Analytical and experimental studies of the evolution of the excess pore water pressure during the deposition of a slurried material

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ABSTRACT
The mining industry is accompanied by the generation of large volume of tailings, which are usually pumped to tailings pond, made of tailings dams. Tailings can also be used as backfill material to return and fill underground mine stopes. Similar practice in civil engineering is the disposal of dredged sludge excavated from river or sea beds in a containment structure. Among these practices, a common point is the disposal of a slurried material in a confining structure. To ensure the stability of this structure, it is important to have a good estimation of the pore water pressure (PWP) during the placement of the slurried material in the confining structure. Recently a truly analytical solution has been developed by the authors based on a model proposed by Gibson. However, the analytical solution has never been validated by experimental results. In this paper, the truly analytical solution is first recalled. A simple laboratory test instrumentation is presented. The measured pressures are compared with the analytical solution. The good agreement between the experimental and analytical results indicates that the analytical solution is validated even though it contains some simplifying assumptions.

RÉSUMÉ
La croissance rapide de l'industrie minière est accompagnée avec la production de grands volumes de rejets de concentrateurs, qui sont normalement pompés dans un parc à résidus miniers ceinturé des digues. Les résidus miniers peuvent également être utilisés comme un matériau de remblai pour remplir les chantiers souterrains. Une pratique similaire en génie civil est l'entreposage des boues de dragage extraites des lits fluviaux ou marins dans une structure de confinement. Parmi ces cas, une pratique courante est l'élimination d'un matériau en suspension dans une structure de confinement. Pour assurer la stabilité de cette structure, il est important de d'avoir une bonne estimation de la pression d'eau interstitielle lors de la mise en place des boues dans la structure de confinement. Récemment, une solution analytique a été proposée par les auteurs à partir d'un modèle proposé par Gibson. Cependant, cette solution analytique n'a jamais été validée par des résultats expérimentaux. Dans cet article, la solution analytique sera d'abord rappelée. Une simple instrumentation d'essais au laboratoire sera présentée. Les pressions mesurées sont comparées avec la solution analytique. La bonne corrélation entre les résultats expérimentaux et analytiques indique que la solution analytique est validée même si elle contient des hypothèses simplificatrices.

1 INTRODUCTION

The rapid growth of mine industry is accompanied by the production of large quantity of mine wastes. These mine wastes are in terms of tailings and waste rock, which needs to be properly managed. Tailings usually contain a lot of water. They are sent by pipe to a tailings pond and confined by tailings dams. Tailings are also used to fill the underground mine stopes to improve ground stability, decrease ore dilution and reduce the surface disposal of mine wastes (Hassani and Archibald 1998; Kump 2001; Aubertin et al. 2002; Jung and Biswas 2002; Bussiere 2007; Cui and Fall 2018). In civil engineering, the large amount of dredged sludge accompanied by the cleaning operation of river or sea beds needs to be transported by pipes and disposed in a containment structure. As these slurried materials usually have high water content and low permeability, their deposition is typically accompanied with the generation of excess pore water pressure. A good understanding of the self-weight consolidation and evolution of the excess pore water pressure (PWP) is necessary to access the stability of the confining structures and manage the subsequent filling or deposition operations (Priscu 1999; Azam and Li 2010; Fahey et al. 2010; Farkish and Fall 2014; Zheng et al. 2018a, 2018b).

The self-weight consolidation of slurried material during the deposition or filling operation is a complex issue. With the continuous deposition or filling, the excess PWP can be instantaneously generated and slowly dissipated. This is different from the traditional consolidation theory of Terzaghi (1943), in which the consolidation takes place under an external applied load.

A solution has been proposed by Gibson (1958) by considering a continuous increasing of the slurry thickness. The Gibson (1958) solution contains an integral part, which can only be evaluated through numerical calculation. A truly analytical solution based on the Gibson (1958) model has been developed by Zheng et al. (2018b). The analytical solution constitutes a very useful tool to estimate the evolution of the excess PWP during the slurry deposition. However, the Gibson (1958) model and ensuing analytical solution have never been validated by experimental results.

In the past decades, numerous experimental studies have been conducted to investigate the compressibility and consolidation of slurried materials. Most of them were performed by following the standard consolidation process suggested by ASTM (ASTM D2435-11/D2435M-11 and ASTM D4186/D4186M-12e1). The tests were thus conducted with the application of an external load (Aubertin et al. 1996; Qiu and Sego 2001; Azam 2010). As slurried material usually has high water content and low (no) shear strength, a few researchers have made use of seepage force to investigate the compressibility and permeability behavior of slurried material (Imai 1979; Sridharan and Prakash 1999; Lee and Fox 2005; Janbaz and Maher 2017).

The aforementioned testing methods tend to disturb the drainage condition. The testing conditions are not representative of the field condition of slurry deposition. Self-weight consolidation tests without applying any load were also conducted to study the consolidation characteristics of slurried material (Been and sills 1981; Lin 1983; Pedroni 2011; Li et al. 2013; Saleh-Mbemba 2016). The testing conditions are closer to the field condition than previously mentioned tests, which were however conducted by instantaneously or quickly pouring the slurried material in a column, without noting the filling rate.

To better investigate the consolidation characteristics of the slurried material during the accreting deposition, laboratory tests were conducted by placing slurried tailings in a column with a constant filling rate. Four PWP sensors were installed along the height of the column to measure the PWP variation during the deposition. The measured excess PWP were compared with those predicted by the analytical solution proposed by Zheng et al. (2018b).

2 Analytical solution of the Gibson (1958) model

Figure 1 shows the Gibson (1958) model with an accreting deposition of slurried material on an impervious base. The thickness of the slurried material increases at a constant filling rate *m*. At a given time *t*, the thickness of the slurry reaches *h* (= *mt*). At the end of the deposition operation the final thickness of the slurried material reaches *H*. *x* is the calculation point from the base of the slurry (0 ≤ *x* ≤ *h*)

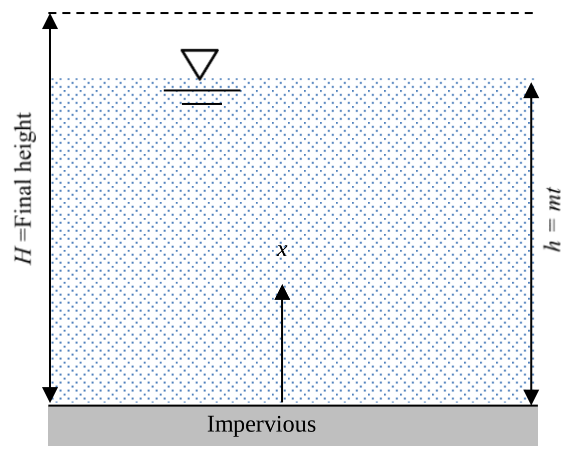

Figure 1. Accreting deposition of slurried material on an impervious base (Gibson 1958).

By applying the same assumptions as the consolidation theory of Terzaghi (1943), Gibson (1958) proposed the following equation to evaluate the excess PWP during the accreting deposition:

$$c_v \frac{\partial^2 u}{\partial x^2} = \frac{\partial u}{\partial t} - \gamma' \frac{dh}{dt} \quad (1)$$

where u (kPa) is the excess PWP; c_v (m^2/h) is the consolidation coefficient; t (h) is the filling time; γ' (kN/m^3) is the submerged unit weight of the slurried material.

Solving Equation (1) leads to the following equation (Sibson 1958):

$$u = \gamma' mt - \frac{\gamma'}{\sqrt{\pi c_v t}} \exp\left(-\frac{x^2}{4c_v t}\right) \times \int_0^\infty \xi \tanh\left(\frac{m\xi}{2c_v}\right) \times \cosh\left(\frac{x\xi}{2c_v t}\right) \times \exp\left(-\frac{\xi^2}{4c_v t}\right) d\xi \quad (2)$$

where ξ is an integration variable ($0 \le \xi \le \infty$).

Equation (2) contains an integral that can only be evaluated numerically. A truly analytical form has been proposed by Zheng et al. (2018b) through the transformation of Goodwin (1943) as follow:

$$u(x,t) = \gamma' mt - \frac{\gamma'}{\sqrt{\pi c_v t}} \times \exp\left(-\frac{x^2}{4c_v t}\right)$$

$$\times \frac{h_0}{2} \sum_{n=-\infty}^{\infty} \left\{ 4c_v tnh_0 \times \tanh\left(mnh_0 \sqrt{\frac{t}{c_v}} \right) \times \cosh\left(\frac{xnh_0}{\sqrt{c_v t}} \right) \times \exp(-n^2 h_0^2) \right\}$$

(3)

where n is a series number ($-\infty < n < +\infty$), h_0 is the step length of x. To obtain stable results, sensitivity analysis should be made on the series number n for a given value of h_0 between 0 and 1. For most cases, Zheng et al. (2018b) have shown that stable results of u can be obtained when n is taken between -91 and 91 and h_0 is taken as 0.3

3 TESTING MATERIAL AND PROCEDURE

3.1 Tailings

The tailings used in this study are from Canadian Malartic Mine. The tailings have a specific gravity of 2.71. They are characterized by a uniformity coefficient of C_u = 5.88 and curvature coefficient of C_c = 0.62. Slurry specimens were obtained by thoroughly mixing dry tailings and water to the desired water content of w = 50% (kg/kg). The obtained tailing slurry has a saturated unit weight 18 kN/m^3.

3.2 Instrumentation

Figure 2 shows a photograph of the test apparatus used to measure the variation of the PWP with the placement of tailings slurry. The column has an inner diameter of 30 cm and a height of 108.5 cm. In order to obtain a homogeneous specimen and minimize any possible segregation, the prepared tailings slurry was stored in a bucket and continuously mixed with a portable mixer during the tests. The filling or deposition operation was performed through pumping. The filling rate is about m = 0.156 m/h. Four PWP sensors were installed along the height of the column at 4.5, 35.5, 65.5 and 95.5 cm from the bottom of the column, respectively to measure the PWP variation during the deposition. The PWP sensors were kept saturated and protected by saturated cigarettes filter to prevent any conglomeration by the fine particles. A layer of sand of 4.5 cm was placed at the bottom of the column. A thin layer of geotextile was placed on the sand layer which is saturated with water before the deposition. The top surface of the geotextile is in the same level as the bottom PWP sensor. The four PWP sensors were calibrated with water before and after each filling test. The linear variation between the voltage and water head indicated that the four PWP sensors are reliable.

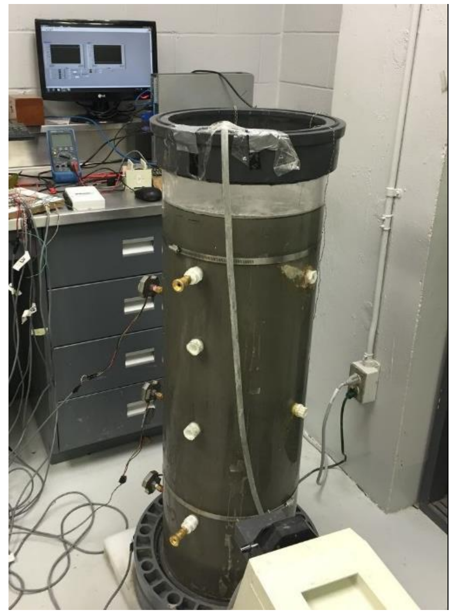

Figure 2. Photograph of the test apparatus used to measure the variation of the PWP with the placement of tailings slurry.

4 TEST RESULTS AND COMPARISONS WITH ANALYTICAL SOLUTION

Figure 3 shows the distribution and evolution of the measured excess PWP along the height of the column. The results calculated with the analytical solution (Eq. (3)) using c_v = 0.025 m^2/h and m =0.156 m/h are also plotted on the figure. The used value of c_v = 0.025 m^2/h is in the range of measured results reported in the previous studies. For example, Essayad (2015) found that the value of c_v should be in the range of 0.0936 to 0.368 m^2/h while Saleh-Mbemba and Aubertin (2017) obtained a range of 0.036 to 0.072 m^2/h for c_v.

It is interesting to note that good agreements are obtained between the experimental results and the analytical results by using a constant c_v. These results indicate that the Gibson (1958) model and ensuing analytical solution can be used to estimate the variation of evolution of the excess PWP during the slurry deposition. Nevertheless, it should be noted that only one group of tests were conducted. More tests are needed to verify if this conclusion is valid under different testing conditions and with different types of slurried tailings.

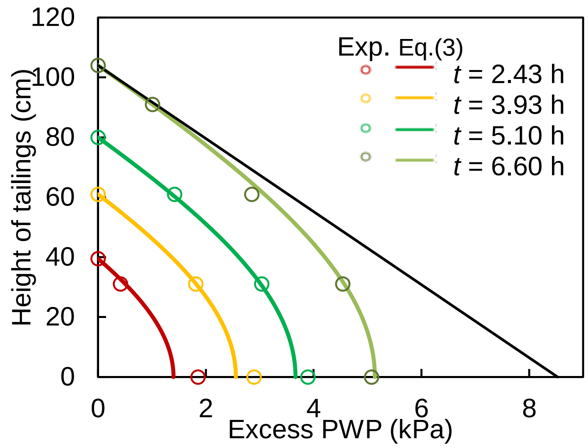

Figure 5. Distribution and evolution of the excess PWP along the height of the tailings, measured from the laboratory tests and calculated with the analytical solution (Zheng et al. 2018b) using c_v = 0.025 m^2/h and m = 0.156 m/h.

5 CONCLUSIONS

In this paper, an analytical solution based on the Gibson (1958) model was recalled. The solution was proposed to evaluate the excess PWP in accreting deposition of slurried materials. A column test was conducted to study the consolidation and excess PWP dissipation in the accreting deposition of tailings with a constant filling rate. The measured excess PWP distributions were compared with those calculated by the analytical solution using a constant value of c_v. The good agreements between the experimental and analytical results indicate that analytical solution can be used to evaluate the variation and evolution of the excess PWP during the accreting deposition, using a constant consolidation coefficient c_v. More tests are needed to verify if this conclusion is valid under other testing conditions.

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