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**SUMMARY OF RISK GAPS AND ANALYSIS**

A summary of the review findings are presented in bullet format below:

• **Reassess the site-specific seismic hazard study**.

The seismic design criteria presented in Section 2.9 of the ATC report appears to under-represent the seismic hazard at the site. ATC indicates use of the 1:10,000 annual exceedance probability (AEP) probabilistic ground motions results resulting in a peak ground acceleration (PGA) = 0.89g resulting from a M=7.5 earthquake. However, published studies of the probabilistic seismic hazard of PNG indicate a PGA in excess of 0.90g for an AEP of 1:475 at the TSF location, and a maximum magnitude of 8.0 – 8.25 for the Ramu–Markham Fault adjacent to the site, and M=8.8 for the offshore subduction zone to the northeast. The site-specific seismic hazard assessment by ATC should be reassessed.

ATCW Response:

We are not aware of any published studies that indicate a PGA in excess of 0.90g for an AEP of 1:475 at the TSF location. Please provide the above-mentioned published study that supports this claim.

The sources of seismic data for the probabilistic seismic hazard analysis (PSHA) conducted by ATCW (2020) are quite comprehensive, which include the ISC-GEM Global Instrumental Earthquake Catalogue (Di Giacomo et al., 2018; Storchak et al., 2015, 2013), the Papua New Guinea seismic hazard map (Ghasemi et al., 2016), and the United States Geological Survey (USGS, 2019) Earthquake Hazards Program.

In addition, due to inherent epistemic and aleatory uncertainty in the seismic source models and attenuation relationship used in the development of any PSHA, the following procedures have been adopted during the seismic hazard analyses:

* We combined the seismic source model used by Gashemi et al (2016) and DIM-ASIA (Dimas and Venkatesan, 2016) with 50% weight of each model to reduce the uncertainty;
* The Gashemi et al. (2016) model considers 13 shallow area sources and three deep area sources.
* The DIM-ASIA model considers 22 shallow area sources and 34 deep area sources.
* It is worth noting that the Ghasemi et al. (2016) area source model adopted a higher Mmax than those adopted by the DIM-ASIA area source model, i.e. Mmax of 8.0 to 8.8 compared to 7.5 to 8.5. Thus, the Gashemi et al. (2016) model tends to give much higher computed ground accelerations.
* We consider shallow and deep crustal earthquakes, as well as subduction earthquakes.
* We have used the most recent NGA-West Ground Motion Prediction Models (GMPE) with different weights, including Abrahamson et al. (2014), Boore et al. (2014), Cambell & Bozorgnia (2014), BC-Hydro (2012), etc.
* We used the industry-standard probabilistic seismic hazard analysis software EZ-FRISK, distributed by Fugro Inco (2015). Thus, we were able to perform robust analyses using this software.
* The results have also been reviewed by Gary Gibson, a prominent Australian seismologist based in Melbourne.
* Thus, the probabilistic seismic hazard analysis conducted by ATCW has been based on comprehensive historical seismic data, a combination of sound seismic source models (Gashemi et al and DIM-ASIA), and has properly considered the epistemic and aleatory uncertainty inherent in probabilistic seismic analysis.
* The results proposed by Gashemi et al. (2016) tend to be slightly higher than those computed by ATCW (Table 1), which adopted a 50% weight of the seismic source models from DIM-ASIA.

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**Table 1. PSHA Results by ATCW (2020)**

A close-up of a graph

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* The results computed by Jury (1982) and Gashemi et al (2020) for 500-year return period earthquake are presented below in Figure 1 and Figure 2, respectively.

A map of the area

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**Figure 1. Current PNG Seismic Zonation Map (Jury et al, 1982). PGA for a 475-year RP earthquake event is 0.22g.**

A map of the pacific ocean

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**Figure 2. Results of PSHA by Gashemi et al., (2020).PGA for a 475-year RP earthquake event is 0.42g.**

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* ATCW's PSHA result for the 475-year return period is about 0.31g, which is between the PGA values in the current PNG seismic zonation map developed by Jury et al., (1982), i.e. 0.22g, and the recent seismic hazard map proposed by Gashemi et al. (2020), i.e 0.42g.
* In conclusion, we believe that the PSHA results carried out by ATCW are more realistic than those computed by Gashemi et al. (2020). Unless we find more convincing data that Mmax for the faults surrounding the site considered in this analysis are higher, we believe that the PSHA results developed by ATCW (2020) are still valid. Therefore, we assess that there is no need to reassess the seismic hazard at the site at present.

• **Obtain in situ shear wave velocity (Vs) measurements to determine Vs, 30.**

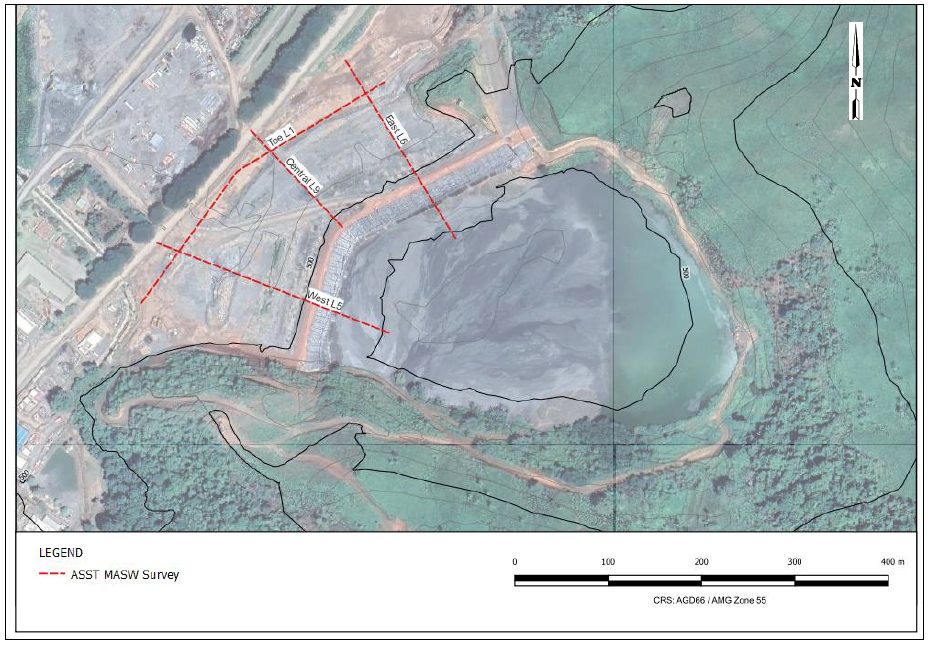
The seismic hazard study presents the anticipated ground motions on rock with a Vs,30 = 760 m/sec. This is likely too high for foundation conditions that include up to 37m of alluvial soils as indicated in Section 2.11.2.1 of the ATC report. Recommend collection of Vs data via downhole or cross-hole methods since the local soil conditions can have a large effect on the seismic response.

ATCW Response:

The 2020 seismic study presents the predicted ground motion on rock with Vs,30 of 760 m/sec. To predict the responses of the topsoil-like stratigraphy, a ground response analysis using SHAKE, PLAXIS or FLAC software can be performed and would require shear wave velocities of the sub-surface materials.

In 2023, a geophysics survey including Multi-channel Analysis of Surface Waves (MASW) was undertaken in the vicinity of the TSF embankment. In total, ten sections were surveyed in the 2023 campaign. The shear wave velocity profiles at four representative sections running through the central, east (north abutment) and west (south abutment) portions of the embankment, as well as a section running along the downstream toe of the TSF embankment. The section locations are presented in Figure 3.

Figure 3: Locations of 2023 MSAW Survey Sections



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Results of the MASW survey and its implications for material liquefaction susceptibility have been discussed in the Liquefaction Assessment & Stability Analysis Report (ATCW, 2024) 116259.37 R01 Rev 0.

Furthermore, downhole seismic surveys have recently been undertaken as a part of the 2024 Stage 3 TSF Raise Feasibility Assessment site investigation. The results of the downhole seismic survey will be presented in the forthcoming 2024 site investigation factual report.

• **Obtain in situ shear wave velocity (Vs) measurements to assess liquefaction risk.**

The boring logs indicated thick sequences of gravelly sand for which no data on in situ density or consistency, and therefore on the potential for liquefaction triggering, is available. Due to the difficulty obtaining accurate SPT blow counts in gravelly soils, liquefaction triggering in these materials should be evaluated using shear wave velocity correlations. In situ measurements of Vs using downhole or cross-hole methods is recommended.

ATCW Response:

The liquefaction susceptibility of foundations has been discussed in the Liquefaction Assessment & Stability Analysis Report (ATCW, 2024) 116259.37 R01 Rev 0. Refer also to response to previous question.

It has been found that the estimated shear wave velocity of the gravelly foundation is higher than the liquefaction threshold recommended by Andrus & Stockoe (2000). As such, this material is considered unlikely to be liquefiable.

• **Refine liquefaction analyses to include low plasticity soils and gravelly sand.**

The liquefaction triggering analysis appears to use simplified procedures to screen susceptible soils based on plasticity.

Soils plotting above the A-line on a Casagrande plasticity chart appear to have been excluded from being susceptible to liquefaction, however details are not provided in the ATC report. It is now widely recognized that low plasticity silts and clays are susceptible to significant strength loss due to cyclic softening and/or large strain, e.g. Seed, et. al. (2003), Boulanger and Idriss (2004), and/ or National Academies Press

(2021). Liquefaction triggering in these soils should be re-evaluated.

GISTM (2020) Requirement 4.6 states “Identify and address brittle failure modes [i.e. liquefaction or cyclic softening] with conservative design criteria, independent of trigger mechanisms, to minimise their impact on the performance of the tailings facility”.

ATCW Response:

The liquefaction susceptibility of foundations has been discussed in the Liquefaction Assessment & Stability Analysis Report (ATCW, 2024) 116259.37 R01 Rev 0, this includes low plasticity soils and gravelly sand.

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* **Seepage and stability analyses should be modified to reflect long-term liner degradation.**

Seepage models performed in conjunction with the stability analyses presented by ATC included the effect of the HDPE liner on the upstream face. Analyses presented by Golder (2004) indicate an unacceptable FOS less than 1.0 for long-term steady state seepage conditions without the HDPE liner.

HDPE liner is typically neglected in seepage analyses to reflect long term conditions and eventual degradation of the liner. Seepage and stability analyses should be reconducted assuming the liner is no longer functional to evaluate long term conditions. ICOLD (2013 Bulletin 153) indicates “*the tailings dam should be able to perform in the event that the geomembrane liner or geosynthetic filters or drains degrade with time and either their function is no longer required or systems can be implemented to mitigate their effect”*.

ATCW Response:

The 2020 Annual Inspection Report by ATCW highlighted critical discrepancies in the stability and seepage analyses conducted by Golder (2004). Specifically, the analyses failed to accurately model the as-built configuration of the TSF (Tailings Storage Facility) embankment. Golder’s model was based on design assumptions that included a chimney drain, blanket filter, and central core—features that do not align with what was subsequently actually constructed.

Additionally, significant changes have been made to the embankment's profile due to the Stage 1A/1B downstream raise. These modifications further deviate from Golder's original analysis, making their predictions unreliable for assessing the current state of the K92 TSF.

It is also important to consider the status of the original liner. Over time, this liner has been buried under tailings. With each new raise, a new liner is installed on the upstream face and its design life is expected to exceed the timeline outlined in the PEA for tailings deposition. Moreover, during the post-closure phase, seepage flow will diminish significantly as reclamation of the tailings surface progresses. As a result, the performance of HDPE liners will no longer be a critical factor in ensuring the embankment's stability.

• **Fully-coupled non-linear dynamic deformation analyses should be conducted for seismic design**.

Deformation under seismic loading was evaluated using simplified empirical methods which are more than 20 years old. This is not consistent with the stand of care for an extreme hazard TSF in a highly seismic area, nor with the ANCOLD (2019) criteria adopted. ANCOLD (2019) indicates that if the deformations estimated by the screening or database methods are not much less than what is tolerable (e.g., crest settlements are much less than the available freeboard prior to the earthquake for the seismic ground motion being considered), use one or more of the simplified methods to estimate deformations. The settlements estimated by ATC using empirical methods exceeds the available freeboard (2m) in many cases as indicated in Table 27. Some of the results listed in Table 27 are for ‘severe’ and ‘collapse’ damage categories with settlements predicted to be greater than 5% of the height of the dam and transverse cracks greater than 0.5m in width. These are high levels of damage. If the earthquake magnitude or PGA are increased as a result of additional seismic hazard study, then the deformations presented in Table 27 would be increased.

For an example of the standard of care in regions with more seismicity than Australia, Alaska Dam Safety requires all Class I [high hazard] and II [significant hazard] dams located in a highly seismic region (with peak ground accelerations greater than about 30% to 40% of gravity or peak shear strains greater than about 2%) to utilize advanced one- and two-dimensional site response analysis techniques to more accurately model the nonlinear behavior of soil subject to earthquake loading (ADNR 2017).

Similarly, USSD (2022) indicates “*the final level of analysis sophistication required will depend on factors such as the importance of the project, the consequence of unsatisfactory performance of the dam, the purpose of the analysis, the intensity of the earthquake ground motion, and the complexity of possible material behavior in the embankment and foundation under earthquake shaking (all of which dictate the necessary degree of confidence and refinement in*

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*the analysis results*)”. USSD indicates “*in cases of moderate or large deformations, of poorly defined deformations, of potential for significant stiffness or strength degradation, or cases that require a refined definition of the spatial distribution of deformation advanced analyses are usually required*”.

In a technical note on seismic risk the World Bank Group’s Water Global Practice (World Bank 2021) states “*The general approach for the seismic design of embankment and concrete dams is to start with simplified methods and use more-rigorous methods until an acceptable and justifiable result is obtained. The level of analysis required for acceptance of a design or remedial design depends on the dam consequence, severity of the potential loading, and characteristics of the dam and foundation. Simplified seismic design will normally be sufficient for low-risk or low-consequence dams, whereas more-detailed analyses will be required for higher-risk or higher-consequence dams.”*

For highly seismic areas ICOLD (2013 Bulletin 153) suggest analyses should also consider the potential effects of accumulated settlements or deformations as a result of more frequent lower magnitude earthquakes over the closure design life.

Finally, GISTM (2020) Requirement 4.5 states: “*Apply design criteria, such as factors of safety for slope stability and seepage management, that consider estimated operational properties of materials and expected performance of design elements, and quality of the implementation of risk management systems.*

*These issues should also be appropriately accounted for in designs based on* ***deformation analyses****.*”

ATCW Response:

Dynamic Deformation analysis has already been performed. Details and outcomes of the analysis can be found in Dynamic Deformation Analysis for Stage 2 Embankment Raise Report (ATCW, 2024) 116259.41 R01 Rev 0.

• **Vertical earthquake ground motions should be incorporated in dynamic analyses.**

USSD (2022) advises that “*using vertical motions in addition to horizontal motions is generally more appropriate than applying horizontal motions only, as the combined motion represents a closer approximation of the seismic loading conditions. Given the potential effects of vertical motions on calculated dam deformations, it is generally advisable to consider vertical motions in nonlinear deformation analyses of embankment dams.”*

ATCW Response:

In dynamic deformation modelling for embankment dams, horizontal ground motion is focused on efficiently addressing the critical risk of failure due to earthquakes. While it is advisable to incorporate vertical ground motion to analyse *concrete gravity dams,* the impact of vertical motion on the earth and rockfill dams generally is not considered to be significant.

An example from a recent case history of earth and rockfill dams subjected to high horizontal and vertical acceleration is the 156-m high Zipingpu dam in China. It was subjected to horizontal and vertical accelerations of 2.0g. No significant damage was observed (Ishihara, 2012).

Table 2. Ground acceleration at the crest of Zipingpu Dam during Wenchuan Earthquake

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Moreover, incorporating vertical ground motion increases the complication of the analysis, while the vertical earthquake loading is often considered less critical than the horizontal ground motion component due to the following reasons:

* Horizontal seismic forces are typically much larger than vertical forces during earthquakes.
* The horizontal components of motion contribute more to the lateral deformation, slope instability, and shear failure mechanisms, which are the primary concerns for embankment dams. Vertical motions, on the other side, cause primarily a variation in compressive stresses along the height of the dam, which the dam is typically well equipped to handle, especially since embankment materials are strong in compression and are not rigid, like concrete dams.
* The effect of vertical ground motion is naturally mitigated by the gravity force acting downward, which stabilises the embankment.

Furthermore, there is no current consensus on the selection of the vertical earthquake motion that might be concurrent with the design of horizontal shaking.

• **Prepare detailed Construction Records Report ‘as-built’ reports.**

No construction records were identified in the documents provided for review. GISTM (2020) Requirement 6.3 includes a detailed construction as-built report for each phase or stage of construction to be signed by the EOR and the Responsible Tailings Facility Engineer (RTFE). Likewise, ANCOLD (2019), ICOLD (2020b Bulletin 194), and MAC (2021) require/advocate/recommend thorough as-built documentation.

An As-built Report was prepared for Stage 1A/1B TSF Raise (116259.26 R01 Rev 1). The As-Built Report for Stage 1C is being finalised.

• **Prepare an Operations, Maintenance and Surveillance (OMS) Manual.**

The Kainantu Gold Mine TSF Operations and Management Plan (K92, 2022) provides many of the required elements of an OMS Manual but upgrades are needed to meet the state of practice standards. GISTM (2020) Requirement 6.4 says to “Develop, implement, review annually and update as required an Operations, Maintenance and Surveillance (OMS) Manual that supports effective risk management”. ANCOLD (2019) indicates that an OMS Manual should be produced prior to commencement of any tailings placement. Likewise, ICOLD (2020b Bulletin 194) and MAC (2021) recommend operations, maintenance, and surveillance plans are detailed in an OMS Manual. This is consistent with the recommendation made in SLR (2022) to develop an OMS Manual by using the existing OMP document as a starting point.

OMS Manual was revised and Issued September 2024, Document 116259.28R01.Rev0 (OMS) and 116259.28R03.Rev0 (TARP).

• **Spillway and Flood Storage Design.** The ATC spillway design (ATC 2021) allowed for the Probable Maximum Flood (PMF) which is consistent with the requirement for the ‘Extreme’ consequence category of the facility. The supporting water balance analysis did not include robust analysis with multiple scenarios which should be considered for an ‘Extreme’ classification facility.

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‘In the 2024 ‘Stage 1B TSF – Spill Risk Assessment’ (Ref:116259-48M02 – 7 May 2024) we state:

The following limitations were identified in the development of the WBM:

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Site daily rainfall records were made only available from 2012 to 2024, with no long-term site rainfall data available at the time of this assessment. Long-term daily rainfall is a key component required for the WBM to run a Monte Carlo simulation. As such a data set was developed in order to estimate rainfall for days beyond the available site records. The ‘CRU TS3.10’ dataset provides monthly rainfall records from 1901 to 2011, and the site daily records were utilised to calculate the daily rainfall ratio for the monthly rainfall totals. Based on these two datasets, the daily ratios from 2012 to 2024 were cycled through the ‘CRU TS3.10’ monthly rainfall dataset to calculate the daily rainfall over the period from 1901 to 2011. The calculated daily rainfall data was scaled with a factor of 1.23 was combined with the site recorded rainfall dataset to set up the Monte Carlo simulation.’

As identified in the Spill Risk Assessment, a high quality site specific dataset was not available to undertake analysis for ‘multiple scenarios’. As conservative approach was undertake to replicate the short site based time series data for a 120 realisation (climatic scenario) Monte Carlo simulation

• **Inspection of TSF - Geotechnical**:

Provided records indicate weekly TSF inspections were completed from the end of March 2023 to April 2023. The inspection summary present status on general site condition with respect to installed monitoring instruments, dam slopes, HDPE liner on the upstream side of the TSF crest, beach angle and supernatant pond, downstream under drainage. It is recommended and may be assumed that documented weekly inspections are undertaken throughout the year, however complete records were not provided.

Weekly TSF 274 Geotechnical Inspections reports have indeed been completed. All completed reports are stored in the site GISTM Knowledge Base directory.

• **Monitoring data.**

No geotechnical instrumentation or performance monitoring data with respect to pore water pressure measurements within the dam fill and foundations were available for review. Google Earth Timeline images do, however, provide some indications how the existing TSF has been operated with respect to a tailings beach, size of the water pool, and available freeboard, as illustrated in Photo 1 to Photo 5.

**Photo 1 – September 2015 (Mine at Care and Maintenance)**

**Photo 2 – June 2018 (Mine at Operations)** K92 TAILINGS STORAGE FACILITY DESIGN REVIEW

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Photo 3 – July 2019 (Mine at Operations)

Photo 4 – September 2021 (Mine at Operations)

Photo 5 – September 2022 (Mine at Operations)

A monthly geotechnical report is prepared that reviews all instrumentation including piezometers, Vibrating Wire Piezometers and SAAV instruments, and can be found at the following location within the site GISTM Knowledge Base directory.

[J:\15000 Projects\S3E 5100 Tailings Storage Facility\GISTM\K92 TSF Knowledge Base\16. Monitoring Data & Surveys\18. Monthy Geotechnical Reports\2024](file:///\\K92\dfs\Data\15000%20Projects\S3E%205100%20Tailings%20Storage%20Facility\GISTM\K92%20TSF%20Knowledge%20Base\16.%20Monitoring%20Data%20&%20Surveys\18.%20Monthy%20Geotechnical%20Reports\2024)

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• **Management and Governance.**

Key individuals responsible for ensuring the safety of the tailings dam such as the Engineer of Record, Accountable Executives, Responsible Tailings Facility Engineer, and an Independent External Tailings Review Board (ITRB) as included in the GISTM (2020), ANCOLD (2019), ICOLD (2020b Bulletin 194), and MAC (2021) were not identified in the documents provided for review.

K92 TAILINGS STORAGE FACILITY DESIGN REVIEW FILE: 704-ENG.VMIN03282-01 | MAY 25, 2023 | ISSUED FOR REVIEW 7 Attachment D - TM\_K92\_TSF\_Review\_DRAFT\_Updated.docx

This is consistent with the suggestion made in SLR (2022) that, to ensure compliance with the GISTM, the roles of the Accountable Executive, Responsible Tailings Facility Engineer (RTFE), EoR (already appointed), and ITRB should be appointed.

K92 is working towards formal adoption of GISTM, and to this end has recently appointed an RTFE.

It has included in its 2025 budget to appoint an ITRB.

K92 has nominated all key individuals responsible for ensuring the safety of the tailings dam in its TSF OMS manual including TARP.

• **Prepare an Emergency Preparedness and Response Plan (EPRP).**

GISTM (2020) Principle 13 says to prepare for emergency response to tailings facility failures by developing and implementing an EPRP. Likewise, ANCOLD (2019), ICOLD (2020b Bulletin 194), and MAC (2021) require some form of a dam safety emergency plan. Although an analysis of flow failure scenarios is presented in the ATC report, emergency preparedness measures for potentially affected people are not identified. This is consistent with the SLR (2022) recommendation to develop an EPRP alongside a Trigger Action Response Plan (TARP). SLR (2022) notes that the existing Emergency Safety Plan (ESP) has numerous gaps relative to the GISTM standards.

An emergency response plan has been developed but is currently being updated following completion of Stage 1C TSF Raise construction, including the installation of an early warning emergency evacuation alarm. When issued, this report will be: 116259.28 R02.

In 2025 as K92 moves towards the formal adoption of GISTM the Emergency response plan will be reviewed to ensure no gaps exist relative to GISTM standards.