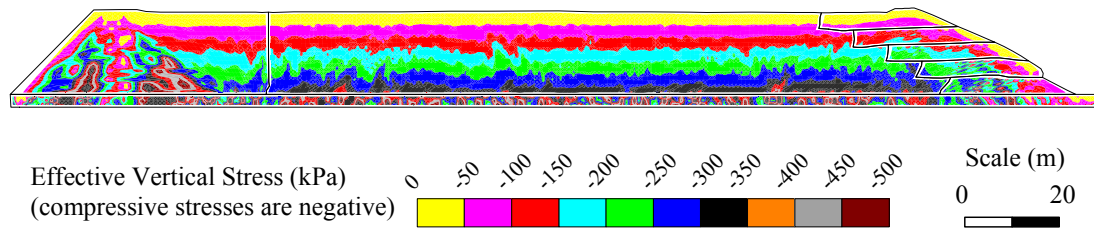


Figure H3-4 – Vertical effective stress at the end of the post-shaking analysis – conventional impoundment, Earthquake E4 ($M_w=7.25$).

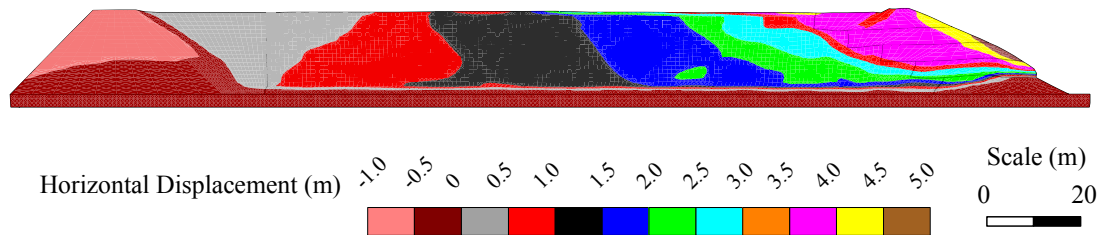


Figure H3-5 – Post-shaking horizontal displacement – conventional impoundment, Earthquake E4 ($M_w=7.25$).

H3.2 The Reinforced Impoundment

During shaking, the excess porewater pressure ratios, r_u , developed during shaking at P1 and P2 are shown on Figure H3-6. At P1 (within the tailings) excess porewater pressure ratios of 0.95 or greater were developed within 6 seconds of the start of shaking and remained relatively constant until $t=20$ s. Afterwards, the r_u values in the bottom (0.275H) and top (0.875H) of the tailings declined to about 0.65 by the end of shaking ($t=37.5$ seconds). The decrease in the r_u values is attributed to drainage from the surface and through the waste rock on the bottom of the impoundment. At P2 (in the center of a waste rock inclusion) the r_u values varied between -3.0 and 0.85 with depth and time. The r_u values at $t=37.5$ s were 0.65, -1.3, -2.15, and -2.0 at 0.275H, 0.475H, 0.675H, and

0.875H, respectively, and indicate substantial increases in the vertical effective stresses (except at 0.275H).

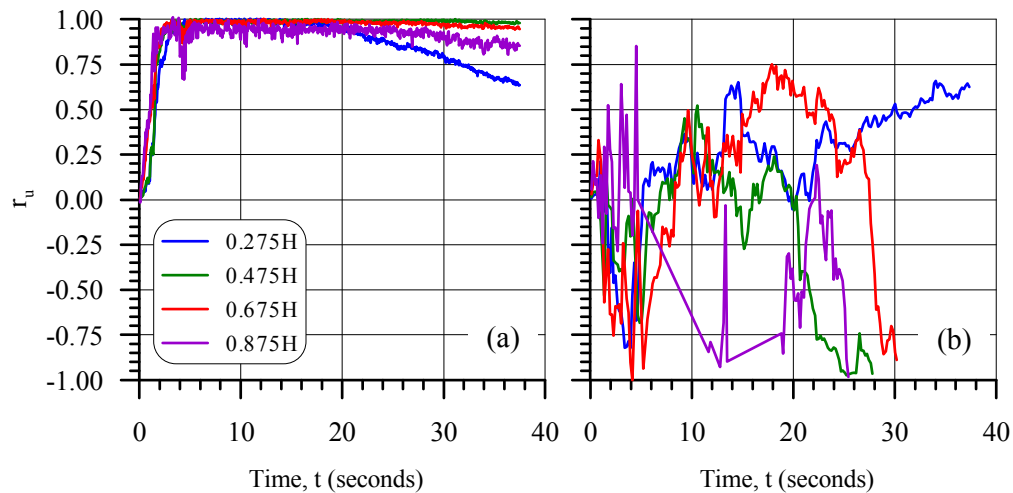


Figure H3-6 – Excess porewater ratio, r_u , developed at P1 (a) and P2 (b)
– reinforced impoundment, Earthquake E4 ($M_w=7.25$).

At the end of shaking, the horizontal and vertical displacements of the crest of the dike were 0.35 m downstream and 0.28 m downwards.

At $t=37.5$ s, the vertical effective stresses within the tailings, both between and upstream of the inclusions, varied from 0 to 50 kPa in the upper 2/3 of the impoundment. In the lower 1/3 of the impoundment, the vertical effective stresses varied from 50 to 350 kPa. Vertical effective stresses in the lower portions of the inclusions, the tailings underlying the dike and the dike and in the starter dike generally varied from 200 to 450 kPa.

The changes in the r_u values at locations P1 and P2 after the end of shaking are shown on Figure H3-7, the dissipation of excess porewater pressures was more rapid at P1 than at P2. Hydrostatic conditions were restored by the end of shaking. At P1 (in the tailings), the r_u values at $t=200$ s varied between -0.25 and 0.1. At P2 (in an inclusion), the r_u

values at $t=200$ s varied between -0.75 and 0.55, indicating significant stress redistribution.

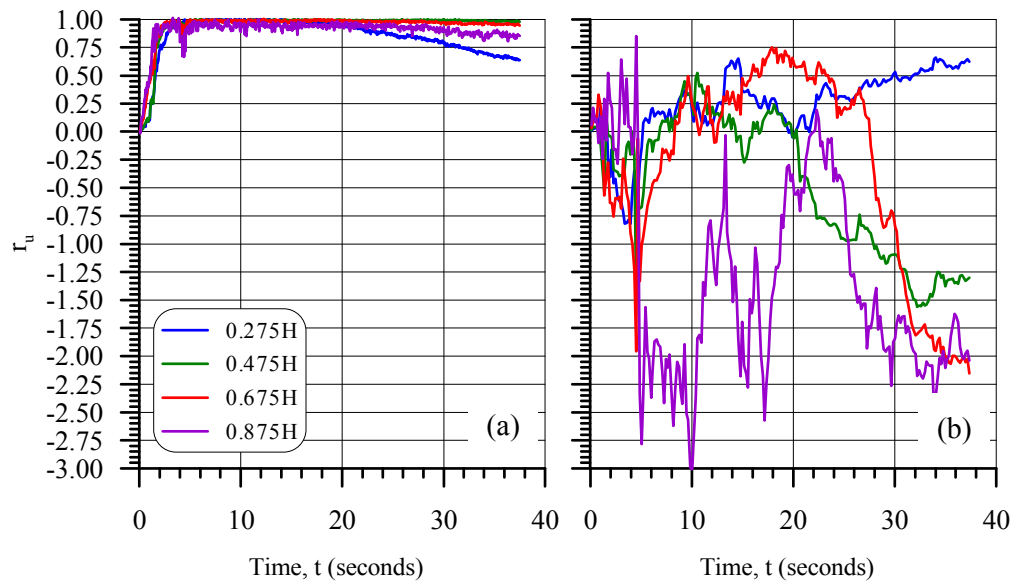


Figure H3-7 – Post-shaking dissipation of excess porewater pressure at P1 (a) and P2 (b) – reinforced impoundment, Earthquake E4 ($M_w=7.25$).

There was no significant displacement of the crest of the dike following shaking.

As shown on Figure H3-8, the vertical effective stresses at the end of the post-shaking analysis varied somewhat from those prior to shaking. Specifically, the differences in the vertical effective stress between the waste rock inclusions and the adjacent tailings were significantly reduced and, generally, there was more variability (less uniformity) of the stress within the waste rock inclusions.

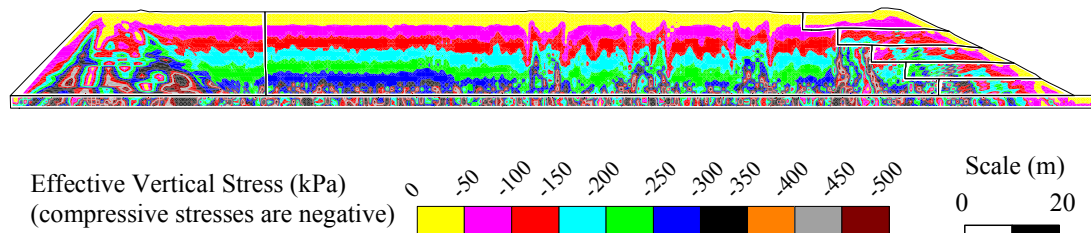


Figure H3-8 – Vertical effective stress at the end of the post-shaking analysis – reinforced impoundment, Earthquake E4 ($M_w=7.25$).

The horizontal displacements in the impoundment at the end of the post-shaking analysis are presented on Figure H3-9. Displacements were generally limited to the area of the dike and a maximum horizontal displacement of about 2.0 m (outwards) developed on the downstream slope of the dike.,

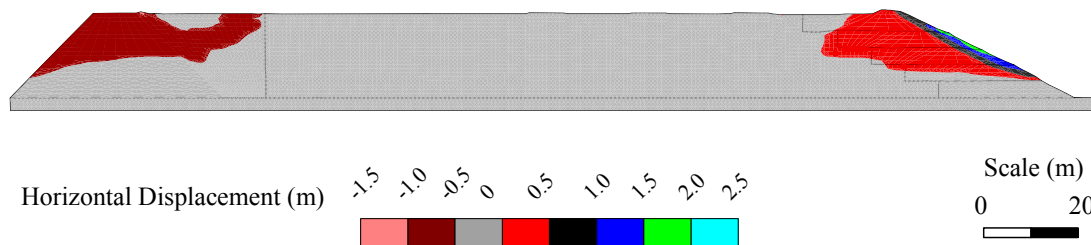


Figure H3-9 – Post-shaking horizontal displacement – reinforced impoundment, Earthquake E4 ($M_w=7.25$).

H4. ANALYSES OF THE CONCEPTUAL IMPOUNDMENTS - EARTHQUAKE E5 ($M_w=7.5$)

The Earthquake E5 ground motion was applied to the models of the conceptual. This ground motion represents a moment magnitude 7.5 event with a fault rupture to site distance of 30 km. The parameters of the simulated ground motion are a PGA of 1.432g (on hard rock) and a duration of 40 seconds.

H4.1 Dynamic Analysis – Conventional Impoundment

During the dynamic analysis of the conventional impoundment under the Earthquake E5 loading, the deformation of one or more elements of the model grid exceeded the capabilities of the FLAC software program and execution was terminated automatically. This occurred 12.8 seconds after the start of shaking.

The site response was evaluated using the amplification factors, F_a , calculated from PGA values extracted from FLAC that are given on Table H4-1. Amplification of the ground motion within the glacial till overlying bedrock was moderately high. On the surface, the amplification factors at P1 and P2 indicate severe damping. Moderate amplification occurred on the crest of the dike.

The excess porewater pressure ratios, r_u , developed in the tailings at P1 and P2 are presented on Figure H4-1. At P1 the ratios increased very rapidly for the first 2 seconds of shaking and values over 0.85 were attained. After the 2nd second, there was a gradual increase in the ratios leading to values above 0.95 by the 5th second of shaking, except at 0.875H where there was significant increases and decreases in the value of r_u for the duration of the analysis and the r_u value at $t=12.8$ s was 0.81. At the other levels, the value of r_u generally remained above 0.95 until $t=12.8$ s. At P2 there was also a very rapid increase in the r_u values during the first 2 seconds of shaking. However, at this location the r_u values at 0.275H, 0.675H and 0.875H rose to at least 0.85 and then varied roughly between 0.85 and 0.99 for the analysis, while the r_u value at 0.475H increased

rapidly to 0.57 by the 2nd second, decreased suddenly to 0.47 and then increased at a moderate rate to 0.9 by t=12.8 s.

Table H4-1 – Calculated amplification factors
– conventional impoundment, Earthquake E5

Location	Peak Horizontal Ground Acceleration, PGA (g)	Amplification Factor (F_a)
Top of bedrock	1.526	-
Top of glacial till	2.394	1.569
Surface of Impoundment at P1	0.229	0.196
Surface of Impoundment at P2	0.135	0.088
Crest of dike	0.888	1.266

The displacements of the crest of the dike during the simulation are plotted on Figure H4-2. Horizontally the crest was displaced 6 m downstream by the end of the analysis and the rate of displacement at that time suggested movement would continue had program execution not been terminated. Horizontally, the crest moved 1.1 m downwards by the 4th second of shaking and then rose slightly such that the displacement was 0.9 m downwards at the end of the analysis.

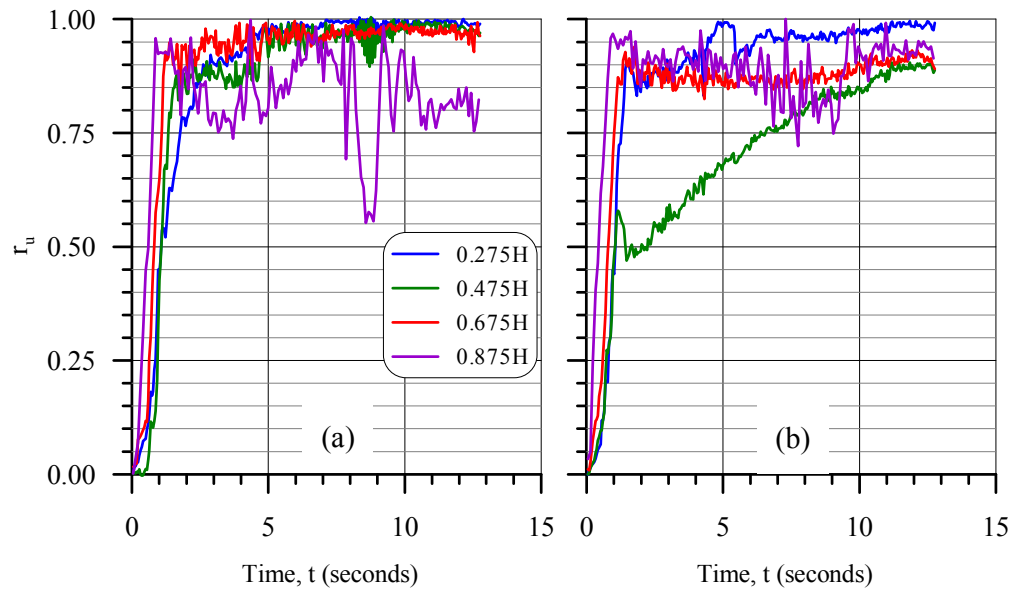


Figure H4-1 – Excess porewater pressure ratio, r_u , developed in the tailings at P1 (a) and P2 (b) in the conventional impoundment – Earthquake E5 ($M_w=7.5$).

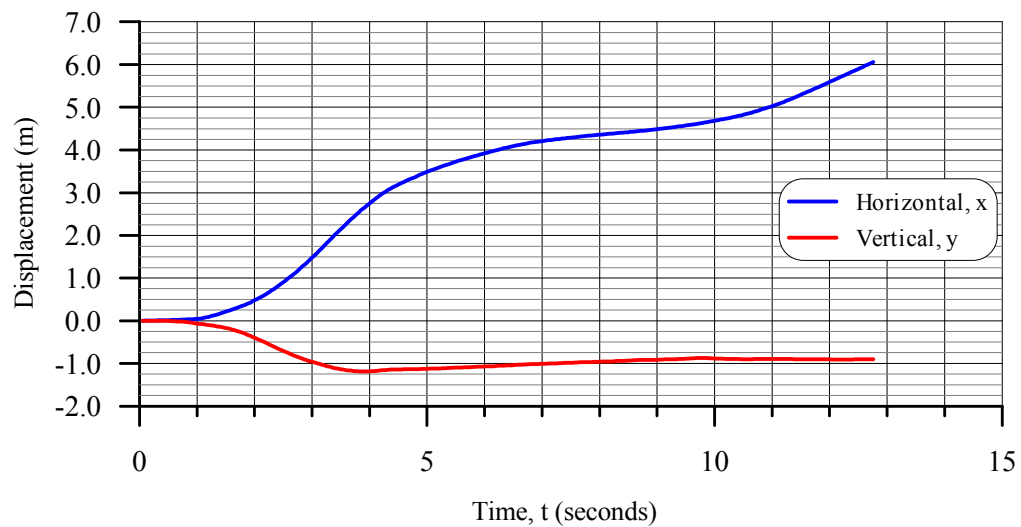


Figure H4-2 – Displacement of the crest of the dike during shaking – conventional impoundment, Earthquake E5 ($M_w=7.5$).

The vertical effective stress in the impoundment at $t=12.8$ s is contoured on Figure H4-3. Within the retained tailings the stress varied from 0 to 50 kPa, significantly lower than the 0 to 350 kPa prior to shaking. In the tailings underlying the dike, the vertical effective stresses were also significantly reduced and generally varied from 0 to 200 kPa at the end of the simulation.

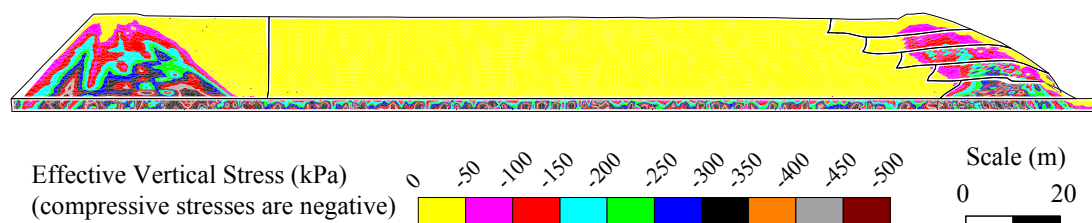


Figure H4-3 – Vertical effective stresses at $t=12.8$ seconds
– conventional impoundment, Earthquake E5 ($M_w=7.5$).

The horizontal displacements within the impoundment at the shaking are shown on Figure H4-4. The maximum displacement consisted of downstream movement of the downstream slope of the dike of more than 9 m. Displacements extended the length of the impoundment.

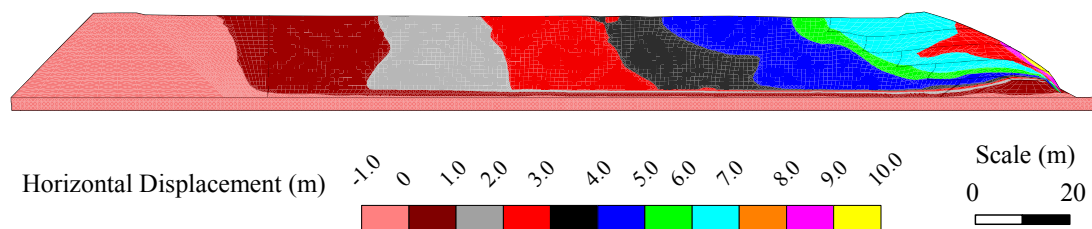


Figure H4-4 – Horizontal displacement at $t=12.8$ seconds – conventional impoundment,
Earthquake E5 ($M_w=7.5$).

The occurrence of excessive distortions to one or more elements sufficient to halt program execution during the dynamic analysis, prevented continuation of the analysis or the initiation of post-shaking analysis.

H4.2 Dynamic Analysis – Reinforced Impoundment

The site response of the reinforced impoundment to Earthquake E5 was interpreted from the amplification factors, F_a , which are listed in Table H4-2. The factor of 2.068 calculated at the top of the dense glacial till was representative of high amplification within the glacial till. On the surface of the impoundment at P1 a factor of 0.537 indicated high damping within the underlying tailings, while at P2 a factor of 1.233 indicated moderate amplification on the top of a waste rock inclusion. On the crest of the dike, high amplification of the horizontal accelerations resulted in a factor of 1.708.

Table H4-2 – Calculated amplification factors – reinforced impoundment, Earthquake E5

Location	Peak Horizontal Ground Acceleration, PGA (g)	Amplification Factor (F_a)
Top of bedrock	1.539	-
Top of glacial till	3.182	2.068
Surface of Impoundment at P1	0.826	0.537
Surface of Impoundment at P2	1.882	1.233
Crest of dike	2.629	1.708

The development of excess porewater pressures (and vertical effective stresses) in the impoundment at P1 and P2 are represented on Figure H4-5. At P1 the excess porewater development was characterized by rapid increased in the value of r_u in the first second of shaking, resulting in values exceeding 0.75. From then until the 4th second the excess porewater pressure development was characterized by very rapid increases and decreases

resulting in r_u values that varied between 0.05 and 1.0. After the 4th second the r_u values were relatively stable and varied from 0.08 at 0.275H to 0.96 at 0.475H, 0.675H and 0.875H when shaking ceased ($t=40$ s). At P2 the excess porewater pressure development was characterized by very rapid and very dramatic changes and r_u values generally varied between -1.0 and 1.0 during shaking.

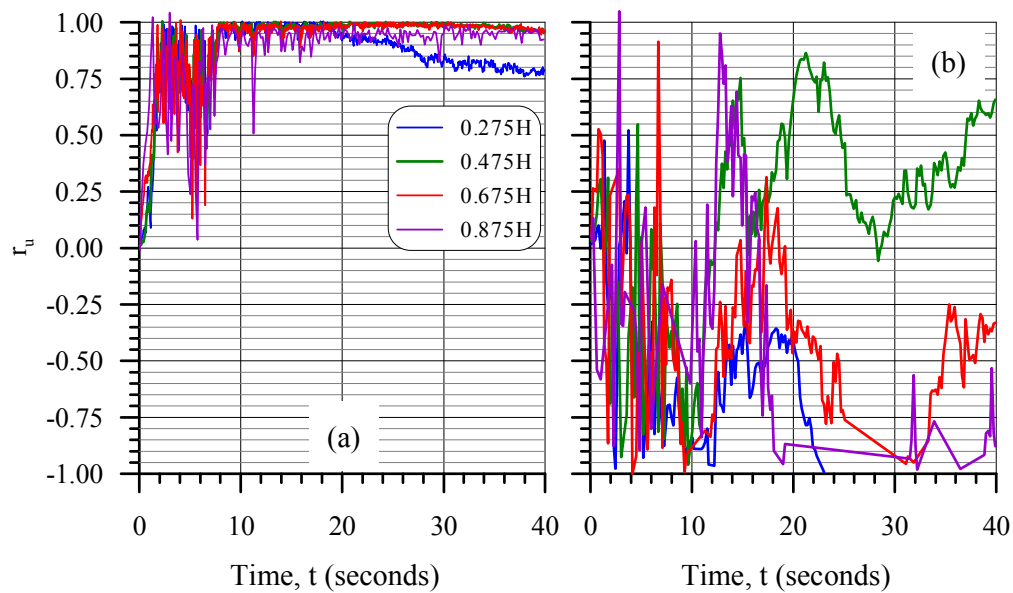


Figure H4-5 – Excess porewater pressure ratio, r_u , developed at P1 (a) and P2 (b) in the reinforced impoundment – Earthquake E5 ($M_w=7.5$).

Figure H4-6 shows the displacements of the crest of the dike during shaking. At $t=6$ s the crest moved 1.35 m downstream, by the 19th second 1.55 m and by the end of shaking the crest had moved back slightly such that it was 1.4 m downstream. Vertically, the crest displaced 0.5 m downwards by the 6th second and 0.85 m downwards by the end of shaking ($t=40$ s).

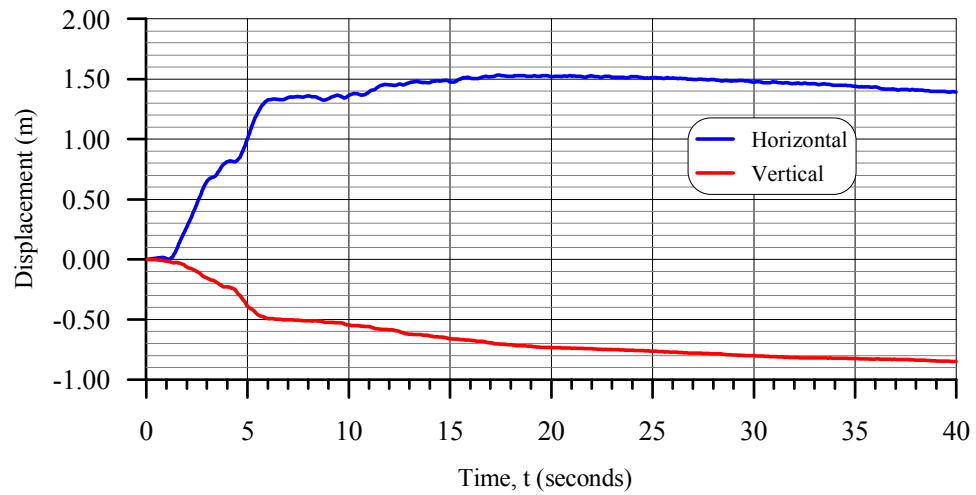


Figure H4-6 – Displacement of the crest of the dike during shaking – reinforced impoundment, Earthquake E5 ($M_w=7.5$).

Contours of the vertical effective stress in the impoundment at the end of shaking are presented on Figure H4-7. Relative to the vertical effective stresses prior to shaking, the stresses in the upper 17 m of tailings were significantly lower, varying between 0 and 50 kPa.

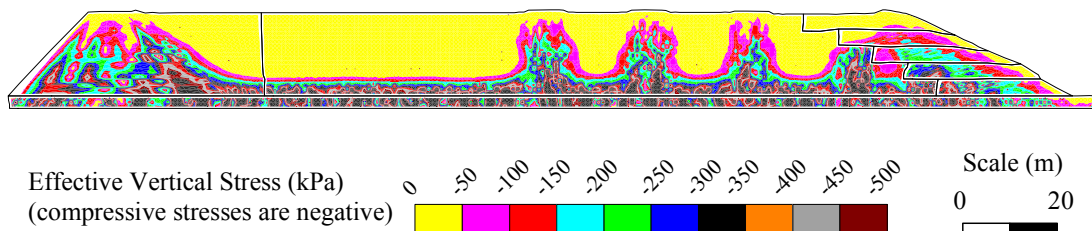


Figure H4-7 – Vertical effective stresses at the end of shaking – reinforced impoundment, Earthquake E5 ($M_w=7.5$).

Figure H4-8 presents the horizontal displacement of the reinforced impoundment at the end of shaking. The largest displacements occurred on the downstream slope of the dike and varied between 3 and 3.5 m (downstream direction). Significant displacements were generally limited to the dike and adjacent areas.

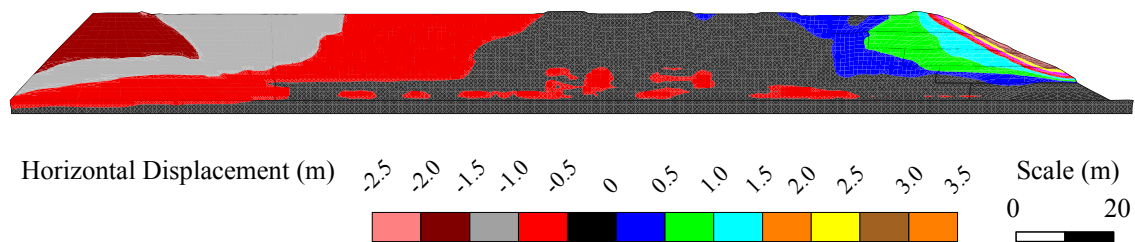


Figure H4-8 – Horizontal displacement at the end of shaking
– reinforced impoundment, Earthquake E5 ($M_w=7.5$).

H4.3 Post-shaking Analysis – Reinforced Impoundment

Post-shaking dissipation of the excess porewater pressures and changes in the vertical effective stresses were interpreted from plots of the excess porewater pressure ratio presented on Figure H4-9. At P1 (in the tailings), excess porewater pressures dissipated quite rapidly when shaking ceased and dissipation was essentially complete by the 50th second. After the 50th second there was an increase in the r_u values at P1 that was attributed to stress redistribution within the tailings. At the end of the post-shaking analysis, the r_u values were relatively stable and ranged from -0.35 to -0.12, indicating a 12 to 35% increase in the vertical effective stresses in the tailings at this location.

At P2 (the center of an inclusion), there was a moderate, but rapid increase in the r_u values after shaking that is attributed to flow from the adjacent tailings. The increases were followed by a rapid decrease (attributed to dissipation of excess porewater pressures), gradual increases and then sudden increases before leveling off towards the end of the analysis ($t=200$ s).

The increase in the r_u values at P1 and P2 after $t=60$ s are attributed to stress redistribution and the final r_u values indicate an increase in the effective stress within the tailings (P1) and a decrease in the effective stress within the inclusion (P2).

The displacements of the crest of the dike are presented on Figure H4-8. There was no appreciable post-shaking displacement of the crest.

The vertical effective stress distribution in the impoundment at the end of the post-shaking analysis is shown on Figure H4-11. In comparing this stress distribution to that prior to shaking, it's evident that much of the stress transfer that resulted in lower stress the tailings and higher stress in the inclusions has been significantly reduced. However, the amount of localized variation in the stress was increased, particularly within the waste rock inclusions. Generally, in the tailings, the vertical effective stress varied nearly uniformly from 0 at the surface of the impoundment to about 300 to 350 kPa at the bottom of the tailings, similar to that of the tailings in the conventional impoundment prior to shaking.

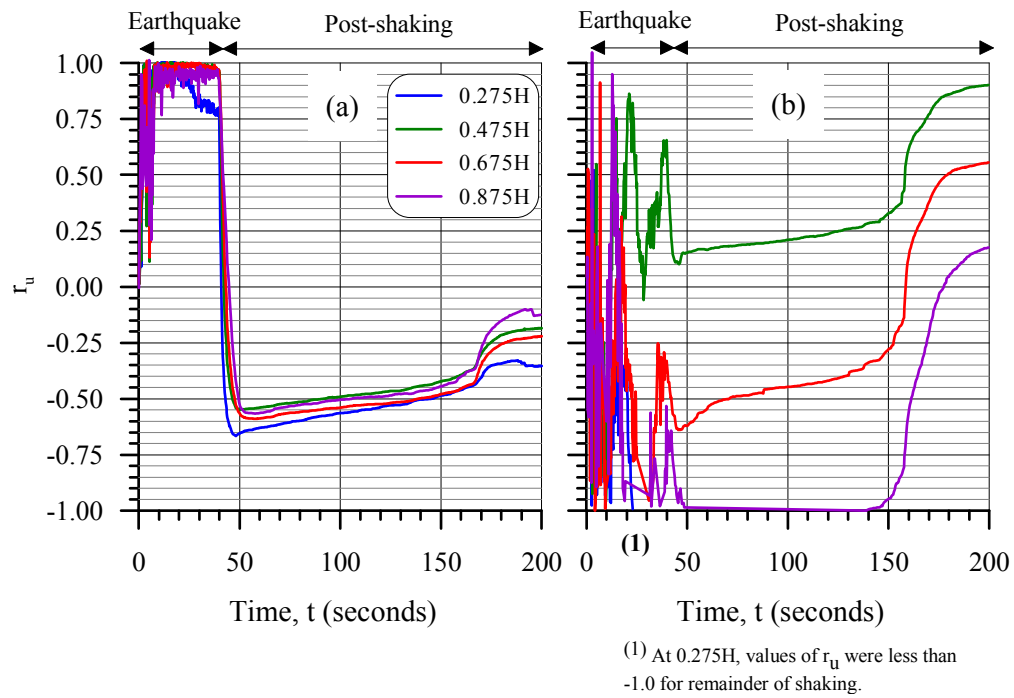


Figure H4-9 – Post-shaking dissipation of porewater pressure at locations P1 (a) and P2 (b) – reinforced impoundment, Earthquake E5 ($M_w=7.5$).

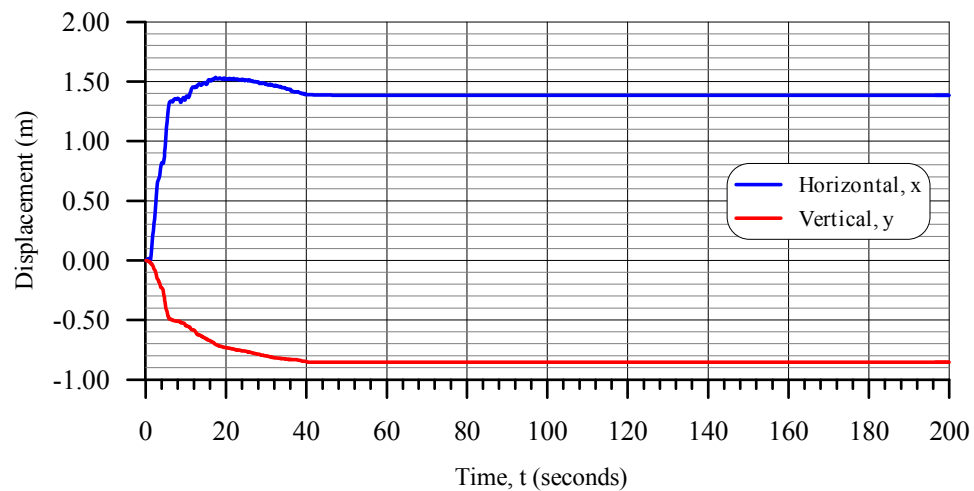


Figure H4-10 – Post-shaking displacements of the crest of the dike – reinforced impoundment, Earthquake E5 ($M_w=7.5$).

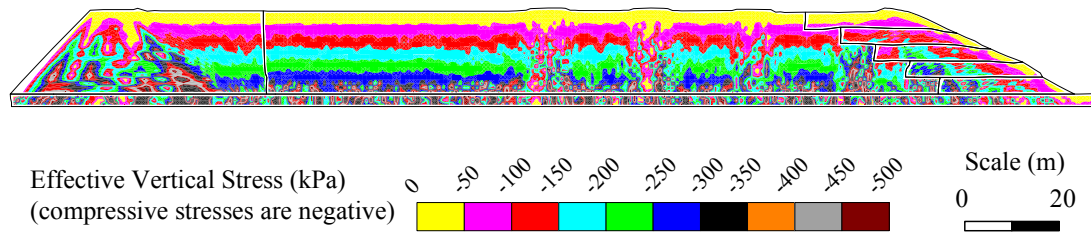


Figure H4-11 – Vertical effective stresses at the end of the post-shaking analysis
– reinforced impoundment, Earthquake E5 ($M_w=7.5$).

There was no significant horizontal displacement of the impoundment during the post-shaking analysis.