Mine Closure 2021 – AB Fourie, M Tibbett & A Sharkuu (eds)

https://papers.acg.uwa.edu.au/p/2152_04_Mahayasa/

Wanagon overburden stability; Grasberg surface mine closure

M Mahayasa *Freeport-McMoRan, Inc., USA*

M Simanjuntak *PT Freeport Indonesia, Indonesia*

M Johnson *PT Freeport Indonesia, Indonesia*

Abstract

The key objective of managing overburden from a mine closure perspective is to ensure the overburden stockpile remains stable long-term. This is accomplished by using effective environmental and safety controls that minimize environmental impacts and financial risk to the company after the mine is closed.

Grasberg surface mine was one of the world's largest copper and gold mining operations until mining there ceased in January 2020. It is operated by PT Freeport Indonesia (PTFI) and located in Papua Province, Indonesia.

Grasberg is now focused on mine closure activities, including overburden stabilization, infrastructure demolition and reclamation. The Wanagon overburden stabilization is a large scale and technically challenging project focused on mitigating slope stability and overburden erosion rates. The drainage below the Wanagon Overburden Stockpile (OBS) routes by a mountain village and joins with the existing mill tailings system referred to as the ModADA (Modified Ajkwa Deposition Area).

To create a long-term stable landform at the Wanagon Overburden Stockpile, it will be regraded to a 2:1 slope for single-slope heights of 45 to 60 m, creating sufficient catch benches for the drainage system to manage flows on the stockpile. There are 24 catch benches that effectively flatten the 1,000 m slope height to an overall slope of 3:1. The slope surface has been armored with engineered rock cover D50 = 55 mm to reduce erosion potential.

This paper presents various design development challenges, such as geotechnical structure, civil structure of the drainage system, water management (surface and subsurface), erosion, geochemistry, reclamation and revegetation.

Keywords: *Grasberg mine closure, Wanagon overburden, slope stability, erosion control, acid rock drainage, water management*

1 Introduction

Grasberg surface mine, one of the world's largest copper and gold mines, ended open pit mining in January 2020. Underlying the Grasberg pit is the Grasberg Block Cave mine that is currently ramping up production and will be mined for the next 20-plus years. The surface operation is now focused on closure activities that include overburden stabilization, infrastructure demolition, reclamation and mitigation of Acid Rock Drainage (ARD). The Grasberg open pit mine was discovered in 1988 and begun producing ore in 1990, with a rapid increase in production capacity starting in 1993 after the completion of a road that allowed the transport of large mining equipment. The Grasberg surface mine achieved its highest production of material moved in 2009 with an average 720 ktons/day. Material from the pit was delivered to specific destinations with ore hauled to two locations: Higher grade material went to the crushers, while the lower grade ore was delivered to the Bali Low-Grade Stockpile. During mine operations, overburden from the Grasberg open pit went into several overburden stockpiles (OBS) around the perimeter of the pit excavation. As shown in Figure 1, four main overburden stockpiles were developed: Carstenzweide Stockpile on the east side of the Grasberg Open Pit and Upper Wanagon, Middle Wanagon and Lower Wanagon on the west side of the Grasberg Open Pit.

An important consideration of the Grasberg overburden management was that approximately 25% of the overburden was limestone.

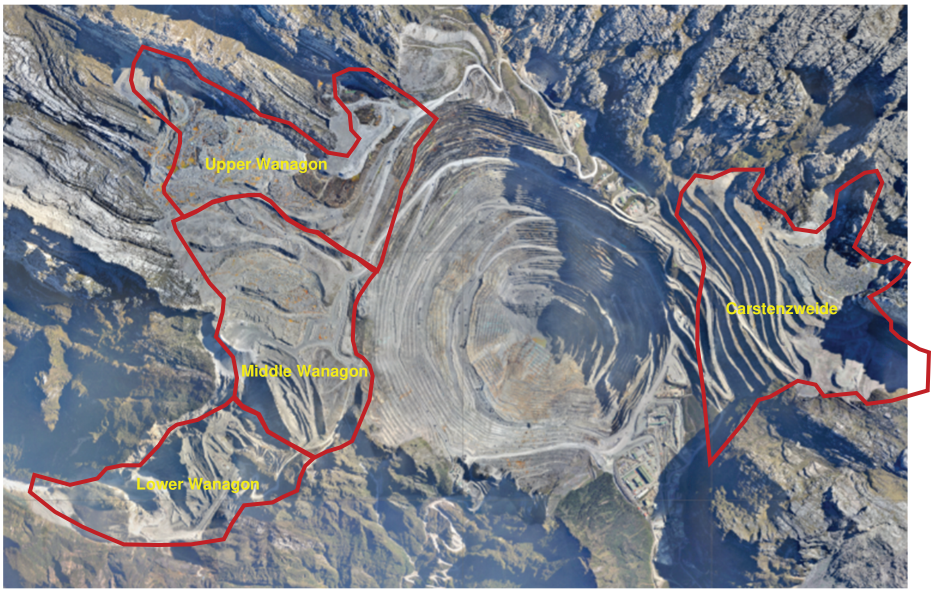

Figure 1 Grasberg Overburden Stockpile Layout

2 Grasberg Overburden Management

The topography around the Grasberg pit is extremely steep and rugged. PT Freeport Indonesia (PTFI) managed overburden stockpiles to minimize their footprint and impact to drainage while maintaining geotechnical stability and minimizing acid rock drainage. Standard operating procedures included classification of overburden materials by geotechnical and geochemical characteristics before the material was removed from the Grasberg pit. The haul trucks transporting the material routed overburden materials to appropriate stockpile locations based on material classifications. Material that may potentially generate ARD, including a limited amount of higher sulfide overburden, was placed at a specific area at Upper Wanagon, where we are able to control the ARD that is generated from this location. Material with a pyrite content of more than 20% by weight was classified as heavy sulfide material. Middle Wanagon received a mixture of ARD and non-ARD (limestone and low sulfide intrusive rocks) material, transported by a combination of haul trucks and a crusher and conveyor-fed stacker. Similar to Middle Wanagon, Carstenzweide Stockpile on the east side of the Grasberg open pit was filled with a mixture of ARD and non-ARD material hauled by truck only. Limestone overburden from the pit was blended to ensure the Lower Wanagon overburden was non-acid forming. The Lower Wanagon overburden was developed with an Acid Neutralizing Capacity (ANC) 15 times the Net Acid Generation (NAG) and with a coarse-to-fine material ratio of 2. These ratios mitigate ARD generation while ensuring geotechnical stability (Geotechnical Service Department, 2017). All overburden placed outside of the mine water collection system was non-acid forming.

Carstenzweide and Upper Wanagon were constructed in lifts from the bottom up, and there are no slope stability concerns for either stockpile. Some of the Middle and Lower Wanagon were constructed top down, using haul trucks and an Overburden Handling System (OHS) that consisted of an in-pit overburden crusher, fixed conveyor system, grasshopper conveyors and 135 m long stacker. This system was selected to place material in the Lower Wanagon area with steep and inaccessible topography not safely or economically reached by trucks. The crusher and conveyor system are fixed facilities. The grasshopper is a semi-mobile conveyor that connected the fixed conveyor to the stacker. The grasshopper also served as a deflection point when the stacker needed to fill the stockpile from a specific direction. The stacker is a large, semi-mobile machine used to place material over the crest of the OBS into the valley. This system developed the overburden top down and segregated the material by gravity, allowing bigger rocks to roll to the bottom while the finer material stayed near the top. It was used from 2000 to 2016 and placed ~600 million tons of overburden in the Wanagon. The Lower Wanagon overburden was developed in three levels – 4150L, 3845L and 3685L as shown on Figure 2. The toe of the higher overburden is interlocked with the crest of the lower overburden. The pile at 4150 was developed between 2000 and 2003 using both the stacker and haul trucks. The stacker was moved to 3845 in 2003 and stayed there through 2011 when it was moved for the last time to the 3685 level. The system was shut down in 2016 when the volume of overburden from Grasberg pit was minimal.

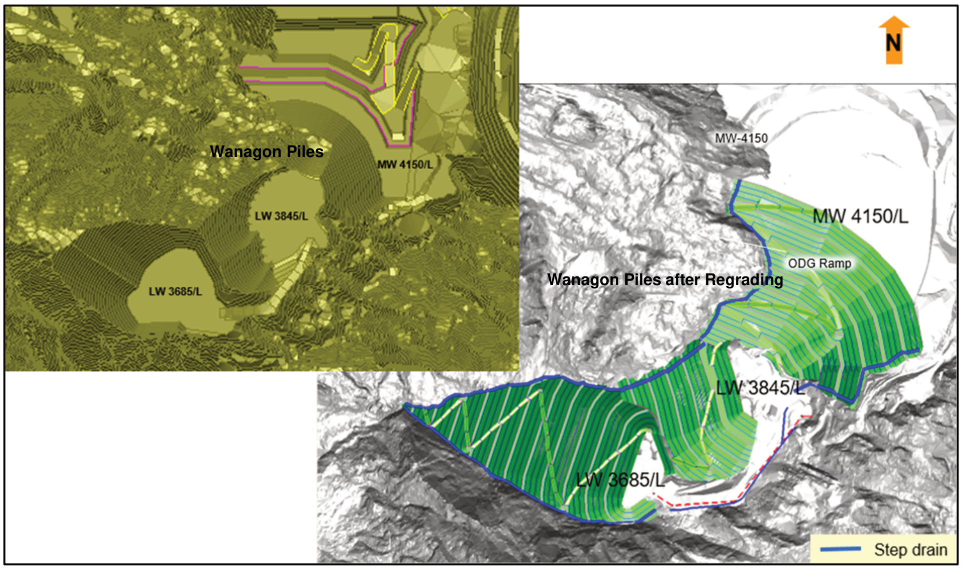

Figure 2 **Wanagon Piles Before and After Regrading**

3 Erosion at Lower Wanagon Overburden

Natural erosion in the Papuan Highlands is quite high because of the high rainfall (Milliman, 1995). Obviously, managing the erosion is challenging but a significant consideration in the overburden management.

The Wanagon stockpiles are regraded to slope 2:1 during mine closure to stabilize the pile slope and reduce the erosion as shown on Figure 2. The rainfall at PTFI's project area is very high, about 4,000 mm annually. Unfortunately, a 2011 labor issue occurred while the stacker was being moved to 3685. Erosion and slope stability became an issue at the stockpile when dumping activity ceased due to the work stoppage. This also impacted the ability to manage the surface water. The erosion began at the toe, which destabilized the stockpile resulting in a slope failure.

Surveys and other measurements in 2014 indicated about 60 percent of the material placed had eroded or failed. Most erosion is caused by factors relating to the high rainfall at the project sites. Periods of high rainfall can cause local saturation of overburden stockpile materials, leading to debris flow, especially in the West Drainage Gully, the large erosional feature that cuts through the west side of the Lower Wanagon Overburden Stockpile. The eroded material migrates downstream, beyond the Wanagon Valley, and eventually discharges to the Modified Ajkwa Deposition Area (ModADA) as can be seen on Figure 3. ModADA is an area that has two levees (West Levee and East Levee) designated for tailings and other natural sediments deposition and management. The two levees were studied, permitted and constructed as part of PTFI's mill tailings and mine erosion management plan. During mine operation, the levees are maintained at a certain height above the tailings surface to contain a probable maximum flood. Surveys are done regularly to monitor the sediment deposition rate within the ModADA, and those monitoring results are used to supply data to establish the levee construction plan for the following years.

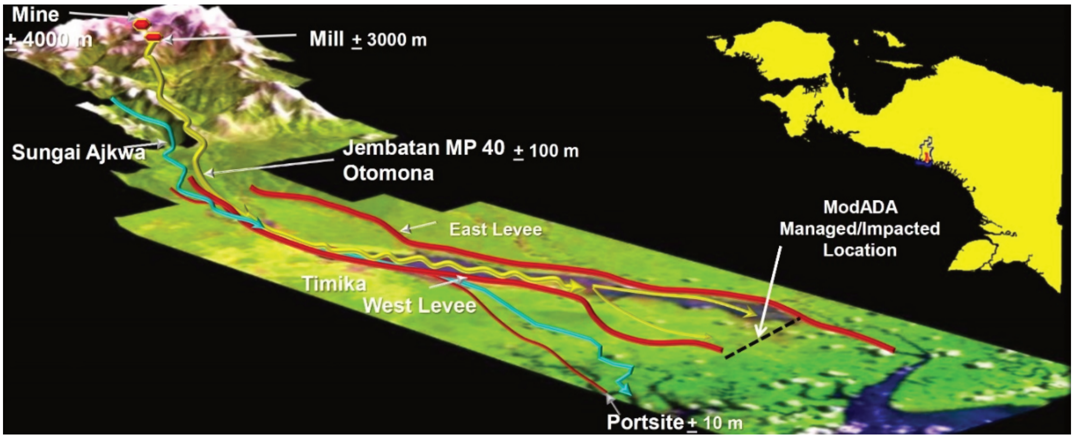

Figure 3 Modified Ajkwa Deposition Area (ModADA)

Based on a review in 2013, the erosion that resulted from the 2011 work stoppage required a new plan to achieve regrading of the Wanagon OBS. The amount of cut material was not sufficient to fill the area to form the slope ratio of 2:1 even though another 40 million tons of material from the stacker or pit was available. This was because much of the placed overburden had eroded or failed; hence the cut and fill was not balanced and would require significant additional material. This material was generated by mining the adjacent limestone ridge. This new mining-for-closure area is referred to as the West Wanagon Slope Stabilization (WWSS) as shown on Figure 4.

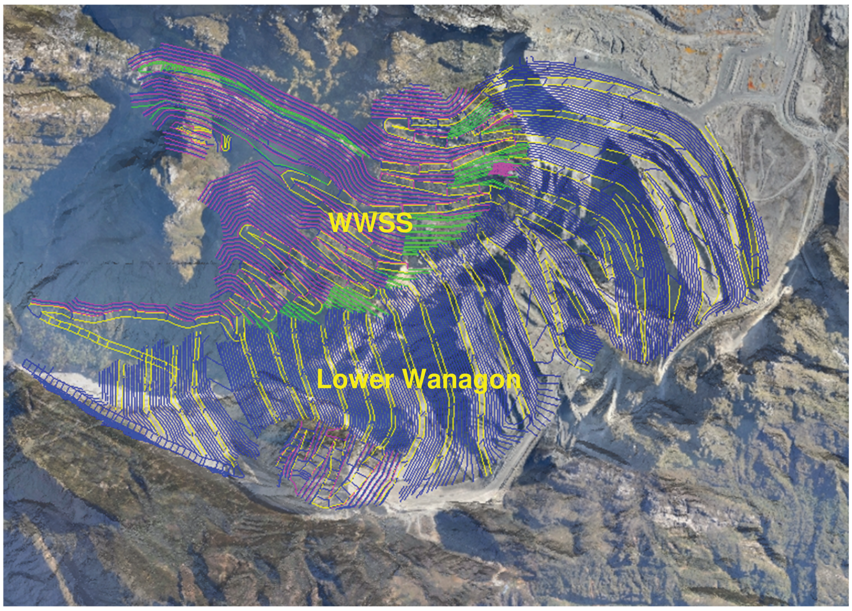

Figure 4 Mining Area at WWSS and Regrading Plan at Lower Wanagon

The closure design incorporates regrading stockpiled material to prevent erosion and make slopes more geotechnically stable, covering stockpile material to limit infiltration of rainwater and controlling surface water to direct stormwater flow away from the covered surface.

4 Erosion Mitigation

Wanagon basin is a long valley and drainage basin. The water comes from runoff and several springs around the valley. At one point, there was a lake in the middle of the valley with an outlet embankment shape known as the Wanagon Lip. The water from upstream (Upper Wanagon), filled the lake and overflowed to the lower area (Lower Wanagon) through the bedding planes and voids in the limestone lip. Erosion and slope stability challenges had been anticipated before and during the overburden construction due to the steep and rugged terrain and high rainfall in the Wanagon Valley. An erosion assumption of 10,000 tons per day was included in the management plan. To maintain its stability, the stockpile was designed so water would flow underneath, with further stability efforts made before and during the construction including:

- Developing a drain zone
- Segregating overburden material and implementing the coarse-fine ratio for material dumped into Wanagon

Water is the main concern at Wanagon Stockpile. To maintain its stability, the water-saturated zone at the stockpile base should be less than 30 m in height. Otherwise, the pore pressure at the stockpile toe could potentially result in instability. A drain zone as shown on Figure 5 was developed along the valley before the stockpile reached this zone to allow water to flow underneath the stockpile. Developed between the years 2006 and 2009 at the Upper Wanagon, the drain zone was 50 m tall, 150-200 m wide, and 2,000 m long. Super coarse material (> 1.2m) was used to develop it, with fine material comprising less than 10%. The drain zone corridor is connected to the Lower Wanagon Stockpile developed using the stacker. The tie-in is located above the rock lip, which was covered with overburden from the truck and stacker.

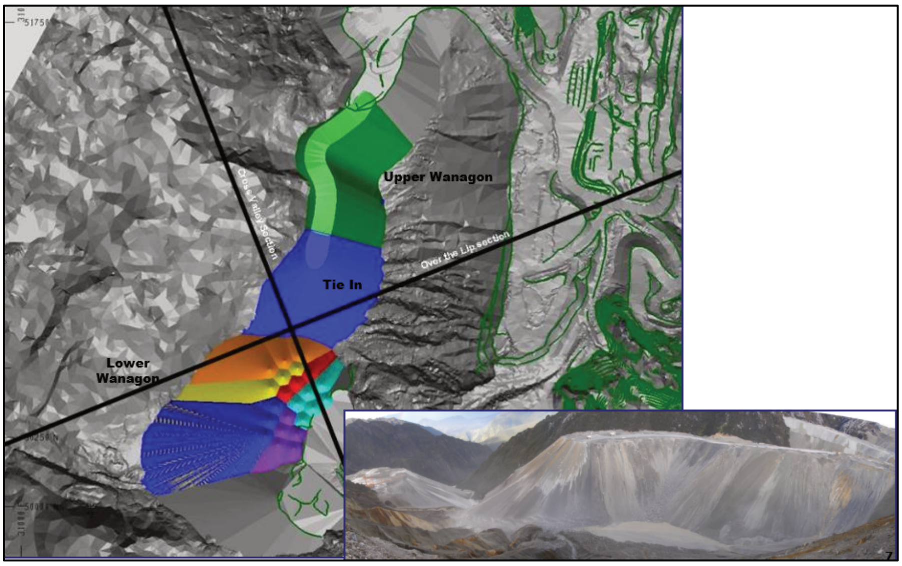

Figure 5 Drain Zone

After the tie-in, the drain zone development was extended in the Lower Wanagon using the stacker. The material delivered to Wanagon through OHS used a coarse to fine ratio of 2:1 so natural segregation occurs where coarse material accumulates at the stockpile toe. The material was crushed before processing through the stacker, with a maximum size of 20 cm. The coarse material accumulation at the bottom of the stockpile has a high permeability and works as the drain zone, allowing water to flow underneath the stockpile from Upper Wanagon through Lower Wanagon.

During the work stoppage of 2011, erosion occurred because no overburden or drainage system maintenance work could be completed. Surface water could not be controlled and flowed unabated, creating a large gully of erosion between the original rock and stockpile. The following efforts were done to minimize erosion at Wanagon:

- Constructing a ramp on Wanagon Stockpile from 4150L to 3685L
- Dumping at multi-levels to cover the source of erosion and increase the controlled area
- Increasing and maintaining the stockpile thickness in front of the rock lip at 3505L
- Utilizing the Wanagon Drainage Drift (WDD) to reduce the amount of water at Wanagon
- Stabilizing the Wanagon Stockpile

The Wanagon Stockpile has a long, single angle of repose slope with no breaks. Continuous dumping is required to maintain the toe and the slope on the stockpile, as the high rainfall could erode the slope or toe. If the toe is eroded, the slope will be undercut which could trigger slope slumping. The accumulation of slumping material has the potential to create a pond that eventually overtops and erodes surrounding material. If this process is repeated, significant erosion occurs. A ramp was constructed on the Wanagon Stockpile from elevation 4150 to 3685 starting in March 2015. This was done to help prevent erosion because the slope could not be maintained due to limited overburden from the Grasberg pit and the unavailability of the stacker, which was being used on the lowest pile (3685L). Constructing the ramp broke the long, single slope, controlled surface runoff and created access for haul trucks to the Lower Wanagon. Figure 6 shows pictures of before and after ramp construction on Wanagon stockpile.

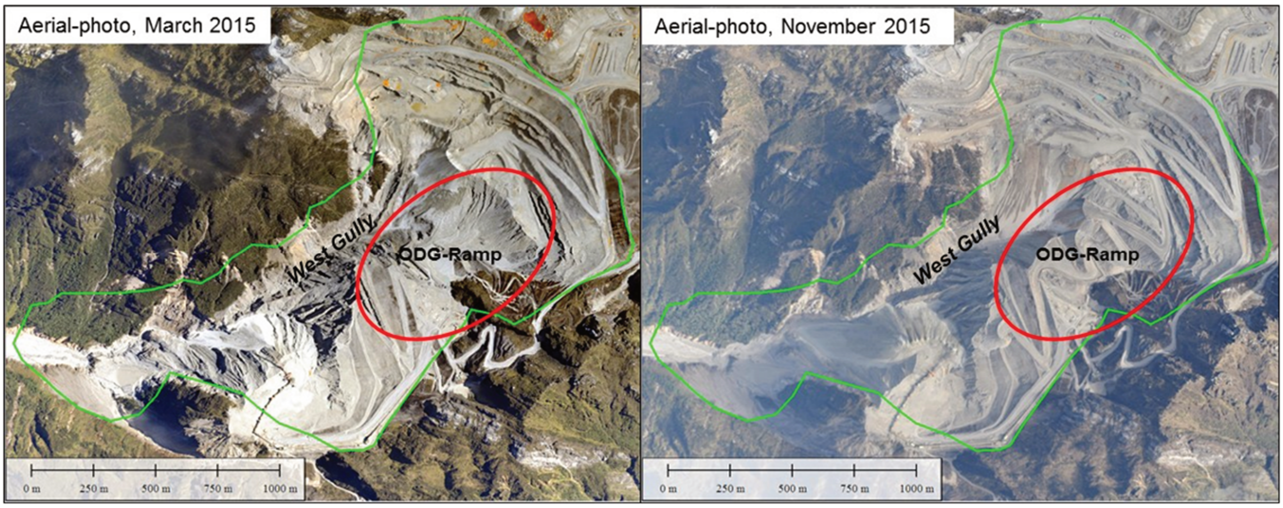

Figure 6 Ramp Construction on Wanagon Stockpile

West Gully was the main source of erosion at Wanagon and required fill material to manage OBS erosion. With haul truck access to Wanagon available, there was an opportunity to fill the gully from several levels to accelerate the filling rate. This effort significantly reduced erosion because the runoff water was diverted into the ramp system instead of going into the West Gully. Figure 7 shows the pictures before and after West Gully filled with material.

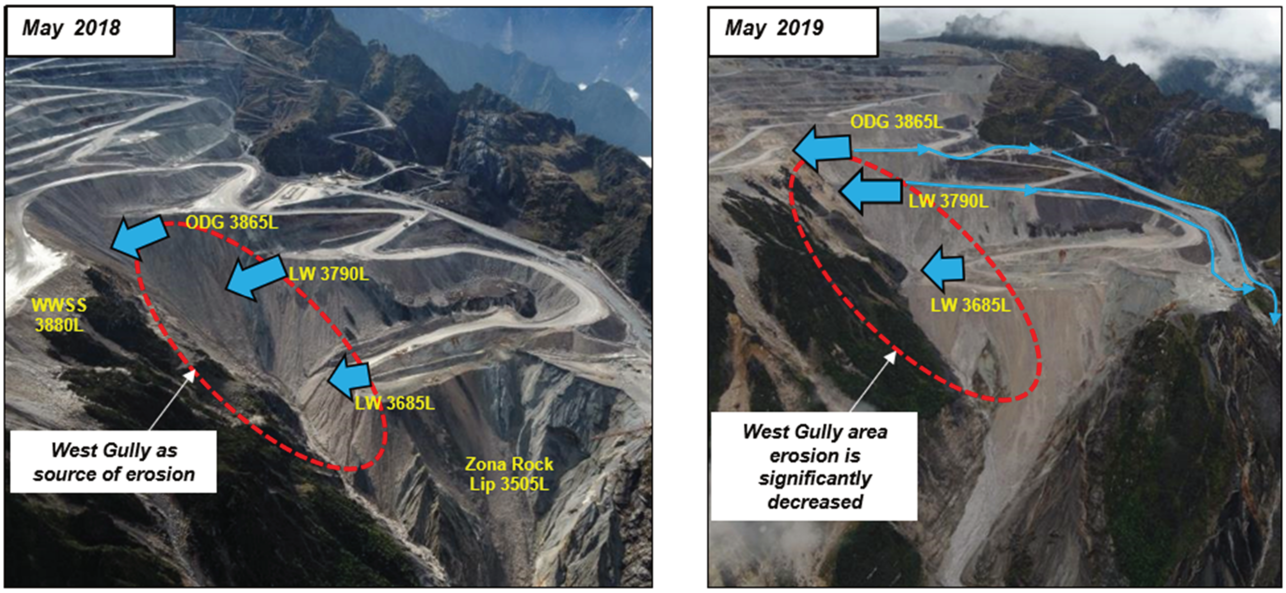

Figure 7 Dumping Material into West Gully at Multi-levels

The lowest slope at the Wanagon Stockpile is the largest single slope and covers the second rock lip at elevation 3505L. The toe of this slope also is a water discharge point coming from the Wanagon Stockpile, making this slope very sensitive to erosion from the toe, rock lip and scouring on the upper slope. To prevent this, the slope must be maintained by continuously filling new material to increase and maintain the slope thickness. This will mitigate the driving force of water coming from the rock lip, maintain the toe of the slope, and eliminate scouring due to water flow on the slope surface. Over three years, the thickness of this slope increased about 125 m as shown on Figure 8.

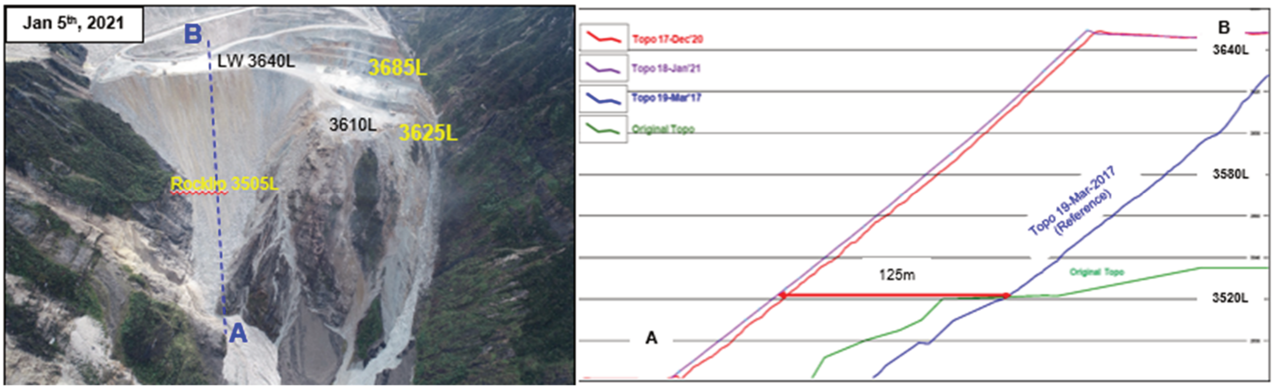

Figure 8 Lowest Slope at Lower Wanagon

Wanagon Drainage Drift (WDD) as shown on Figure 9 initially was prepared as part of the mine water management system to capture potential ARD water from the Upper and Middle Wanagon overburdens. The WDD is used as a dewatering system to control the water level for the Wanagon overburden and is a significant feature of the Wanagon overburden slope mitigation program. Development of the 2,000 m long WDD was completed in 2012. The portal is located on the Heavy Equipment Access Trail (HEAT) road and ends below the Wanagon Stockpile. The drift dimensions are 5 x 6 m with a 3% gradient. It contains 17 dewatering holes drilled both downstream and upstream of the 3775L rock lip of Lower Wanagon and is capable of draining 6,000 gpm or 40% of the total average flow at the Wanagon Stockpile (Widijanto et al. 2015).

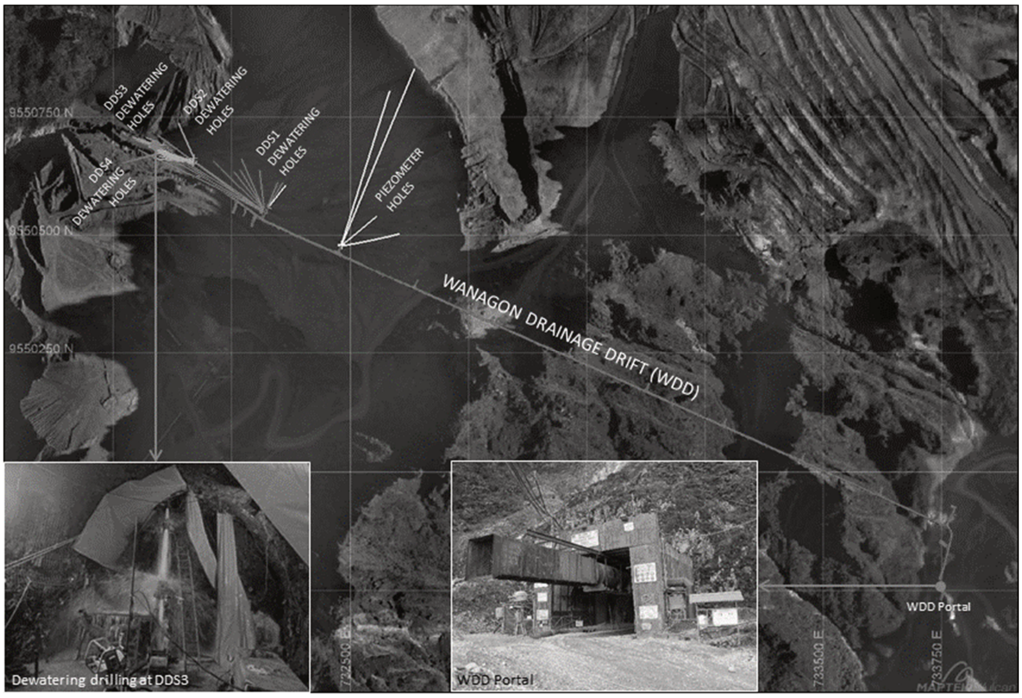

Figure 9 Wanagon Drainage Drift

All efforts above succeeded in significantly reducing erosion at Wanagon. Figures 10 and 11 below show the result of those efforts where the erosion and Total Suspended Solid decreasing significantly.

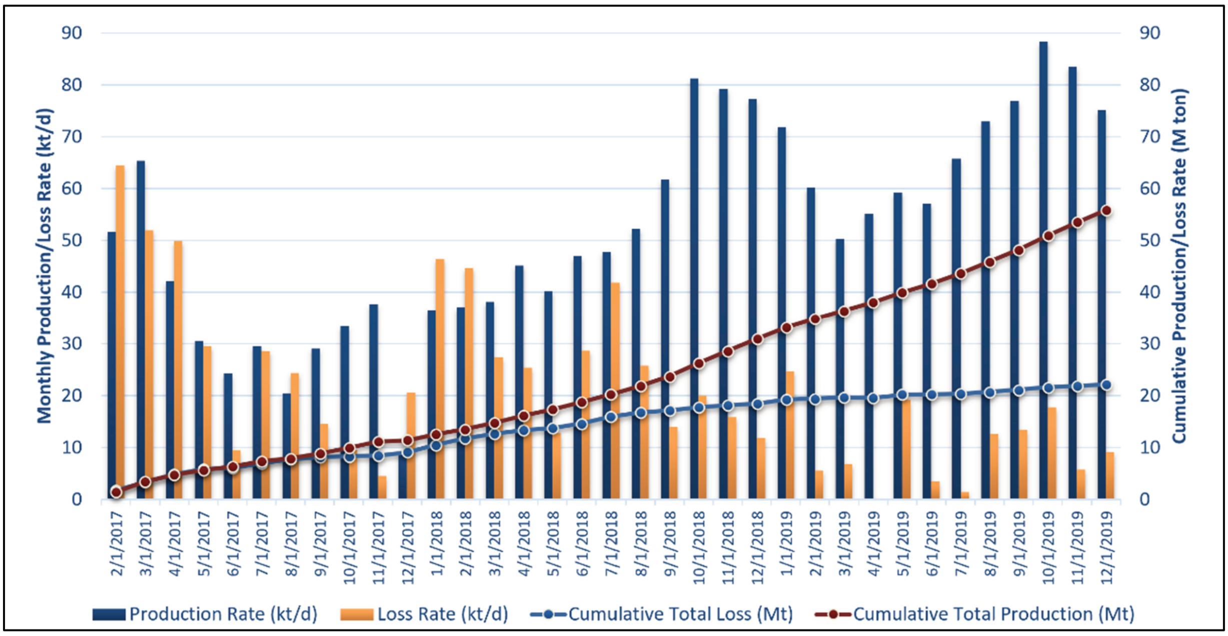

Figure 10 Production vs. Erosion Rate

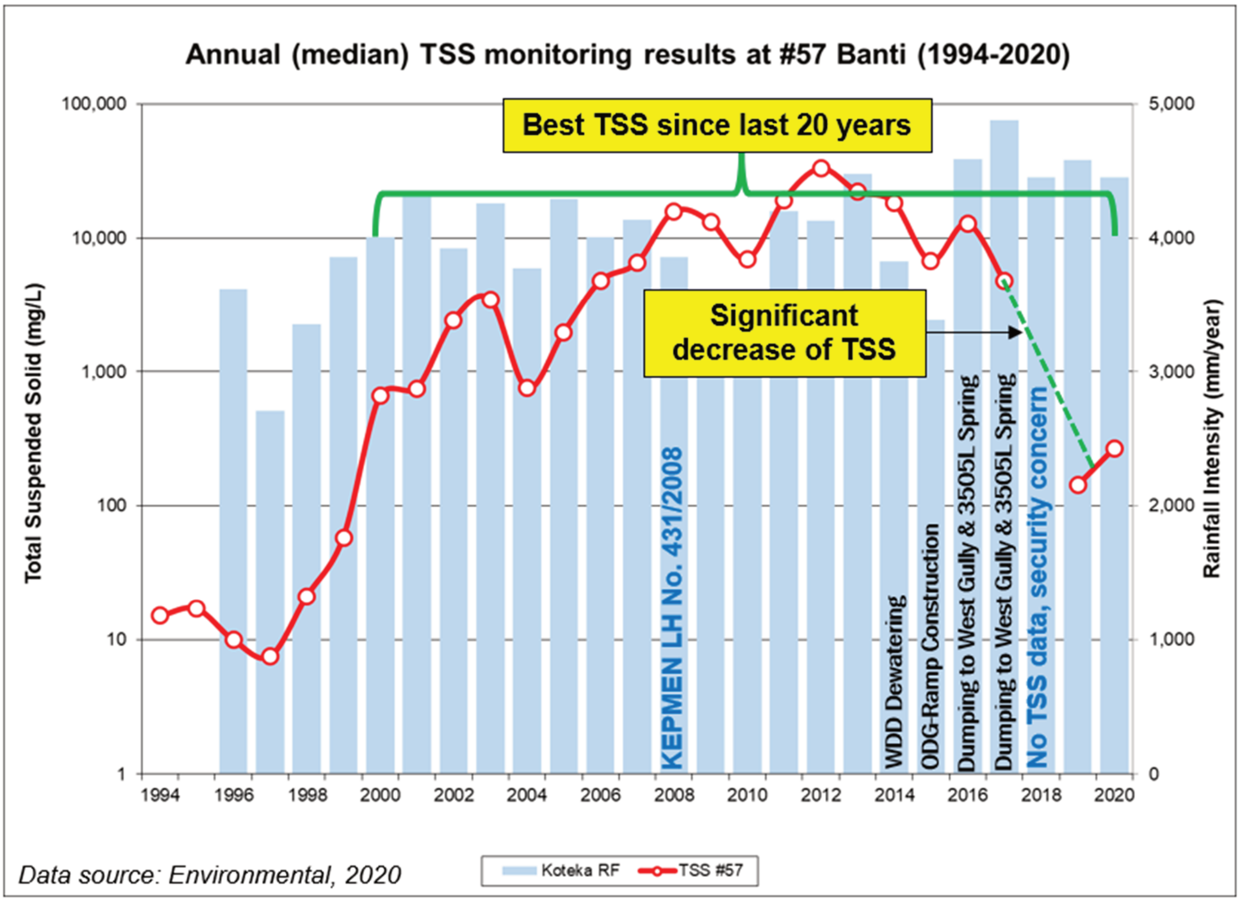

Figure 11 Total Suspended Solid (TSS) at Banti #57

Based on the top 10 daily rainfall intensity as shown in the Table 1, the methods above have succeeded in stabilizing and minimizing erosion at the Wanagon Stockpile despite the project not being fully completed.

Table 1 Lower Wanagon Geotechnical Stability Analysis

No.	Date	Intensity (mm/day)
1	January 2, 2021	93.3
2	August 5, 2019	61.8
3	April 12, 2020	58.0
4	March 16, 2020	53.6
5	March 15, 2020	51.0
6	August 1, 2019	48.6
7	January 28, 2019	47.8
8	March 14, 2019	47.4
9	March 24, 2019	46.6
10	July 30, 2019	44.2

5 Wanagon Design

To manage the long-term stability of the Wanagon OBS, PTFI re-sloped the stockpile to achieve a toe elevation of 3,200 m. The overburden stabilization effort started in 2008 with construction of a rock drain and maintaining a ratio 2:1 of coarse to fine material dumped to the Lower Wanagon 3845/L by stacker. However, the prolonged work stoppage in 2011 resulted in the delayed delivery of material to Lower Wanagon and increased erosion, jeopardizing the successful 3,200 m closure plan. Because of limited overburden available from the Grasberg Surface Mine which was nearing completion, additional material volumes of 80 to 120 mt were needed to reach the toe elevation of 3,200 m. The mining area on the west side of Wanagon Overburden Stockpile (WWSS) as shown on Figure 12 has suitable material (limestone) for the closure project that started in the second quarter of 2014.

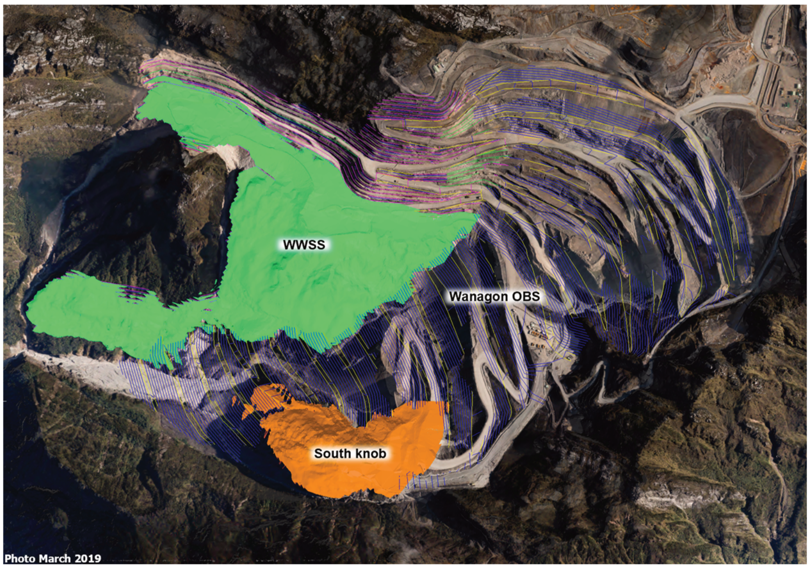

Figure 12 West Wanagon Slope Stability Area (WWSS)

5.1 Design Criteria

The Grasberg Surface Mine Overburden Management Plan, developed by PTFI in 2006, provides guidance and management tools to minimize the long-term risks and environmental and geotechnical impacts of the Grasberg Overburden Stockpile. The following are objectives for managing overburden stockpiles through operation, closure and beyond:

- Design must balance operating objectives with effective environmental and safety controls.
- Overburden stockpiles are geotechnically stable.
- Adequate drainage (surface and subsurface) is provided and erosion minimized.
- ARD formation are mitigated, collected and/or treated to minimize impacts to surface and groundwater quality.
- Limestone rock is used to effectively mitigate ARD and ensure stockpile geotechnical stability.
- High-sulfide zone (HSZ) material is selectively mined and segregated to facilitate ARD collection.
- Overburden stockpile surfaces are prepared to facilitate reclamation: surface drainage and revegetation.

Based on the closure objectives above, detailed design criteria for the Wanagon Overburden Stockpile was developed by PTFI, Stantec, Rio Tinto and CNI in 2014. Below is summary of design criteria:

- Erosion of Overburden Stockpile materials to ModADA must be minimized.
- Mobilization of potential Acid Rock Drainage (ARD) from Middle Wanagon must be prevented.
- Construction must proceed in an appropriate sequence that minimizes safety risk.
- An engineered toe must be constructed at the regraded slope to allow a free-flowing under drain and to provide geotechnical stability and resistance to erosion.
- Rockfill and other additional construction materials should come from the West Wanagon Slope Stability area (WWSS).
- Five meters of rock cover will be placed on elevation 3,775 m above, with 3 m of rock cover below 3,775 m.

5.2 Wanagon Overburden Stockpile Grading and Benching

The Wanagon Overburden Stockpile will be regraded to an overall slope of approximately 2.8:1, with a crest elevation of approximately 4,150 m and a toe elevation of 3,250 m. The regraded stockpile will be comprised of benches and inter-slopes. Bench widths will be variable, with a minimum width of 15 m, and inter-slopes will have 2:1 slopes. The 100 year benches will be formed with a 5% cross-slope in the bench that creates an elongated “V” section at the back of the bench while the longitudinal slope of the channel will go from 3% on the upstream side of the channel to 5% on the downstream side of the channel. This longitudinal slope will be sufficient to produce positive drainage slopes after long-term settlement that meets the design criterion of 2%. A PVC liner will be installed at the toe of the inter-slope bench. The Wanagon drainage bench will drain surface water from the Wanagon Overburden Stockpile to WWSS bench channels or to the South Channel. Benches typically will be located at approximately 45 m vertical intervals to give inter-slope lengths of approximately 100 m. Figure 13 is the cross section of bench channel construction below and above 3775/L (Stantec, 2016).

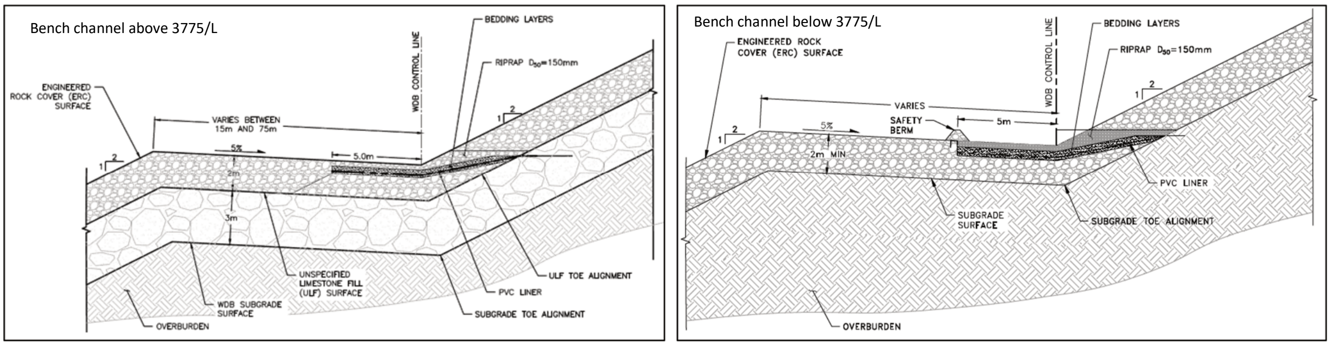

Figure 13 Typical Bench Channel Section

Geotechnical analysis shows the final Lower Wanagon Overburden Stockpile design satisfies the geotechnical criteria. Stability analysis indicated that additional buttressing of the Lower Wanagon Overburden Stockpile is not required for geotechnical stability or excessive seismic deformations. The liquefaction potential of the stockpile cannot be conclusively determined with the available data at site. Wanagon Lake sediments are expected to have the highest potential for liquefaction. To evaluate the liquefaction consequences, the stability analysis for Lower Wanagon Overburden Stockpile for the design basis earthquake (DBE) and Maximum Credible Event (MCE) earthquake uses a post liquified strength of the lakebed sediments as shown on Table 2.

Table 2 Lower Wanagon Geotechnical Stability Analysis

<table>
<tr><th colspan="4">STATIC AND PSEUDO-STATIC ANALYSIS</th></tr>
<tr><th>Design Event</th><th>Acceleration</th><th>Minimum FS</th><th>Calculated FS</th></tr>
<tr><td rowspan="3">Static</td><td rowspan="3">0 gravitational acceleration (g)</td><td>Deep seated failure =1.5</td><td>1.84</td></tr>
<tr><td>Shallow/bench slope failure = 1.3</td><td>1.89</td></tr>
<tr><td>Toe structure = 1.5</td><td>1.86</td></tr>
<tr><td>OBE (475-year RP) pseudo-static</td><td>0.36 g</td><td>1.1</td><td>1.21</td></tr>
<tr><th colspan="4">DYNAMIC</th></tr>
<tr><th colspan="2">Design Event</th><th>Acceleration</th><th>Maximum Computed Displacement at Embankment (m)</th></tr>
<tr><td colspan="2">MCE (2,475-year RP)</td><td>0.67 g</td><td>0.4</td></tr>
</table>

To mitigate potential ARD migration and minimize erosion of overburden material, rock cover will be placed on the slope and bench of the regraded overburden stockpile. Potential ARD will be mitigated by placing a nominal 5 m of limestone rock over the area of the Wanagon Overburden Stockpile surface up-valley from the 3775L rock lip. Laboratory and full-scale stockpile trials indicated a limestone cover with a minimum thickness of 5 m is required for ARD Mitigation. Meanwhile, ARD mitigation down slope of the 3,775 m rock lip is not required because the overburden stockpile material has been characterized as non-acid generating; however, a cover is required for erosion protection. The rock cover thickness down slope of the 3775L rock lip can be limited to 2 m as a practical placement thickness and to provide protection against exposure of stockpile material during a seismic event.

Erosion on the Lower Wanagon Overburden slope will be determined by the peak runoff rate on the slope, which is dependent on the peak rainfall intensities and the inter-slope length. The 2 m of engineered rock cover (ERC) on the top layer of the slope and bench will be used to prevent erosion of the overburden. A median rock size of 45 mm is estimated to be adequate in this area for 100-year peak rainfall intensity. ERC will have rock fragments that meet the criteria as shown on Table 3: angular and interlocking, generally cubic in shape, individual rock fragments shall be dense, sound and resistant to abrasion and shall be free from cracks, seams and other defects that would unduly increase their destruction by water and weathering.

Table 3 ERC Material Quality Requirements

Characteristic Test	Criterion	Standard
Schmidt Hammer	≥60	ASTM C5873
Specific Gravity	≥2.6	ASTM C127
Sodium Sulfate Soundness	<10% Weight loss after 5 Cycles	ASTM C5240
L.A. Abrasion	≤20% Loss after 500 Revolutions	ASTM C535
Absorption	≤2%	ASTM C127
Acid-Base Accounting	Non-Acid Generating	US EPA 600/2-78-054

5.3 Surface Water Control

The surface water management strategies in Lower Wanagon OBS and WWSS need to be long-term solutions, must safely convey peak flows from a 100-year flood event and minimize the need for long-term maintenance. The final configuration of Lower Wanagon OBS includes 23 bench channels; the catch bench will drain surface water from Lower Wanagon OBS inter-slopes to the WWSS bench channel or to the South Channel. The tie-in of Lower Wanagon OBS grading to the WWSS grading should meet certain specifications for surface water control. The Lower Wanagon OBS must tie in from above the WWSS so surface water runoff is from the Lower Wanagon OBS into the WWSS. The Lower Wanagon OBS bench channel angle should not be less than 120 degrees when meeting with the WWSS bench channel. Above an approximate elevation of 3,735 m, the WWSS channel will discharge flows to the Far Western Drainage (Outlet Channel 1 and 2), and below elevation 3,735 m, the WWSS channel will discharge flows into the WWSS Central Drainage. Figure 14 shows the direction of surface water when the project is done.

The South Channel will capture stormwater runoff from the bench channel of Lower Wanagon OBS and from the natural slope at South Hill. This channel is divided into three sections: (1) Upper, (2) Middle and (3) Lower. Channel base widths range from 2 m to 8.5 m with the channel armored with large riprap as required by steep slope and high-design flows. The riprap D_{50} range from 380 mm to 610 mm. The Upper South Channel runs adjacent to the upper east edge of the Lower Wanagon OBS, along the existing Henry Walker Road. This channel is expected to be native rock and be armored with riprap. The Upper South Channel terminates into a natural depression that has outlets through a chute and plunge pool into the Middle South Channel. The Middle South Channel has two branches: (1) the Middle Southern Stockpile Channel that runs adjacent to the Lower Wanagon OBS and receives flow from the bench channel and (2) the Middle South Hillside Channel that receives flow from the natural catchment to the south of the Lower Wanagon OBS. Both branches will be armored with riprap. The Lower South Channel conveys stormwater runoff from the natural catchments south of the Lower Wanagon OBS and follows the existing natural drainage over bedrock. A plunge pool will be constructed and channel transition to a riprap-armored channel that outlets into the existing Lower Wanagon drainage below the toe of the Lower Wanagon OBS.

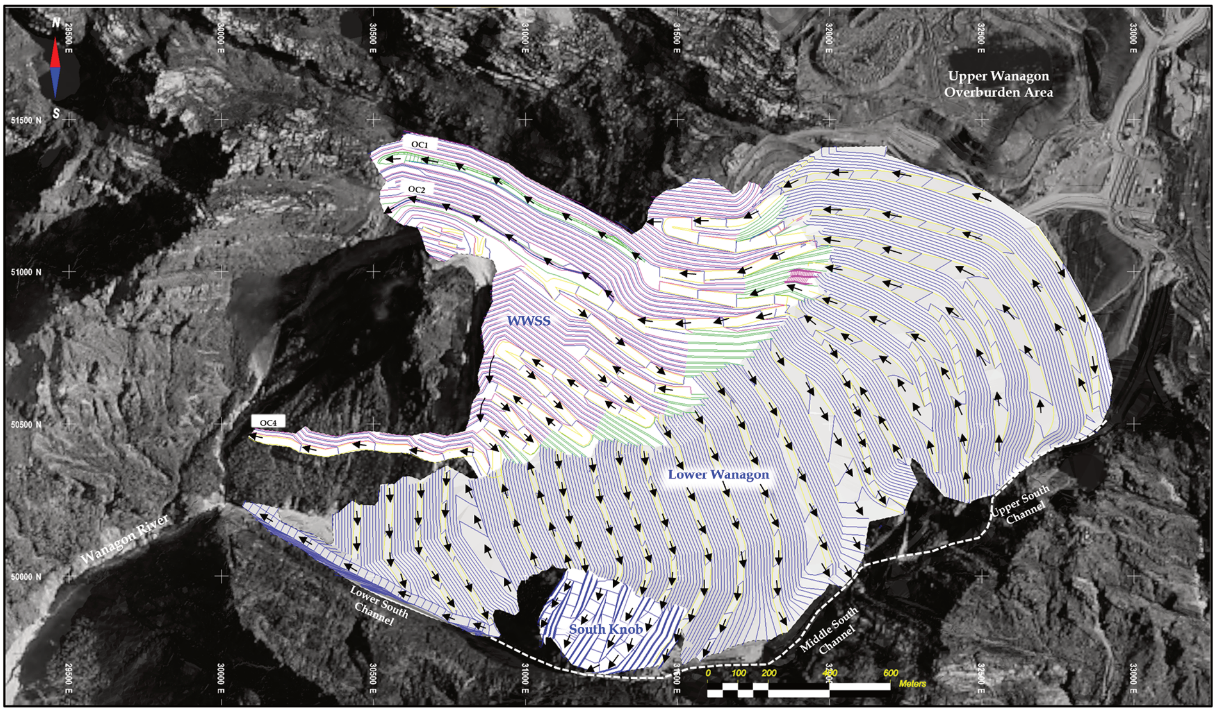

Figure 14 **Surface Water Control**

This stabilization project at Wanagon is ongoing and is estimated to be completed in 2025. The design is meant to reduce long-term maintenance and to remain stable for a 100-year storm event.

6 Conclusion

Top-down overburden construction creates an angle of a repose stockpile. The slope is likely unstable long-term, especially if it is a long slope without a break in slope and influenced by ground and surface water. Erosion could drive the slope instability or vice versa. Several mitigation efforts are required if this construction method is unavoidable. These mitigation measures include breaking the continuous slope heights, controlling the water, creating haul truck access for maintaining the slope, and regrading the slope to a minimum 2:1 ratio.

The methods above have succeeded in stabilizing and minimizing erosion at the Wanagon Stockpile despite the project not being fully completed during the high rainfall as shown on Table 1.

The cost of stabilizing Wanagon is high with the current budget estimated at USD 600 million. The benefit should be much higher than the stabilization cost when deciding the top-down overburden construction.

Acknowledgement

The authors would like to thank the leadership of PT Freeport Indonesia and Freeport-McMoRan for permission to publish this paper. The contribution of personnel from Strategic Planning, Earthwork Division and the GeoEngineering Division gratefully are appreciated

References

Geotechnical Services Department, 2017, ‘Management of Overburden Placement at Lower Wanagon Stockpile with Geotechnical and Geochemical Consideration’, *Standard Operating Procedure*

Milliman, JD 1995, ‘Sediment Discharge to the Ocean from Small Mountainous Rivers: The New Guinea Example’, *Geo-Marine Letters* vol. 15 pp. 127-133

Stantec, 2016, ‘Lower Wanagon Overburden Stockpile Closure’, *Civil Construction Phase Stage 1 Design Report*

Widijanto, E, Setiawan, I, Prasetyo, G, 2015, ‘Dedicated Underground Drainage Drift for Dewatering Wanagon Overburden Stockpile, Grasberg Mine – PT. Freeport Indonesia’, *Prosiding TPT XXIV dan Kongres Perhapi*