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KEMESS MINE TAILINGS STORAGE FACILITY – INVESTIGATION AND EVALUATION OF LIQUEFACTION POTENTIAL USING IN-SITU BLASTING

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ABSTRACT

The Kemess Mine is an operating Copper-Gold mine located in northern British Columbia, Canada, and includes a large earthfill dam to retain the process tailings. Owing to concerns over the potential effects of seismic loading of the tailings in the south abutment area, a comprehensive evaluation of the liquefaction potential of the impounded tailings in that area was undertaken, involving multiple field and laboratory investigations over a six year time span. Two piezocone sounding programs indicated penetration resistance within the tailings suggestive of low to moderate seismic liquefaction resistance; however the measured dilative dynamic pore pressure response to piezocone penetration suggested differently. Instrumented test blasts within the tailings, carried out to evaluate in situ the response of the tailings to dynamic loading, indicated a pore pressure response much lower than would have been expected on the basis of previous experience with blasting in looser sand/silt tailings. The observed behavior at the Kemess site demonstrates the utility of monitored test blasts as a means of assessing in situ dynamic response. This case history also demonstrates the limitations of standard piezocone-based liquefaction assessment techniques that make no use of indicators of volumetric response as provided by dynamic pore pressure response during piezocone advance.

Introduction

This paper provides a summary of investigation data and analyses performed relating to the liquefaction potential of the impounded tailings in the south abutment area of the Kemess Mine tailings dam. Seepage conditions in the south abutment area are controlled by the above-water tailings beach that separates the dam from the water pond. Despite the demonstrated success of this measure, there were concerns over the potential effects of seismic liquefaction of the tailings, and resultant increased hydraulic gradients and pore pressures. As such, a series of field and laboratory investigations were undertaken to evaluate the dynamic response of the tailings to the seismic loading from the design earthquake, with particular interest in pore pressure response.

This paper presents a summary of the liquefaction evaluation of the tailings, with

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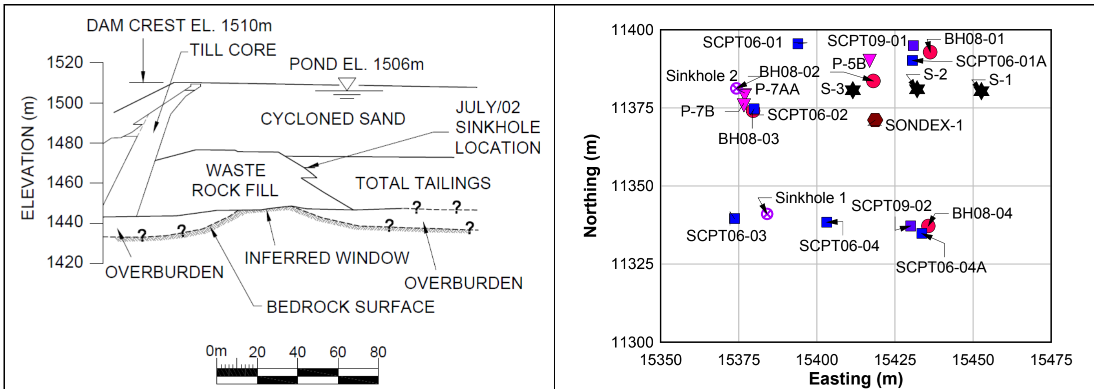
particular emphasis on the use of in-situ blasting as a means of investigating the in situ dynamic response of the tailings. In 2007, single hole blasting trials were performed to assess the in situ pore pressure response, following piezocone soundings undertaken in 2006 that had indicated, on the basis of tip resistance, the potential for significant pore pressure build-up within the tailings under design levels of seismic shaking. The blasting trials were subsequently followed by additional rotary borings (including Standard Penetration Testing [SPT]), undisturbed piston sampling, and cyclic direct simple shear (CDSS) laboratory testing in 2008, and by a second piezocone program in 2009, to further assess the seismic liquefaction resistance of the tailings. This paper presents the resulting pore pressure response of the tailings sands to the single hole blasting trials with comparison to the inferred pore pressure generation potential deduced from penetration-based methods of evaluation.

Background

Mill tailings produced from the Kemess Mine are retained behind a central, low hydraulic conductivity glacial till core earthfill dam approximately 1 km in crest length, and 120 m in height. Much of the dam is underlain by a pre-sheared glaciolacustrine varved silt and clay unit with low operative shear strength, and the south abutment of the dam is underlain by highly fractured volcanic bedrock. Seepage is controlled by the compacted till core, till and glaciolacustrine units, and tailings. Apart from relatively shallow consolidation grouting of bedrock exposed in the core contact trench along the south abutment, the bedrock foundation is not grouted. For the early years of construction of the dam, potentially acid generating waste rock from the open pit was placed to the upstream of the core to achieve flooding and prevent acid rock drainage. The fractured bedrock in the south abutment represents the most hydraulically conductive of the units. At higher elevations on the abutments, where overburden cover over bedrock is thin to nonexistent, it is the tailings that serve to limit seepage into the bedrock.

The south abutment of the Kemess Mine tailings dam has always warranted particular attention due initially to seasonally-elevated (due to groundwater recharge during snowmelt), artesian groundwater pressures in the fractured bedrock. In the summer of 2002, to control increasing foundation pore pressures in the confined bedrock aquifer, three groundwater relief wells were installed at the downstream toe of the dam in the south abutment area. Some months later, with tailings discharge occurring against the upstream waste rock shell, episodic discharges of tailings fines (material finer than 74 microns, typically colloidal material) from the relief wells were noted. The whole tailings (about 55% finer than 74 microns) gradation was not observed in the discharges. For the initial week of such discharges, two small sinkholes were noted in the tailings against the rockfill toe. Development of the above water tailings beach, and commissioning of a cycloned sand plant later that same year, and use of this plant for discharge of cycloned sand in the south abutment area, put an end to such episodes. Thereafter, waste rock was no longer used to provide upstream support for the till core raises, but rather cycloned sand tailings was used. These changes resulted in reduced seepage gradients and pressures, and the relief wells were subsequently decommissioned in 2005.

It was postulated that the migration of tailings fines to the relief wells discharge occurred via a hydraulic connection which was inferred to consist of upstream rockfill directly in contact with exposed fractured bedrock. This created a pathway termed the “2002 window” for tailings fines migration via the foundation bedrock, bypassing the till core of the dam, and is shown conceptually in Figure 1a.



a) Conceptual south abutment section.

b) 2002 Sinkhole and Investigation locations.

Figure 1. Conceptual south abutment section and investigations plan.

Despite the cessation of discharge of tailings fines from the relief wells, and the success of the above-water tailings beach in limiting seepage gradients and pressures, the south abutment continued to be an area of attention relating to long term closure of the tailings dam. Specifically, concerns were raised over the potential effects of seismic liquefaction of the tailings, which could result in pore pressures up to double those under static loading conditions. Accordingly, field and laboratory investigation programs were carried out in the area in 2006 through 2009 inclusive in order to understand the seepage regime and characterize the behaviour of the deep tailings in the vicinity of the window. These investigations were focused on the assessment of a postulated failure mechanism in which resumption of tailings fines migration into the fractured bedrock could be initiated following a major design earthquake. The latter maximum credible earthquake (MCE) event was defined as a magnitude 6.0 event with a peak horizontal ground acceleration of 0.19 g (bedrock outcrop). Fines migration into the bedrock could result from the very high gradients that would occur if the tailings liquefied and pore pressures effectively doubled (assuming full liquefaction), or, at the very least, substantially increased relative to pre-earthquake conditions.

Piezocone and Drilling Investigations: 2006 through 2009

Several field programs (see Figure 1b) were performed to investigate and characterize the deep tailings using a combination of rotary borings and the piezocone soundings (CPT). A total of 12 piezocones and 5 rotary borings were conducted in the upstream tailings beach adjacent to the south abutment between 2006 and 2009. Of the 12 piezocones performed, four were advanced to depths consistent with the inferred “2002 window” below elevation 1465 m, identified as CPT06-01A and CPT06-04A in 2006, and SCPT09-01 and SCPT09-02 in 2009. Standard Penetration Tests (SPT’s) were also performed at various depths in 3 of the 5 rotary holes.

The 2006 piezocone soundings suggested relatively loose tailings at depth with stress level normalized tip resistance values in the range of q_{c1} = 4 to 5 MPa, whereas the 2009 piezocone soundings suggested a slight increase in q_{c1} of about 1 MPa or 25% for the 3 year period between programs. This increase likely corresponds to stress densification due to the deposition of an additional 20 m of tailings in the south abutment area between the programs and possibly “ageing” effects. Despite the moderate tip resistance measurements experienced by both piezocone sounding programs, all the soundings recorded net negative dynamic pore pressure responses during piezocone penetration, indicative of dilatant conditions inconsistent with typical piezocone experience in tailings that would be considered loose. When penetration was halted for dissipation testing, the pore pressures rapidly rose to approximately hydrostatic equilibrium conditions. All 12 of the piezocone soundings measured similar trends in tip resistance, friction ratio and pore pressure with depth. Figure 2 presents the data collected at SCPT09-01 which is considered to be a representative piezocone sounding for the south abutment. Figure 3a illustrates the improvement in q_{c1} at depth between the 2006 and 2009 piezocone programs. Shear wave velocity profiling was undertaken for both piezocone programs, and those data, summarized on Figure 3b, indicated a similar improvement in the stress-normalized shear wave velocity (V_{s1}) from 2006 to 2009. The shear wave velocity profiles indicated an approximately 13% increase in characteristic V_{s1}, suggesting a consequent increase in the stress-normalized small strain shear modulus (G_{max}) of about 25% over the three year period between the investigations. Given the addition of 20 m of tailings beach between the 2006 and 2009 piezocone campaigns, it was judged that the indicated improvements in q_{c1} and V_{s1} were the result of stress densification as opposed to a reflection of ageing effects.

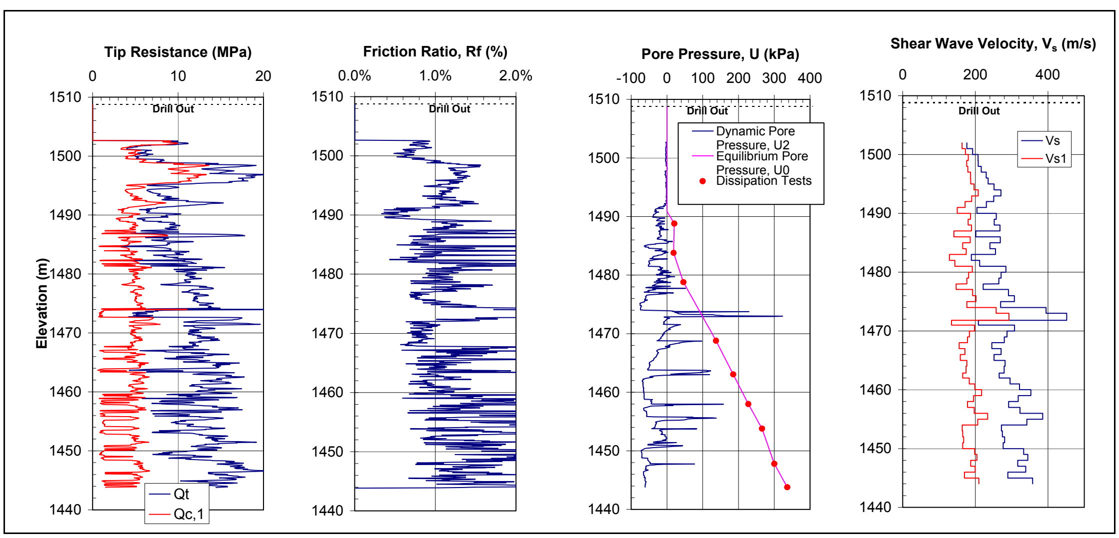
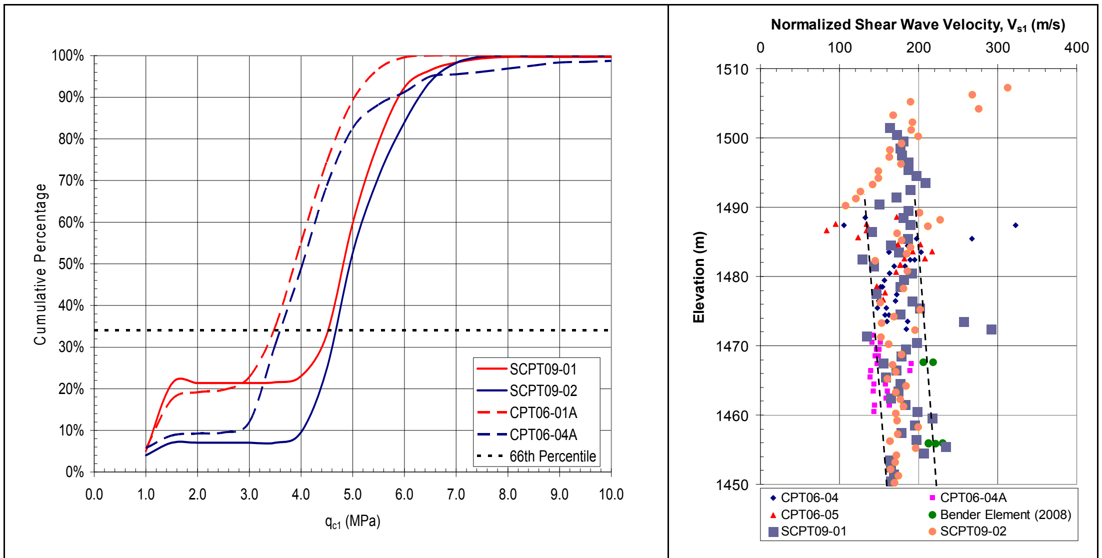


Figure 2. Interpretation of SCPT09-01 data.



a) q_{c1} data comparison	b) V_{s1} data comparison

Figure 3. 2006 to 2009 comparisons: q_{c1} and V_{s1}

Figure 4 shows the piezocone-based $(N_1)_{60}$ values (based on Jefferies and Davies, 1993) from the 2009 piezocone soundings, and the SPT-based $(N_1)_{60}$ values (Youd et al. 2001) derived from the 2008 drilling.

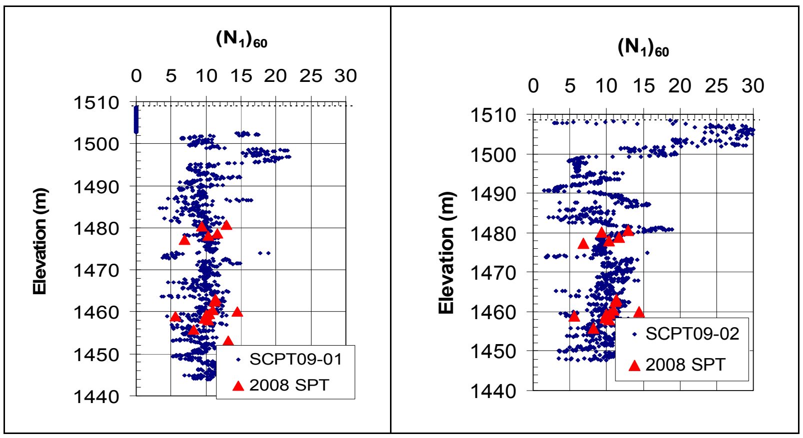


Figure 4. Piezocone vs. SPT-based $(N_1)_{60}$ values

Single Hole Blasting Program - 2007

Typical field practice for assessment of liquefaction triggering due to earthquake shaking is based on SPT or CPT-based methods (Anderson, Byrne et al. 2007; Youd et al. 2001). The 2006 liquefaction triggering assessment was based on stress level normalized cone tip resistance and indicated that, while full liquefaction would not occur under the design earthquake loading, the Kemess tailings could develop significant excess pore pressure build-up under the design seismic event. CPT methods are based solely on tip resistance and do not directly account for dynamic pore pressure response, thereby discounting an indicator of volume change response to shear. Tip resistance is non-uniquely related to relative density, being also strongly affected by compressibility. As such, the CPT-based methodology was judged to be potentially overly conservative. The pore pressure response was further investigated via in situ blasting trials performed within the tailings in the south abutment area, which afforded the means to directly measure pore pressure response under cyclic strain and stress levels representative, at a modest field scale, of the design earthquake loading.

The primary objective of the single hole blasting trial discussed herein was to confirm the dynamic response of the tailings in order to facilitate optimization of the design of a larger scale (multiple hole) blasting trial that had as its objective generation of significant excess pore pressures in the tailings to hydraulically "stress" the abutment in a manner similar to the design earthquake. The blasting would be monitored using an extensive instrumentation array of piezometers, geophones, sondex tubes and monitoring wells to check for any resumption of tailings fines migration. The intention of the multiple hole blast program was to approximately simulate the effect of earthquake-induced pore pressure generation caused by a design level earthquake. The intent of the blasting was to generate a target excess pore pressure ratio, $R_{u\text{-excess}}$ (u_{excess}/σ_{vo}') within the tailings of 0.5 in the immediate vicinity of the postulated window based on approximate correlations between factor of safety against liquefaction triggering and excess pore pressure using CPT-based methods of liquefaction evaluation. It was expected that high excess pore pressures in close proximity to a particular blast hole would induce liquefaction ($R_{u\text{-excess}}$ = 1) within the tailings. However, pore pressures would decrease with distance from a blast hole array, and would also be a function of charge weights per delay, number of charges detonated sequentially, tailings density, and distance. The blasting program was designed to avoid inducing full liquefaction of the tailings in the vicinity of the postulated window, instead targeting an $R_{u\text{-excess}}$ of about 0.5 as mentioned above. Peak particle velocities (PPV) would be limited to 100 mm/sec at the dam core to prevent any cyclic degradation of the compacted till core.

On July 18, 2007 a series of two single hole test blasts were performed using blast holes S1 and S2 as shown on Figure 1b. The purpose of the single hole blasts was to check pore pressure response in the tailings to permit fine tuning of charge weights per delay for the multiple hole blast and to finalize the multiple hole blast design. Based on earlier experience with blasting of looser tailings sands for the charge weights being detonated, it was expected that tailings liquefaction would occur within 15 m or so of a blast hole. Three electric piezometers were installed for the test blast; one at P5 (denoted P5B; about 13 m west of CPT06-01A and SCPT09-01, and 15 m and 40 m from Blast Holes S2 and S1 respectively) and two at P7 (denoted P7AA and P7B; about 5 m north of CPT06-02, and 35 m from Blast Hole S-2). The instrument locations are also shown on Figure 1b. Surface geophones were positioned adjacent to piezometers P5 and P7. Two additional geophones were positioned above the dam core. One Sondex tube was also installed adjacent to blast hole S2.

The blast holes were loaded with 6 decks of explosive charges separated with about 5 m of gravel stemming and targeted the interval between El. 1445 m and 1475 m. The unit charge weight was about 7.3 kg of Dyno TX per lineal meter length of blast hole and a total charge weight of 132 kg per hole. Charge weights varied between 15.5 kg for the upper deck and 28 kg for the lower deck. Time delays of 75 msec between decks were used for both blast holes. During the blasting it was observed that both blasts were quiet but noticeably shook the ground at the point of observation (over 400 m south of the blast holes). A jet of water was observed from S1 but not from S2. No visible ground disturbance was observed adjacent to either blast hole. PPV's were about 25 mm/sec at the ground surface in the vicinity of the dam core, well below tolerable limits.

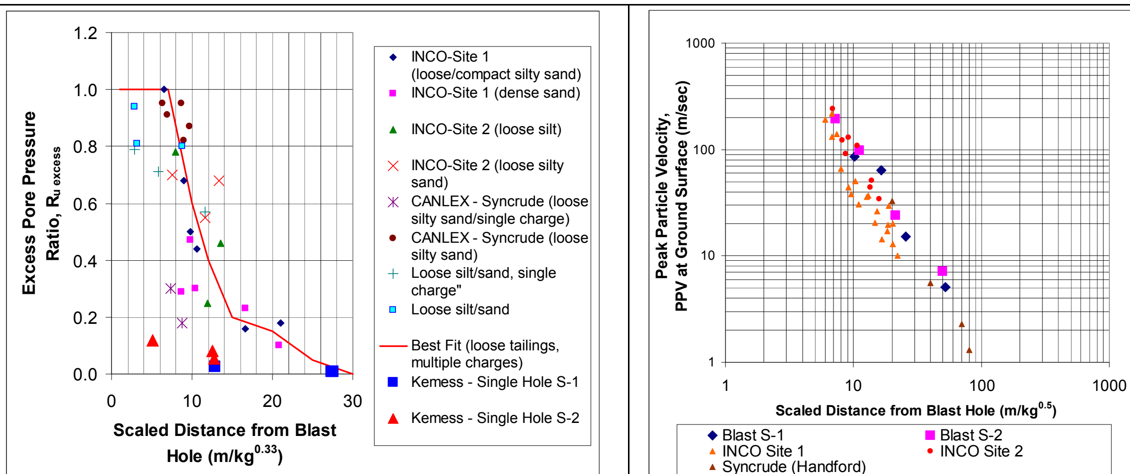
The three installed piezometers (P5B, P7AA and P7B) only recorded minor increases in pore pressure response resulting from the two blasts. The pore pressure increases were substantially less than had been expected on the basis of the tip resistance values from the 2006 piezocone soundings and based on previous experience with blasting in looser tailings. The maximum excess pore pressure ratio, $R_{u\text{-excess}}$ recorded several hours after the two blasts, is listed in Table 1. The pre-blast effective stress and maximum excess pore pressure is also listed in Table 1. The excess pore pressures recorded immediately after the blast were smaller than those recorded later on following redistribution of pore pressures.

Table 1 (Blast S-2) illustrates that there were very slight increases in pore pressures, even at Piezometer P5B which was located only 11 m away from blast hole S-2. Pore pressure increases were considerably smaller for Blast S-1. The maximum excess pore pressure ratio recorded several hours after the blast was 0.121 at P5B which was much lower than the anticipated value of 0.9 to 1.0 (liquefaction) at that location. Figure 5a compares the resulting $R_{u\text{-excess}}$ from the Kemess test blast to other case studies in similar sand and silty sand tailings. The hypocentral distance (i.e. distance between the piezometer tip and the average depth of all 6 decked charges in the blast holes) was normalized by the cube root of the average charge weight per delay for all 6 charges (i.e. 22 kg) in order to compare the Kemess test blasts with the other case studies. Figure 5a further illustrates the much lower than expected pore pressure response in the Kemess tailings induced by the blasting when compared to other sites.

Table 1. Pore Pressure Response to Test Blast S-2

Piez. Location	Distance to Blast Hole S-1 (m)	Pre-Blast Eff. Stress, σ_{v0}' (kPa)	Max Excess Pore Pressure, u_e (kPa)	Excess Pore Pressure Ratio, $R_{u\text{-excess}}$ - (u_e / σ_{v0}')	
				Immediately After Blast	Max. Excess Pore Pressure Ratio
P5B	11	425.7	51.7	0.049	0.121
P7AA	35	522.2	42.7	0.013	0.082
P7B	35	475.3	26.9	0.026	0.057

Figure 5b compares the peak particle velocities, PPV's recorded at the ground surface for the two blasts at Kemess with other case studies (again normalized by hypocentral distance and charge weight). This illustrates that the peak particle velocities, and thus the strains induced by blast holes S-1 and S-2, are consistent with other blasting programs. The program conducted at the INCO site (shown on both Figures 5a and 5b) was designed to induce liquefaction for the purpose of densifying the tailings to facilitate further raising of the tailings dam; the actual program achieved the desired results. This confirms that the charge weights used in the Kemess test blast were large enough to induce liquefaction in loose (contractant) silty sand and combined with the resulting pore pressure response, further suggesting that the Kemess tailings in the vicinity of the test blast are denser than expected and possess a significant resistance to liquefaction, a result consistent with the dynamic pore pressure measurements obtained for the 2006 and 2009 investigation programs that indicated dilative response to piezocone penetration.



a) Excess pore pressure ratio vs. distance   b) Peak particle velocity vs. distance

Figure 5.   Excess pore pressure and peak particle velocity data

The blast data suggests that the Kemess tailings were denser than inferred from the CPT tip resistances. The recorded pore pressure response suggests that the 6 blast pulses induced localized ground strains and immediate pore pressure build-up, which was suppressed due to the higher density of the tailings. Shear straining of the soil mass also caused dilation which tended to draw in water to the blast zone. This resulted in time dependent pore pressure increase following the blasting, followed by gradual pore pressure dissipation as the blast induced pore pressure gradients were redistributed as shown in Figure 6. The majority of the excess pore pressures were dissipated within 5 hours of charge detonation and measurements recorded the following morning indicated almost 100% dissipation. The dilative response inferred from the pore pressure response following blasting was consistent with the piezocone dynamic pore pressure measurements which yielded pore pressures lower than equilibrium as determined from dissipation tests.

This type of behavior, in which there was 1) limited pore pressure response during blasting, and 2) time dependent increase in pore pressure immediately following blasting, is indicative of a moderately dense and dilative material. The latter interpretation is inconsistent with standard accepted relative density correlations based on penetration resistance (i.e. q_{c1} = 4 - 5 MPa and $(N_1)_{60}$ = 8-10 blows/0.3m for the deep tailings which indicates loose to medium dense material), but entirely consistent with the piezocone dynamic pore pressure response. The low measured penetration resistance could be a function of the high silt content (i.e. >10%) in the tailings which increases the compressibility of the soil and results in reduced resistance during penetration.

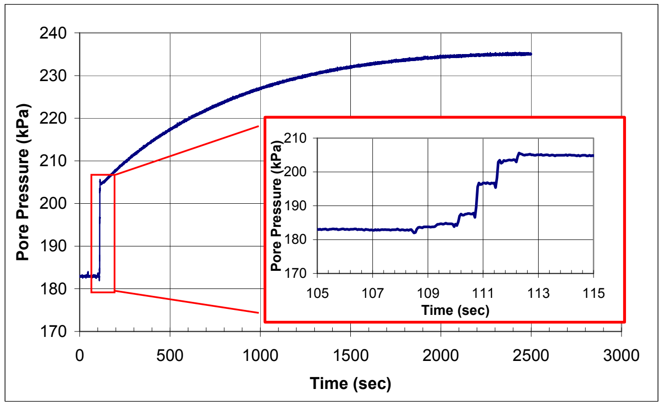
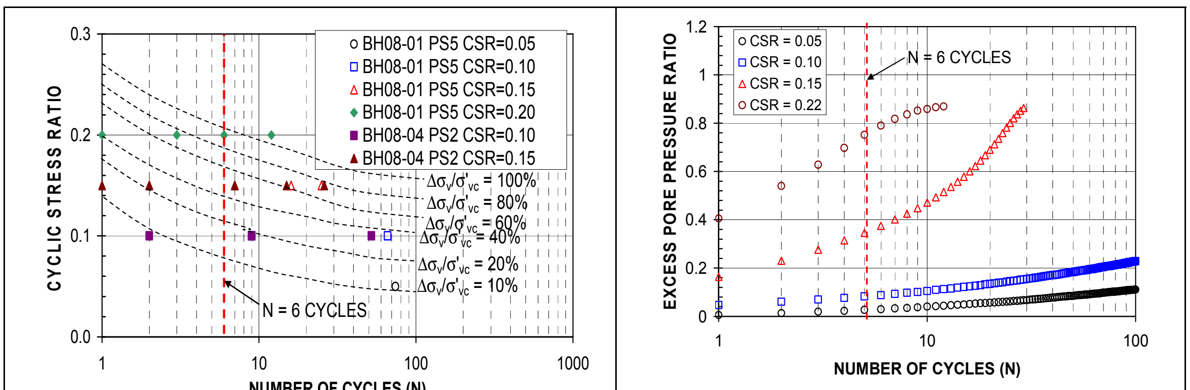


Figure 6. Excess Pore Pressure response at P5B to blast hole S-1

“Undisturbed” sampling and cyclic laboratory testing: 2008

Piston tube sampling to obtain high quality samples for CDSS testing was carried out during the additional borehole investigation in 2008. The cyclic resistance curves yielded by this program are shown in Figure 7a, while the relationship of cyclic pore pressure buildup versus number of cycles for a range of cyclic stress ratio (CSR) values is given in Figure 7b. The Kemess design earthquake loading is equivalent to 6 uniform stress cycles.



a) cyclic resistance curves

b) cyclic pore pressure data

Figure 7. Summary of CDSS test results.

The intent of this work was to provide corroboration of the blast testing which indicated a significant liquefaction resistance within the tailings. The piston samples were examined via gamma ray scans to evaluate potential sample disturbance and to select the highest quality samples for testing. Bender elements were included within the CDSS testing in order to determine the shear wave velocity of the samples for comparison to the shear wave velocity profiling undertaken with the piezocone soundings. The bender element data is included in Figure 3b, and indicates results significantly higher V_{s1} than the 2006 piezocone soundings (conducted when the tailings beach elevation was about 15 m lower than in 2008), but in line with the upper bound trend from the 2009 piezocone soundings (conducted when the tailings beach was about 5 m higher). While not entirely conclusive, the field vs. lab V_{s1} data does not discount potential sampling-induced densification, and thus calls into question the degree to which the CDSS testing is representative of field conditions. This highlights a key problem in application of cyclic laboratory testing to assess in situ soil response and points to the utility of developing reliable in situ evaluation methods for seismic liquefaction evaluation. It is interesting to note that the $R_{u\text{-excess}}$ obtained from the test blasts, about 0.10, is reasonably consistent with that which would be obtained from the cyclic resistance curves in Figures 7a and 7b on the basis of 6 equivalent cycles, and the CSR values estimated from the design earthquake on the basis of one-dimensional total stress site response analysis.

Summary

Investigation of the seismic liquefaction susceptibility of the tailings impounded by the Kemess Mine tailings dam in the south abutment area incorporated conventional field penetration resistance methods (CPT, SPT) and recovery of "undisturbed" samples for laboratory CDSS testing. The CPT approach, based on tip resistance that is non-uniquely related to relative density, indicated a degree of liquefaction resistance at odds with the dilative response indicated by the dynamic CPT pore pressures, highlighting a weakness of the traditional approach. The "non-traditional" in situ approach of instrumented test blasts corroborated the dilative behavior indicated by the CPT pore pressure data, as well as the laboratory CDSS testing, although there remains uncertainty as to the applicability of the lab data owing to field versus lab shear wave velocity discrepancies. Instrumented test blasts is judged a promising addition to available methods for in situ evaluation of liquefaction susceptibility.

Acknowledgments

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