

## Satellite monitoring of a large tailings storage facility

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### ABSTRACT

Minera Peñasquito, S.A. de C.V., operates a tailings storage facility (TSF) that currently covers 650 hectares (ha) and will have an ultimate dam length of approximately 11 kilometers (km) at their mine in the state of Zacatecas, Mexico. Historically, the size of the Peñasquito TSF has presented challenges with respect to monitoring and documenting construction and operational activities. Ground-based observation and topographic survey methods have been time-consuming, labor-intensive, and have been limited by site distances, shallow relief of tailings beaches, and restricted access to the tailings beach. Utilization of outside contractors to perform large-scale as-built surveying with unmanned aerial systems (drones) has been successful but also time-consuming and expensive, due to mobilization and site logistics.

Through the innovative application of both publically and commercially available satellite data and data processing techniques developed by Photosat Ltd., Golder Associates Inc. (Golder) has been able to provide cost effective and reliable topography and aerial imagery to monitor and document the development of the Peñasquito TSF. This data has provided valuable insights into the construction progress and operational performance of the facility.

Landsat Survey Infrared Construction Operation Capacity.

### 1. INTRODUCTION

Visual observation and as-built surveys are common aspects of TSF operation, maintenance, and surveillance (OMS) plans; however, for large facilities, these activities can be time-consuming, labor-intensive, and costly. Ground-based observation and topographic survey methods can be limited by site distances and shallow relief of tailings beaches. Further restrictions can include safe access to the tailings beach, dam slopes, or surrounding natural topography. Unmanned aerial systems (commonly referred to as drones) are an increasingly popular tool for developing topography and aerial imagery as a convenient alternative to light aircraft survey methods. However, drone systems require a qualified operator and spotter to be mobilized to the TSF, may require multiple flights to cover the complete survey area, and can be costly to complete on a routine basis, if multiple mobilizations are required. Furthermore, governmental regulations may restrict where and how drones may be used. Collecting survey data and imagery using satellites, however, is largely unencumbered by these limitations.

Since 2013, Golder has been providing the mine with weekly moderate-resolution satellite imagery of the entire mine site and TSF from the USGS/NASA Landsat program. Although limited in physical resolution, the high temporal resolution provides valuable insight to the operation and performance of the TSF, in particular the behavior of the tailings beach and water reclaim pond.

On a monthly basis since December 2014, Golder has also contracted with PhotoSat Ltd. (PhotoSat) to produce high-resolution satellite imagery and digital elevation models using stereo satellite imagery. The topographic survey data is used for construction quality assurance review

of TSF including monitoring of the deposited tailings volumes; tracking of TSF dam construction quantities; validation of storage capacity estimates and monitoring of average in-place density of deposited tailings.

These powerful tools have significantly enhanced the monitoring of the TSF at considerable savings with respect to costs, labor, and time compared to similar comprehensive methods.

## 2. BACKGROUND

### *Minera Peñasquito*

The Peñasquito mine, operated by a wholly owned subsidiary of Goldcorp Inc., produces gold, silver, lead, and zinc from a mixed sulfide and oxide ore body. Oxide ore is leached and sulfide ore is processed by floatation and grinding. The sulfide circuit has a capacity of 130,000 tonnes per day (tpd) and the discharged tailings are transported as a slurry to the TSF.

The TSF is a three-sided, 11 km long hybrid rockfill and cycloned sand dam. The dam is raised continually via centerline-raise methods. Rockfill for the dam construction is hauled via truck from a local waste rock stockpile and cycloned sand tailings, which is used as a transition zone between the rockfill and deposited tailings, are placed by hydraulically utilizing paddock construction and deposition methods. The Peñasquito TSF includes a water reclaim pond that must be managed to achieve minimum beach lengths, while maintaining the required minimum water storage volumes for reclaim.

### *Landsat Program*

Since 1972, the U.S. Geological Survey and NASA have launched and successfully orbited a series of seven earth-observing satellites under the Landsat program (USGS 2013a and 2013b). The newest satellite, Landsat 8, was launched on February 11, 2013, and was fully operational on April 11, 2013. Landsat 8 orbits the Earth once every 99 minutes, collecting 185-km wide images and providing a revisit time of 16 days. Landsat 7 follows an offset orbit to allow a revisit time of 8 days for every point on the planet with the Landsat program.

Landsat 8 carries optical and thermal sensors that collect 11 spectral bands of data at pixel resolutions of 15 to 100 m, as summarized in Table 1. A typical natural-color image produced from Landsat 8 data is shown as Figure 1. This image is produced by combining data from the blue, green, and red data bands. The panchromatic band, with a higher 15 m resolution, is used to pansharpener the color imagery.

Table 1. Landsat 8 Data Bands (USGS 2013a).

Spectral Band	Wavelength	Resolution
	$\mu\text{m}$	m
Band 1 – coastal/aerosol	0.43-0.45	30
Band 2 – blue	0.45-0.51	30
Band 3 – green	0.53-0.59	30
Band 4 – red	0.64-0.67	30
Band 5 – near IR	0.85-0.88	30
Band 6 – SWIR 1	1.57-1.65	30
Band 7 – SWIR 2	2.11-2.29	30
Band 8 – panchromatic	0.50-0.68	15
Band 9 – cirrus	1.36-1.38	30
Band 10 – TIRS 1	10.60-11.19	100
Band 11 – TIRS 2	11.50-12.51	100

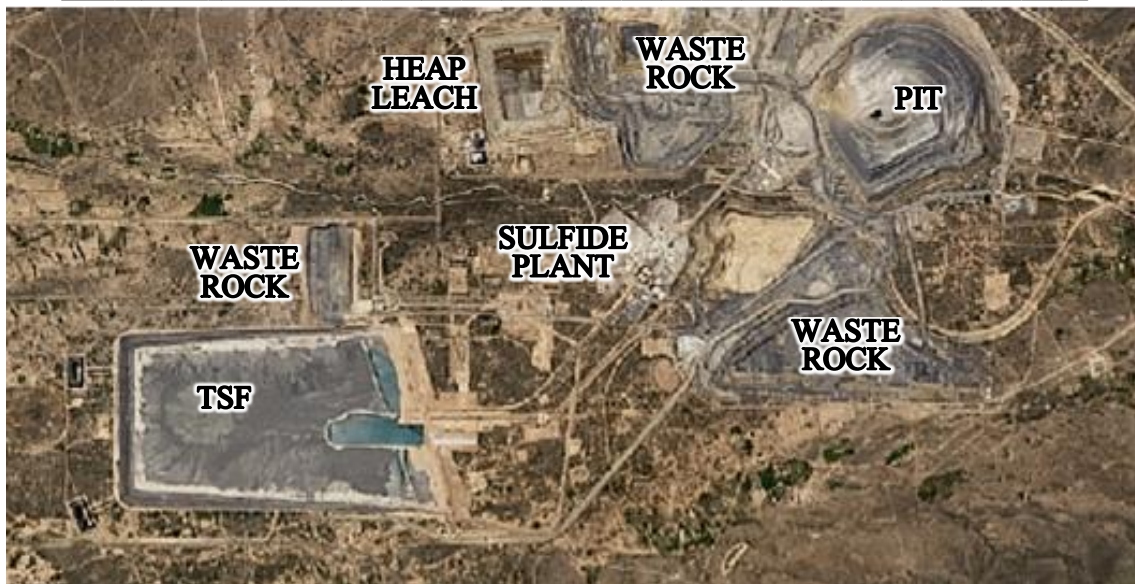


Figure 1. August 19, 2015 Landsat image of the Peñasquito Mine (USGS/NASA Landsat).

Landsat data is terrain-corrected by USGS and provided at no charge and without user restrictions. Data is typically available for download from <http://earthexplorer.usgs.gov> within 24 hours of acquisition.

Data for the Peñasquito project is downloaded, processed to produce the panshaped, natural color imagery and analyzed with typically less than 2 hours of labor effort. This provides an inexpensive, frequent source of imagery data with 15-m resolution.

#### *PhotoSat Topographic Mapping*

Many satellite vendors offer digital elevation products based on stereo imagery. Horizontal and vertical accuracies of these surveys are typically limited to approximately 1 m. Measuring small elevation and slope changes on tailings beaches and dam walls typically requires greater elevation accuracy than can be achieved with these conventional satellite photogrammetry methods.

To achieve accuracy better than 30 cm, PhotoSat uses algorithms that were derived from Oil and Gas seismic data processing. These algorithms and processing methods result in an accuracy improvement of about 5x over the best photogrammetry methods. Producing stereo satellite surveying accurate to better than 30 cm in elevation requires knowledge of the specific characteristics of each of the various types of stereo satellite photos. Over the past seven years, PhotoSat has measured satellite photo characteristics using dozens of accuracy studies and in over 500 client satellite survey projects. These projects include continuous monitoring of some mine sites and their tailings facilities. Using these case histories, PhotoSat has built a database of processing parameters and procedures that routinely achieve better than 15 cm surveying accuracy at some mine sites. With these methods, accurate surveys of areas exceeding 100 km<sup>2</sup> can be rapidly produced, with typical elevation model grid spacing of 1 m.

Imagery for the Peñasquito project is acquired monthly using DigitalGlobe's WorldView-1, -2 and -3 satellites. These satellites provide panchromatic ground resolution of 0.31 to 0.5 m (DigitalGlobe 2013, 2014a, and 2014b). WorldView-3 is the most advanced satellite in the fleet, with 0.31-m panchromatic imagery, 1.24-m resolution multi-spectral and near infrared imagery in eight bands covering 0.400 to 1.040  $\mu\text{m}$ , and 3.7-m resolution shortwave infrared imagery in eight bands covering 1.195 to 2.365  $\mu\text{m}$ . Among the three satellites, revisit times of less than one day can be achieved, subject to a prioritization hierarchy lead by government tasking requests. An example WorldView-2 image is shown as Figure 2.

After stereo satellite images are acquired, PhotoSat processes them using their proprietary algorithms. The code for these runs on massively parallel multicore GPUs. This allows surveys to be processed, projected into any coordinate space (including custom mine grids), and then delivered within a few days of imagery acquisition. Surveys are projected to the mine coordinate system and vertical accuracy evaluated using photo-identifiable ground control points (GCP). Following construction and initial survey of these points, no action is required from on-site personnel.

For the Peñasquito project, surveying costs are less than \$12,000 USD for an imagery area of 100-km<sup>2</sup> covering the active mining and TSF areas and an elevation model area of 23-km<sup>2</sup> covering the TSF. The elevation model area could be expanded to the full extent of the stereo imagery and can also be developed using archival stereo imagery.

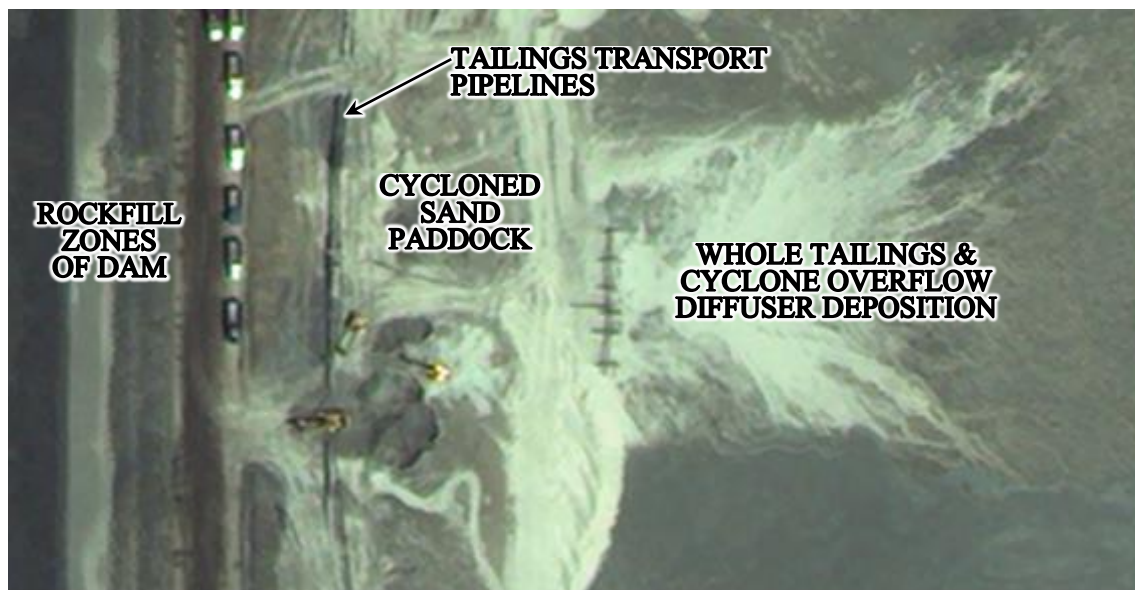


Figure 2. July 16, 2015, WorldView-2 Image of Construction Equipment and Deposition Piping at the Peñasquito TSF.

### 3. APPLICATION OF SATELLITE DATA AT MINERA PEÑASQUITO

#### 3.1 Change Monitoring

Minera Peñasquito is located at the edge of two adjacent flight paths of Landsat 8, allowing alternative 7- and 9-day repeat coverage. As Landsat 7 has a mechanical fault that results in bands of data gaps across the imagery, it is not used for new imagery in the Peñasquito project. However, data from Landsat 7 has been used to develop a complete image history of the TSF dating back to pre-construction starting in 2008.

Example imagery developed from the Landsat 8 data from 2013 to 2015 is shown as Figure 3. As seen in this imagery, the advancement of the tailings deposit, liner system construction, and development of the reclaim pond can be readily identified.

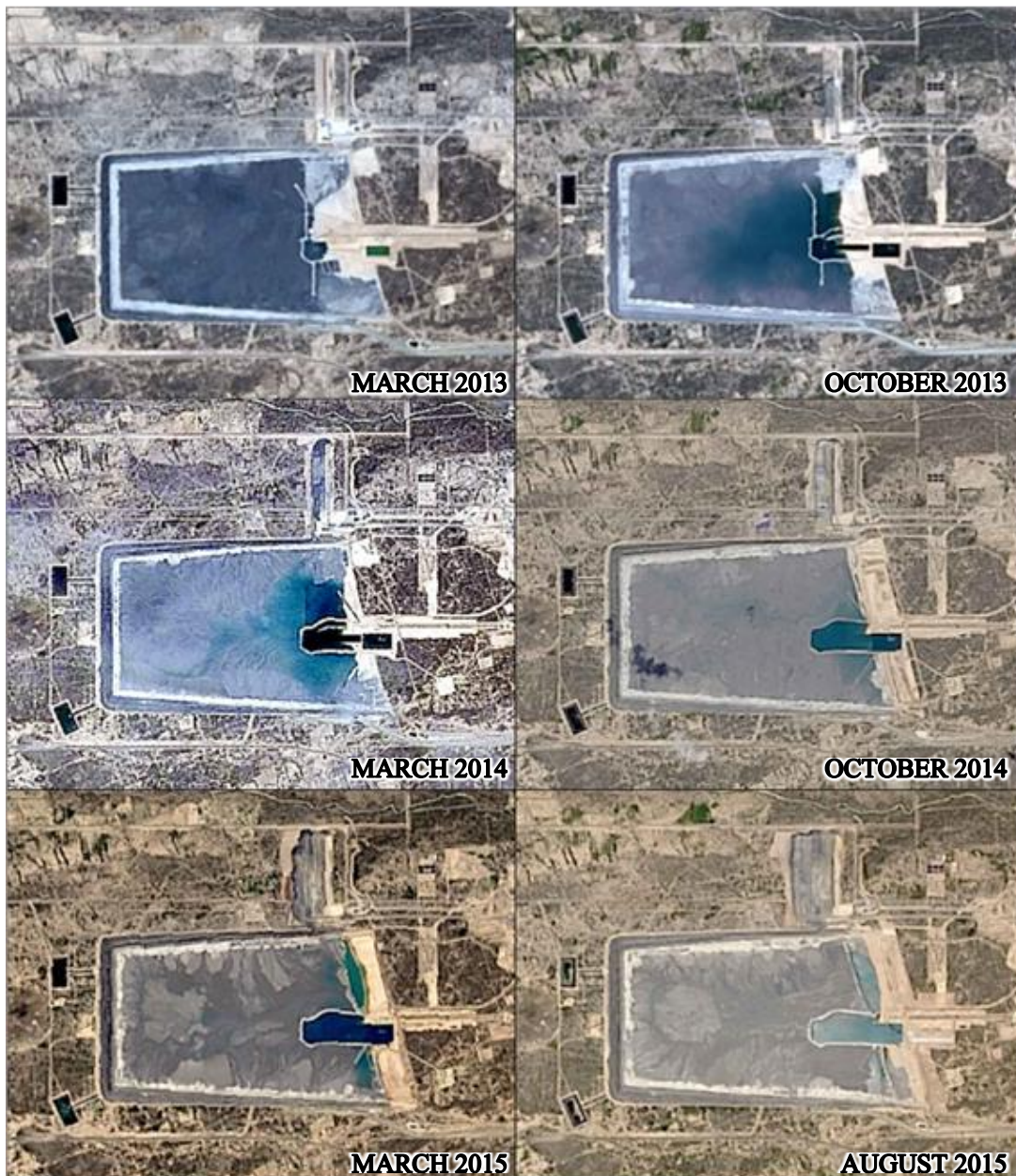


Figure 3. Landsat Imagery of Peñasquito TSF (USGS/NASA Landsat).

### 3.2 Topographic Survey

Golder has contracted PhotoSat to produce monthly, high-resolution imagery and digital elevation models of the TSF. Example images with 10-m and 0.5-m interval elevation contours from the July 16, 2015, survey of the TSF are shown as Figures 4 and 5, respectively. The survey has been matched to the site coordinate system using four GCP and matches their ground survey elevations to within approximately 20 cm. As shown in Figure 5, the stereo satellite survey can measure the topography of the relatively flat tailings deposition cones (approximately 0.5% grade).

As additional facilities have been designed in and around the TSF, the stereo satellite survey has provided a valuable resource of current topographic data for construction planning, reducing the amount of field verification survey required.



Figure 4. July 16, 2015 Satellite Imagery and Topography by PhotoSat (10-m Interval Contours).

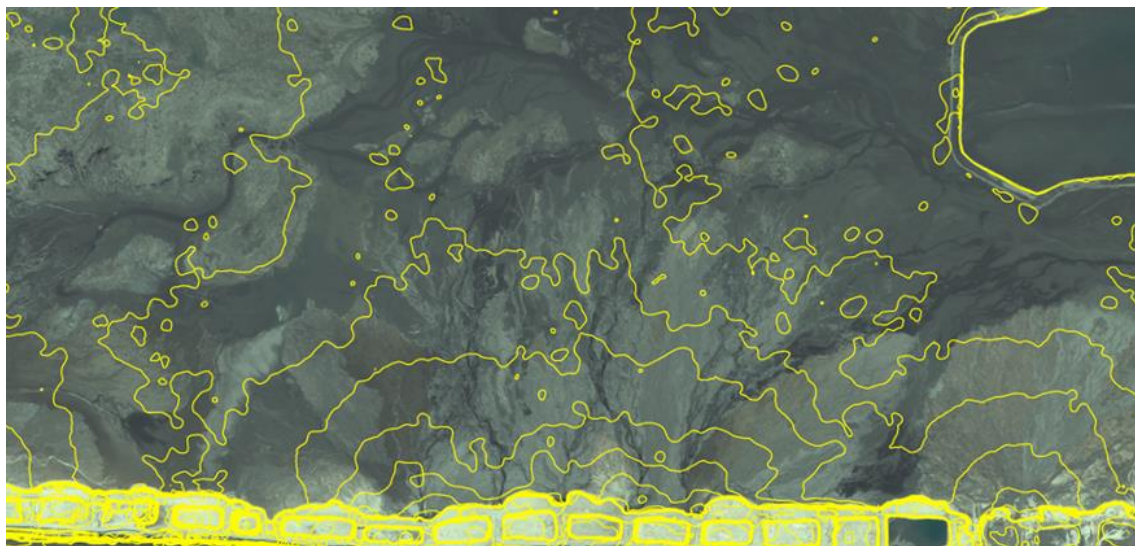


Figure 5. July 16, 2015 Satellite Imagery and Topography by PhotoSat (0.5-m Interval Contours).

### 3.3 Construction Quality Assurance

The stereo satellite survey maps provided by PhotoSat have been used to produce as-built drawings to track construction of the dam and water reclaim management facilities at the Peñasquito TSF. Golder plots cross sections of the as-built dam construction to evaluate conformance with the design line and grade of the dam, as shown in Figure 6. The surveys are also used to evaluate the minimum freeboard elevations, minimum beach lengths, construction progress and conformance of cycloned sand tailings paddock construction requirements.

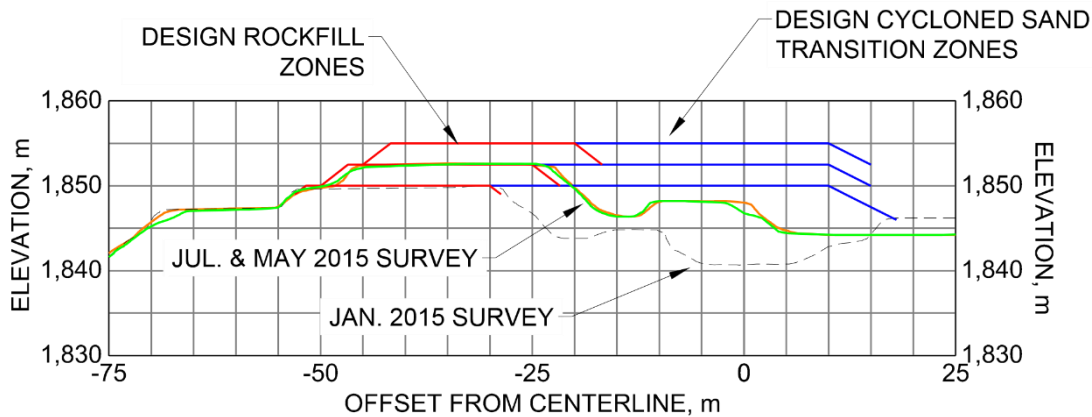


Figure 6. Typical As-Built Construction Cross Section.

In addition to generation of as-built drawings, the monthly survey is used to estimate construction volumes by comparing month-to-month surveys, providing an independent measure of material contract payment quantities. As-built drawings are also used to evaluate the remaining freeboard, the remaining tailings storage volume, and the monthly rate of construction. These enable the mine to improve forecasts and schedule future construction activities.

### 3.4 Water Reclaim Pond Tracking

The Peñasquito TSF includes a water reclaim pond that must be managed to maintain minimum beach lengths and water storage requirements. Satellite imagery is used to monitor the reclaim pond size and shape through the topographic survey and natural color imagery (both Landsat and Photosat surveys). Additional satellite data bands are used to enhance the visualization of water across the TSF.

Historically, the Peñasquito TSF had relatively flat tailings beach grades (less than 0.5% beach slope) resulting in large areas of shallow water that were difficult to identify and delineate in the natural color imagery. Taking advantage of water's poor reflectance of infrared light, the Band 7 shortwave infrared Landsat 8 data and near infrared band of the WorldView satellites is used to colorize the surface of the TSF and highlight the areas of water or very wet tailings.

More recently, improved tailings deposition strategies have been implemented increase the tailings beach grades to between 0.5 and 1.25% slopes. Examples of the flatter and more steep tailings beaches and resulting water reclaim pond are shown as Figures 7 and 8, based on the source natural color imagery shown in Figures 1 and 4, respectively. The shortwave infrared data from Landsat 8 provides a more clear delineation of the water/wet areas, which is particularly beneficial due the limited resolution of the Landsat imagery. WorldView-2 does not carry a shortwave infrared sensor.



Figure 7. August 19, 2015, Water Area Enhanced Landsat Image (USGS/NASA Landsat).

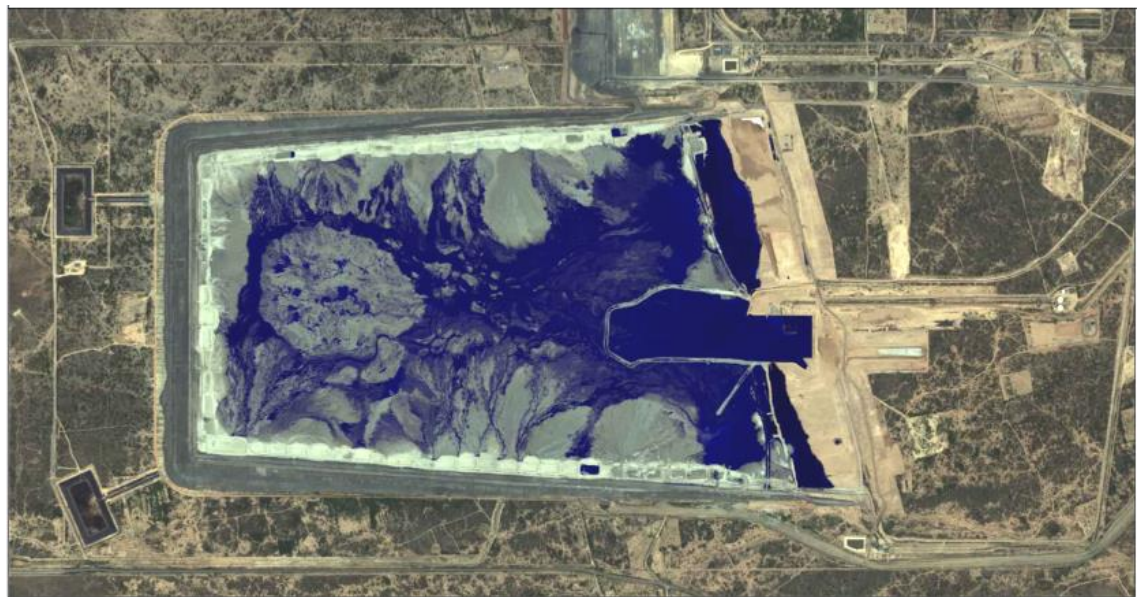


Figure 8. July 16, 2015, Water Area Enhanced WorldView-2 Image.

### *3.5 Tailings Deposition Monitoring*

The accuracy of the PhotoSat survey allows for detailed monitoring of the tailings beach grades and calculation of the volume of the deposited tailings. An example profile of the tailings beach from the December 2014 to July 2015 monthly surveys is shown as Figure 9. The total volume of tailings contained behind the dam in July 2015 was estimated to be 119.7 million m<sup>3</sup>. Monthly satellite topographic survey allows for evaluation of the remaining storage capacity of the TSF compared to the design stage-storage relationship of the facility.



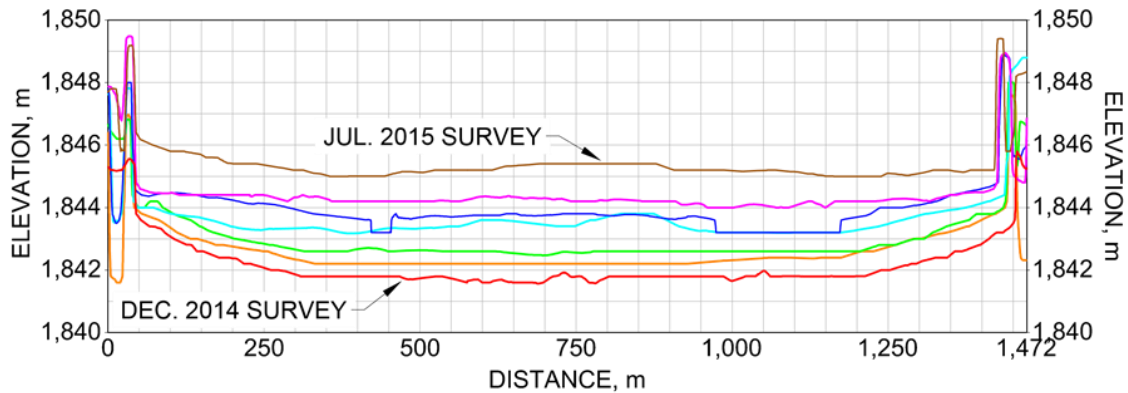


Figure 9. PhotoSat Stereo Satellite Survey Tailings Beach Profiles, December 2014 through July 2015.

### 3.6 Storage Capacity Validation

A key aspect of monitoring the storage performance of the Peñasquito TSF is measurement of the in-place density of the tailings. Golder developed a large-strain consolidation model to predict the density of the tailings through time. Satellite survey data is evaluated monthly to compare calculated in-place tailings densities against the predictive model. This allows the mine to compare the future life of the facility against future mine production plans. Calculated in-place tailings density estimates have compared favorably to the predictive model as shown in Figure 10. These values have also compared favorably with the results of a geotechnical drilling and sampling and cone penetration test program of the tailings beach completed by Golder in 2014 and 2015.

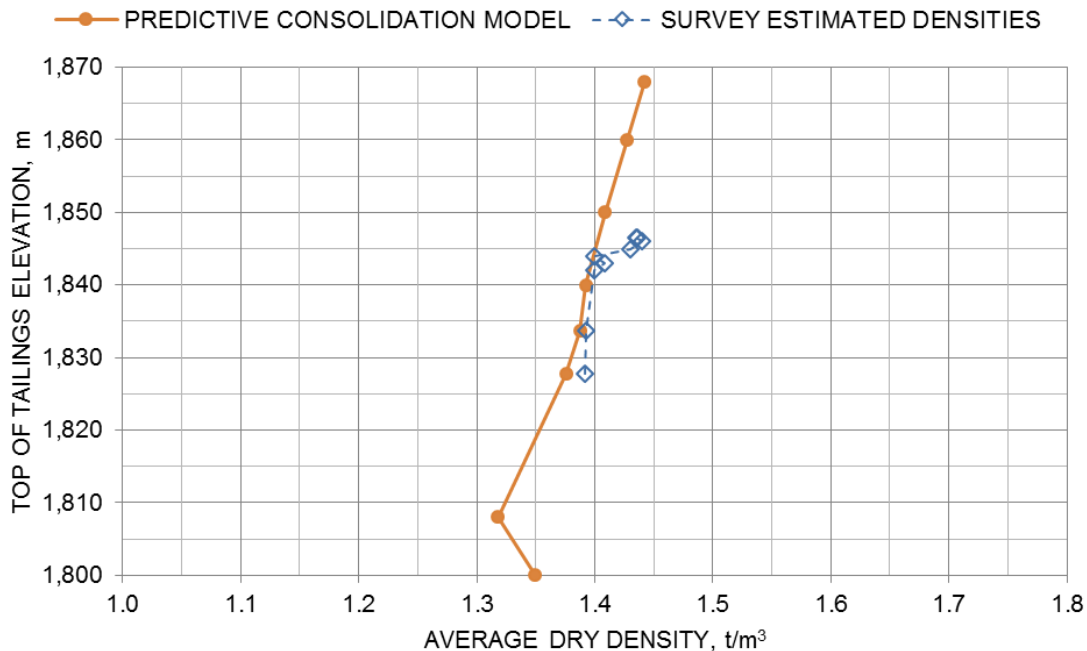


Figure 10. Stereo Satellite Survey Estimated Density versus Predictive Consolidation Model.

## 4. SUMMARY

Satellite monitoring has provided a valuable, cost-effective, and timely source of data for observing, evaluating, and managing the development of the Minera Peñasquito TSF. Through

both commercial and public data sources, data is collected to prepare aerial imagery and topographic models to evaluate dam construction, tailings deposition, and reclaim water storage. The use of satellites eliminates a significant amount of field labor compared to traditional ground, light aircraft, or even unmanned aerial imagery system survey methods.

## 5. REFERENCES

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