STEWARDING MINE DUMP MASS MOVEMENTS BY REGIONAL LANDSLIDE ANALOGY

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Abstract

The Porgera Mine in Papua New Guinea utilizes the concept of `erodible' dumps for managing the incompetent rock and overburden materials that are produced by the large open pit mining operation. Placement of these materials in conventional waste dumps was deemed unacceptable for both the operational hazard and the long-term stability risks this would represent. The erodible dumps, developed in valleys with pre-existing colluvial landslides, create complex mass movements not readily assessed by limit-equilibrium methods more commonly used on mine waste dumps. As part of an overall assessment of the long-term risk and continued viability of the erodible dump concept, an evaluation of the geomorphologcal characteristics of the dumps in comparison to regional mass movements was carried out. It was found that the erodible dumps create mass movement morphologies that are essentially the same as those related to the natural events ubiquitous in the region.

1. INTRODUCTION

The Porgera Gold Mine is a 250,000 tonne per day open pit and underground gold mine located in the Highlands of Enga Province of Papua New Guinea. The mine site, which is at approximately five degrees south latitude, receives more than three metres of rainfall annually. Site relief is intense with more than 1000 metres differential elevation between various mine waste management facilities. The geology is complex with a number of sedimentary sequences that have been variably influenced by intrusive features characterizing the area of the mine. The area is also seismically active with a M7.5, PGA 0.25 g event being the operating basis earthquake event with M7 events since mine start up. Waste management comprises separation and disposal of competent, semi-competent and erodible wastes. The competent and semi-competent wastes tend to be intrusive and altered sediments, respectively. Both competent and semi-competent material are placed in stable waste dumps in the mountainous terrain on prepared foundations, while the erodible wastes are dumped into the headwaters of small valleys, creating a man-made, slow moving, landslide. There is limited ground for stable dumps and inclusion of erodible wastes would lead to operating and long-term instability concerns deemed unacceptable.

The trial creation of erodible dumps for the Mine began in Anjolek Creek in 1992. The successful trial led to approval from regulators and the evolution of two erodible dumps; the Anawe Dump and the Anjolek Dump. As of March 2002, these dumps have had approximately 223 x 10^6 tonnes (223 Mt) of erodible material placed in them with this material comprising soil, colluvium and weak rock such as mudstone and sheared black sediments.

While it is true that the terminus of the landslides formed with the erodible wastes is eroded by fluvial activity although the actual erosive mechanisms are far more complex. The term *"erodible"* is not as strictly correct as per the original concept and trial. However, the nomenclature has remained to differential these dumps from the "stable" dumps for competent and semi-competent materials. . The present operating concept for these dumps has been integral to the viability of the mine since 1992, and will continue to be through to mine closure.

There are three basic facts that apply to the erodible dumps:

1. The erodible dumps are a necessary component of a viable Porgera Mine
2. The erodible dumps are essentially landslides of similar scale to landslides in the immediate area of the mine site
3. Landslides are a ubiquitous part of the landscape in the highlands of Papua New Guinea.

From these facts, two fundamental questions arise:

1. Are the erodible dumps any more, or less, hazardous than natural landslides in the region?
2. What will happen to the erodible dumps in the long term?

The behaviour of the erodible dumps is complex and not readily described by geomechanical and/or fluvial transport models. Moreover, while the Anawe and Anjolek dumps are similar, there are subtle and significant differences in the characteristics of each dump. This paper will describe the behaviour of the erodible dumps based on analogies to regional landslide processes.

2. PROJECT DESCRIPTION AND MINE DUMPS

2.1 General

The Porgera Joint Venture (PJV) operates the Porgera Gold Mine (Porgera) located in the highlands of Papua

New Guinea (PNG). The overall climate is moist temperate, with average daily temperatures ranging from 5°C to 25°C and yearly rainfall from about 3100 mm to 4400 mm. Porgera is located in the mountainous highlands at elevation 2200m to 2700m and an active seismic zone, with recorded activity up to M7.0. The mine commenced operation in 1989 using underground extraction methods and has since expanded to include a large open pit operation that mines approximately 210,000 tonnes per day (tpd) as of 2001. Waste rock, incremental ore for stockpiles, and soil overburden from the operation are currently placed in one of four active dumps: Kogai competent dump, Anawe North competent dump, Anawe erodible dump and Anjolek erodible dump. The incremental ore is placed exclusively in the Kogai dump.

The Porgera mine is located in a geologically complex area. The major waste rock and soil types encountered are listed below:

- *Black Sediments;*
- *Brown Mudstone;*
- *Altered Sediments;*
- *Calcareous Sediments;*
- *Intrusive Rocks; and*
- *Minor amounts of surficial soil, colluvium and general organic rich detritus.*

Waste rock production increased dramatically in the 1990's when open pit mining began. The pit is being developed in several different *"stages"* to smooth out the stripping ratio (of ore to waste) extracted in any given development period. To date, pit development has been planned in five stages, denoted Stages I to V respectively. At the time of the Panel's review, Stage I and II pits were complete, and mining was ongoing from Stages III, IV and V at a nominal mining rate of 210,000 tpd. Mining is expected to continue until 2006, with stockpiling milling to continue for approximately an additional four years.

A general layout plan of the open pit and mill in relationship to the competent and erodible dumps is presented in Figure 1.

2.2 Competent Dumps

During project initiation, competent (traditional stable) dumps were initially envisioned to endure for the life of the mine. The difficulty with this was locating sufficient storage areas within reasonable proximity to the ore body. The mine started as an underground operation. As the initial open pit was developed, the Mungarenk Valley, directly adjacent to the open pit, became the preferred location although the likely ability to develop a stable dump in the valley for the full life of the mine was highly uncertain. Starter dumps (A, B and C) were planned and Starter Dump A was nearing a few million tonnes when movement in the toe area of a portion of the Mungarenk slide complex began.

Following the perceived loss of stable dump potential for the majority of the Mungarenk Valley due to this movement, evaluation of another valley adjacent to the open pit, the Kogai Valley, found that it would be able to provide stable dump storage for nearly the life of the mine provided some ground improvement was completed at the toe.

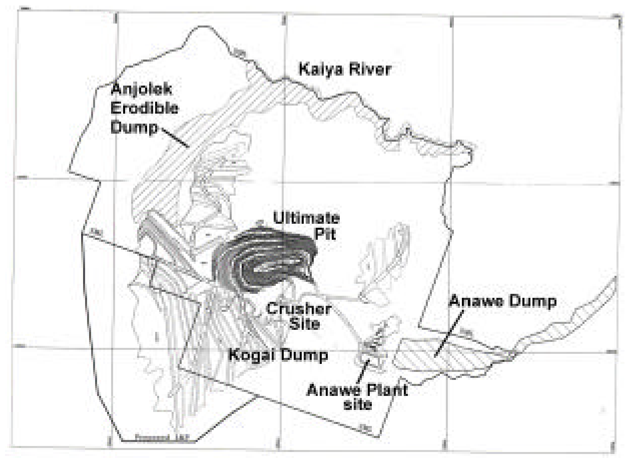

Figure 1 Schematic Plan of Porgera Mine Site

2.3 Erodible Dumps

The Anawe erodible dump is situated in Anawe Valley immediately east of the plant site. In-situ materials comprise clay colluvium overlying mudstone. Landslides dominated the valley morphology prior of mine activity, including portions of the Anawe and Maiapam landslide complexes.

Weathered mudstone was stripped from the infrastructure development during 1989 to 1991. The excavation spoil was disposed of in the Anawe Valley and, not surprisingly, pre-existing landslide movements accelerated. The area behaved as a viscous flow possessing the characteristics of regional mudslides. Following cessation of intensive dumping in 1991, velocities slowed to the point where movements were not readily discernible to the eye.

From 1992 to the end of 1996, the Anawe dump was primarily used for colluvium disposal stripped for the preparation of the Kogai stable dump foundations and other infrastructure and mine developments. In January 1997, the valley was re-opened as an erodible dump for waste rock that included black sediments, brown mudstone, colluvium, and oxidized pit rim material. As of July 2001, the cumulative total of waste rock material placed in Anawe dump was 73.2 Mt. The Pongema River at the base of the dump has actively eroded the toe over the dump's life.

The Anawe erodible dump has also been the riverine tailings disposal site since mine start up. Tailings, at a nominal rate of 18,000 tpd, are end-of-pipe discharged near the dumphead, directly adjacent to the mill.

The Anjolek dump is situated in the Anjolek and Mungarenk Valleys. As with Anawe, the original foundations comprised very thick deposits of clay colluvium overlying mudstone. Landslides also characterized the morphology in this area, including the Mungarenk Landslide Complex. The Mungarenk Valley was originally assessed as the preferred location for a stable waste dump in the 1980s, but was evaluated as an erodible dump in 1992 based on the performance of Anawe during mine construction. Placement of mine waste in Anjolek Creek commenced in August 1992. Use of the Mungarenk landslide area commenced in 1993.

Since 1992, the Anjolek dump has been used steadily, although the large majority (>90%) has been placed from the dump heads close to the open pit (top of Mungarenk Valley) as opposed to the top of the Anjolek Valley. To July 2001, over 130 Mt have been placed in the Anjolek dump.

The Kaiya River at the base of the dump actively erodes the dump margins but unlike the Anawe dump, the toe has advanced considerably over the years.

3. PROJECT TERMINOLOGY

To avoid confusion when addressing the behaviour of the erodible dumps and the natural land movement in the mine site region, a consistent set of nomenclature was adopted for the project. Cruden and Varnes (1996) define 'landslide' as, *"the movement of a mass of rock, debris, or earth down a slope."* This definition was adopted the term is used in reference to mass movements without any inference as to the type of movement. Cruden and Varnes (1996) go on to identify five fundamental types of landslide movement, fall, topple, slide, spread, and flow. Flows were the focus of the evaluation of the Porgera erodible dumps and the regional landslides found to analogous to the dumps as noted later in this paper.

Similar work on flows has conferred on them a number of descriptive terms, including earthflows, mudflows, mudslides and others. To avoid possible ambiguity, the project adopted the most recent geomorphologic nomenclature (Hungr et al. 2001). Two types of flow are prominent amongst landslides affecting natural and engineered slopes in the Porgera area, earth flows and mud flows. The definitions and salient characteristics of each are as follows:

Earth Flow

"Earth flow is a rapid or slower, intermittent flow-like movement of plastic, clayey earth."

- The velocity profile shows:
    - Basal and lateral shear surfaces normally associated with slide movement.
    - Dominant mechanism is sliding at residual strength;
- High velocities are only achieved if there is a collapse related pore pressure rise; and
- An earth flow acts as a conveyor belt between the source of material and a sink. Rapid episodic movement of the upper part leads to thrusting and over riding of the material farther downslope. This increases total stress, which can cause a concomitant increase in pore pressure, resulting in acceleration of the earth flow as a kinematic wave that can sweep the entire length. Large kinematic waves are referred to as surges.

Mud Flow

"A very rapid to extremely rapid flow of saturated plastic debris (PI>5%) in a channel, involving significantly greater water content relative to the source material."

- The clay fraction modifies the rheology of the material, which is important for dynamic modeling; and
- Under certain conditions, clayey colluvium can become diluted beyond its liquid limit. Clay retards both dilution by water and drainage, thereby causing larger runouts.

The foregoing details indicate that rate of movement is an intrinsic part of describing and distinguishing these two flows. For purposes of clarification, rates of movement noted for the local landslides and for dump movements conform to the definitions shown in Figure 2.

Velocity Class		Velocity (mm/sec)	Typical Velocity
7	Extremely Rapid		
		5×10^{3}	5 m/sec
6	Very Rapid		
		5×10^{1}	3 m/min
5	Rapid		
		5×10^{-1}	1.8 m/hr
4	Moderate		
		5×10^{-3}	13 m/month
3	Slow		
		5×10^{-5}	1.6 m/year
2	Very Slow		
		5×10^{-7}	16 mm/year
1	Extremely Slow		

Figure 2 Proposed Landslide Velocity Scale (Adapted from Cruden and Varnes 1996)

Table 1 defines the probable destructive significance of landslides for each velocity class shown in Figure 2. This terminology was also adopted by the project.

As with any empirical-based relationship, such as shown in Table 1, the actual destruction caused by any given event is a function of multiple variables. Where landslides are concerned, the type and rate of movement must be considered in the context of the total area affected before the destructive influence can be gauged. For example, a slope with a large area moving at moderate velocity is likely to cause much less *"damage"* and not have the concern for injury or loss of life when compared to a small, but very rapid, mass movement (Cruden and Varnes 1996).

Several large Quaternary stratovolcanoes also occur within the highlands region of the Papuan Fold Belt (Dow 1977, Stead 1990).

Table 1 Definition of Probable Destructive Significance of Landslides of Different Velocity Classes (Adapted from Cruden and Varnes, 1996)

Landslide Velocity Class	Probable Destructive Significance
7	Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
6	Some lives lost; velocity too great to permit all persons to escape
5	Escape evacuation possible; structures, possessions, and equipment destroyed
4	Some temporary and insensitive structures can be temporarily maintained
3	Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase
2	Some permanent structures undamaged by movement
1	Imperceptible without instruments; construction possible with precautions

4. GEOLOGICAL SETTING

Interaction of the Indo-Australian and Pacific plates has, for 200 Ma, controlled the geological evolution of Papua New Guinea. The present boundary is along the north coast where uplift rates of about 1 mm/year are amongst the highest in the world.

For most of the last 60 Ma, the boundary was located in the New Guinea Mobile Belt south of its present location. This tectonic province is about 150 km wide and it wraps around another situated still farther south called the Papuan Platform, or locally the Papuan Fold Belt. The Lagaip Fault Zone demarks the contact between the mobile belt and the platform, and also the northeastern limit of the Indo-Australian plate (Dow 1977, Dow et al. 1972, Pain 1972).

Sediments of the New Guinea Mobile Belt were laid down in a geosyncline and originated from a volcanic arc to the north. The Papuan Fold Belt, on the other hand, contains sediments derived from the Australian continent and laid down in shelf conditions. These comprise fine-grained mudstones and siltstones overlain by coral limestones (Pain 1972).

Porgera is situated in the fold belt a short distance south of the Lagaip Fault Zone. Although on the relatively stable Papuan Platform, orogenic activity at the nearby plate boundary caused uplift and tectonic thickening of the platform sediments. The Porgera area is therefore, characterized by foreland folds and thrusts verging southward from the central orogenic belt.

Rock type is the single most important variable in the evolution of the 'ridge and V-valley' landscape that characterizes the Porgera area of the central highlands. This landform can be described as ridges with steep slopes, narrow and sharp crests, separated by V-shaped valleys with steep gradients (Löffler 1977, Pain 1972).

The Chim Formation comprises local subcrop. Its mudstones break down rapidly on exposure, especially when alternately wetted and dried. The resulting saprolites and residual soil are inherently weak and unstable. In combination with the high rate of uplift (see 'Uplift Rates' below) and high precipitation (roughly 3 to 4 metres per year), this maintains slopes that are characteristically unstable. Denudation rates far outstrip the rate of weathering as widespread landslide activity serves as a ubiquitous conveyor moving saturated colluvium from slopes to valley channels (Pain 1972).

These channels serve as conduits for collection and removal of colluvium shed from the slopes; this is in addition to any incision by streams. The colluvium moves down-channel as undifferentiated earth and mudflows until landslide processes are overtaken stream erosion and remaining colluvium is entrained and removed in suspension or as bed load. Streams draining the 'ridge and V-valley' landscape thus carry sporadic and sometimes very heavy sediment loads (Pain 1972).

Papua New Guinea is also an active seismic region, having between 5 and 10% of the world's total earthquake occurrences. In recognition of this, the country is divided into major earthquake zones and contoured in terms of seismic intensity. The mobile and fold belts are areas of medium risk within this area of active seismicity (Stead 1990).

Earthquake-induced landslides are a major factor in landform development in Papua New Guinea (Löffler 1977) with average recurrence intervals of 200 years reported for the mountains along the north coast (Pain and Bowler 1973).

5. LANDSLIDES IN THE CENTRAL HIGHLANDS OF PAPUA NEW GUINEA

Falls, slides and flows all occur in the Porgera area. These include debris slides, translational slides, and flows.

Debris slides are shallow, involving only the soil profile and weathered mantle. They occur where original bedding planes, planes of foliation, intense fracturing by joints and faults, and weathering profiles provide pre-existing zones of weakness dipping steeply parallel to the topographic slope. These are the most common initial landslide events in the Porgera area. Put another way, they are first onto the ‘landslide conveyor belt’ in the upper portions of drainage basins.

Mules (1992) postulates a large deep-seated translational slide mechanism extending north from the intrusive rocks at Porgera into the Kaiya River valley as shown in Figure 3. He attributes this to rebound and spreading. The full extent is unknown.

Figure 3 Landslide Geomorphology of the Kaiya River Valley at Porgera, Papua New Guinea (after Mules 1992)

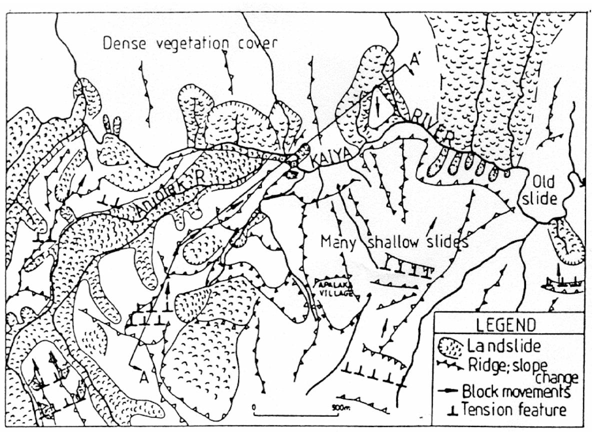

Figure 3a Geomorphology of the Kaiya River Valley near Porgera

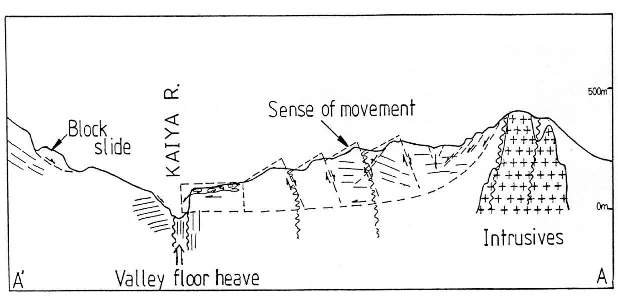

Figure 3b Cross-Section A’-A Showing the Interpreted Large-Scale Translational Slide Failure Mechanism. Direction of View Approximately West to East

Flows occupy the greatest areal extent of any landslide type in the central highlands, including the Porgera area. For example, the 5 to 6 km long access road to the Porgera mine site crosses at least 12 earth flows, at least four of which have been recently active (Blong 1985, Blong and Eyles 1989). Virtually all of the landslides shown in Figure 3 are of the flow type.

Geotechnical properties of colluvium comprising natural earth flows are summarized in the left column of Table 2 and properties of the Anawe Dump in the right hand column. The range of grain sizes are very similar between the natural earth flow colluvium and the waste dumps although, clearly, variation exists.

Table 2 Comparison of Geotechnical Properties for Colluvium in Earth Flows and Waste in the Anawe Erodible Dump

Index Test	Natural Colluvium	Anawe Waste Dump
Water Content	10 to 59 %	21 to 42 %
Liquid Limit	30 to 50 %	35 to 44 %
Plasticity Index	7 to 25 %	15 to 22 %
Bulk Density	9 to 17.7 kN/m^3	15.4 to 17.6 kN/m^3
% passing 74 μm	44 to 95	32 to 57
% passing 5 μm	20 to 61	20 to 35
Peak vane strength	34 to 98 kPa	35 to 70 kPa
Peak strength	ϕ = 14° to 25° c = 0 to 100 kPa	ϕ = 25° to 28° c = 0 to 100 kPa
Residual vane strength	17 to 43 kPa	28 to 55 kPa
Residual undrained strength (back analysis)	Variable; 20 to 50 kPa	27 to 48 kPa
Residual drained strength (back analysis)	ϕ= 12° - 18°	ϕ= 17°

6. POSTULATED MECHANISM FOR ERODIDLE DUMPS

While the term *“erodible”* is not as strictly correct as per the original concept and trial, the nomenclature has remained. The behaviour of the erodible dumps is complex and not readily described by a simple geomechanical model. Moreover, while the Anawe and Anjolek dumps are similar, there are subtle and significant differences in the characteristics of each dump. Beyond the terminus of each dump’s slide lobe, fluvial processes dominate that can likely be more accurately modeled than the internal phenomena within each dump. The following list provides a general summary of the behaviour of the erodible dumps.

1. Dumped material moves relatively quickly (in the order of magnitude of meters/day) from the dump

head to mix with previously dumped material, runoff and, in the case of the Anawe dump, tailings. Competent boulders (diorite, altered and calcareous sediments) tend to raft or become emulsed in the viscous matrix. The liquidity index of the matrix is at/near unity at placement void ratio and the matrix moves within the initial dump tract variously as a mudflow (visco-plastic rheology with yield stress and viscosity governing flow rate) or earth flow (shear at/near residual strength dominates basal and lateral sliding surfaces). Matrix material is largely saturated but clasts of mudstone and black sediments are typically not saturated.

2. The majority of dump material moves downslope in quasi-unison analogous somewhat to a conveyor belt. Disaggregation of the mudstone and black sediments, and lesser competent altered and calcareous sediments, is progressive and increases the overall bulk void ratio as these clasts decompose. The ‘conveyor belt’ is now operative as long as new material is introduced at the dump head. The matrix material will remain at/near a liquidity index of unity as long as material is added and/or additional water is available to saturate the mass as required to maintain the rheology (Blong and Goldsmith, 1993).

3. Most of the material entering the dumps is being removed by fluvial action. Although rates of fluvial removal vary from year to year, about 60 percent of the sediment dumped at both Anawe and Anjolek to November 2000 had been eroded by October 2001 by fluvial action and transported down the Kaiya and Pongema Rivers, respectively, into the Porgera River.

4. In the upper sections of the dump, disaggregation of the waste materials occurs at relatively constant moisture content (surface infiltration is minimal due to the low hydraulic conductivity of matrix materials) so the liquidity index will fall as the number of material surfaces increases due to particle breakdown. As the liquidity index falls, both the undrained strength and void ratio will increase even though it is typical in soil mechanics that an increase in shear strength is related to a void ratio reduction. Saturation levels will fall in proportion to void ratio increase; there is limited pore moisture for all the pore space present. In general, the long-term trend is for gradual strength gain in the dump matrix that remains in the dump tract prior to removal at the dump toe by fluvial processes. This process is highly dependent upon dump activity and is therefore dominant in the upper tracts of the dumps.

5. As saturation decreases and void ratio increases, compressibility increases and the effective stresses are increased. This will locally decrease void ratios and increase the degree of saturation. As the system saturates, undrained strengths will decrease for a given void ratio and dump mobility may re-occur through an earth flow mechanism. However, the consolidation that occurs will tend to increase undrained strength as noted above in point 4. This process is more dominant in the lower dump tract areas away from the direct impacts of active dumping. This is a very complex mechanism that is at variance with the more simplistic concept of tract lock-up and then rapid movement upon trigger.

6. Where there are sufficient surface water flow velocity and volume, dump erosion will occur on the surface and more significantly at the margins and the toe area with fluvial transport mechanisms. As material is eroded, lateral and toe support to the dump is decreased leading to localized movements. These movements can lead to avulsion events that would enhance erosion of the dumps.

7. Dump movement slows as soon as material is no longer added at the dump head. Appreciable movement for the majority of the dump, based upon observational history, may cease within as little as one to two months following the cessation of dumping.

8. Following mine closure, seismic events may create localized strength loss due to the cyclic mobility of the materials, but these events will not be sufficient to create a large-scale rapid mass movement. The dump material will have significant damping potential and the majority of the dump matrix will remain in a plastic state not susceptible to brittle strength loss (liquefaction).

9. Erosion of lateral banks of natural colluvial slopes by the Pongema and Kaiya Rivers will lead to progressive localized movement of these areas. Self-armouring of the channels will slow the down-cutting process.

From a thorough review of the regional landslides, it was determined that the long-term behaviour of these dumps following mine closure will not be substantially different from the larger scale colluvial landslides in the region (Maiapam, for example) and will probably be more favourable in terms of movement surges due to the higher levels of kinetic energy in their (the dumps) formation from the relative rapid development of the “colluvium” in comparison to natural processes. The increased rate of production tends to homogenize the material properties.

Figure 4 shows an oblique photograph of the upper tract of the Anawe erodible dump with the lower reaches of the Maiapam landslide in the background.

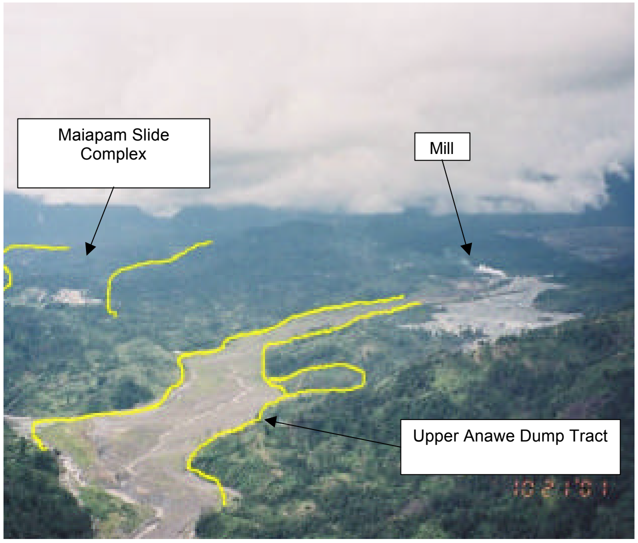

Figure 4 – Upper Area of Anawe Erodible Dump

7. SUMMARY AND CONCLUSIONS

The stewardship of the Porgera Mine erodible dumps involves anticipating the near and long term behaviour of these mass movements. Various modeling and monitoring programs have been undertaken to assess near term behaviour but perhaps the most informative evaluation of these dumps near and long term behaviour has been in comparing them with regional mass movements.

From a comparison with regional mass movements, two questions can be raised and answered:

1. Are the erodible dumps any more, or less, hazardous than natural landslides in the region?

The answer is a qualified no. The qualification comes from certain operating conditions, e.g. dump heads, which create can create short-term hazard issues that need to be addressed by appropriate dump stewardship. However, in the long-term (i.e. following mine closure), these damps do not represent any different land use hazard than exists with any other colluvium filled valley in the region.

2. What will happen to the erodible dumps in the long term?

The answer is essentially that which happens regularly to natural landslides in the region. Stream blockage, aggradation, erosion, etc. will occur with these dumps in a very similar fashion. The region is both very active from a geomorphological perspective and natural vegetative reclamation of land occurs rapidly in the temperature high rainfall environment. Being able to discern these dumps from other mass movements in the region following a few years following the cessation of mining operation will be difficult.

The behaviour of the erodible dumps is complex and not readily described by geomechanical and/or fluvial transport models. Although there are differences, the Anawe and Anjolek dumps are similar and are not unlike the natural landslide hazards common to the highlands area of Papua New Guinea. This similarity has facilitated confident operational and closure planning and allows a non-conventional mine waste management method to be practised in one of the few regions of the world where it in balance with the site setting based upon the prevailing engineering geological conditions.

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