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Shear wave velocity of gold tailings

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To evaluate the liquefaction potential of tailings impoundments, the in situ void ratio and the effective stresses are required. While stresses can be estimated with relative accuracy, the void ratio of tailings has proved difficult to obtain, especially below the water table. The development of in situ seismic techniques has presented new opportunities to determine the in situ void ratio of geomaterials. In addition, these seismic methods can be used to evaluate the liquefaction potential of gold tailings. However, the method currently relies on the shear wave velocity–void ratio relationships developed for sands, while gold tailings is essentially a silty material. This raises the question of the validity of such relationships for tailings material. A triaxial apparatus was modified to accommodate bender elements and the shear wave velocity of gold tailings was determined at various void ratios and effective stresses. The results show that there is a relationship between void ratio and the normalised shear wave velocity of gold tailings. They also show that the shear wave velocity for gold tailings is more sensitive to changes in effective stress than to changes in void ratio and that the shear wave velocity is virtually independent of the overconsolidation ratio. Application of the shear wave velocity–void ratio relationship in conjunction with critical state theory indicates that at the same shear wave velocity, gold tailings have a lower susceptibility to liquefaction than sands.

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INTRODUCTION

The static liquefaction of tailings dams poses a potential threat to the environment. Two well-known examples of tailings dam failures in South Africa are the Bafokeng and Merriespruit failures in 1974 and 1994 respectively (Jennings 1979; Blight 1997; Wagener 1997). Been and Jefferies (1985) introduced the concept of a state parameter which allows the susceptibility for static liquefaction of a sand to be evaluated. The ability to evaluate the static liquefaction potential of tailings dams, which consist primarily of silt-sized particles, would be valuable for quantifying the risk of an impoundment. However, in order to quantify the static liquefaction potential, the in situ void ratio and the effective stress conditions of the material are required. The stress conditions within a tailings dam can be estimated with relative accuracy if the position of the water table and pore fluid flow regime is known. Since tailings material is deposited as a slurry, it is very difficult to obtain undisturbed samples from which the void ratio can be determined, especially from below the water table. Without knowledge of the in situ void ratio of the tailings, the susceptibility of the tailings material to liquefaction can, at present, not be determined with any confidence.

Robertson *et al* (1995) suggested a technique whereby the liquefaction potential of sand may be evaluated directly using in situ seismic measurements, but the technique implicitly assumes that a relationship exist between shear wave velocity and void ratio. Seismic methods measure the elastic wave velocity of the material and, since shear wave velocity is also a function of the stress conditions of the medium through which the wave propagates, it is necessary to isolate the influence of effective stress in order to obtain a unique relationship between shear wave velocity and void ratio. On the basis of elasticity theory, Sykora (1987) suggested an equation for shear wave velocity normalisation against effective stress:

$$V_{s(n)} = V_s \left(\frac{P_a}{\sigma'_v} \right)^{0,25} \qquad (1)$$

Where:
$V_{s(n)}$ is normalised shear wave velocity
V_s is shear wave velocity
P_a is atmospheric pressure (usually taken as 100 kPa) and
σ'_v is the major principle effective stress

Figure 1 is a compilation of results from a number of workers. It shows that unique but different relationships exist between normalised shear wave velocity and void ratio for sands (Hardin & Richart 1963; Robertson & Fear 1995) and clays (Pennington *et al* 1999; Tika *et al* 1999; Silvestri *et al* 1999). It appears reasonable that a similar relationship may exist for silt. Despite the possible practical applications, no such relationship has been developed to date. The objective of this study was to develop such a relationship for gold tailings empirically.

The particle size of gold tailings depends on the methods by which the gold bearing rock is broken down. Such processes may include crushing, milling and grinding (Vermeulen 2001). In addition, sorting of particle sizes may occur as a result of delivery techniques such as spigot or cycloning or as a result of the depositional environment on the dam itself. In general, however, gold tailings particles are predominantly of silt size.

EXPERIMENTAL METHODS

Gold tailings were tested in a triaxial apparatus modified to accommodate bender elements. Shear wave velocity measurements were made at known stress conditions and void ratios.

Keywords: Shear wave velocity; void ratio; bender elements; gold tailings; seismic methods, static liquefaction

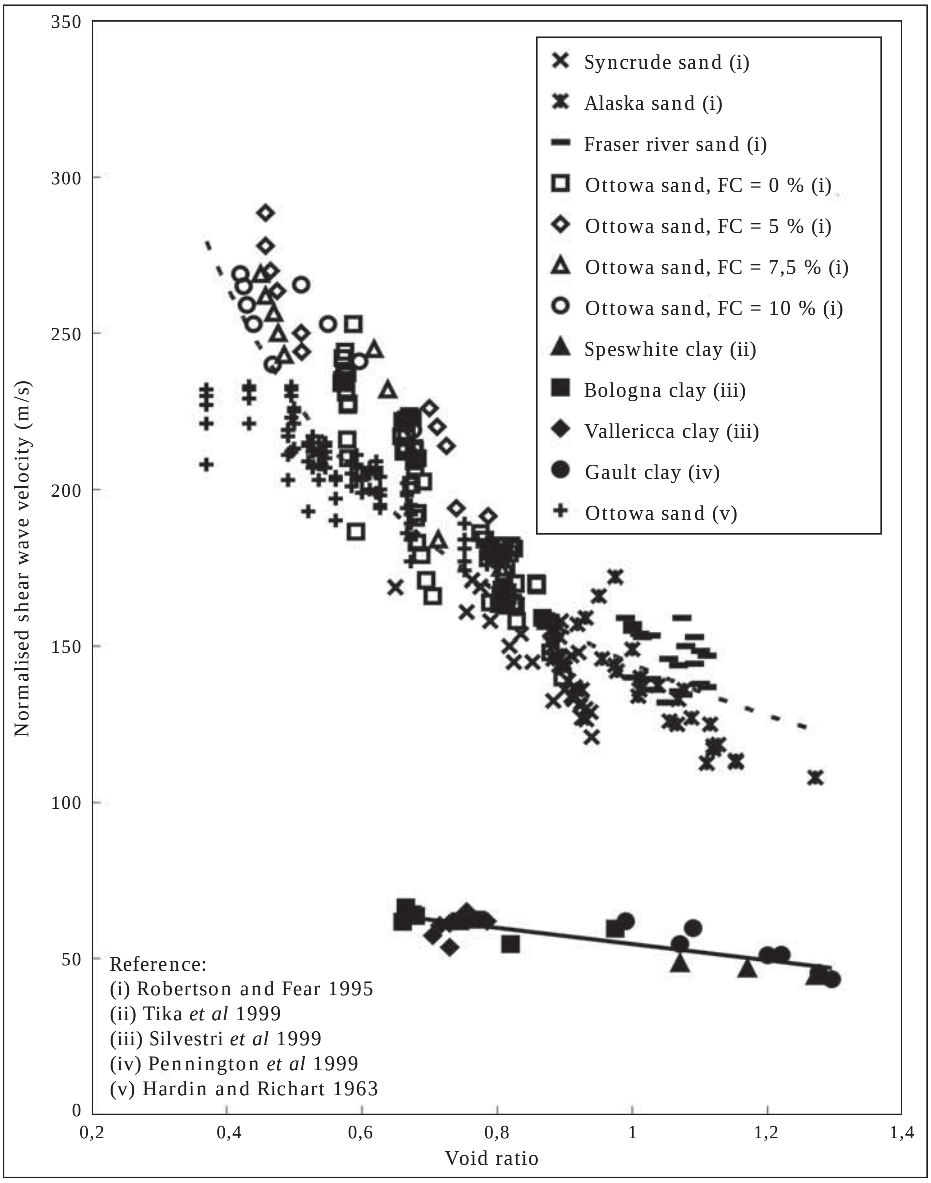

Figure 1 Void ratio against normalised shear wave velocity for various sands and clays

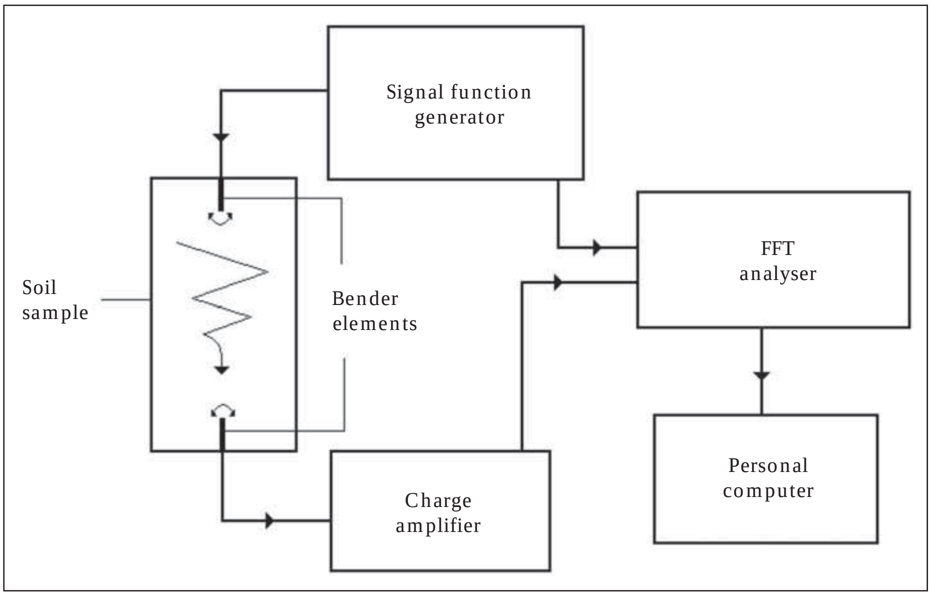

Figure 2 Schematic representation of the bender element system

Specimens were prepared at various initial void ratios and tested during a loading cycle at effective stresses of 25, 50, 100, 200 and 400 kPa and unload cycle at the same stresses. The effect of over-consolidation on the shear wave velocity could therefore be assessed.

Test apparatus

Shear waves were generated using bender elements (Shirley & Hampton 1978) which were embedded in the top cap and the base pedestal of a triaxial cell. Bender elements consist of piezoceramics which elongate or shorten in response to a driving voltage. When two piezoceramics are rigidly bonded and driven with opposite polarity, one element extends while the other shortens, causing the composite element to bend. Conversely, the bender element can also be used as a receiver, as any movement detected by the bender element induces a pulse, which generates a potential difference as output. As bender elements are high impedance devices, it is necessary to waterproof the elements when used in saturated soil. The bender elements were encapsulated using epoxy and the details of the procedure are given by Chang (2004).

Using bender elements mounted within the top cap and base pedestal allows shear waves to be transmitted from the first bender element, through the soil specimen to the second bender element. The travel time of the waves between the two bender elements can be measured and the shear wave velocity of the specimen determined.

The bender element setup used in this investigation was similar to that described by Dyvik and Madshus (1985), but was modified to improve the quality of the output signal. Apart from the bender elements, the system included a signal function generator, a charge amplifier, and a recording device in the form of a real-time Fast Fourier Transform Analyser. The full bender element system is shown in figure 2. Recorded data were downloaded and stored in a personal computer and later processed.

Test material and sample description

The material used was gold tailings originating from the Free State goldfields. Vermeulen (2001) classified tailings material from the Free State as low to high plasticity silty sand to silt, with a specific gravity of 2,75 and an effective angle of internal friction of 34°. The grading of the material (figure 3) showed that it had a fines content (silts sized particles and smaller) of 65 %. The figure also shows the envelope of gradings for typical South African gold tailings (Blight & Steffen 1979) and indicates that the test material was relatively coarse compared with typical South African gold tailings. Scanning electron micrographs of the material used for this project showed the tailings consisted mainly of bulky, angular particles with some platy particles (Figure 4).

Many investigators have shown that the position of the critical state line (also referred to as the steady state line) is highly dependent upon the fines content (Sladen *et al* 1985; Pitman *et al* 1994; Lade & Yamamuro 1997; Thevanayagam 1998; Papageorgiou *et al* 1999). According to Thevanayagam *et al* (2002), there is a certain threshold fines content which defines the soil's response to shear behaviour for a given global void ratio. With fines content above the threshold value, the coarse-grained particles become dispersed within the fines and the shear behaviour is dominated by the fines. Below this threshold, the shear behaviour of the soil is dominated by the coarse-grained particles. According to the classification by Thevanayagam *et al* (2002), the shear behaviour of the tailings shown in figure 4 should be dominated by the fines (silt-sized particles or smaller), with the sand-sized particles acting as a reinforcing element.

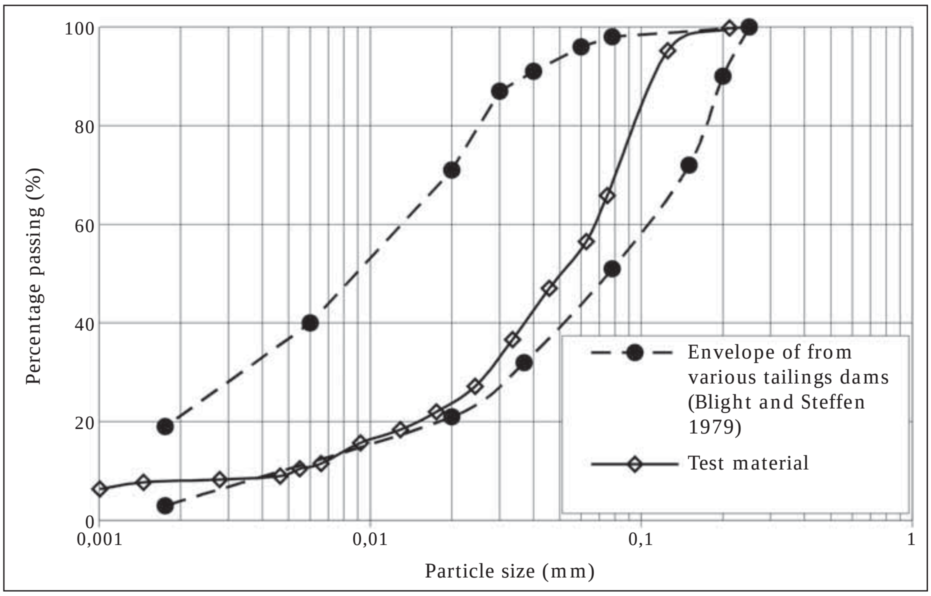

Figure 3 Particle size distribution of gold tailings test material and envelope for typical gold tailings in South Africa

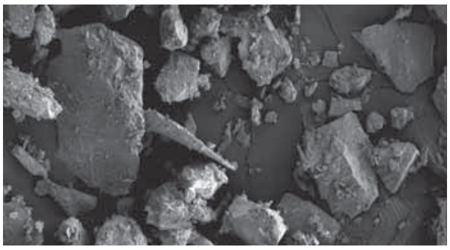

Figure 4 Scanning electron micrograph of gold tailings test material

Table 1 Typical in situ void ratios (Blight 1969)

	Typical void ratio
After deposition	1,7
After evaporation	1,25
After sun drying	0,5

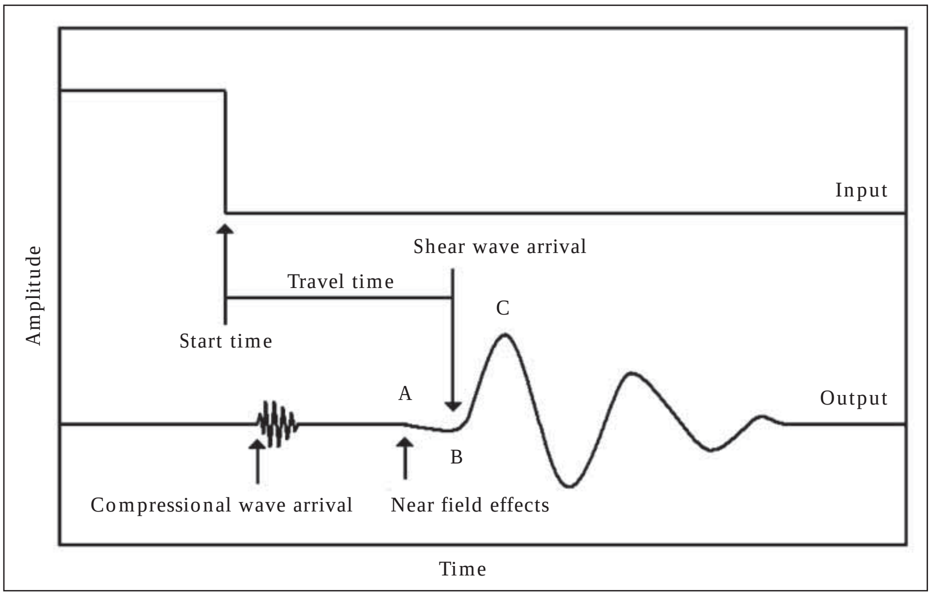

Figure 5 Schematic representation of bender element signal

Triaxial samples with a height of 100 mm and a diameter of 50 mm were prepared at various target void ratios at a moisture content of 14 % using the moist tamping method (NITRR 1982). During the research it was difficult to obtain a high void ratio after flushing has taken place, as the samples tended to collapse into a denser state upon wetting. This is in agreement with the work of Papageorgiou *et al* (1999), who noticed that tailings material from Merriespruit exhibits collapse behaviour upon wetting.

The volume reduction during flushing was determined using a digital pressure controller which measured the volume change of the cell fluid. The initial void ratio was obtained from the initial volume, moisture content, mass and specific gravity of the specimen. Volume change measurements were taken throughout the test and these volume measurements were used to determine the void ratio at the various stages. After completion of the test, the final void ratio was determined from the moisture content. Back analysis using the volume change data allowed the independent determination of the void ratio at any stage of the test. A forward analysis using the initial volume and a back analysis using the final water content was done for every set of tests. The difference in void ratio determined from the forward and back analyses ranged between 0,002 and 0,07 with an average of 0,032. The void ratios obtained from the six specimens ranged between 0,47 and 0,87. Typical in situ void ratio values given in table 1 (Blight 1969) indicates that the laboratory void ratios corresponded to those found in tailings dams some time after deposition.

Shear wave velocity analysis method

To obtain the shear wave velocity (V_s), both the distance between the bender elements (L) and the travel time from the sender to the receiver (t) are required. Shear wave velocity can then be determined by:

$$V_s = \frac{L}{t} \qquad (2)$$

On the basis of results obtained using samples of different length, Viggiani and Atkinson (1995) recommended that the travel distance be taken as the distance between the tips of the sender and receiver. The travel distance was modified during the test to account for changes due to volumetric strains as a result of consolidation or swelling. Since the travel distance can be determined with an accuracy of ± 0,5 %, the error in shear wave velocity measurement is caused primarily by errors in travel time determination. Various methods have been used to determine travel time and the methods can be divided into two categories, namely time of flight techniques (Shirley & Hampton 1978; Dyvik & Madshus 1985; Brignoli *et al* 1996; Jovičić *et al* 1996) and phase sensitive detection techniques (Blewett *et al* 1999). The main difference between the two categories is that the time of flight technique uses a single pulse, while the phase sensitive detection technique uses continuous waves. Both methods have advantages and disadvantages and for this project the time of flight method which measures the time of a single pulse to travel between the two bender elements was used.

Input and output data were sampled at 256 samples per channel within 2,45 milliseconds at a rate of 104,5 kHz per channel. The amplitude of input waves was 10 volts peak to peak, while the amplitude of output waves varied between 5-300 µV peak to peak for different samples.

Figure 5 schematically shows a square pulse bender element input and its corresponding output signal. The first wave that arrives at the receiving element is the compressional wave, which in saturated soil travels significantly faster that shear waves (eg Heymann 2003). The arrival of the shear wave is often obscured by an initial deflection, known as the near field effect, before the actual arrival of the shear wave, indicated by point A (Brignoli & Gotti 1992; Viggiani & Atkinson 1995; Jovičić *et al* 1996). Sanchez-Salinero *et al* (1986) explained the near field component as the result of coupling between waves that exhibited the same particle motion but propagate at different velocities and attenuate at different rates. The extent of this near field component determines the accuracy with which the travel time, and thus shear wave velocity can be determined. Sanchez-Salinero *et al* (1986) also suggested that in order to

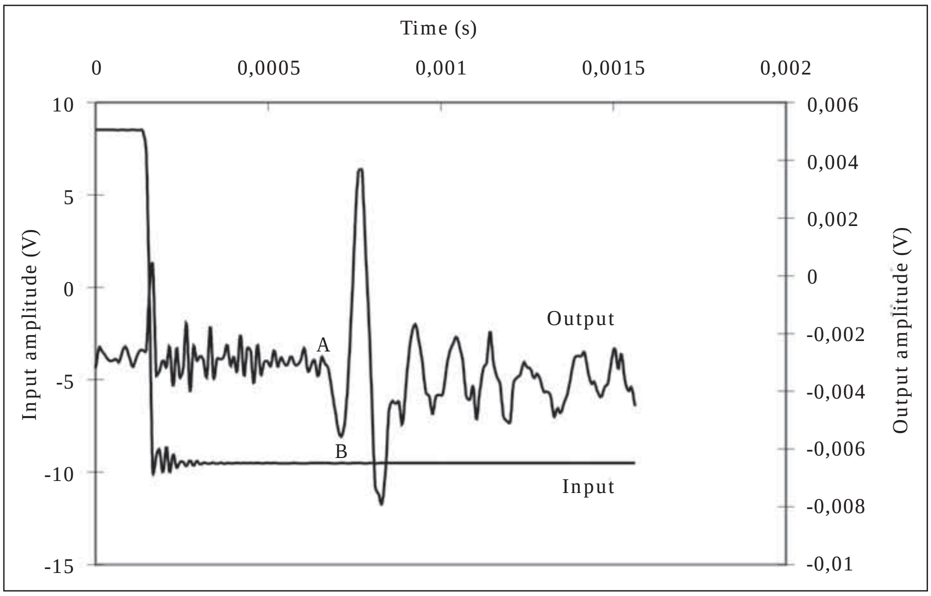

Figure 6 Typical bender signal

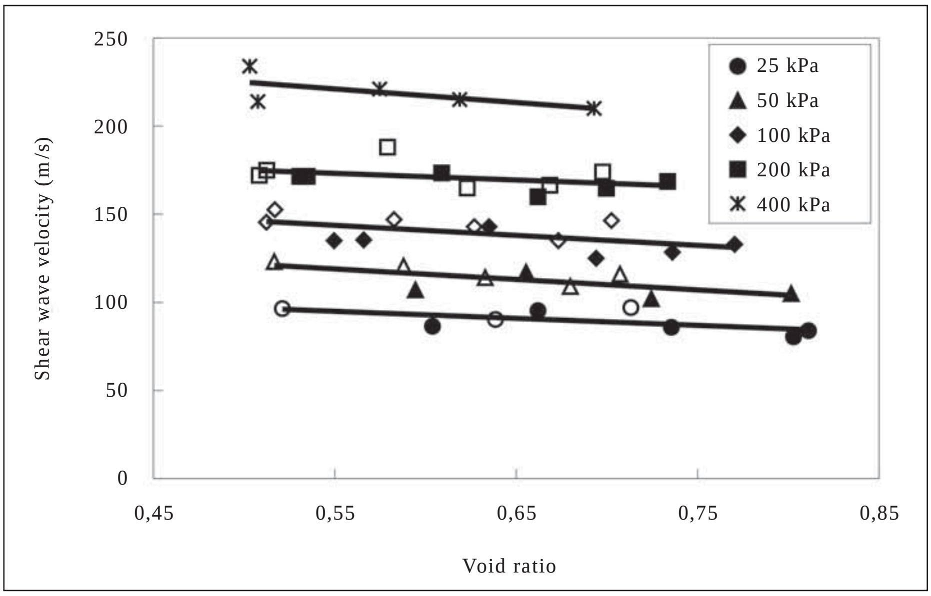

Figure 7 Shear wave velocity against void ratio for gold tailings

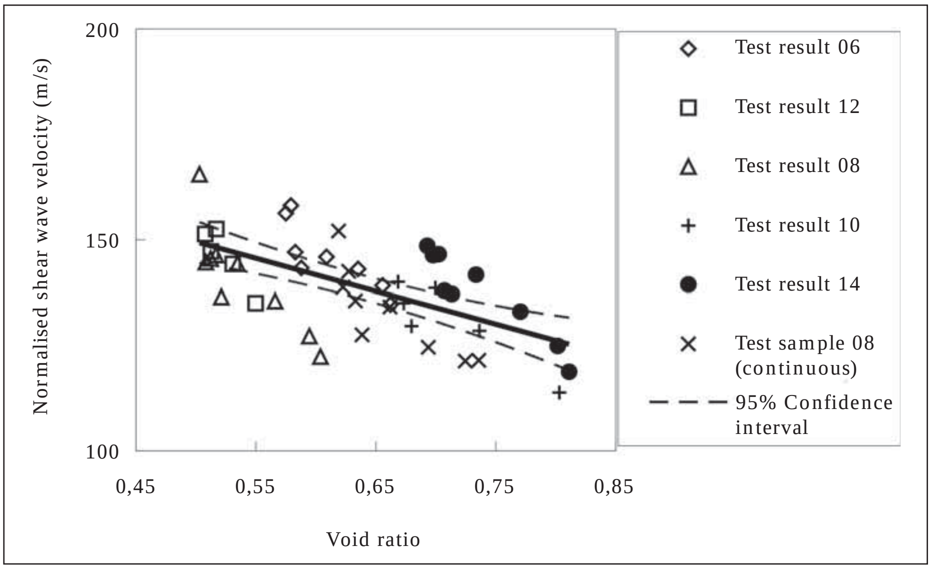

Figure 8 Normalised shear wave velocity against void ratio for gold tailings

minimise near field effects, the ratio of effective travel distance to wavelength L/λ should be kept between 6 and 9.

Another potential problem with the use of pulses is that any pulse contains a wide range of frequencies. These varying frequencies give rise to the possibility of distortion due to the natural propagation by and within physical subsystems possessing a non-uniform response to each frequency component (Santamarina & Fam 1997). In addition, many authors have commented on the time lag between the driving pulse and bender element movement, with typical values of between 0 and 5 µs being quoted (Dyvik & Madshus 1985; Brignoli & Gotti 1992; Gajo *et al* 1997). In this case, the time lag of the bender element system was ignored, as the lag would produce shear wave velocity errors of less than 0,1 %.

In keeping with other workers, the arrival of the shear wave was defined as the first reversal, as shown by point B in figure 5 (Brignoli & Gotti 1992; Robertson *et al* 1995; Jovičić *et al* 1996; Gajo *et al* 1997). The travel time is thus defined by the time difference between 'start time' and 'shear wave arrival'. As the shear wave only arrives some time after the near field component a 'maximum possible' wave velocity may be defined using the travel time computed from the arrival of the near field component (point A). This may be used to quantify the uncertainty of each shear wave velocity value as the difference in percentage between shear wave velocity and the maximum possible shear wave velocity. Shear wave velocities determined at various void ratios and effective stresses ranged between 81 and 252 m/s with a maximum uncertainty of 18 %. This is in agreement with the findings of Ricketts *et al* (1996), who suggested that in general the shear wave velocity of a geomaterial can be estimated to be within 10–20 %.

RESULTS AND DISCUSSION

Figure 6 shows a typical test result. The output signal shows the initial downward deflection (A) as the arrival of the near field component, followed by the reversal (B) indicating the first arrival of the shear wave. Figure 7 shows a graph of shear wave velocity plotted against void ratio for the gold tailings. Solid data points indicate normally consolidated samples while open data points indicate over consolidated (swelled) samples. The straight lines in the figure shows the relationship between wave velocity and void ratio for different samples at the same stress condition. This relationship is insensitive to the stress history of the material, as the consolidation and swell points appear to conform to the same relationship.

During the analysis, it was found that the exponential factor of 0,25 in the normalisation equation (equation 1) suggested by Sykora (1987) did not yield the best normalisation. Although a factor of 0,28 yielded a slightly better normalisation for gold tailings, the results are presented with a normalisation factor of 0,25 to allow direct comparison with published data. Figure 8 shows the relationship of normalised shear wave velocity against void ratio, including the 95 % confidence interval of the dataset. From the figure it can be seen that a relationship exists between normalised shear wave velocity ($V_{s(n)}$) and void ratio (e). The relationship can be approximated by the following straight-line equation:

$$V_{s(n)} = -77{,}7e + 188 \qquad (3)$$

Figure 9 shows the trend line for silt (from figure 8) as well as the trend lines for sands and clays (from figure 1) on the same plot. It can be seen that the trend line for the

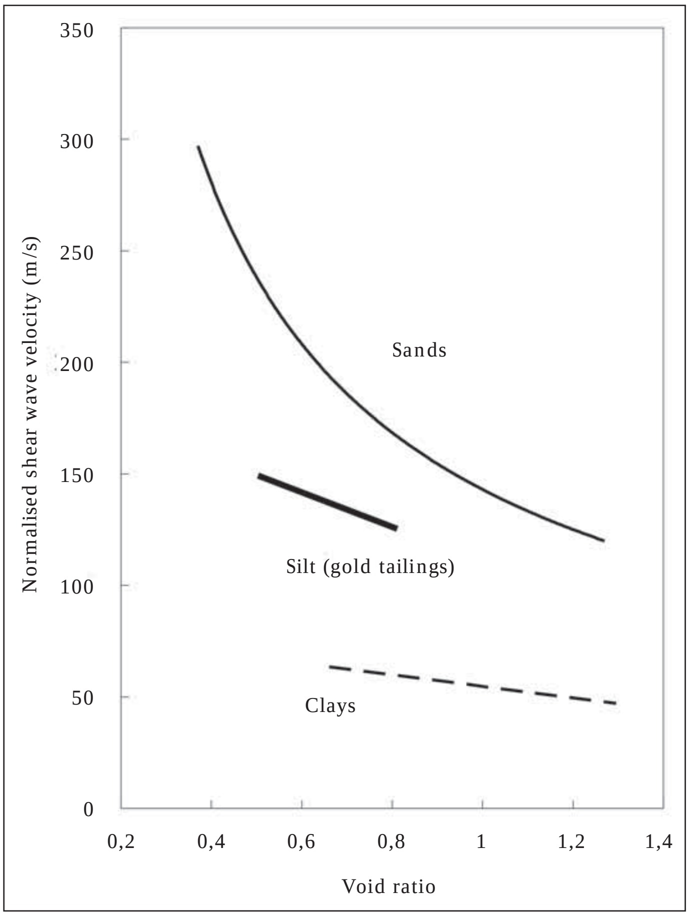

Figure 9 Trend lines for normalised shear wave velocity against void ratio

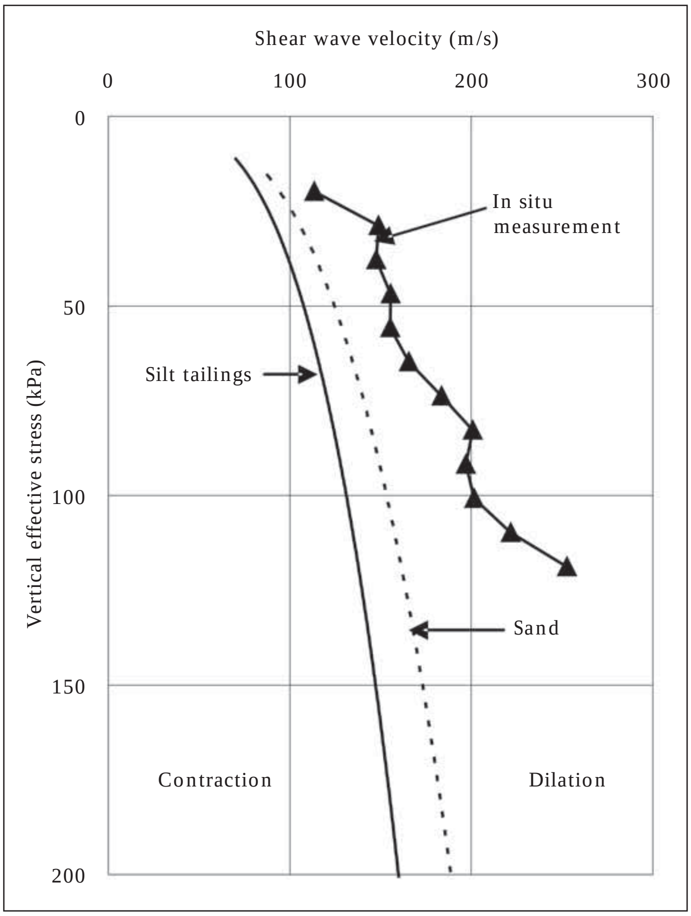

Figure 10 Boundary of liquefaction for in situ shear wave velocity measurements

gold tailings plots between the trend lines for sands and clays, indicating that the normalised shear wave velocity is sensitive to particle size. It also shows that as the material becomes finer, the sensitivity (slope) of the relationship between normalised shear wave velocity and void ratio reduces. The observed results can be explained within the framework of the 'inter-granular matrix diagram classification' proposed by Thevanayagam *et al* (2002). According to Thevanayagam, the shear behaviour of the sands will be dominated by the coarse grains. In the case of the gold tailings tested as part of this research, the fines content was 65 % and the sand sized grains will be immersed in the fines with the shear behaviour dominated by the fines.

The question arises whether this variation in normalised shear wave velocity is simply as a result of particle size or possibly because of a more complex mechanism based on particle shape. Clay particles are predominantly platy and sands are generally rotund, whereas the silt used in this study was a combination of platy and rotund particles. Hardin and Richard (1963) compared rounded Ottawa sand with crushed (angular) quartz and found that at the same void ratio and effective stress conditions the sensitivity of the angular material to be consistently lower. Also, Theron (2004) combined two sands of different shape, one being rotund and one platy and found the behaviour of the sand to conform to the typical shear behaviour observed for clay when the platy particles exceeded 10 %.

APPLICATION

From Critical State Soil Mechanics theory it may be shown that soils which exist at a state above the critical state line in e vs p' space will contract during undrained shear and soils that exist below the critical state line will dilate on shear. Static liquefaction is possible for soils that contract on shear. Theoretically, by combining the critical state line of gold tailings and the shear wave velocity–void ratio relationship derived in this research, the shear wave velocity can be used to estimate the static liquefaction potential of gold tailings impoundments. Figure 10 shows the boundary between contractive and dilative behaviour developed using the relationship shown in equation 3 and the critical state line reported by Papageorgiou *et al* (1999) for gold tailings with a fines content of 60 %. The boundary for sands as suggested by Robertson and Fear (1995) is also shown. Figure 10 also shows a plot of in situ shear wave velocity against vertical effective stress for gold tailings measured using a seismic cone in the day wall of the same dam from which the laboratory samples were taken. Values lying to the right of the boundary imply no susceptibility to liquefaction and values to the left of the boundary imply possible liquefaction. In this particular case, the tailings are in a stable condition and liquefaction should not occur. It can also be seen that the boundary for the tailings material lies to the left of the boundary for sands. This indicates that for the same wave velocity, sand would be more susceptible to liquefy than silt tailings.

CONCLUSIONS AND RECOMMENDATIONS

To date the estimation of in situ void ratio of tailings has been difficult. Without knowledge of the void ratio, the state and thus liquefaction potential of tailings cannot be determined with any confidence.

Using a triaxial apparatus modified to accommodate bender elements, shear wave velocity was measured at various void ratios and effective stress levels for silt derived during processing of gold-bearing quartzite. The results show that there is a relationship between normalised shear wave velocity and void ratio for gold tailings. It was found that this relationship plots between similar relationships derived for sands and clays. In addition, the sensitivity of the normalised shear wave velocity–void ratio relationship was found to reduce as the amount of platy particles increases. It is also evident that the shear wave velocity is independent of the stress history of the material.

Application of the shear wave velocity–void ratio relationship in conjunction with the critical steady state line for gold tailings yields a boundary for contractive and dilative behaviour. The result from this research therefore provides engineers with a tool to assess the in situ void ratio and liquefaction potential of gold tailings.

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REFERENCES

Been, K and Jefferies, M G 1985. A state parameter for sands. *Géotechnique*, 35(2):99–112.

Blewett, J, Blewett, I J and Woodward, P K 1999. Measurement of shear wave velocity using phase-sensitive detection technique. *Canadian Geotechnical Journal*, 36:934–939.

Blight, G E 1969. Shear stability of dumps and dams of gold tailings waste. *Transactions, South African Institute of Civil Engineers*, 11(3):49–54.

Blight, G E and Steffen, K H 1979. Geotechnics of gold mining waste disposal. In *Current geotechnical practice in mine waste disposal.* New York: ASCE:1–53.

Blight, G E 1997. Destructive mudflows as a consequence of tailings dyke failures. *Proceedings of the South African Institute of Civil Engineers*, 125:9–18.

Brignoli, E G M and Gotti, M 1992. Misure della velocita di onde elastiche di taglio in laboratorio con l'impiego di trasduttori piezoelettriei. *Riv Ital Geotec*, 26(1):5–16.

Brignoli, E G M, Gotti, M and Stokoe, K H 1996. Measurement of shear waves in laboratory specimens by means of piezoelectric transducers. *Geotechnical Testing Journal*, 19(4):384–397.

Chang, H P N 2004. The relationship between void ratio and shear wave velocity of gold tailings. MEng thesis, University of Pretoria.

Dyvik, R and Madshus, C 1985. Lab measurement of G_{max} using bender elements. In V Khosla (ed), *Advances in the art of testing soil under cyclic conditions.* New York: ASCE:186–196.

Gajo, A, Fedel, A and Mongiovi, L 1997. Experimental analysis of the effects of fluid-solid coupling on the velocity of elastic waves in saturated porous media. *Géotechnique*, 47(5):993–1008.

Hardin, B O and Richart, F E Jr 1963. Elastic wave velocity in granular soils. *Journal of Soil Mechanics and Foundation Division*, ASCE, 89(1):33–65.

Heymann, G 2003. The seismic cone tests. *Journal of the South African Institution of Civil Engineering*, 45(2):26–31.

Jennings, J E 1979. The failure of slimes dams at Bafokeng: mechanisms of failure and associated design considerations. *Civil engineers in South Africa*, 21(6):135–141.

Jovičić, M, Coop, R and Simić, M 1996. Objective criteria for determining G_{max} from bender element tests. *Géotechnique*, 46(2):357–362.

Lade, P V and Yamamuro, J A 1997. Effects of non-plastic fines on the static liquefaction of sands. *Canadian Geotechnical Journal*, 34:918–928.

National Institute for Transportation and Road Research (NITRR) 1982. *Technical methods for highways: standard methods for testing road construction material.* CSIR.

Papageorgiou, G P, Fourie, A B and Blight, G E 1999. Static liquefaction of Merriespruit gold tailings. *Proceedings*, 12th Regional Conference for Africa on Soil Mechanics and Geotechnical Engineering, Durban, South Africa:61–72.

Pennington, D S, Nash, D F T and Lings, M L 1999. The dependence of anisotropic G_0 shear moduli on void ratio and stress state for reconstituted Gault clay. In Jamiolkowski, Lancellotta and Lo Presti (eds), *Proceedings*, 2nd International Symposium on Pre-failure Deformation Characteristics of Geomaterials, Rotterdam:229–238.

Pitman, T D, Robertson, P K and Sego, D C 1994. Influence of fines on the collapse of loose sands. *Canadian Geotechnical Journal*, 31:728–736.

Ricketts, G A, Smith, J and Skipp, B O 1996. Confidence in seismic characterization of the ground. In *Advances in site investigation practice*. London: Thomas Telford.

Robertson, P K and Fear, C E 1995. Application of CPT to evaluate liquefaction potential. *CPT '95, Linkoping*, Swedish Geotechnical Society, 3:57-79.

Robertson, P K, Sasitharan, S, Cunning, J C, and Sego, D C 1995. Shear wave velocity to evaluate in-situ state of Ottawa sand. *Journal of Geotechnical Engineering Division*, ASCE, 121(3):262–273.

Sanchez-Salinero, I, Roesset, J M and Stokoe, K H 1986. Analytical studies of body wave propagation and attenuation. *Report GR 86–15*, University of Texas, Austin.

Santamarina, J C and Fam, M A 1997. Interpretation of bender element tests (discussion). *Géotechnique*, 47(4):873–877.

Shirley, D J and Hampton, L D 1978. Shear wave measurement in laboratory sediments. *Journal of the Acoustic Society of America*, 63(2):601–613.

Silvestri, F, D'Onofrio, A and Vinale, F 1999. Local measurement of radial strain in triaxial apparatus: a new device. In Jamiolkowski, Lancellotta and Lo Presti (eds), *Proceedings*, 2nd International Symposium on Pre-failure Deformation Characteristics of Geomaterials, Rotterdam:257–264.

Sladen, J A, Hollander, R D D and Krahn, J 1985. The liquefaction of sands, a collapse surface approach. *Canadian Geotechnical Journal*, 22:564–578.

Sykora, D W 1987. Creation of a data base of seismic shear wave velocities for correlation analysis. *Geotech Lab Misc Paper GL-87–26*, US Army Engineer Waterways Experimental Station, Vicksburg, MS.

Theron, M 2004. The influence of fine platy particles on the behaviour of rotund sand. PhD thesis, University of Southampton.

Thevanayagan, S 1998. Effects of fines and confining stress on undrained shear strength of silty sands. *Journal of Geotechnical and Environmental Engineering*, 124(6):479–491.

Thevanayagam, S, Shenthan, T, Mohan, S and Liang, J 2002. Undrained fragility of clean sands, silty sands and sandy silts. *Journal of Geotechnical and Geoenvironmental Engineering*, 128(10):849–859.

Tika, T H, Kallioglou, P and Pitilakis, K 1999. Laboratory measurement of dynamic properties of natural soils. In Jamiolkowski, Lancellotta and Lo Presti (eds), *Proceedings*, 2nd International Symposium on Pre-failure Deformation Characteristics of Geomaterials, Rotterdam:239–244.

Vermeulen, N J 2001. The composition and state of gold tailings. PhD thesis, University of Pretoria.

Viggiani, G and Atkinson, J H 1995. Interpretation of bender element tests. *Géotechnique*, 45(1):149–154.

Wagener, F 1997. The Merriespruit slimes dam failure: overview and lessons learnt. *Journal of the South African Institution of Civil Engineering*, 39(3):11–15.