Applications of Explosive Compaction for Tailings Volume Reduction

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ABSTRACT: Applications of the sequential detonation of explosives to cause tailings volume reduction in tailings ponds are discussed. The method is expected to be effective where the dominant tailings components comprise granular, low to non-plastic silt/sand mixtures. The paper discusses the mechanisms associated with explosive compaction, factors influencing design, and typical ground response (vibrations, settlements, pore water pressures) observed. Finally, methodologies and approximate unit costs associated with applying the technique to densification of a generic tailings pond are described.

1 INTRODUCTION

The sequential detonation of below ground explosives placed in cased boreholes has been widely used in civil and mining engineering for over 70 years. Previous applications have included foundation compaction of predominantly granular soils for earth dams, bridges, buildings and offshore oil structures (Gohl et al, 2000). This has been largely driven by the need to increase seismic or static liquefaction resistance in granular soils. A potential new application of explosive compaction (EC) is discussed in the present paper with respect to volume reduction of previously impounded mine tailings in tailings ponds.

EC involves placing single or multiple (decked) charges in a borehole drilled over the depth of soil to be densified. Several charges are fired sequentially, with delays selected to minimize offsite vibrations and also to promote cyclic loading of the subsoil. In general, the process is repeated a number of times to cause progressive soil compaction. Pore pressures generated in saturated soils following each blast sequence are allowed to dissipate before further blasts are carried out.

In saturated ground, the energy released by an explosive detonation causes liquefaction of the soil close to the blast point and causes cyclic shear straining of the soil. This process increases pore water pressures and provided strain amplitudes and number of strain cycles are sufficient, the soil mass liquefies. Liquefaction of the soil followed by time-dependent dissipation of the water pressures causes re-consolidation within the soil mass. This re-consolidation happens within hours to days following blasting, depending on the permeability of the subsoils and drainage boundary conditions, and is reflected by release of large volumes of water at the ground surface or up blast casings. “Short term” volume change is also caused by passage of the blast-induced shock front through the soil mass. At close distances from a charge detonation, the hydrodynamic pressures are large enough to cause compression of the soil-water system even though the bulk compressibility of the system is relatively small. The mechanisms of blast-induced liquefaction are discussed more fully by Finn (1979).

The EC method is expected to be most effective where the tailings comprise granular, low to non-plastic, silt/sand mixtures. Experience has indicated that the degree of volume change obtained by blasting depends on the initial density of the subsoils, the total amount of explosive used per unit volume of soil (charge density), and the geometry of the blast pattern. The density of initially loose deposits typically increases considerably to relative densities of up to 70-80% for higher charge densities. Soils with initial relative densities of 60 to 70% can only be densified by a small amount. Thus, the initial density of the tailings controls how much settlement can be expected from the EC process.

2 PREVIOUS EXPERIENCE WITH EC IN MINE TAILINGS

The authors have recently completed 2 EC test programs (Sites 1 and 2) in loose mine tailings (sand/silt mixtures) at a tailings dam site in Northern Ontario. The principal author was also involved in initial design of blasting trials for the Canadian Liquefaction Experiment, referred to as Site 3. The latter was carried out at Syncrude's J-pit outside of Fort McMurray, Alberta (Wride et al, 2000). Other EC data reported in the engineering literature concerning compaction of silt/sand mine tailings has also been reviewed (Klohn et al, 1981; Handford, 1988; Gohl et al, 2000), referred to as Sites 4, 5 and 6, respectively.

The basic geotechnical characteristics of the above mine tailings materials and the charge density used for each EC project, are summarized in Table 1. Charge density is defined as the sum of charge weights used in blast holes located within the interior of the test area to be densified plus ½ the sum of charge weights for blast holes located around the perimeter of the area, all divided by the total volume of soil. This definition of charge density accounts approximately for blast energy radiated away from the zone to be densified for perimeter blast holes.

Table 1. Summary of geotechnical properties for EC test sites in mine tailings.

Site No.	Soil Type	Avg. Initial Dr (%)	Layer Thk.* (m)	Avg. Vert. Strain**	Charge Density (gm/m^3)
1	Silty sand	~50	10	0.10	53
2	Silt & Sand	~50	18	0.105	74
3	Silty sand	~40	12	N.R.	6
4	Silt & Sand	~30-40	7	0.043	5
5	Sand	<60	7	N.R.	4
6	Silt	~35	12	0.025	5

* Loose layer thickness (H_0) with estimated initial Dr less than 60%.

** Average of post-EC settlement at tailings surface over test area divided by H_0.

N.R. = not reported.

2.1 *Post-EC Settlements*

Table 1 indicates that a range of loose silt/sand tailings mixtures have been successfully blast densified, achieving average settlements over the loose layer thickness of up to about 10%. Maximum settlements are achieved using higher charge densities, which implies the use of relatively close blast hole spacings, multiple decks of explosives, and repetitive blast sequences. Post-EC settlements averaging 2 to 4% of the loose layer thickness over the test area have been achieved using relatively low charge densities of around 5 gm/m^3. The latter have been based on larger blast hole spacings, typically in the range of 10 to 20 m.

Settlements decay with distance from a blast hole, forming a bowl-shaped depression around each blast hole as pore pressures generated by blasting dissipate. Since shear strains and hydrodynamic blast pressures attenuate with distance from a charge detonation, this settlement reduction with distance should be expected. Depending on the spacing and pattern of blast holes fired, these depressions gradually level out with successive blast sequences, corresponding to the effects of adjacent blasts causing additional cyclic straining within a partially settled area.

The effect of several blast sequences on local settlement within the center of a test EC area (Sites 1,2 and 4) is shown in Figure 1, showing the progressive tailings shakedown with each blast series. For Sites 1 and 2, each blast sequence involved the sequential detonation of several charges. For Site 4, only 1 charge detonation was used for each blast series. The data indicate that initial soil liquefaction following the first blast series typically caused vertical settlements equal to 5 to 6% of the loose layer thickness within a few metres of a blast hole. This corresponds to zones of largest shear strain in close proximity to the blast hole. Several blast series result in large vertical settlements around the blast hole, in the range of 12 to 14% of the loose layer thickness. These localized settlements typically exceed the average settlement over the test area.

Ishihara and Yoshimine (1992) suggest that post-liquefaction settlements in loose sands (initial relative densities of 40 to 50%) equal to 3.5 to 4.5% of the loose layer thickness should be expected following earthquake shaking. Larger earthquake settlements should be expected for looser sands. For blast loading, the effects of large shear strain amplitude, number of strain cycles, and hydrodynamic blast pressures apparently leads to larger post-liquefaction settlements locally around a blast hole compared to that caused by earthquake loading.

Experience with blasting in loose sands and silts suggests that the zone of significant settlement is approximately ½ of the radius of liquefaction. The looser the soil, the broader the radius of liquefaction and radius of significant settlement. Field trials are typically carried out to confirm the amount of actual settlement achieved since this will depend on the initial densities and other geotechnical properties of the tailings, the size of charge detonation per delay, the number of charges detonated sequentially, and the depths of charge burial.

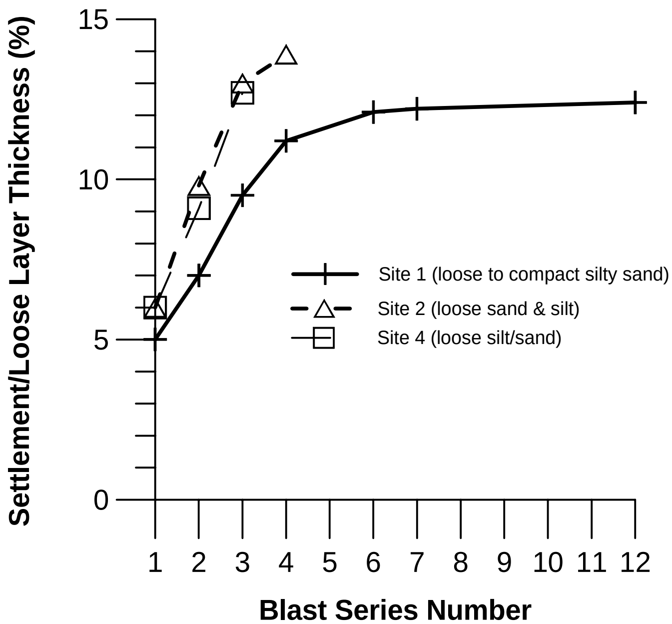

Figure 1. Effect of using a progressive series of blasts on silt & sand tailings shakedown near the centre of the test areas for Sites 1, 2 and 4.

2.2 *Pore Pressure Response*

Charge detonations lead to stress wave propagation away from a blast hole, producing dynamic changes in mean stress and shearing stress within the soil medium. The changes in mean stress are typically very high (MPa range) within a few metres of a blast hole (for the typical charge sizes used by the authors in EC projects), leading to transient hydrodynamic pore pressures. The shearing stresses developed are limited by the undrained strength of the tailings materials, leading to permanent shear strain offsets in a soil element following passage of the shock front. The shear strain pulses are considered primarily responsible for build-up in residual pore water pressure. In close proximity to a blast hole, high amplitudes of dynamic mean stress may also lead to residual pore pressure build-up if the soil-water compressibility is such that soil skeleton volume change occurs. This would also lead to residual pore pressure buildup. High pressure, load-unload hydrostatic compression tests on saturated soil elements would be required to confirm this effect.

The typical pattern of transient pore pressure pulses and the gradual buildup of residual pore pressures are seen in Figure 2 for a multiple hole detonation sequence at Site 2. The rate of data acquisition used was not rapid enough to accurately capture all the hydrodynamic pressure pulses, but the general trend of gradual buildup in residual pore pressure is evident. The distance of the nearest blast hole to the point of pore pressure measurement is considered far enough that the effects of dynamic mean stress on residual pore pressure change is minor. Pore pressure build-up resulting from shear straining is considered to be the dominant factor.

The amount of residual pore pressure buildup at a reasonable distance from a blast hole (neglecting hydrodynamic pressure effects) depends primarily on shear strain amplitude and number of strain cycles (Dobry et al, 1982). These in turn will depend on charge weight per delay, distance from a charge detonation, and number of charges detonated sequentially. In the extreme, if the residual pore pressures over and above the pre-blast static water pressures in the ground equal the initial vertical effective stresses, then a condition of soil liquefaction results. The residual excess pore pressures divided by the initial vertical effective stress is defined as a pore pressure ratio, PPR.

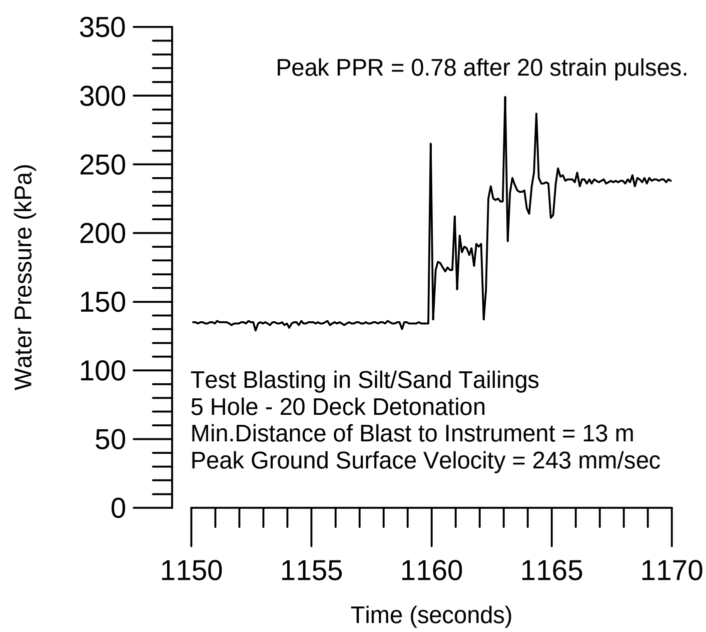

Figure 2. Pore pressures versus time during sequential blasting at Site 2, showing peak hydrodynamic pressures and residual pore pressure buildup. The rate of data acquisition was not high enough to accurately capture all the hydrodynamic pressure –pulses.

A plot of PPR versus scaled hypocentral distance (R) and average charge weight (kg) per delay (W) for Sites 1 to 4 is shown in Figure 3. Reliable pore pressure data were not available for Sites 5 & 6. Here the hypocentral distance R refers to the distance (metres) between the pore pressure measurement point and the nearest charge detonation. The data include both single and multiple charge detonations. The data indicate that PPR increases with increasing charge weight per delay, decreasing distance between a blast point, and increasing number of charge detonations. The data indicate that a radius of liquefaction (where PPR $\geq$ 0.9) can be estimated as equal to $\alpha W^{0.33}$ in loose tailings material with α values in the range of 3 to 9. For design, the available data suggest that an average radius of liquefaction equal to $6W^{0.33}$ may be presumed, assuming multiple charge detonations are employed.

Data from cyclic, strain controlled triaxial tests on loose sands (relative densities of about 45%) indicate that it is necessary to achieve peak shear strains during one strain cycle of about 0.3% to produce soil liquefaction after 4 to 10 strain pulses (Dobry et al (1982). Thus, design estimates of maximum shear strain versus distance from a charge detonation may be used in advance of blasting field tests to estimate maximum radii of liquefaction around blast holes. The procedures used are described in Section 3 on Blast Design, involving the use of nonlinear blast analysis.

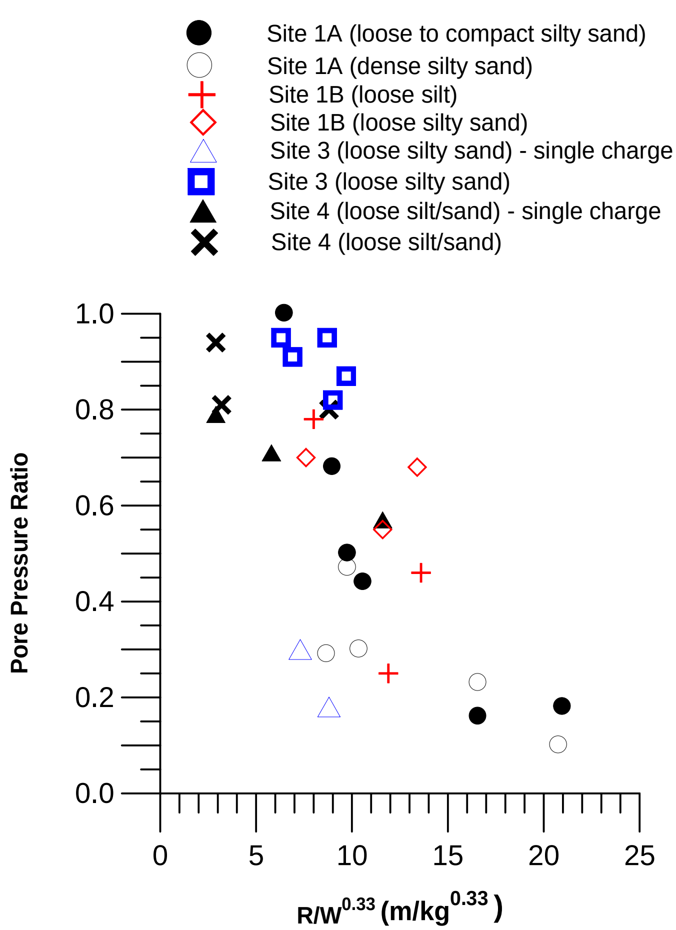

Figure 3. Peak PPR versus scaled distance for 4 EC tests in loose mine tailings.

2.3 *Offsite Blast Effects*

It is desirable to maximize the charge weight per delay in order to employ the broadest blast hole spacings but achieve acceptably large radii of liquefaction and zones of settlement around a blast hole. However, the charge weights cannot be so large so that unacceptable levels of ground vibration or residual pore pressure occurs at locations of interest.

Blasting field trials are typically used to measure peak ground surface velocities and residual pore pressures as a function of charge weight per delay and closest distance to a charge detonation. Figure 4 shows peak particle velocities (PPV's) measured at the ground surface versus scaled distance and charge weight per delay ($R/\sqrt{W}$) from data obtained at Sites 1,2 and 5 where PPV data were reported. Here R refers to the horizontal distance (metres) between the measurement location and the closest blast hole. Such site-specific plots may be used in blast design to estimate off-site vibration effects.

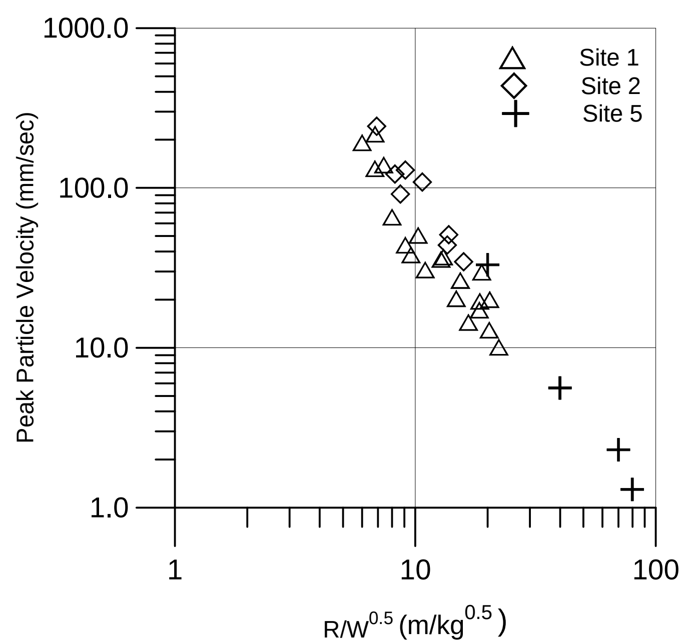

Figure 4. PPV versus scaled distance for 3 EC tests in loose mine tailings.

When blasting in tailings ponds in proximity to existing earth dam structures, the level of residual pore pressure in dam foundations is important in order to assess dam stability based on effective stress principles. Figure 5 shows data relating PPR at different depths within the tailings deposits to measured PPV at the ground surface above the location of pore pressure measurement. Such data are useful in order to be able to set safe PPV limits so as not to exceed critical pore pressure levels within dam foundations. The data obtained from Sites 1 and 2 suggest that surface PPV's of up to 100 mm/sec may be experienced without residual PPR's exceeding 0.6 at the depths measured. This would provide a factor of safety against liquefaction of at least 1.66 which is typically considered adequate for dam stability.

The critical levels of PPR not to be exceeded in tailings dam foundations must be carefully reviewed by experienced geotechnical personnel prior to blasting. Since PPR is fundamentally related to the shear strains induced in the dam foundations by the sequential blasts, blast analysis is sometimes necessary to estimate the levels of shear strain at different distances from a blast hole. Data for loose sands from Dobry et al (1982) indicate that PPR's should not exceed 0.6 after about 20 strain pulses (similar to the maximum number of charge detonations likely to be detonated during 1 blast series) provided shear strains do not exceed about 0.1%. Limiting strain levels will depend on soil gradational characteristics, relative density and number of strain pulses. This provides another useful criterion for blast design to limit off-site PPR's in dam foundations.

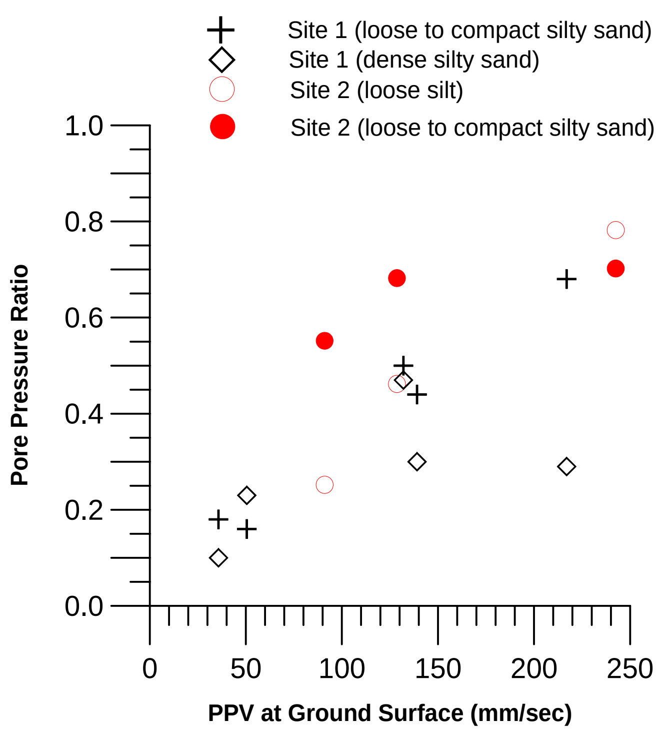

Figure 5. Peak PPR at various depths versus PPV at the ground surface for Sites 1 and 2 in loose mine tailings.

3 ECONOMICS OF THE EC PROCESS AND TYPICAL BLAST DESIGN

The main issue in assessing the economics of tailings compaction is evaluating how many blast holes and what charge densities are required within a tailings pond in order to achieve a given amount of surface settlement. The number of blast holes and associated explosive times the unit cost per blast hole gives the total cost of the EC project. The volume recovered in the pond through blasting may be expressed in terms of an equivalent weight of tailings solids as (pond area) x (settlement) x (average dry density of unconsolidated tailings). Then the total cost of tailings compaction may be expressed in terms of a unit cost of EC per dry unit weight of tailings recovered through volume reduction in the pond.

The number of blast holes over a tailings pond area is proportional to the inverse square of the hole separation distance. Thus, the economics of the EC process are a balance between how much tailings pond settlement can be achieved for a given blast hole separation distance and total charge weight per hole. The selection of charge weight per delay is made so as not to exceed critical ground velocity and pore pressure levels at locations of interest, for example, within the foundations of retention dam structures surrounding the tailings pond.

An example of blast design in a generic tailings pond is given in the following sections. The pond is assumed to be 40m deep with an average relative density of 45% comprised of saturated, silty sand. The tailings beach area is assumed to be 40m wide and to be unsaturated to the 20m depth. The crest of the tailings dam is assumed to be 60 m from the edge of the saturated zone of tailings. It is considered desirable to limit PPR's to 0.6 or less beyond the beach zone at a minimum horizontal distance of 40m and at depths of 20 m or greater. It is also desired to keep PPV's less than 100 mm/sec on the crest of the tailings dam.

3.1 *Maximum Charge Weights Per Delay*

The use of maximum charge weights per delay is desirable in order to increase charge density for a given blast hole spacing and thereby increase tailings settlement. Using Figures 3, 4 and 5, a maximum charge weight per delay of 22.5 kg. is selected for this example so as not to exceed the safe limits of PPR and PPV at the locations of interest.

The maximum charge weight per delay is site-specific, depending on blast design criteria and site-specific relationships between PPV, PPR, distance and charge weight per delay. Depths of burial for each charge must be selected to avoid surface cratering. Special explosives are selected which are resistant to sympathetic detonation and desensitization due to high transient overpressures. The time delays between charges must also be carefully selected and implemented to avoid excessive offsite vibration or pore pressure build-up.

3.2 *Nonlinear Blast Analysis*

Wu (1995, 1996) developed a non-linear, spherically symmetric finite element program that assumes that a charge detonation may be idealized by assuming a blast pressure – time input applied normal to the surface of a spherical cavity. With the assumption of spherical symmetry, the dynamic equations of motion of the system reduce to a radial displacement component, which varies with radial distance from the charge detonation. Three normal stress and strain components exist in the spherically symmetric model. The maximum in-plane shear stress is defined by ½ the difference between the radial and tangential normal stresses. The maximum in-plane shear strain is defined as the difference between the radial and tangential normal strains.

The Wu model considers soil layering in an approximate way by analyzing dynamic soil response along a number of radial lines extending out from a particular charge location. These radial lines are inclined at different directions to the horizontal. For a particular angular orientation of the radial line, soil properties at various locations along the line are based on the soil layer intersected. The shear stress – shear strain relationship used to model soil response within a soil layer is based on a hyperbolic backbone curve, using the Masing criterion to represent cyclic load-unload response. The backbone curve characteristics are defined by the peak shear resistance and the small strain shear modulus (GMAX) of the soil at a given depth. GMAX is defined by the shear wave velocity (V_s) of the soil using the isotropic elasticity equation GMAX = ρV_s^2. The bulk modulus (B) of the soil-water system is also computed from elasticity-based relationships linking B to the shear and P-wave velocity (V_p) of the tailings. Thus, measurement of V_s and V_p within the tailings materials is helpful to the modeling process.

The high strain rates with blast-induced cavity expansion require a viscous component of strength in the model for realistic predictions: a simple linear (Newtonian) dependence on shear strain rate is used. The program outputs dynamic shearing strains, ground accelerations and velocities, plastic volume change potential and residual pore water pressures for both single and multiple charge detonations. Superposition of spherically symmetric models, allowing for the relevant radial distances, simulates 3-D arrays of blast holes with decked charges. Reasonable predictions of ground surface settlement and residual pore pressures are obtained, provided that the model is first calibrated by analysis of test blasts at the site in question.

For purposes of assessing potential settlements in the generic tailings pond being considered, different blast hole spacings and numbers of decked charges in a blast hole have been modeled. The 40m deep soil profile has been split into layers and shear strengths, V_s and V_p distributions estimated consistent with the assumption of an average relative density of 45% in the tailings. The Wu model has been calibrated for a single, multiple deck detonation considering a maximum charge size per delay (W) of 22.5 kg. to give the following results: (a) average post-liquefaction settlements around a blast hole equal to 5.5% of the tailings thickness, and (b) maximum shear strains for each detonation equal to about 0.30% at a distance in metres of $6W^{0.33}$. Calibration criterion (a) comes from consideration of Figure 1. Criterion (b) comes from review of Figure 3 and that cyclic shear strains of about 0.3% are estimated as being required to induce initial liquefaction (PPR ≅ 1.0) in loose tailings.

Computed average settlements for 2 different assumptions of blast hole layouts and charge densities are summarized below:

<u>Blast Hole Layout 1:</u>

Average charge density = 11 gm/m^3
Computed average surface settlement = 1.9 m
Computed average vertical strain = 1.9/40 = 0.047

<u>Blast Hole Layout 2:</u>

Average charge density = 17 gm/m^3
Computed average surface settlement = 2.8 m
Computed average vertical strain = 2.8/40 = 0.070

Computed post-EC settlements are sensitive to the soil properties and relative densities assumed. A looser overall tailings profile than assumed in the calculations will result in more settlement. The settlements computed locally around blast holes are greater than the average settlements cited above, and reflect the settlement variation in a grid of blast holes caused by blast energy attenuation. The average vertical strains (settlement divided by tailings thickness) are generally consistent with previous EC experience in tailings deposits (see Table 1) for the charge densities proposed. The use of higher charge densities, requiring closer blast hole spacings, would result in greater amounts of overall average settlement. However, the resulting increased costs expressed per tonne of increased storage of tailings solids are not as economic as the case where broader hole spacings are used but with reduced overall settlement. This is because EC costs are roughly proportional to the inverse of the square of the blast hole spacing.

3.3 *Estimated Unit Costs*

Costs to install and load blast holes using bulk explosive on tailings ponds have been estimated at current (2003) prices based on the charge densities and tailings pond depths cited previously. Reduced pond depths would reduce unit costs per blast hole roughly proportional to the depth of tailings to be densified. It is necessary to use barge-mounted drilling equipment capable of working in limited depths of water on the tailings pond, or equivalent "swamp buggy" equipment that can operate on the tailings pond surface.

Assuming that the generic tailings pond has a plan area of 800 m x 400 m and that the dry density of tailings is 1.2 tonne / cu.m., the unit costs for tailings volume reduction using the 2 different blast hole layouts are estimated as follows:

Blast Hole Layout 1: Estimated cost = $1.45/tonne
Blast Hole Layout 2: Estimated cost = $1.85/tonne

These unit prices (in U.S. dollars) should be reviewed on a project-specific basis, and are strongly dependent on tailings pond depth and the initial densities of the tailings. The figures cited are intended to indicate general economic viability of the EC process.

It is noted that the EC techniques proposed for tailings pond compaction result in significantly reduced charge densities compared to those typically used by the authors in foundation compaction projects. In the latter case, densification criteria and the uniformity of densification are generally more stringent than required for volume reduction in tailings ponds. The stringent requirements for foundation compaction (as opposed to tailings volume reduction) result in increased unit costs.

It is understood that costs for increasing heights of tailings dams and pond storage capacities vary widely. These costs are based on a number of factors: size of tailings disposal operation, proximity of the plant site to the tailings pond, the type of mine commodity involved, local proximity of borrow materials for tailings dams, material placement costs, and environmental audit – engineering design costs. Consequently, tailings storage costs vary from $0.2 to $10.0/tonne depending on the mine (Davies, 2003, personal communication). Thus, for certain cases, the use of EC to increase pond storage capacity may be an economically viable tool.

The other benefit of EC is that it can be carried out relatively quickly. The time involved for environmental and safety reviews, design engineering, and construction of higher tailings dams may be relatively lengthy. Where tailings storage capacity is rapidly running out, compounded by delays in the permitting process to allow raises in tailings dams, mine owners may need to consider short term solutions to temporarily increasing storage capacity. The use of EC is one such option.

The use of EC for tailings pond reclamation following closure may also prove attractive. The EC will reduce density and permeability of the tailings, which should result in reduced water flow through the tailings. This should reduce potential for development of acidic leachate and problems with acid mine drainage. The tailings densification should also improve the ability to operate on the tailings pond surface, following drawdown of the pond water levels. This will facilitate the pond reclamation process.

4 CONCLUSIONS

Explosive compaction has been used effectively for a wide variety of civil and mining engineering projects, primarily with respect to improving foundation soil resistance to static and seismic liquefaction. A new application of the EC process is proposed to reduce the volume of previously impounded mine tailings, thereby increasing storage capacity within the tailings pond.

Previous experience with EC in non-plastic silt/sand tailings materials indicates that significant volume change can be induced by blasting in saturated materials. The amount of volume change largely depends on charge density, which is governed by blast hole spacing and the charge weights used in each hole. The geometry of the blast pattern further influences the uniformity of the compaction process. Data collected from previous EC field trials in tailings materials allow one to carry out preliminary design of the EC process. Estimates of post-EC settlement as a function of tailings depth and soil properties, blast hole layouts and charge densities are facilitated by application of nonlinear blast analysis.

The economics of the EC process to cause shakedown of tailings deposits are improved by using maximum blast hole spacings and the highest charge weights per delay, consistent with limiting offsite vibration and pore pressure generation. Analysis of costs for EC, expressed as a cost per dry tonne of increased tailings storage, indicate that the method may be economic for some classes of tailings storage operations. In some circumstances, the time involved in raising tailings dams or delays caused by the permitting process dictate that a shorter term solution must be found to temporarily increase pond storage capacity. EC is attractive in this instance. Finally, EC should prove helpful in tailings pond reclamation through possible reduction in potential for acid mine drainage and improving trafficability on the tailings surface following pond water lowering.

Blasting field trials using a limited number of blast holes are required to optimize blast hole spacings and charge weights and confirm the extent of settlement possible in loose tailings. The amount of settlement largely depends on the initial relative density of the tailings and that these materials be comprised of predominantly low to non-plastic silt/sand materials. Field tests are necessary to finalize unit costs associated with increasing storage capacity of a particular tailings pond.

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