Air lifted wick drains to enhance the consolidation of tailings dams

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ABSTRACT

The consolidation of soft soils requires the reduction of pore pressure. The use of wick drains reduces the drainage path and speeds this process. Such drains have the limitation that they cannot lower the pore pressure below hydrostatic. To speed the process and to induce overconsolidation, the process of loading the surface is often undertaken. However, this is an expensive and energy intensive operation.

This paper presents an alternative. This is the use of wick drains which incorporate internal tubing to permit the operation of air lift pumping. These can be installed as normal wick drains and then connected to a piping network to supply compressed air to each of them. Using air lifting it is possible to lower the pore pressure well below hydrostatic and thus induce overconsolidation. The vertical stress profile reached by this means of consolidation is different from that caused by placing a surcharge on the surface. It has higher vertical stresses at depth. It is therefore particularly suited to the consolidation of existing tailings dams where increasing the resistance to liquefaction at depth is particularly important. The air lift wick drain is not however limited to this application.

The use of air lifted wick drains is generally more energy efficient than the placement and removal of surcharge loads. In areas where there is plenty of sunshine, it can be advantageously used in combination with solar power to drive the compressor.

RÉSUMÉ

Plusieurs barrages de retenue de résidus miniers s'approchent d'une rupture catastrophique par liquéfaction. C'est ce qu'illustrent les ruptures au Mont Polley en Colombie-Britannique, à Fundao et Brumhadino dans le Minas Gerais au Brésil (289 morts) et à Jagersfontein dans l'État libre d'Afrique du Sud (4 morts). Toutes ces ruptures sont associées à de graves dommages environnementaux.

L'amélioration de leur stabilité est souvent difficile et coûteuse. L'utilisation de drains à mèche, développés pour la consolidation de sols mous et peu perméables, est une option qui a été exploitée avec un certain succès au niveau des résidus miniers. Cette option est limitée dans la mesure où elle ne peut pas abaisser la pression de l'eau en dessous de la hauteur de la charge hydrostatique. Une pratique existante pour augmenter la résistance des sols consiste à induire une consolidation en ajoutant du remblai à la surface afin que le fluide soit expulsé du sol vers les drains à mèche. Il s'agit d'un processus coûteux car il implique de déposer le remblai et l'enlever par la suite. L'utilisation de remblai n'est pas toujours possible en raison de la nature fragile du sol ou parce que sa surface est sous l'eau.

Cet article décrit une méthode pour faciliter le drainage et la consolidation du sol en abaissant la hauteur d'eau dans les drains à mèche par l'utilisation d'un système de pompage à air (airlift pumping). Un tel système peut être aisément incorporé à la structure du drain a mèche, est peu coûteux et est simple à utiliser.

1 INTRODUCTION

Many tailings dams exist which sit on the edge of catastrophic failure by liquefaction. This has been exemplified by the failures at Mount Polley in British Columbia, at Fundao and Brumhadino in Minas Gerais in Brazil (with 289 deaths) and Jagersfontein in the Free State in South Africa (with 4 deaths). All of these failures have been associated with massive environmental damage.

Improving their stability is frequently difficult and expensive. The use of wick drains, developed for the consolidation of soft, low permeability soils, is an option that has been used with some success in tailings. Its limitation is however that it cannot lower the water pressure below the hydrostatic head. A practice that exists to raise the strength of soils is to induce consolidation by adding fill to the surface so that fluid is squeezed out of the soil into the wick drains. This is an expensive process because it involves moving fill in and then removing it. The use of fill is not always possible because of the weak nature of the soil or because its surface is underwater.

This paper outlines a method to induce drainage and consolidation of the soil by lowering the water head within the wick drains by the use of air lift pumping. Such a system may be simply incorporated by the structure of the wick drain and is low cost and simple to operate.

2 PRACTICES IN TAILINGS DAM CONSTRUCTION

Tailings dams are used to dispose of the waste from ore processing. These usually consist of finely ground material that has had the ore component extracted and which now needs to be parked for an indefinite period. This infinite time span poses problems as all structures need at least to be monitored, and some need maintenance to survive. Tailings dams are no different. However, in most cases the structure of the tailings dam is less than ideal and the consequence of the dam failure can be catastrophic for those downstream.

Tailings dams have some sort of barrier which is created to prevent downstream flow. The tailings are then discharged hydraulically behind this. Particles settle out at different rates, with the coarser material descending most quickly near the discharge point and the finer material travelling further over the low slope, known as the beach, to the decant pond. Layer after layer of tailings is built up by this process. When the limit of the initial barrier is reached then it must be raised. This can be done by building a higher downstream embankment or, more usually, building this embankment upstream as this reduces the amount that it needs to be raised. Building upstream requires the material below the raised embankment to be able to support the additional height. Figure 2 conceptually shows a tailings facility, but without additional height raising.

This entire process is less than ideal from a geotechnical viewpoint. The hydraulic construction of water storage dams was halted decades ago, after some spectacular failures, but it is a fundamental part of tailings dam operation. The problem with this type of hydraulic construction is that consolidation only occurs through self weight gravitational loading and that because much of the material is fine the rate of pore pressure dissipation is very slow. The result is frequently a soil mass that is on the edge of dynamic liquefaction should there be a seismic event, or in some cases static liquefaction. The latter can be a consequence of another layer of material being added to the top leading to shear failure. Such shear failure is associated with compaction as the material moves and as a consequence, pore pressures rise.

To avoid liquefaction problems, it is highly desirable to have much of a tailings dam compacted sufficiently that further compaction with associated pore pressure rise does not occur on shearing, but rather dilation occurs instead. This requires some careful design, implementation and monitoring. The key to much of this is proper drainage of the tailings. This may be implemented through drainage pipes, drainage layers, or wick drains. In some cases, some positive means to ensure compaction without causing failure may be desirable.

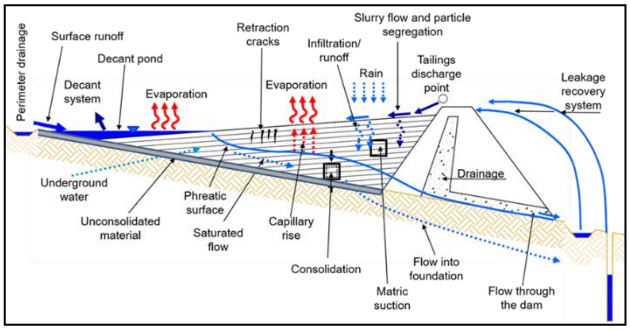

Figure 1. A conceptual diagram of a tailings dam from “(Zandarin et al, 2009)”.

New tailings dams may be built using drainage layers. These can be deliberately placed layers of coarser material which may be enhanced by the use of geofabrics. These can be designed to drain out of the embankment. This process does however take significant care and effort to make it work.

There is also a more recent move to remove a lot of the moisture from the tailings and then to ‘dry’ stack them in an unsaturated form “(De Avila, 2011)”. This process has many advantages but it requires considerable energy and capital to remove the moisture and to stack the material.

While these two modern solutions provide benefits in the construction of new tailings storage, they do not resolve the problem of dealing with existing tailings facilities that are potentially dangerous as they lie too close to the limit of stability. Many of these would only require a slight movement brought about by a natural or mining induced seismic event to trip them into failure and liquefaction. Surface movement associated with negligible seismicity may also lead to failure.

The fact remains that there are thousands of tailings dams in existence. Many of these have been built in a less than optimal manner and their stability needs to be determined. This requires an assessment of what is there. This requires inspections that will frequently include testing using piezo cone penetrometers or vane shear equipment. Direct testing for liquefaction potential by a vibrating probe can also be useful. Once those tailings dams have been identified something needs to be done to stabilise them. As many tailings dams are of considerable height the consequences of failure are extreme. For example the Brumhadino tailings dam in Brazil had a height of approximately 80 m prior to failure “(Lumbroso et al, 2021)”.

3 SOFT SOIL STABILISATION USING WICK DRAINS

The key to stabilising any material is either to reduce the load on it that will lead to failure (shear stress) or to make it stronger. The process by which soil like materials are strengthened is to consolidate them and reduce their void ratio (volume of void/volume of solids). Doing this means that they will tend to dilate on shearing thus lowering the pore fluid pressure and making them more stable.

Consolidation requires the removal of water from the soil. This can be achieved by drainage. If the pore pressure is higher than hydrostatic pressure natural drainage will occur to the surface, but not below this level. The depth of many tailings dams makes the drainage path extremely long and it is quite possible to drive pore pressures above hydrostatic by stacking new material on top of existing tailings that will not drain at an adequate rate.

Vertical drains have been used to consolidate soft clays for civil engineering purposes for decades. These used to take the form of holes into which sand columns were placed. These have now been replaced by prefabricated vertical drains (PVDs), otherwise known as wick drains, that are made of filter fabric with an internal spreader, which allows water to flow up their core within the external filter fabric. Wick drains are pushed into the ground by a mandrel. This may be a simple pushing action or one assisted by vibration. Once at depth the mandrel is withdrawn leaving the drain in place, anchored at the full insertion depth.

With a sufficiently close spacing of vertical wick drains the drainage path is greatly shortened. Drainage changes from being vertical to horizontal towards the wick drain. Because there are frequently near horizontal layers of greater permeability where sandier material has been deposited in the tailings, these may carry water preferentially toward the wick drain. A schematic view of a wick drain installation system is shown in Figure 2.

Wick drains have been used in tailings dams for some time. “Hill et al (2015)” report on the trial of such drains and more recently they have been installed at Ranger Uranium tailings facilities in the Northern Territory, Australia, with apparent dramatic consolidation of the particularly fine tailings at that location. In this operation the wick drains were installed from a floating platform made up of repurposed shipping containers.

The fundamental limitation on the behaviour of conventional wick drains is that they cannot drain below hydrostatic head at the surface. The normal practice to improve consolidation is to place a pre-load surcharge on the surface so that the total vertical stress on the ground below it is increased. In fine soils the pore pressure rises with the pre-load and effectively this water is squeezed out to the wick drains thus driving the soil into an overconsolidated state. It is normal practice to then remove the surcharge loading. Moving several metres of fill on and off a site to induce pre-loading is very energy intensive. Following the removal of the surcharge the groundwater pressure will resume a state approaching hydrostatic below the phreatic zone.

The practice of assisting the operation of wick drains by vacuum has been in use in some civil engineering applications. This is normally undertaken in combination with preloading “(Indraratna, 2009)”. In this a blanket of permeable material is placed on the ground and this is covered by an impermeable blanket and surcharge placed on the top of it. The permeable material is then subject to vacuum. The effect of the vacuum is to induce a lower pore pressure in the ground to aid pre-consolidation, and it also means that during its operation the water pressure in the soil becomes less than hydrostatic. The theoretical absolute maximum drop in pore pressure using a vacuum is one atmosphere, though the vacuum that can be practically achieved is generally less than half this. This situation is not permanent, because as the vacuum is removed the groundwater pressure will resume a state approaching hydrostatic.

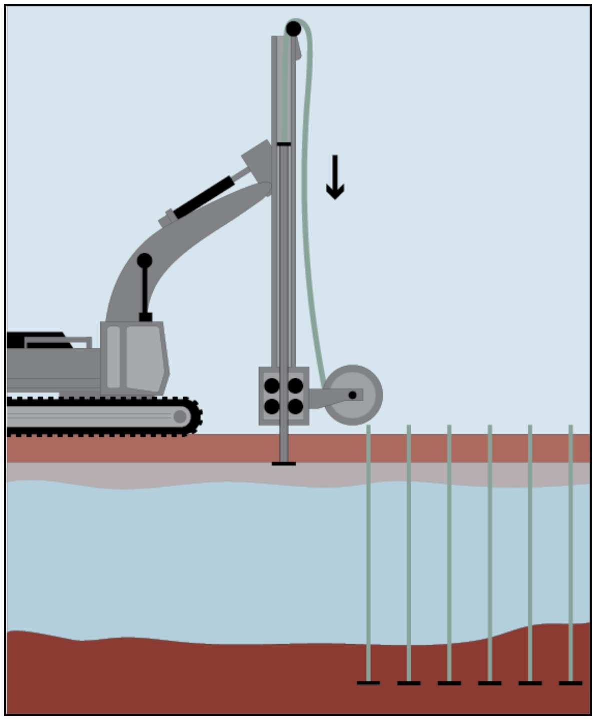

Figure 2. A schematic diagram of wick drain installation

The limitations on the effectiveness of current wick drain installations in inducing pre-consolidation in soils are the surcharge that can be applied to the surface of the soil and the level of vacuum that can be maintained in a vacuum installation. The time for such consolidation is related to the permeability of the soil and the spacing of the drains. It can be expected that the permeability of the soil will decrease with consolidation.

If a wick drain could be pumped to lower the water pressure within it then the pore pressure within the soil being drained could be reduced to below hydrostatic. This would lead to an increase in effective stress which would induce pre-consolidation. The use of mechanical pumps in a wick drain environment is not practical. The use of air lifting to pump from such drains is however eminently practical.

Air lift pumping involves injecting air into a conduit containing water so that bubbles form within it. These bubbles act to lower the density of the water column thus inducing upwards flow within the conduit. Water is thus drawn into the base of the conduit. With an increasing ratio of air to water the bubbles coalesce and slug flow takes place. In this, discrete pulses of water and air are emitted. The inner surface of the conduit remains wetted. With a higher ratio of air the slug flow becomes less regular and is called churn flow. The slugs of water will eventually break through and eventually annular flow is established with some droplets in a mist form. These forms of flow are shown in Figure 3. The most efficient from the viewpoint of lifting water is the slug flow regime.

The use of air lifting is eminently practical for wick drains. It requires no moving mechanical parts and if implemented correctly requires quite a low volume of air to lift the required volume of water. An air lifted wick drain may be in several forms. The first follows the typical form of a ribbon type wick drain currently in use but with the addition of two tubes within the filter fabric sheath. This is shown schematically in Figure 4. In this air is injected into one tube which then terminates in a connector block. This is then connected to a second tube in which the air lift takes place, lifting water from the lower portion of the drain to the surface.

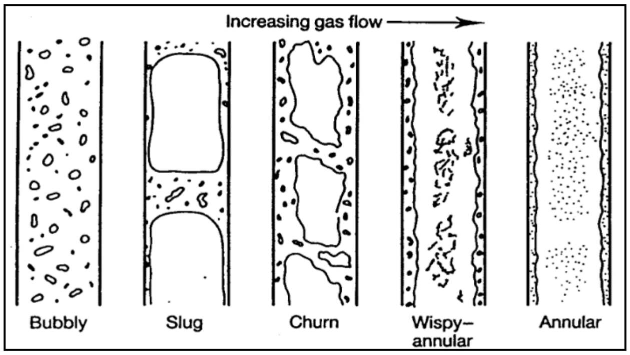

Figure 3. Two phase flow in vertical pipes.

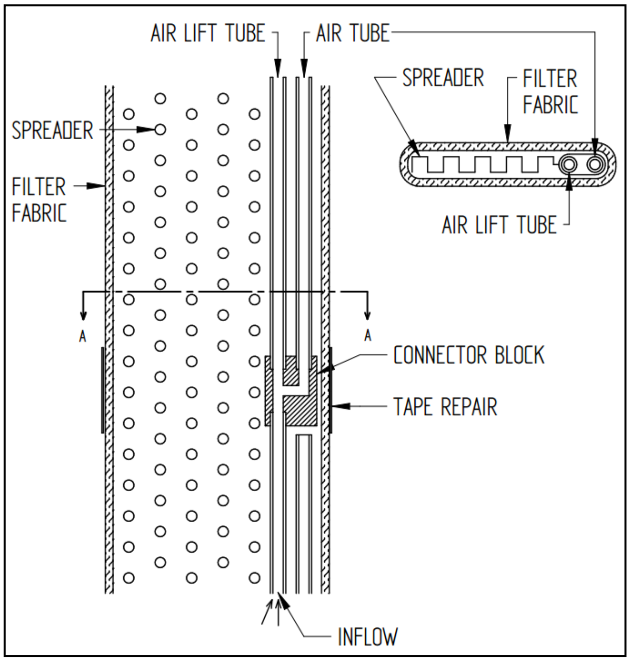

Figure 4. Ribbon type wick drain with air lift.

A second form of wick drain that may be used with air lift involves an air supply tube within an outer conduit. This is shown in Figure 5. In this the filter fabric is wrapped around the outer water and air lift conduit. Inside the outer conduit is an air lift tube to supply compressed air for air lift purposes. After the wick drain is installed and terminated near the surface, the air lift tube may be raised to a level about the base of the drain so that air is not discharged into the ground. The flow path is for water to pass through the filter fabric down the ribbed external conduit to the base of the wick drain and then to be air lifted to the surface. This sort of arrangement is suitable for high volumes but requires a comparatively stiff outer conduit to resist collapse underground pressure.

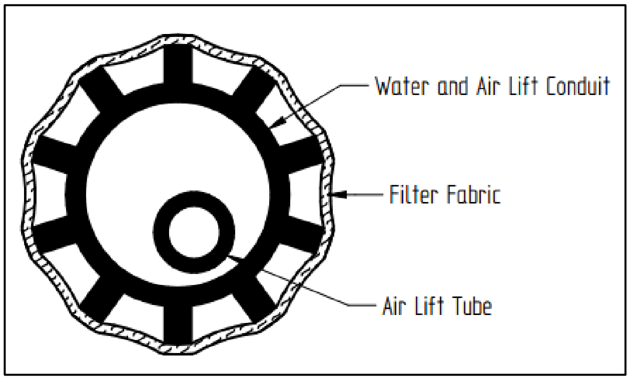

Figure 5. Air lift wick drain with internal air lift tube.

Another form of wick drain arrangement suitable for air lift purposes is a twin conduit system shown in Figure 6. Shown here in Part A the air and water lift and the air supply conduit are incorporated into a ribbed extrusion wrapped in filter fabric. In Part B, a cross port, to enable compressed air injection from the air supply conduit to the water and air lift conduit, has been created by drilling between the two and then sealing the external part of the drill hole with a plug.

The fundamental difference between conventional wick drains and a wick drains with air lift is that the flow of water is downwards between the filter fabric and its supporting core or conduit and up an internal conduit to the surface.

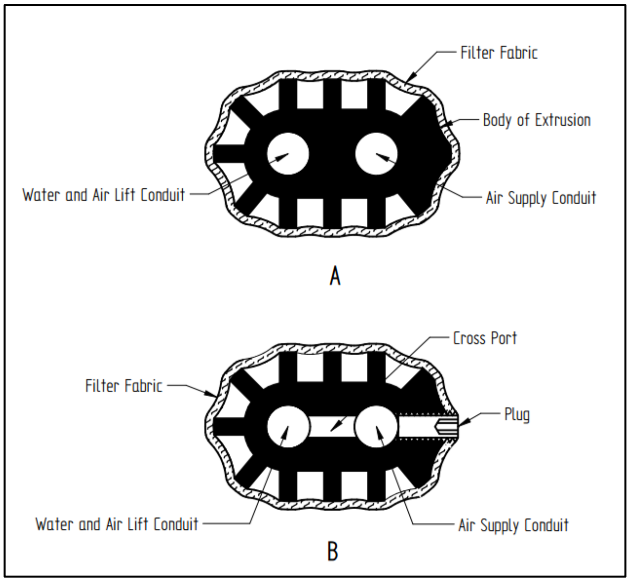

Figure 6. Twin conduit extrusion air lift arrangement.

Figure 7 is an elevational view through the ground of a wick drain with air lift. An air tube is fed with compressed air from a compressed air line via a flow control. Water enters the wick drain along its length and around its base. This water flows down inside the filter fabric to the internal base of the wick drain where it is air lifted to the surface in a second conduit. In this diagram the outer dotted line represents the limit of the cell of influence of the wick drain. This cell boundary is one of zero lateral flow between one cell containing a wick drain and adjacent cells each with their wick drain installation. Two nominal lines of zero piezometric pressure are shown. The first is an upper one corresponding to a zone of reduced vertical permeability. The second is deeper and relates to the bulk of the soil being drained. It should be noted that the head adjacent to, but outside the wick drain, is higher than the water head inside the drain. This relates to a reduced permeability zone adjacent to the drain, which is a function of the disturbance to the soil caused by installation. In the parlance of soil mechanics it is called the smear zone. It corresponds to what is known as well bore damage, or the skin effect in petroleum engineering.

Figure 7 shows piezometric surfaces. By definition the zone above these will have a pore water pressure that is less than atmospheric. However, they are not necessarily drained of water. Indeed, unless the water pressure has been lowered for some considerable time and air ingress and drying has taken place, this will not be the case and the soil will remain saturated. The water that is removed by drainage will come from reducing void space and associated with this will be consolidation.

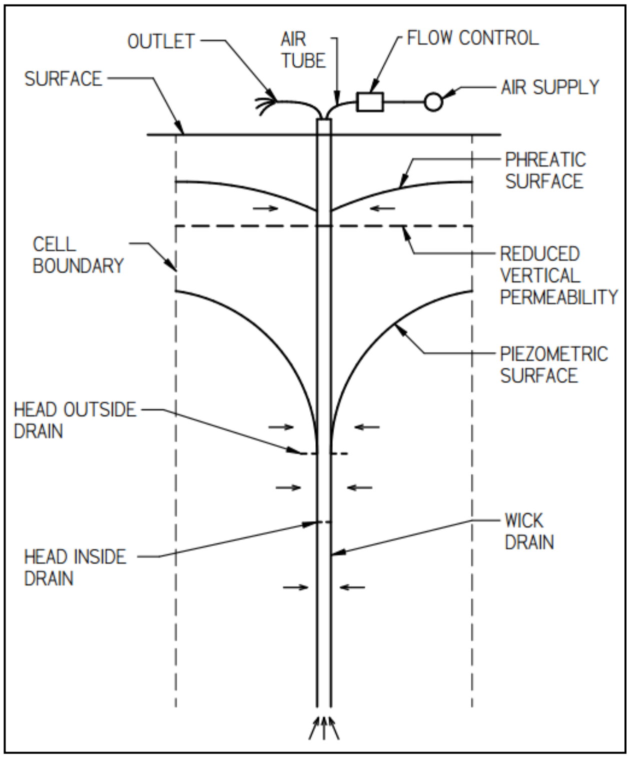

Figure 7. Schematic elevation of a wick drain

Figure 8 shows a schematic plan view of an array of wick drains. In this, a compressor drives air out along a main range to branches, each of which feeds multiple wick drains. The nominal cell boundaries between drains are shown with dashed lines. Logically the branches would be made of a flexible pipe material such as polyethylene. In areas of suitable solar radiation the compressor could be powered by an adjacent solar cell field, with or without batteries to support a night operation.

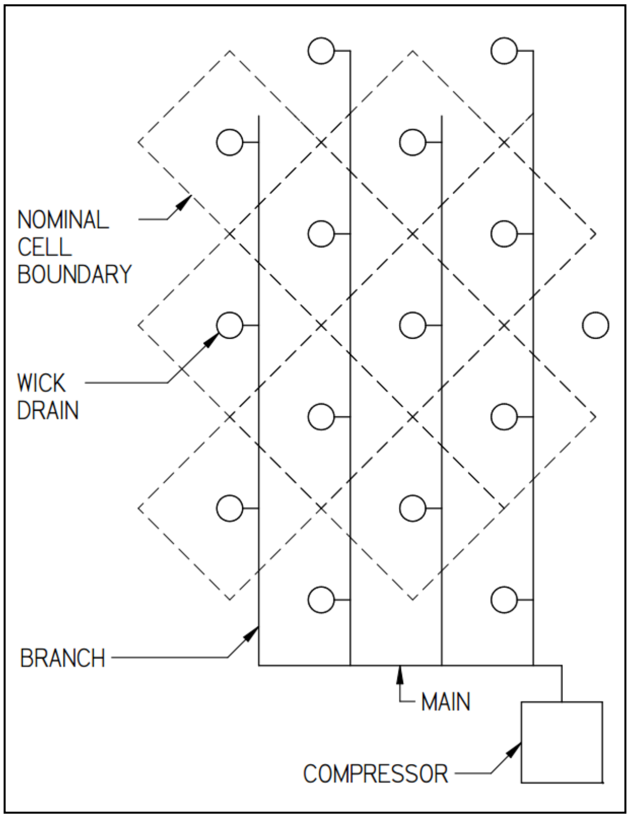

Figure 8. Schematic of wick drain array.

5 COMPARISON OF THE EFFECTIVENESS OF VARIOUS CONSOLIDATION OPERATIONS

The rate of drainage from any wick drain field will depend on the closeness of the drains and the horizontal permeability of the soil, as well as the water pressure in the wick drain itself. Spacings will need to be adjusted to suit the ground to be consolidated. The effectiveness of the wick drain in consolidating the ground will depend on the vertical effective stress reached. The higher the vertical effective stress can become the greater the state of consolidation that can be achieved.

To arrive at a comparison between wick drains on consolidation, the case of an impoundment of tailings is considered. This is a sloppy mix and assumed to have uniform properties, the most salient of which are given in Table **1**.This is placed at an initial void ratio of 1.5 but consolidates under self weight rapidly because of its high coefficient of consolidation.

Figure 9 shows the results of modelling effective stress using a simple consolidation model. It shows the effective stress states reached under the effects of self loading, with a 100 kPa surcharge and dewatering to a depth of 34 m. All the plots assume that drainage has been achieved so that there is no excess pore water pressure. The blue plot is the self loading case. Here consolidation has taken place from what would have been 60 m of tailings at a placement void ratio of 1.5 to a height of 43.19 m. The orange line shows the effective stress reached by a 100 kPa surcharge corresponding to about 6.4 m of fill. Here the height of the tailings is now 41.37 m. The green line corresponds to the effective stress reached by pumping down to 6 m above the floor of the tailings dam. The height of the fill in this case is 40.3 m.

Table 1. Tailings properties used in the example

Particle density	2.65	tonnes/m^3
Water density	1	tonnes/m^3
Initial void ratio at 1 kPa	1.5	
Coefficient of consolidation	0.25	$1/\log_{10}$ cycle
Coefficient of unloading	0.025	$1/\log_{10}$ cycle

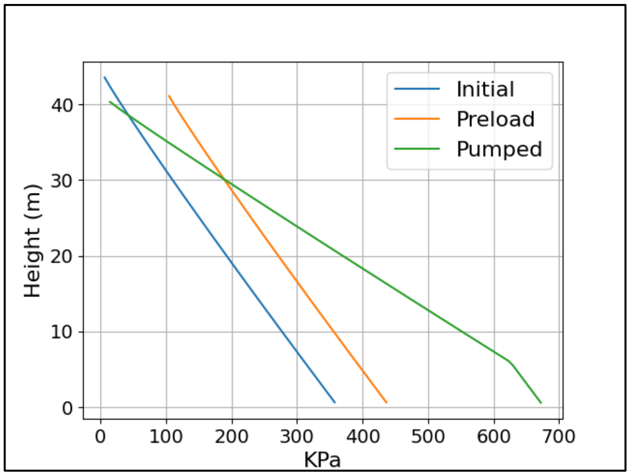

Figure 9. Maximum vertical effective stresses kPa vs height from the floor of the dam

As can be seen from Figure **9** the maximum effective stress reached by dewatering is much greater than that provided by the surcharge over all except in the upper depths of the tailings. This is because the water pressure is no longer governed by hydrostatic pressure over the base of the dam. In each case it is this maximum effective stress that leads to consolidation, and in the case of the surcharge and the pumped wick drain, pre-consolidation. The increased effective stress induced by the wick drains in the deeper levels is particularly effective in reducing the void ratio at depth and therefore the dam fill to a case where liquefaction cannot occur.

While it would appear that the effective stress increase caused by the wick drain at shallow levels is low, it should be appreciated that the analysis undertaken is one of simple consolidation and does not take into account the effect of negative pore pressures that will be generated above the saturated zone. Depending on the capillary pressure characteristics of the tailings the negative pore pressures generated could be very significant and lead to substantial consolidation of the upper levels.

Figure 10 shows the minimum void ratios that would be developed by full consolidation under the three cases being considered. These are natural consolidation, surcharge following its removal, and using the air lifted wick drain with water level recovery to surface.

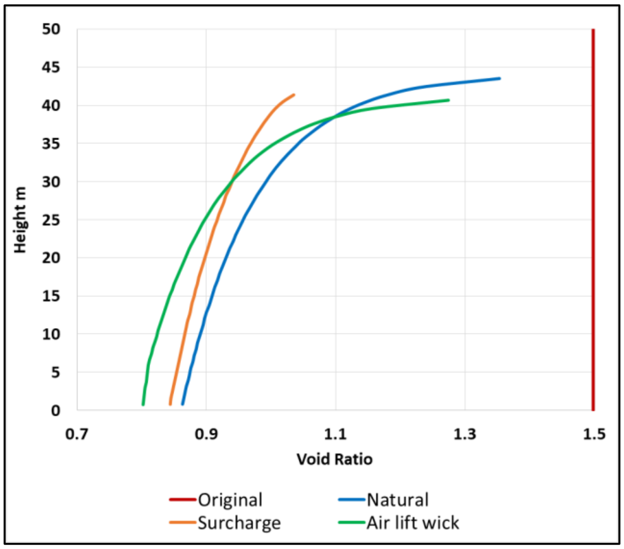

Figure 10. Minimum void ratios developed in consolidation

The higher the level of consolidation stress achieved the less likely is the risk of liquefaction. This applies even when air lifting is complete and water pressure has returned to hydrostatic levels.

The model used assumes that consolidation is complete for the particular loading. It is quite possible that there is excess pore pressure within the tailings before the wick drain is installed. In this case the wick drain will not require air lift to function until this has substantially dissipated.

The rate of consolidation is greatly speeded by the use of wick drains without any form of pumping. The benefit expected to be achieved by the use of pumped drains is directly related to the increased hydraulic gradient brought about by their use. This will tend to speed drainage thus increasing effective stress more rapidly in deeper levels.

6 ENERGY USE

Dewatering tailings for dry stacking require considerable energy and capital plant. Pre-consolidation by placing a surcharge is also extremely energy intensive. This is dependent on how the surcharge material is acquired and how far it needs to be transported. The installation of wick drains is quite low energy compared to plant dewatering or the placement and removal of surcharges. The cost that remains is that of supplying air to the wick drains at sufficient pressure and volume. This amounts to a few litres of air per minute (measured at atmospheric pressure) at a pressure to get it down the hole. Initial calculations on the energy required show this to be a fraction of that required to dig, place and remove surcharge material.

Notwithstanding the total energy use the powering of an air compressor can be from non-carbon intensive sources. Specifically, the use of solar power shows considerable promise in sunny climates.

7 STATE OF TECHNOLOGY

Trials have been conducted on the air lift system in various tube sizes. These have shown that air lifting can be made to work in the smaller size ranges and at very low air volumes. The next stage of the project is a trial planned for a tailings dam in the Northern Territory of Australia. This trial may be initially conducted in holes created by sonic drilling so as to avoid having to set up for production of push in style drains. This calls for major investment.

8 CONCLUSIONS

This paper presents the initial thoughts on use of wick drains which are enhanced by the use of air lifting so that the water pressure within the tailings is reduced below that of hydrostatic pressure from surface. The maximum effective vertical stress developed by such dewatering is much higher than can be achieved by the use of surcharge loads placed on the tailings. This is also distributed favourably with higher effective stresses at depth so that higher levels of preconsolidation are brought about at depth. This is particularly useful in preventing deep seated failures by liquefaction.

It is thought that the action of partially draining the upper layers of the tailings so that hydrostatic pressures do not exist will induce considerable suction and thus also preconsolidate this material.

The system is particularly well suited to dealing with existing deep tailings storage facilities which are teetering on the edge of stability. Whether it can be adapted to active tailings deposition environments has still to be fully investigated. It is also considered that the system has a huge potential in the role of consolidating soft soils for civil engineering construction purposes. Here the reduced energy demand compared to moving surcharge on and off the site is considered to be a significant benefit.

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10 ADDENDUM

For completeness this section contains the basic equations relating to consolidation.

Void ratio $e = \frac{volume\ of\ voids}{volume\ of\ solids}$ [1]

Effective stress $\sigma' = \sigma - p$ [2]

Porosity $\emptyset = \frac{e}{1+e}$ [3]

Void ratio under consolidation $e = e_0 - C_c\, log_{10} \frac{\sigma'_v}{\sigma'_{v0}}$ [4]

Where C_c is the coefficient of consolidation
e_0 is the void ratio at initial effective stress σ'_{v0}
σ'_v is the new effective stress