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Environment contamination by salt tailings, modelling of causes and assessment of control

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Abstract

Contamination of porous media by contaminant carrying liquids dissipated from mine tailings has, in recent years, become a serious environmental concern as these pollutants can increase the levels of dissolved contamination in excess of those acceptable by drinking water standards. This paper describes a scientific study undertaken to assess the release of brine and salt contaminated rain water from tailings piles to the vadose zone and groundwater and to, based on model results, engineer waste management techniques and decommissioning programs which would minimize brine migration and environment contamination.

1 Introduction

The beneficiation of potash ore produces sodium chloride, a waste material which comprises some 60% of the processed ore and which is disposed of on surface in massive tailings piles. Brine is also produced by the beneficiation process and is stored in extensive surface ponds. With changing environmental conditions, government regulations and public attitude toward waste pollution and waste management, contamination of the local environment has become a major concern facing the industry.

Environmental concerns associated with the surface disposal of salt tailings and with the surface storage of process brine include the possibility of contamination of surface water and groundwater resources, surface soil contamination, and air and vegetation contamination resulting from wind erosion of the tailings pile. Current tailings management techniques include the application of effective containment and maintenance techniques through the establishment of tailings piles, the use of large brine storage ponds formed by extensive systems of dykes and the use of brine injection wells. Of these, gravity driven injection well systems are the most practical for long term tailings management. Possible alternative waste management solutions sought to eliminate environmental contamination include capping the tailings to isolate the pile from the environment, salt tailings dissolution and deep well injection, underground disposal, dry stacking, and surface burial of salt waste. The feasibility of long term application of such techniques would be determined by economics.

The capping of the tailings with a multi-layered soil system to isolate the pile from the environment and to eliminate potential brine discharge into the groundwater is a potential method as it has been effective and commonly used in land reclamation practices. The soil cover acts as a barrier to reduce movement and percolation of precipitation into the tailings pile thus minimizing acidic discharge into the ground. Studies concerning soil characteristics, soil blanket thickness and capillary barriers, vegetation and species growth, climate and precipitation would have to be conducted to verify the applicability of the method.

A number of potash operations use deep well injection to eliminate excess brine stored on surface. Depending on the injection rate, the deep wells are capable of disposing of 5 to 20 percent of the waste salt produced at a mine. Typical formations used for brine injection are naturally saline, very thick and porous. These formations may be able to safely accept increased quantities of waste salt, possibly making deep well injection a viable option. The possibility of using gravity injection and low quality groundwater must be considered, the brine volumes which can be practicably and safely injected into deep formations must be estimated and the costs associated with brine dissolution must be assessed before deep well injection can be feasibly used for the disposal of existing salt tailings.

Although underground storage is considered a technically feasible option, with the added advantage that much of the salt waste remains underground, application of salt backfilling is uneconomic. A combination of the underground pre-processing of ore utilizing electrostatic separation with high extraction methods may however be a promising option for handling and disposing of salt waste which will be produced in the future. Utilization of a high extraction system with salt paste backfill would assist in the control of surface subsidence and potential brine inflows and would result in improved resource recovery. However, high initial capital costs would be required for the establishment of the paste backfilling program and several mining trials would have to be explored before full production is implemented.

In this paper, simulation studies of the transport phenomena of dissolved salts from industrial waste through the tailings pile to the vadose zone and the potential environmental damage due to contamination in the subsurface are presented. Two physical models have been developed to simulate the phenomena of flow and transport of brine through salt tailings: centrifuge modelling of brine flow through tailings and brine injection through consolidated salt tailings. Three methodologies and strategies - soil capping, tailings dissolution for deep well injection and salt backfilling - that may

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eliminate the risks and consequences of salt tailings contamination were also simulated and are presented.

2 Simulation studies of brine flow through salt tailings

Two studies were developed to simulate and understand the flow behaviour of brine through salt tailings, centrifuge modelling and brine injection through quasi-static consolidated tailings. Such simulation techniques not only provide critical information to calibrate and validate numerical models but to complement limited field measurements. The salt tailings material consisted mainly of halite, with some sylvite and some clay minerals. The specific gravity of the salt material was measured as 2.175 g/cm^3; grain size distributions indicated that the material had an effective grain size of 0.64 mm and a coefficient of uniformity of 7.8, indicating a graded material.

2.1 Centrifuge modelling of contaminant transport

Centrifuge modelling offers an advantage to field validation of contaminant transport. For example, transport taking ten years in the field can be reproduced at 1/100 scale in the centrifuge in less than nine hours. The centrifuge can thus be used as the 'field data' to which results of numerical simulations could be compared.

A 33 g-tonne, geotechnical centrifuge, designed and built at Queen's University, was used to simulate the long term flow of brine through salt tailings. The variables incorporated into the testing program included applied stress, time and brine inflow volume and pressure. In the developed experimental procedure, a column of tailings, at 12% moisture content and density of 1.67 g/cm^3, is placed in the centrifuge strongbox and allowed to drain under the influence of the increased gravity field of the centrifuge. After a predetermined length of time has passed, brine is introduced at a point source at the top of the tailings column. The brine tracer is allowed to infiltrate into the material for a set length of time, after which the tailings column is removed from the centrifuge and partitioned into horizontal slices for determination of water content and brine concentration. In the testing program (6 tests total) each model was loaded to 50 g (0.6 MPa) or 100 g (1.2 MPa), and creep consolidated for 6 months or 12 months. Between 15 ml (1879 litres) and 3.8 ml (3808 litres) of brine was then injected and the tailings creep consolidated for 3 months after injection.

A schematic of a typical model is shown in Figure 1. A soil column mold, 30 cm in length and 10 cm in diameter and a base plate with a porous filter to permit uniform drainage of brine from the end of the tailings column were used. A moveable top plate was used to transfer load (via a 9.8 kgf surcharge lead shot column) to the tailings column, to continuously measure tailings consolidation (with a direct current displacement transducer, dcdt, attached to a reference plate) and to allow brine addition to the column to simulate flow. A data acquisition system was used for dcdt data collection, the sampling rate was set at 15 seconds. A brine feed tank assembly, mounted on the centrifuge arm, near the centrifuge center of rotation (shaft), was used to supply a premeasured quantity of brine to the tailings column while in flight. A brine receiving tank was placed below the tailings column to receive and measure the outflow brine during flight.

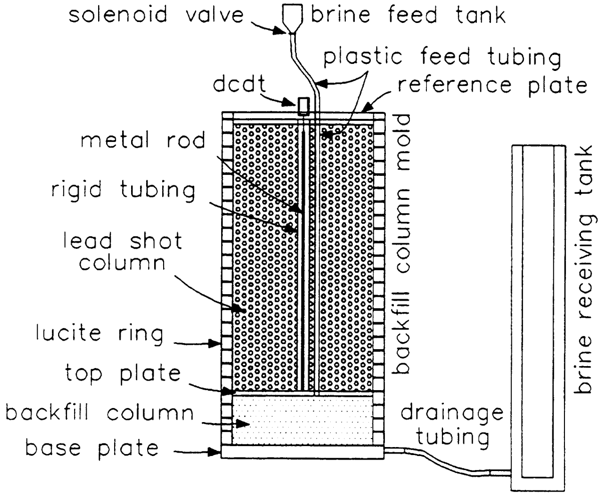

Figure 1. Centrifuge flow test model

The salt tailings presented a maximum strain of 4.11% at a consolidation stress of 0.6 MPa and 4.62% at 1.2 MPa. These strain values were noted after 12 month creep, with drainage of preparation brine and prior to brine injection. The occurrence of flow, simulated by the injection of brine, increased the maximum strain to 4.51% and 5.25% at a consolidation stresses of 0.6 and 1.2 MPa, respectively. These results clearly show the influence of stress and brine flow after consolidation on tailings behaviour. The volume of injected brine did not seem to influence tailings behaviour; by doubling the amount of brine flow volume (from 1904 litres to 3811 litres) no substantial difference in tailings strain was noted. Brine drainage analysis has indicated that, in general, 80% of the initial tailings brine volume is expulsed during consolidation. Measurements of brine drainage after injection have also indicated that brine drainage volumes increase with increasing injection volumes. In general, approximately 60% of the injected brine was expulsed three months after injection. The salt tailings presented a final water content of approximately 2% after 12 month creep and prior to brine injection, thus representing a reduction in 85% of the initial water content. After injection and 90 day creep, final water content values approximated 3%. These very low values of water content reflect the rapid brine drainage experienced by the tailings column. The above results indicate that poorly consolidated tailings may have a negative impact on the environment as brine will freely drain through the pile and into the top soil and vadose zone.

2.2 Flow through consolidated tailings

The flow of brine through consolidated tailings is complex in nature, due to the physical and chemical interactions that can occur between the brine and the tailings material. Brine has the ability to dissolve the solid salt tailings and, as it becomes saturated, the reverse reaction can occur, in which brine liberates or precipitates solid salt crystals. The net effect of salt tailings dissolution and brine precipitation is perceived to be a respective increase or decrease in salt tailings porosity, which in turn may respectively lead to an increase or decrease in tailings' ability to transmit brine to the environment.

A quasi-static simulation study was undertaken to examine the interaction between various key parameters influencing the flow of brine through the fill. A tailings compression cell, mounted on a 5000 kN MTS loading frame, was used to control salt tailings compression and creep, and a brine pressurization cell, mounted on a 890 kN MTS loading frame, was used to simulate flow (Figure 2). Approximately 2 kg of salt tailings with a brine content of 16% by mass was compacted in the tailings compression cell to develop a constant height of 142.24 cm with a dry density of 1.5 g/cm^3. After placement the sample was slowly loaded to a target stress of 6.89, 13.79 or 20.68 MPa and compressed for a period of 3, 18 or 87.5 hours. At the end of the compression period approximately 1600 ml of brine (4.4 original pore volumes) was injected at constant flow rates of 3.80, 7.60, 15.20 and 30.40 ml/s, into the compressed tailings sample which was still being held at the target stress level. Throughout the compression and injection periods, load and displacement values from each MTS machine were simultaneously measured and recorded at prescribed intervals using a data acquisition system. Recorded data values were then reduced to yield useful engineering quantities like axial strain (%), total porosity (%), brine injection pressure (MPa), brine injection head (m of brine), brine injection volume (ml), and estimated values of hydraulic conductivity, K (cm/s) of the tailings material.

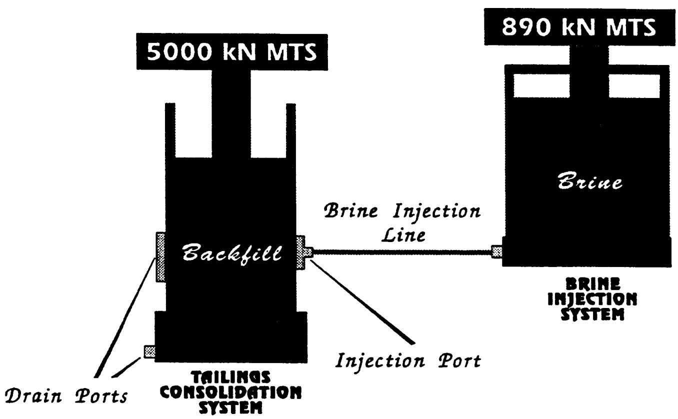

Figure 2. Quasi-static flow test model

This unique procedure could directly assess the flow behaviour of brine through consolidated salt tailings. The study has indicated that strain during consolidation can reach 33% with a corresponding reduction in total porosity to more than 90% of the original resulting in porosities as low as 2%; that the tailings can develop hydraulic conductivities from 7.05 x 10^{-5} to 3.7 x 10^{-2} cm/s which is similar to that of silt to coarse sand or even lower (unmeasurable) values; and that very high brine pressures (16-26 MPa) are required to initiate flow in such tailings material. Such measured values of hydraulic conductivities correlate well with field measurements based on infiltrometer and open-caisson infiltration tests. Brine content analysis has also indicated that zones of 'no flow' occur in the tailings model during brine injection. During injection a minimum change in total porosity is experienced and, after breakthrough, the tailings material has demonstrated the ability to maintain resistance to brine flow pressures in the order of 4 MPa. Such results have indicated that although poorly consolidated salt tailings could easily be leached by brine, a long term compressed tailings structure may retard or totally impede the flow of brine, thus indicating its impact on the environment.

3 Simulation studies of tailings management options

Having developed an understanding of the flow behaviour of brine through salt tailings and of its effect on the environment, three management techniques which could minimize the long term adverse environmental effects associated with surface salt tailings disposal were tested.

3.1 Soil capping

Capping of the tailings with a soil layer to isolate the pile from the environment represents an economically feasible tailings management option. Simulation tests of rain fall over a tailings pile were conducted to assess the release of brine and salt contaminated rain water from tailings piles to the vadose zone and groundwater. The apparatus for physical modelling included a flow column, a sprinkler system and lysimeter assemblies (Figure 3). The column was 18.415 cm in diameter and 1.575 m high. A base plate had a filter used to support the weight of the tailings column and to permit uniform drainage of contaminated water from the base of the column. The sprinkler system consisted of 187 precision glide needles and was designed and calibrated to permit simulation of rainfall rates ranging between 1.4 and 4.2 ml/s. The lysimeter system permitted sampling of contaminated water in four positions along the column. The sampling points were at positions 27.7 cm, 53.4 cm, 78.5 cm and 105.2 cm from the column base. The lysimeters were round bottom, straight wall porous ceramic cups, 19.05 cm long, with an outside diameter of 3.988 cm and 0.508 cm wall thickness. The lysimeter cups had an air entry value of 0.5 bar, a saturated hydraulic conductivity of 3.11 x 10^{-5} cm/s and a pore size of 6.0 μm.

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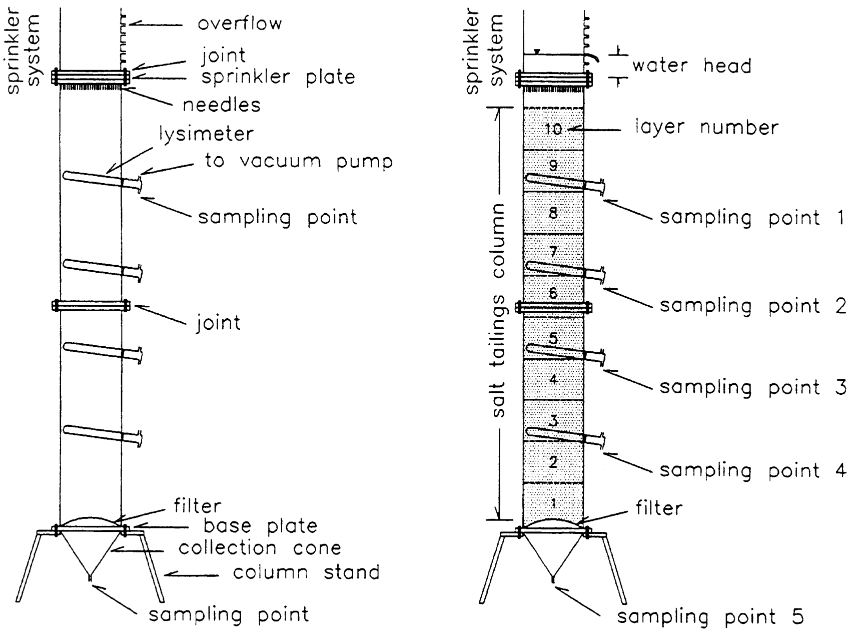

Figure 3. Flow column assembly

The tailings material was first compacted at a controlled density in the cell, in ten 12.7 cm thick layers. The tailings column height was 1.27 m. The sprinkler system was then assembled on the column top and rainwater simulation was started. Water sampling, at the four lysimeter points (sample points 1 - 4) and at the column base (sample point 5), was performed at 3 hour intervals, and tailings height was measured at 1 to 3 hour intervals, depending on dissolution conditions. A Perkin-Elmer atomic absorption spectrophotometer was utilized to determine changes in contaminant concentration and to investigate dissolution reactions between the contaminant liquid and the tailings mass. Samples from the test runs were analyzed for Na^+ and K^+.

Model simulations incorporated continuous rainfall simulations of constant flow volume of 1.4 ml/s over periods ranging between 76 and 94.5 hours. Models were run with and without a soil cap, such that an assessment of the effectiveness of capping techniques in minimizing salt dissolution and contamination was permitted. A plot of tailings height versus time for capped and uncapped models is shown in Figure 4.

Dissolution rates for the uncapped model were estimated as 370 cm^3 of salt per hour for a 1.389 ml/s rainflow on a 266.34 cm^2 tailings surface area, and for the capped model as 101 cm^3/h. Capping of salt tailings with soil drastically reduces - by approximately 73% - the dissolution rate of salt and greatly minimizes water contamination levels (from 250 g Na^+/l to 120 g Na^+/l). This clearly indicates that capping of salt tailings offers a viable solution to waste management and environment contamination control.

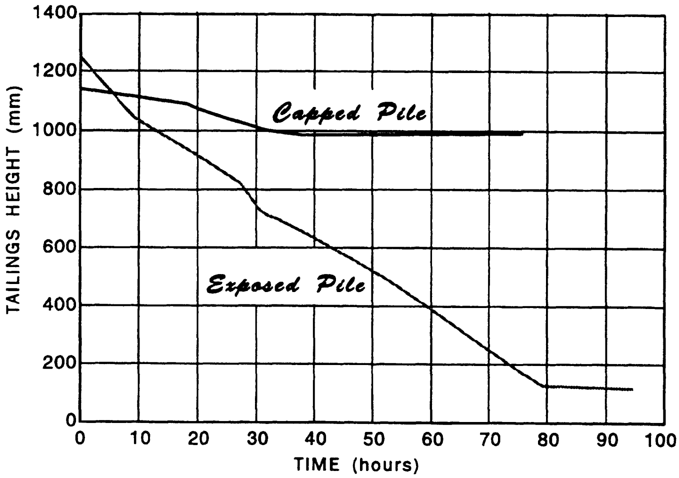

Figure 4. Salt tailings height versus time

3.2 Tailings dissolution for deep well injection

As previously discussed, a number of potash operations already use deep well injection to eliminate excess process brine stored on surface. Such operations could also dissolve the solid waste salt to produce brine for storage in deep formations. A technical study was developed to assess the performance of a tailings dissolution system utilizing water monitors.

Simulation tests of tailings dissolution were performed using a tailings column and a spray nozzle system (Figure 5). The column was 18.415 cm in diameter and 0.66 m high. The nozzle system incorporated a pressure gauge, a flowmeter and valves to control water flow rates. Water temperature was continuously monitored using an RTD thermistor temperature probe. Production brine was collected via a hose passing through the center of the

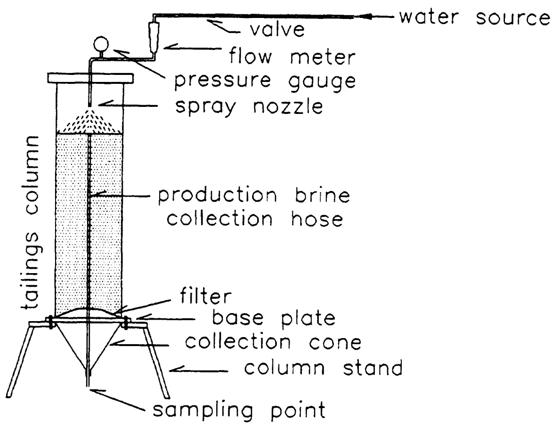

Figure 5. Assembly for tailings dissolution tests

tailings column. Atomic absorption spectrophotometry was utilized to determine brine concentrations; the higher the Na^+ concentration the better was the system performance. The tailings material was first compacted at a controlled density in the cell, in four 12.7 cm thick layers and then dissolution was simulated using the nozzle system. Model simulations incorporated three nozzle volume rates (0.013, 0.017 and 0.020 l/s) and three water temperatures (11, 34 and 43°C). As the column was dissolved, the nozzle was moved such that its distance from the top of the tailings material was kept at 10 cm. A plot of dissolution rate (given as the percent change in tailings height over time) as a function of temperature and flow rate is shown in Figure 6.

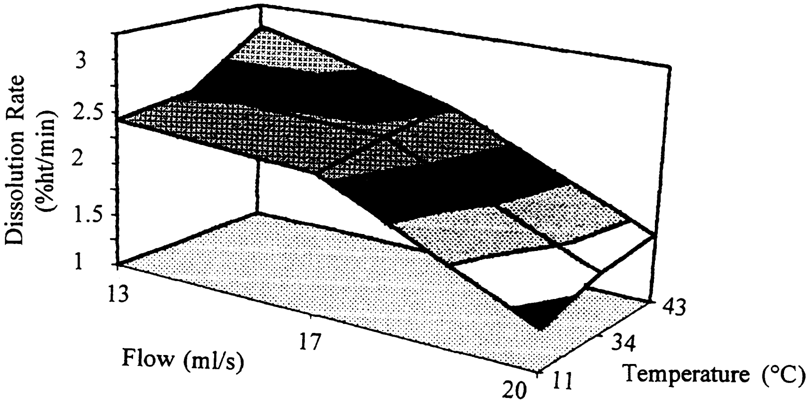

Figure 6. Tailings dissolution as a function of water temperature and flow

Dissolution rates ranged between 1.4%ht/min (at 11°C and 0.013 l/s) and 3.4%ht/min (at 43°C and 0.02 l/s). This corresponds to between 3 and 2 m^3 of fresh water being required to dissolve one tonne of salt tailings. Analysis of Na^+ concentration indicated that performance increases linearly with temperature and decreases with increased volume rate. Production brine concentrations reached 100 g/l thus indicating that a system of monitors could effectively produce highly concentrated brine, making deep well injection a technically viable solution to salt tailings management.

3.3 Salt backfilling

A salt tailings assessment program and its application as mine backfill for improved mine safety and environmental control has been studied. The time dependent creep-consolidation behaviour and strength development of the waste salt when used as a backfill has been assessed, and its suitability to control underground deformations and surface subsidence has been evaluated. Testing included static consolidation tests, creep tests, uniaxial and triaxial strength tests and shear tests.

Static consolidation tests under low stress (0.19-1.43 MPa) have indicated that maximum compaction (35%), maximum density (1.8 g/cm^3), and minimum porosity (11%) are achieved when backfill placement is at initial moisture contents between 8% and 10%. Following placement, and during the initial stages of load uptake due to room closure, only a weak, friable backfill is formed, exhibiting minimum unconfined strength (0.63 MPa). A maximum triaxial compression strength of 1.74 MPa was obtained using a confining stress of 0.34 MPa. High stress consolidation tests (3.45-20.68 MPa) have indicated that the backfill can develop in situ equivalent loads (20.68 MPa) under a small amount of consolidation (24% strain) and develop high strength (unconfined strength averaging 4.5 MPa). A maximum triaxial compression strength of 7.79 MPa was obtained using a confining stress of 1.38 MPa. The backfill failure mechanism is one of shear failure, characterized by its developed cohesion (45 KPa) and angle of internal friction (35°). The increase in strength with consolidation is explained by mechanisms of grain bonding which occur during consolidation. Creep testing under applied stresses equivalent to in situ values (20.68 MPa) have indicated that up to 99% reduction in initial moisture content may occur, producing final moisture contents between 0.2% to 1%. High increases in density are also predicted, to give relatively high final densities, corresponding to 96 to 98% the material true solids density. Decrease in porosity from 83% to 90% of the initial value will produce final values in the range of 1.5% to 4.0%, indicating the potential use of backfill for bulkheads to isolate areas of brine inflow. Convergence may reach 27% to 40% the original mine opening height; this indicates a potential reduction in surface subsidence due to mining of up to 73% for ideal backfill placement.

Parametric analysis, using developed constitutive relations and field instrumentation data, has indicated that after approximately 7 months, 36% creep-consolidation, corresponding to 36% backfill strain, would occur, this being the approximate time necessary for the backfill to achieve full strength and full load support.

4 Conclusions

Recent evaluations of the subsurface environment adjacent to surface tailings piles have revealed that salt, in solution, leached by rainfall is migrating outward from these tailings piles at large rates. This uncontrolled movement of salt is perceived as a major environmental problem by regulating bodies currently reviewing this issue. This has encouraged the author to investigate realistic and practical engineering solutions for the successful management of salt tailings, and to study three alternative methods of tailings management: soil capping, deep well injection of a fluid solution containing dissolved salt tailings, and backfilling. Although the three investigated techniques have been shown to be technically feasible, they may not be economically justifiable. The most promising technique is that of deep well injection, although soil capping may provide an attractive alternative. The developed laboratory simulation techniques not only provide complementary information to limited field measurements but critical data for accurate calibration and validation of numerical models.