Proceedings Tailings and Mine Waste 2015
Vancouver, BC, October 26 to 28, 2015

Strength gain of fine tailings/slimes resulting from secondary compression

I. Contreras, K. Schimpke, and R. Ver Strate
Barr Engineering, USA

ABSTRACT

The offset upstream construction method consists of constructing tailings impoundment dams on top of previously deposited fine tailings/slimes. The undrained shear strength of iron ore fine tailings/slimes underlying offset dams has been observed to increase over time, which is referred to as strength gain. The strength gain consists of two components: (1) increase in undrained shear strength due to increasing confining stress from fill placement and (2) increase in undrained shear strength under constant effective stress, which occurs after the end of primary consolidation (EOP). The second component of strength gain can be explained using the secondary compression concept.

This paper presents field and laboratory testing used to characterize the strength gain of fine tailings/slimes due to secondary compression. Results of cone penetration test (CPT) soundings in addition to laboratory vane shear and consolidation tests are presented. Findings based on this testing are described, and recommendations for implementing strength gain due to secondary compression in tailings dam design are included.

1 INTRODUCTION

The offset upstream construction method is a technique that has been successfully utilized to raise tailings dams without increasing the overall footprint of the tailings basin. In this method, the foundation of the offset upstream dam is typically constructed during the winter on top of previously deposited fine tailings/slimes which are frozen, as shown in Figure 1. The authors have used this construction method to raise dams with combined heights (perimeter and offset upstream dams) up to 37 meters (m) tall, with some projected to be up to 55 m tall when the ultimate dam crest height is reached.

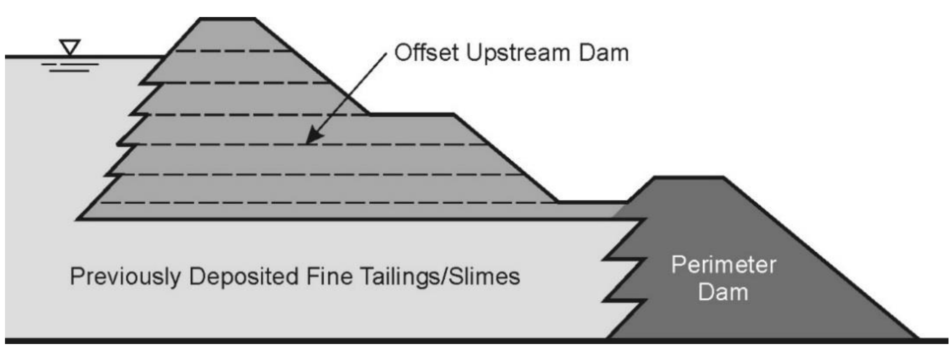

Figure 1. Offset upstream construction method

It has been observed that the undrained shear strength of the fine tailings/slimes underlying the offset upstream dams increases over time, which is referred to as strength gain. This strength gain consists of two components. The first component is the undrained shear strength increase due to loading (i.e. fill placement resulting in an increase in confining stress), which can be explained using the undrained shear strength ratio (USSR) at the end of primary consolidation (EOP). The second component is the increase in undrained shear strength under constant effective stress, which occurs after the EOP. This second component of undrained shear strength increase can be explained by secondary compression. Typically, this second component of strength increase is not included in the analysis and design of tailings dams. However, this increase may be significant, as demonstrated herein. Strength gain due to secondary compression is particularly relevant when evaluating dams constructed over fine tailings/slimes under undrained conditions, provided there is sufficient time to allow secondary compression to occur and the strength gain to be realized.

This paper presents the findings from a laboratory and field assessment of the undrained shear strength increase of fine tailings/slimes due to effective stress increase and secondary compression. However, the main focus of this paper is on the undrained shear increase due to secondary compression. Field observations and laboratory testing results are presented to provide evidence of strength gain due to secondary compression. Based on the field and laboratory tests, conclusions and recommendations for implementing strength gain due to secondary compression in tailings dam design are presented.

2 UNDRAINED SHEAR STRENGTH RATIO (USSR)

The undrained shear strength increase resulting from loading due to fill placement can be explained using the USSR. This section describes how the USSR is used to evaluate the fine tailings/slimes undrained shear strength increase observed in the field.

In practice, the undrained shear strength of soft soils is typically expressed in terms of the USSR. The USSR was initially introduced by Skempton (1948a, 1948b), and is often referred to as the *c/p* ratio for staged construction on soft soils. In general terms, the USSR is defined as the ratio between the undrained shear strength (s_u) and the pre-consolidation pressure (σ'_p), as described by Terzaghi et al. (1996).

However, in the case of fine tailings/slimes which are deposited hydraulically, the material is normally consolidated and the pre-consolidation pressure (σ'_p) is equal to the effective overburden stress (σ'_{vo}). This is because these deposits have not undergone any of the mechanisms responsible for the development of a pre-consolidation pressure (σ'_p), such as loading greater than current load, aging, desiccation, or cementation. The tailings pond water level is typically not lowered enough to cause extensive drying, which would result in desiccation within the upper material resulting in a material that is over-consolidated. Also, the fine tailings/slimes have not undergone a chemical change, and thus are not bonded or cemented. Therefore, for the fine tailings/slimes, the USSR is defined as the ratio between the undrained shear strength (s_u) and the effective overburden stress (σ'_{vo}) such that USSR = s_u / σ'_{vo}.

Natural soft clays and silts generally exhibit a constant USSR (Terzaghi et al., 1996). This observation is extrapolated to fine tailings/slimes, which classify as fine-grained soils with low plasticity. A constant USSR in the field results in a linearly increasing undrained shear strength with depth. A constant USSR also indicates that an increase in effective stress, such as that generated by fill placement and dissipation of the excess pore-water pressures, results in an increase in undrained shear strength, such that the USSR remains constant at the EOP.

3 SECONDARY COMPRESSION

Secondary compression refers to the continual decrease in void ratio after excess pore-water pressures have dissipated following primary consolidation. During secondary compression, a reduction in void ratio takes place at a constant effective stress (i.e. no additional load is applied). The major mechanism responsible for secondary compression is particle rearrangement to establish an internal equilibrium under constant effective stress (Mesri and Castro, 1987). In the field this process occurs over a period of time, typically on the order of years. The rate of secondary compression is generally governed by the secondary compression index, C_α, which represents the compressibility with respect to time.

The concept of C_α/C_c, which was developed by Mesri and Godlewski (1977), states that a direct relationship exists between the compressibility with respect to time (C_α) and the compressibility with respect to effective stress (C_c). The ratio of these two values (α) is constant, as shown below in Equation 1.

$$C_\alpha/C_c = \alpha \ (\alpha = \text{constant}) \tag{1}$$

Figure 2 illustrates the C_α/C_c concept and shows the relationship between void ratio (e), effective stress (σ'), and time (t). The value C_c represents the slope of the e – log σ' curve, while the value C_α represents the slope of the e – log t curve. It can be seen from Figure 2 that at a given time t, the ratio C_α/C_c can be computed. This interrelationship holds true during both compression and recompression.

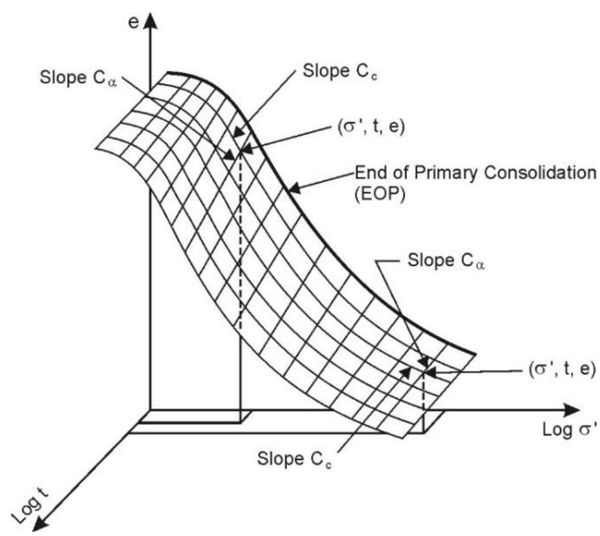

Figure 2. Interrelationship between C_a and C_c (Mesri, 1987)

The value of the C_α/C_c ratio falls into a fairly narrow range for various geo-materials, as shown in Table 1. It is postulated that this concept also applies to fine tailings/slimes.

Table 1. Values of C_α/C_c ratio for Various Geo-Materials (Terzaghi et al., 1996)

Geo-material	C_α/C_c
Granular Soils	0.02±0.01
Shale and Mudstone	0.03±0.01
Inorganic Clays and Silts	0.04±0.01
Organic Clays and Silts	0.05±0.01
Peat and Muskeg	0.06±0.01

This interrelationship between C_α and C_c explains multiple phenomena observed in soils, including (Mesri, 1987):

- secondary compression after loading
- secondary compression after unloading
- shape of the deformation curve at the transition from primary consolidation to secondary compression
- strain rate effect on pre-consolidation

- pre-consolidation pressure resulting from secondary compression
- secondary compression and time to failure effects on undrained shear strength
- secondary compression effect on shear modulus
- secondary compression effect on the coefficient of earth pressure at rest

The work presented herein focuses on the increase in undrained shear strength due to secondary compression. Secondary compression has been observed at tailings basins in the form of continued offset dam settlement after dissipation of construction-induced excess pore-water pressure. It is also believed that secondary compression is responsible for the observed increase in undrained shear strength with time, under constant effective stress, after the excess pore-water pressure has been dissipated. These field observations are further described below.

4 FIELD OBSERVATIONS

Evidence of secondary compression of fine tailings/slimes has been observed in the field in the form of increased corrected CPT tip resistance with time. This observation is further discussed in the proceeding section. Additionally, other field observations are described, which were used to help develop the laboratory testing program described later.

4.1 CPT tip resistance versus depth

Figure 3 shows the change over time in corrected CPT tip resistance (q_t) versus elevation within a fine tailings/slimes deposit. A change in corrected tip resistance is an indication of a change in undrained shear strength, assuming no change in total stress and undrained conditions during the test. Figure 3 includes the results of three CPT soundings performed adjacent to each other in 1997, 2004, and 2006. Included in this figure is the ground surface elevation when each of the CPT soundings was performed. Figure 3 illustrates the two components of strength gain within the fine tailings/slimes deposit. The tip resistance increase between 1997 and 2004 is mainly the result of an increase of effectives stress due to continued fine tailings/slimes deposition and some secondary compression. The component associated with effective stress increase can be explained by the USSR concept. The tip resistance increase between 2004 and 2006 is the result of secondary compression since no increase in effective stress occurred during that period.

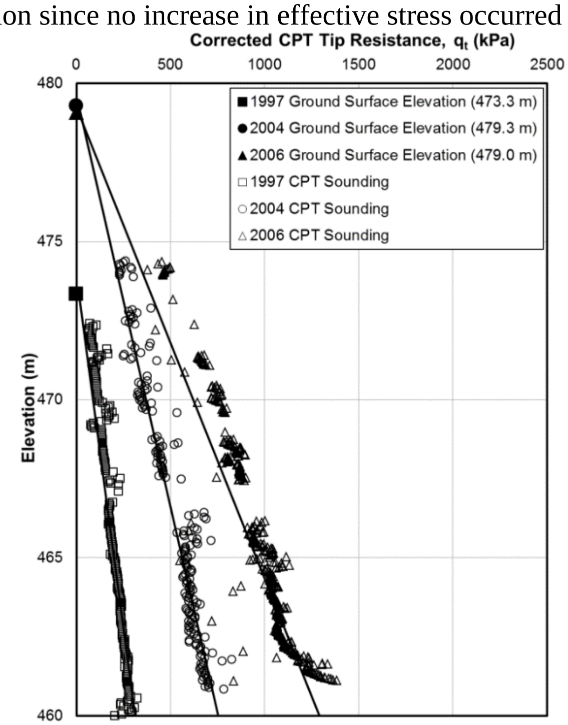

Figure 3. Corrected CPT tip resistance vs. elevation

It is interesting to note in Figure 3 that the slope of the 2004 data is different than the slope of the 1997 data. Similarly, there is a change in the slope between the 2004 and the 2006 data. This change in the slope has consistently been observed at other locations within the tailings basin where offset upstream construction has been used. This change in slope results in an additional increase in undrained shear strength beyond the one generated by the effective stress increase (i.e. fill placement), and results in an increased USSR. This increase in USSR is attributed to secondary compression.

4.2 Water content profile

The fine tailings/slimes assessed in this study are deposited in the field as a slurry, with water contents after deposition typically ranging from 40 to 60 percent. Following deposition, self-weight consolidation of the fine tailings/slimes begins. The water content of fine tailings/slimes decreases due to increasing confining stress as additional material is placed above it. This additional material is typically either fill placed during dam construction or continued deposition of fine tailings/slimes.

Figure 4 shows the water content profile versus depth obtained at a separate location in the basin before offset upstream dam construction. It can be seen from this figure that the water content at a depth of 1.5 m is approximately 49 percent, and then decreases with depth to an average of approximately 32 percent below a depth of about 10 m. The maximum water content is 51 percent and the minimum is 26 percent, with an overall average of 36 percent. This information was used to select target water contents for laboratory specimens tested as part of this study.

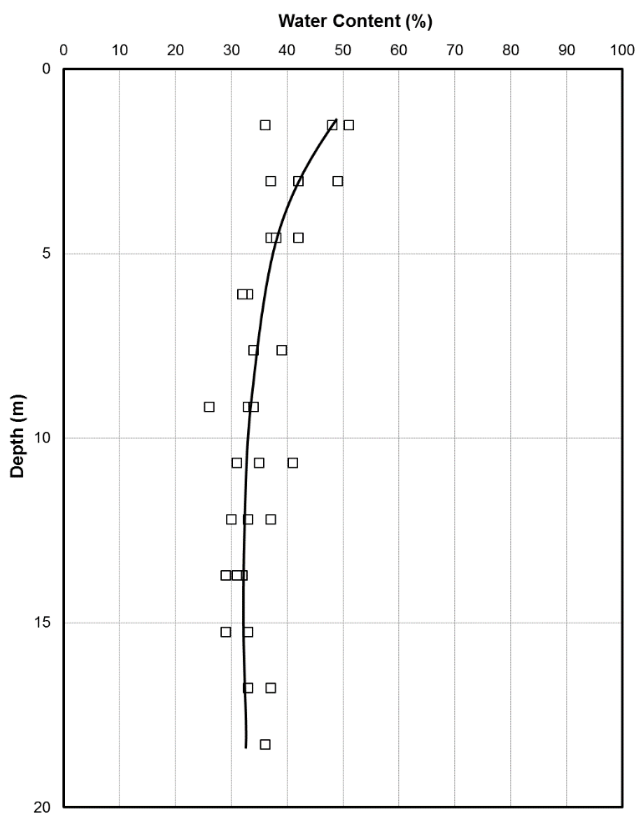

Figure 4. Water content vs. depth

In saturated soils, the water content is directly related to the void ratio via the specific gravity ($e = w\ G_s$); where w is the water content and G_s is the specific gravity. As a result, Figure 4 provides an indication of the void ratio distribution in the fine tailings/slimes deposit. The water content distribution in this figure shows a clear trend in the data - higher water contents (higher void ratio) at the top of the deposit where lower confining stresses are present and lower water contents (lower void ratio) at the bottom of the deposit where higher confining stresses are present.

4.3 Excess pore-water pressure dissipation

Figure 5 shows measured excess pore-water pressure versus time within the fine tailings/slimes deposit at a separate location in the basin after an initial lift of offset upstream construction. This figure includes the excess pore-water pressure versus time at three depths (4.57 m, 17.98 m, and 19.81 m) and surface settlement. It can be seen in this figure that the time to EOP is typically on the order of 130 days. As described below, this information was used to develop the laboratory testing program such that it represents observed field conditions. It is interesting to note in Figure 5 that the excess pore-water pressure exhibits little to no dissipation between 60 and 80 days. This is attributed to placement of a thin fill lift during that period, which generated excess pore-water pressures and slowed dissipation.

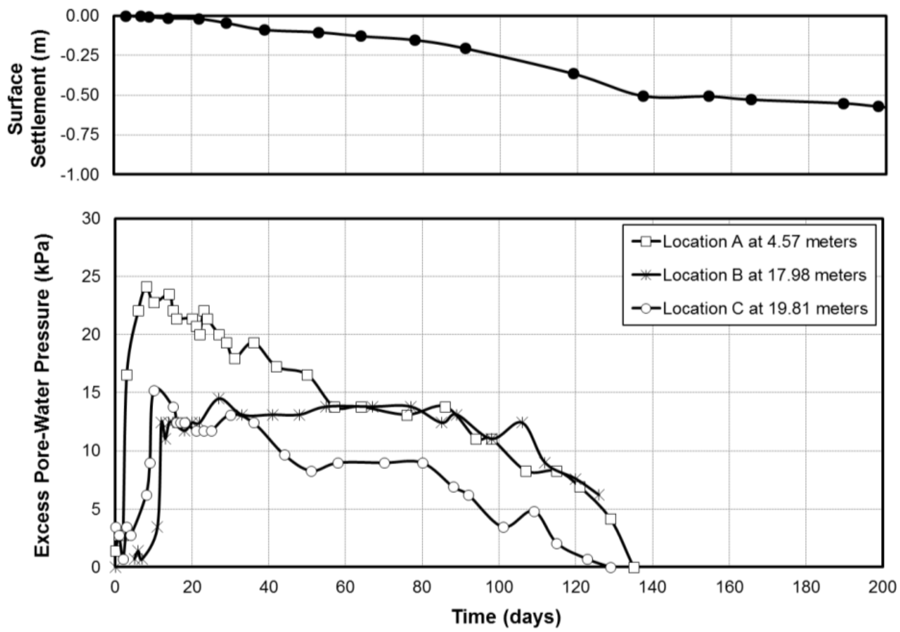

Figure 5. Measured excess pore-water pressure and surface settlement vs. time

5 UNDRAINED SHEAR STRENGTH INCREASE RESULTING FROM SECONDARY COMPRESSION

According to Mesri (1987), the effect of secondary compression on undrained shear strength can be estimated using Equation 2.

$$\frac{(s_u)_2}{(s_u)_1} = \left(\frac{t_2}{t_1}\right)^{C_\alpha/C_c} \qquad (2)$$

Where $(s_u)_1$ and $(s_u)_2$ are the undrained shear strengths at times t_1 and t_2, respectively.

If $(s_u)_1$ and t_1 are the undrained shear strength and time at the EOP (i.e. $(s_u)_1 = (s_u)_{EOP}$ and $t_1 = t_{EOP}$), respectively, an estimate of the undrained shear strength $(s_u)_2$ at time t_2 (sometime after EOP) can be made knowing the compressibility ratio C_α/C_c of the deposit. Equation 2 indicates that the undrained shear strength increase depends on the amount of time after the EOP and the compressibility ratio C_α/C_c of the fine tailings/slimes.

The typical time to complete primary consolidation for the fine tailings/slimes at the site used in this assessment is approximately 130 days (0.36 years), as described in the previous section. The anticipated time to basin closure at the site is about 18 years, which corresponds to approximately 50 times the EOP (i.e., 18/0.36 = 50) and thus the nomenclature t_{50xEOP} is used.

In general, strength gain due to secondary compression in natural soils is insignificant, and perhaps more importantly, takes a long time to be realized. This is because the time to complete primary consolidation in natural soils is often very long, typically tens or hundreds of years in thick, natural soft clay deposits. As a result, the practice of ignoring strength gain due to secondary compression has been carried over and adopted in tailings basin design. However, the time to complete the primary consolidation in these iron ore fine tailings/slimes is typically much shorter due to their low clay content and relatively high permeability as compared to soft clay deposits. Also, fine tailings/slimes are relatively weak as compared to native soils; therefore any additional strength that can be realized is beneficial. For these reasons, incorporation of strength gain due to secondary compression is both practical and beneficial for tailings dam design.

6 LABORATORY TESTING PROGRAM

A laboratory testing program was developed with the purpose of assessing the validity of Equation 2 for fine tailings/slimes and to quantify the amount of strength gain due to secondary compression. Vane shear tests were used to measure the strength gain represented by the left side of Equation 2, while consolidation tests were used to assess the compressibility represented by the exponent on the right side of Equation 2. By evaluating each component of this equation independently, the validity of the equation can be assessed and the mechanism responsible for the field observations can be confirmed.

To assess the compressibility of the fine tailings/slimes, a comprehensive laboratory testing program was performed and a C_α/C_c ratio for the material was measured. The laboratory testing included consolidation testing with pore-water pressure measurements to allow accurate determination of the EOP.

To assess the undrained shear strength increase due to secondary compression, a series of laboratory vane shear tests (VSTs) were performed. One set of laboratory VSTs was performed shortly after the EOP to determine $(s_u)_{EOP}$. Another set of laboratory VSTs was performed after an elapsed time of approximately 50 times the EOP to determine $(s_u)_{50xEOP}$.

The results of the laboratory consolidation and vane shear testing are described below, as are the results of index testing performed on the fine tailings/slimes.

Index testing

Prior to consolidation and vane shear testing, tests such as grain size, specific gravity, and Atterberg limits were performed on the fine tailings/slimes. The fine tailings/slimes classify as low plasticity clay (CL) based on the Unified Soil Classification System (USCS), with a fines content (passing #200 sieve) and a clay-size fraction (<0.002 mm) of 94.6 percent and 10 percent, respectively. The measured specific gravity was 2.93. The Atterberg limits indicate a liquid limit of 30.4 percent, a plastic limit of 21.1 percent, and a plasticity index of 9.3 percent.

6.1 Consolidation testing

6.1.1 Consolidation test sample preparation and testing procedure

Compressibility was assessed by performing laboratory consolidation tests on specimens prepared from a slurry that was collected in the field. The fine tailings/slimes slurry was prepared to obtain three initial water contents (63.7%, 56.8%, and 42.6%) which are representative of freshly deposited fine tailings/slimes. These water contents are also similar to values measured in the upper portions of the fine tailings/slimes deposit in the field (Figure 4).

The material was placed in an oedometer ring with a diameter of 63.5 mm (2.5 inches) and a height of 25.4 mm (1 inch). The slurry placement method was intended to simulate the hydraulic deposition that takes place in the field. The free water that rose to the surface after solids had settled was removed and additional slurry material added until the oedometer ring was filled. Any excess material was trimmed with a surgical blade until the top of the fine tailings/slimes material was flush with the top rim of the oedometer ring. The water contents reported above are after the free water was removed.

The oedometer ring and specimen were placed in a cell to allow the specimen to be back-pressure saturated and pore-water pressures to be measured during incremental load application, which allowed a more accurate determination of the EOP. The specimen was back-pressure saturated until a B coefficient greater than 0.95 was obtained, which indicated that the specimen was sufficiently saturated. After excess pore-water pressures dissipated and EOP was reached, the load was maintained for at least one secondary compression log cycle to help accurately determine the coefficient of secondary compression, C_α.

6.1.2 Consolidation test results

Figure 6 shows the void ratio-effective stress relationships at the EOP for fine tailings/slimes specimens. Figure 7 shows data from the consolidation tests in Figure 6 in terms of the compression index (C_c) and the secondary compression index (C_α), using the procedure outlined in Mesri and Castro (1987). This data indicates that the measured C_α/C_c ratio for the fine tailings/slimes is 0.0428, which agrees well with the typical values for inorganic clays and silts shown in Table 1.

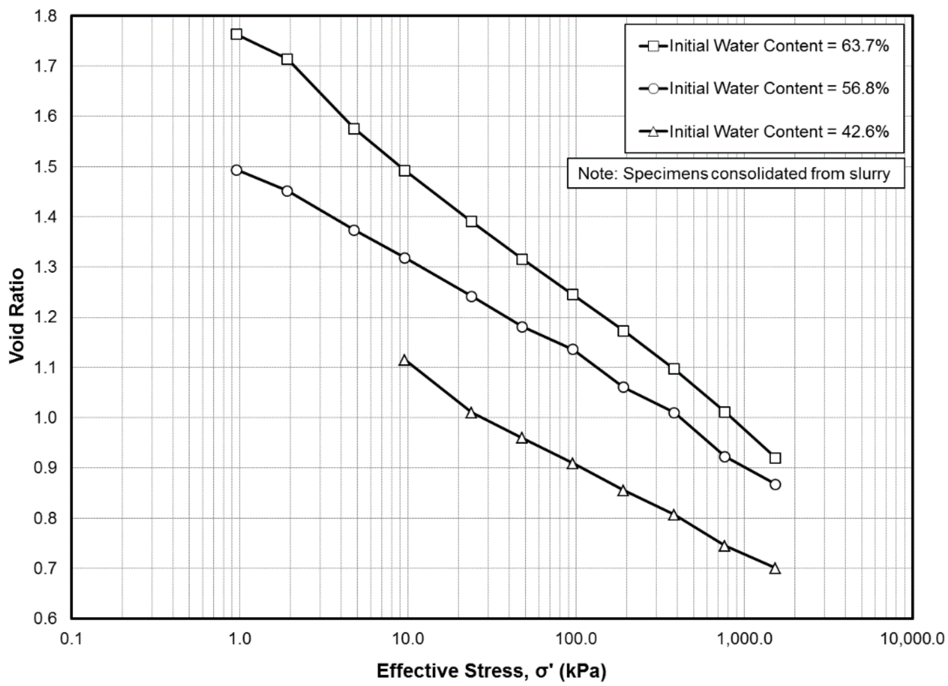

Figure 6. Void ratio-effective stress relationship at the EOP

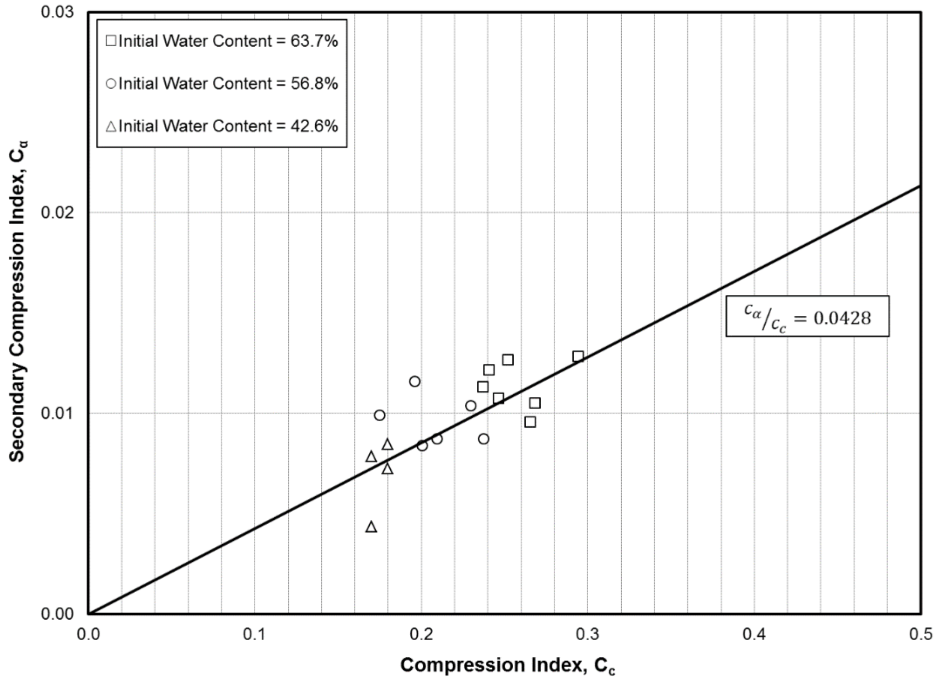

Figure 7. C_c vs. C_a from laboratory consolidation tests

6.2 Strength testing

6.2.1 VST sample preparation and testing procedure

The shear strength increase due to secondary compression was measured directly in the laboratory through a series of VSTs. The fine tailings/slimes were prepared by adding water to obtain an initial water content of 42.6 percent, which corresponds to the water content of one of the consolidation test specimens and is similar to typical water contents found in the field near the surface of the deposit. The fine tailings/slimes were placed in a stainless steel cylindrical container with a diameter of 203 mm (8 inches) and a height of 279 mm (11 inches), specifically manufactured for laboratory vane shear testing. The container was equipped with a porous stone at the bottom to allow drainage. Similar to the method used to prepare the consolidation test specimens, the fine tailings/slimes for the VST specimens were prepared from a slurry to simulate the hydraulic deposition that takes place in the field. The free water that rose to the surface after the solids settled was removed and additional slurry material added until the cylindrical container was filled. Any excess material was trimmed with a surgical blade until the top of the fine tailings/slimes material was flush with the top rim of the container.

6.2.2 VST procedure

After preparation, the fine tailings/slimes specimens were subjected to one-dimensional compression by applying a vertical load (consolidation load) through a stainless steel platen placed at the top of the specimen container. A load cell was used to determine the actual load applied to the specimen, independent of side friction. The vertical load was applied incrementally to minimize soil extrusion between the specimen container and the top platen. Vertical deformation was monitored during each load increment until the EOP was achieved. Subsequent load increments were applied until the desired consolidation load was reached.

Two VSTs were then performed on separate specimens under the same consolidation load. The first VST was performed after the specimen reached the EOP. The second VST was performed on a separate specimen that was first consolidated under the same load as the first specimen, was held constant for an elapsed time of approximately 50 times the EOP.

The VSTs were performed by pushing a vane (35 mm x 70 mm) into the specimen to the desired test depth and then rotating it at a rate of 0.2 degrees per second while maintaining the consolidation load. The vane rotation rate was determined to be fast enough to develop undrained conditions during the test based on laboratory and field data and the procedure described by Blight (1968). The measured shear stress versus rotation relationship was used to determine the peak undrained shear strength.

After completing the VST, disturbed fine tailings/slimes samples were taken at the test depth to perform water content measurements. The water content determination was performed for both the EOP VST and the 50xEOP VST, as described below.

6.2.3 VST results

Figure 8 shows a comparison between a VST conducted in fine tailings/slimes in terms of the shear stress-vane rotation relationship at a consolidation stress of 311 kPa shortly after the EOP and a VST conducted after an elapsed time of approximately 50 times the EOP at the same consolidation stress. It can be seen in this figure that undrained shear strength increases from 54.9 kPa at the EOP to approximately 64.2 kPa at 50 times the EOP, representing an increase of about 17 percent. It is postulated that this strength increase is due to secondary compression.

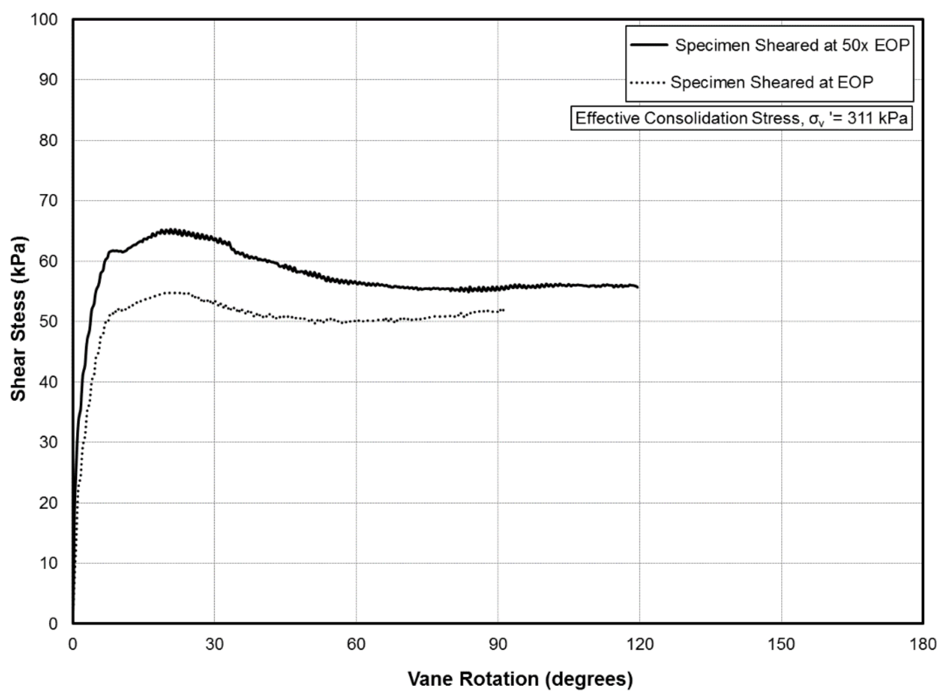

Figure 8. Laboratory VST results at the EOP and the 50xEOP

6.2.4 Failure envelope for VSTs at the EOP

A series of VSTs at different consolidation stresses were performed shortly after the EOP. Figure 9 shows the undrained shear strength envelope for specimens sheared shortly after the EOP. Data in in this figure indicate an average USSR of 0.172 ($USSR_{EOP}$ = 0.172). This ratio is slightly lower, but still comparable to the average USSR measured in the field using CPT soundings, which typically ranges between 0.17 and 0.22.

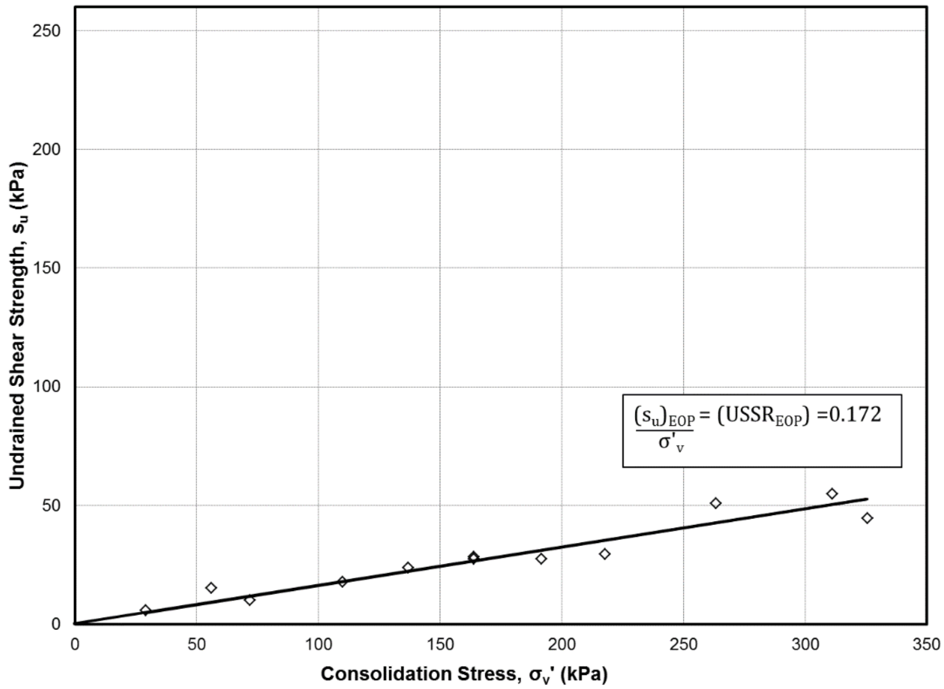

Figure 9. Failure envelope based on laboratory VSTs performed at the EOP

6.2.5 Failure envelope for VSTs at the 50xEOP

Similarly, a series of VSTs at different consolidation stresses were performed after an elapsed time of approximately 50 times the EOP. Figure 10 shows the undrained shear strength envelope for these specimens. Data in this figure show an average USSR of 0.199 ($USSR_{50xEOP}$ = 0.199). This indicates an average increase in the USSR of 16 percent, with respect to the $USSR_{EOP}$.

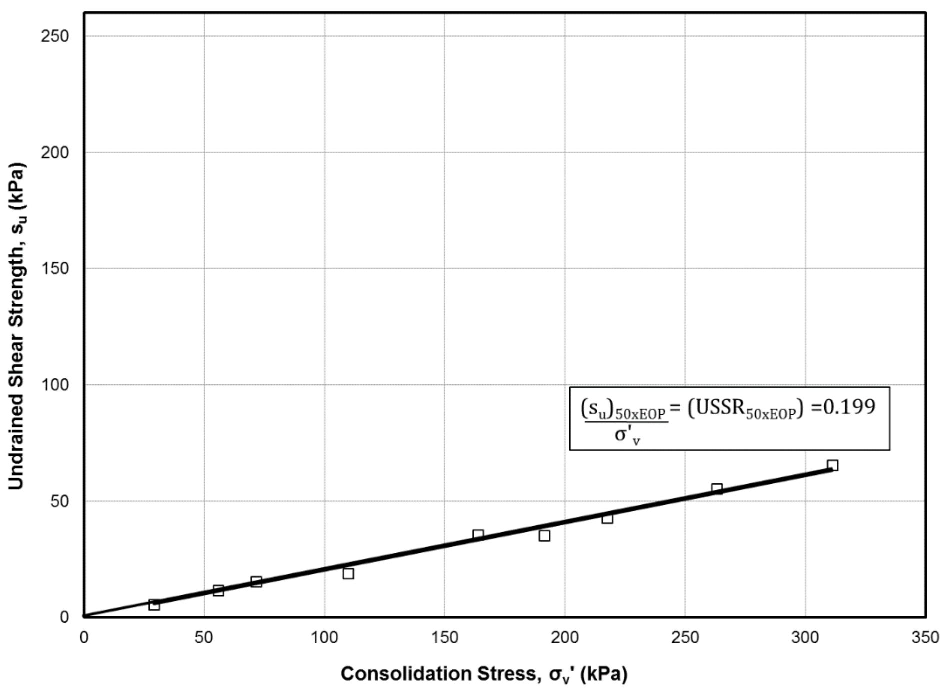

Figure 10. Failure envelope based on laboratory VSTs performed at the 50xEOP

6.3 Water content testing

Figure 11 shows the water contents measured in a few of the specimens after completion of the VST at different consolidation stresses. Data in this figure include the water content of the specimens sheared shortly after the EOP and at approximately 50 times the EOP. It can be seen in Figure 11 that the water content for the specimens sheared shortly after the EOP is 29.8 percent for a consolidation stress of 72 kPa and it decreases with increasing consolidation stress to a value of 26.3 percent at a consolidation stress of 311 kPa. This reduction in water content with increasing consolidation stress reflects the decrease in void ratio of the specimen as a result of the increase in consolidation stress. In other words, the reduction of water content (and therefore void ratio) with increasing consolidation stress can be associated with the increase in shear strength with increase of consolidation load or effective stress. This increase can be quantified with the use of the USSR, as previously described.

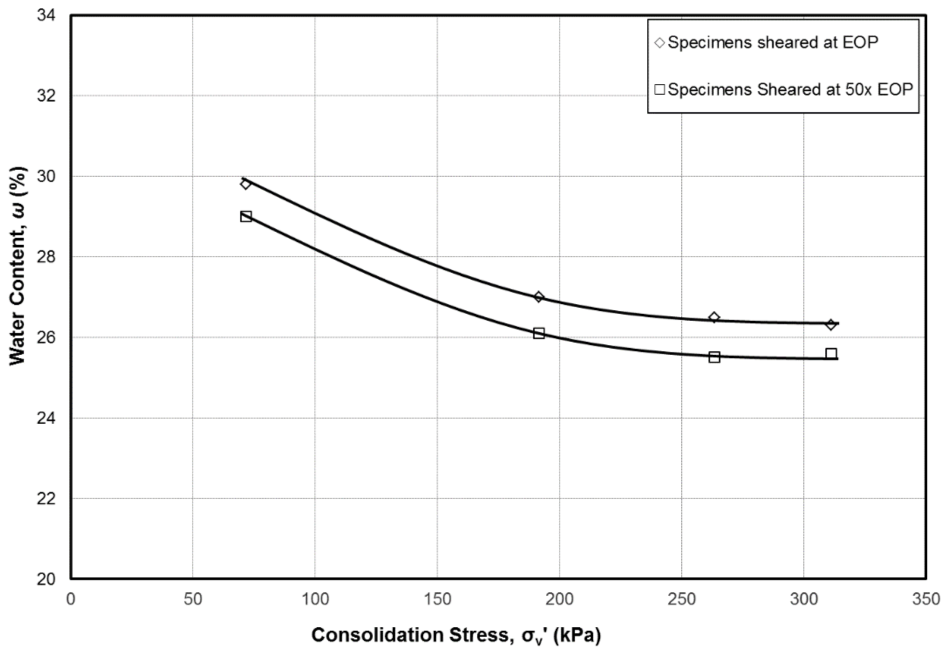

Figure 11. Moisture content after completion of VSTs

Figure 11 also shows that the water content for the specimens sheared after an elapsed time of approximately 50 times the EOP is 29 percent for a confining stress of 72 kPa, and decreases with increasing consolidation stress to a value of 25.6 percent at a consolidation stress of 311 kPa. In general, the water contents at 50 times the EOP are lower than the values for specimens sheared shortly after the EOP. This decrease in water content (and in turn void ratio) is further evidence of secondary compression. The associated increase in undrained shear strength resulting from secondary compression can be quantified using Equation 3, which is presented below.

7 COMPARISON OF MEASURED UNDRAINED SHEAR STRENGTH INCREASE

Equation 2 can be rewritten to facilitate a comparison between the predicted and measured undrained shear strength increase, as follows:

$$\frac{\left[\frac{(s_u)_{50\text{xEOP}}}{\sigma_v'}\right]}{\left[\frac{(s_u)_{\text{EOP}}}{\sigma_v'}\right]} = \left(\frac{t_{50\text{xEOP}}}{t_{\text{EOP}}}\right)^{c_\alpha/c_c} \qquad (3)$$

Equation 3 is similar to Equation 2, but has been normalized by the effective vertical stress, σ'_v, and the nomenclature changed to reflect undrained shear strength and times at the EOP and approximately 50 times the EOP. Equation 3 can then be rewritten as Equation 4 below. The value of USSR at the EOP was measured as 0.172 based on the VST results shown in Figure 9. The USSR at approximately 50 times the EOP was measured as 0.199 based on the VST results shown in Figure 10. Substituting these values into Equation 3, the strength gain due to secondary compression can be computed as:

$$\frac{\left[\frac{(s_u)_{50\text{xEOP}}}{\sigma'_v}\right]}{\left[\frac{(s_u)_{\text{EOP}}}{\sigma'_v}\right]} = \frac{USSR_{50\text{xEOP}}}{USSR_{\text{EOP}}} = \frac{0.199}{0.172} = 1.16 \qquad (4)$$

Based on Equation 4 and the results of the VSTs performed as part of this assessment, the increase in the USSR due to secondary compression is approximately 16 percent.

The right side of Equation 3 can be evaluated based on the results of the consolidation testing and the measured C_α/C_c ratio. Equation 5 allows calculation of strength gain due to secondary compression based on the results of compressibility testing performed as part of this assessment. The ratio C_α/C_c for the fine tailings/slimes in this study was found to be 0.0428 (Figure 7). Using this compressibility value and the elapsed times for the EOP and approximately 50 times the EOP, the right side of Equation 2 becomes:

$$\left(\frac{t_{50\text{xEOP}}}{t_{\text{EOP}}}\right)^{C_\alpha/C_c} = 50^{0.0428} = 1.18 \qquad (5)$$

Based on Equation 5 and the C_α/C_c ratio measured by laboratory consolidation testing performed as part of this assessment, the increase in the USSR due to secondary compression is computed as 18 percent. Equations 4 and 5 represent independent methods of computing the increase in undrained shear strength due to secondary compression, and both methods provide good agreement. This finding validates that the observed increase in undrained shear strength of fine tailings/slimes after the EOP is due to secondary compression.

8 CONCLUSIONS

The undrained shear strength of iron ore fine tailings/slimes has been observed to increase with time, which is referred to as strength gain, based on the results of CPT soundings and other field observations. A portion of this strength gain is attributed to loading by fill placement and the resulting increase in confining stress, which is explained by the USSR concept. However, additional strength gain has been observed under constant effective stress, which occurs after the EOP, and is attributed to secondary compression.

To verify and further assess strength gain due to secondary compression in fine tailings/slimes, a laboratory testing program was performed. The results of the laboratory testing confirmed that strength gain occurs in fine tailings/slimes after the EOP under constant effective stress, thereby verifying strength gain as a result of secondary compression.

Strength gain due to secondary compression is typically not included in the analysis and design of tailings dams. However, when utilizing the upstream construction method for dam construction, where the foundation of the dam is constructed over previously deposited fine tailings/slimes, and when sufficient time is allowed for secondary compression to occur, this component of strength gain can be significant and can be included in dam design.

9 ACKNOWLEDGEMENTS

The authors wish to thank Mr. Jed Greenwood, Mr. Rick Sisson, Ms. Karen Kaul, and Ms. Teresa Kes of Barr Engineering Co. for their review of this paper. The authors also want to acknowledge the careful review and manuscript comments provided by Dr. Gonzalo Castro and Prof. Gholamreza Mesri. They also thank Mr. Slade Olson and Mr. John Whelan of Soil

Engineering Testing in Richfield, Minnesota, for conducting the laboratory testing described herein and for their continued support and services. They also wish to thank their client for allowing data collected from their site to be used in this paper.

10 REFERENCES

Blight, G. 1968. A Note on Field Vane Testing of Silt Soils. *Canadian Geotechnical Journal*, Vol. V, No. 3, pp. 142-149.

Mesri, G. 1987. The Fourth Law of Soil Mechanics: The Law of Compressibility. *Proceedings of International Symposium on Geotechnical Engineering of Soft Soils*, Mexico City, Vol. 2. Pp. 179-187.

Mesri, G. and Castro, A. 1987. The C_{α}/C_c concept and K_o during secondary compression. *J. Geotech Eng., ASCE*, 112, No. 3, pp. 230-247.

Mesri, G. and Godlewski. 1977. Time- and Stress-Compressibility Interrelationship. *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 103, No. 5, pp. 283-287.

Skempton, A.W. 1948a. "A study of the geotechnical properties of some post-glacial clays." *Geotechnique*, 1(1), pp. 7-22.

Skempton, A.W. 1948b. "Vane tests in the alluvial plain of the River Forth near Grangemonth." *Geotechnique*, 1(1), pp. 111-124.

Terzaghi, K., Peck, R., and Mesri, G. 1996. *Soil Mechanics in Engineering Practice, Third Edition*, New York, John Wiley and Sons.