Design Ground Motions for Kainantu Gold MinePeer-Review

Kainantu Gold Mine. Papua New Guinea - K92 & Tetra Tech Coffey

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# Support

## PSHA Ground Motions

**ATC/W 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 seismic sources referenced by K92 are the **Ramu–Markham Fault System (RMFS)**, located within 15 km of the tailings facility and capable of full-segment ruptures with magnitudes Mw 8.1–8.3 ([Wallace et al. 2021](#ref-Wallace2021)), and the **New Britain (NB) subduction interface**, known to have produced megathrust events with magnitudes ranging from Mw 8.0 to 8.8 ([United States Geological Survey 2007](#ref-USGS2007)). Published studies reporting PGA values close to 0.90g for the region include those by ([Hadi Ghasemi et al. 2020](#ref-Ghasemi2020)) and the GEM seismic hazard model documentation for Papua New Guinea ([Global Earthquake Model Foundation 2023](#ref-GEM2023)), available online here: ([PDF](https://hazard.openquake.org/gem/pdf/png-report.pdf)). The K92 comment stands.

**ATC/W response:** *Unless we find more convincing data that 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.*

An independent probabilistic seismic hazard analysis was conducted by SRK at the TSF coordinates using the Papua New Guinea seismic hazard logic tree developed by the Global Earthquake Model ([Global Earthquake Model Foundation 2023](#ref-GEM2023)). The internal details of the ATC/W logic tree — including source‐zone definitions, recurrence parameters, GMPE selection, and their assigned weights — are not publicly disclosed. Technical documentation for the ground‐motion equations, source models, and logic trees in the GEM 2020 hazard model is available onlinein the following [URL](https://www.globalquakemodel.org/product/papua-new-guinea-hazard).

The independent SRK analysis produced a peak ground acceleration (PGA) of 0.63 g for reference rock ( m/s) at an annual exceedance probability (AEP) of 1/475. This result is consistent with the range of 0.70–1.10 g reported by the GEM 2023 Global Seismic Hazard Map for the Markham–Kainantu region. For the same return period, ATC/W adopted a PGA of 0.31 g, which is approximately 50.8% lower than the independent result and also below the GEM 2023 range (0.59–0.89 g).

For the Operating Basis Earthquake (1/2,000 yr), the ATC/W 2020 PSHA adopts a PGA of 0.53 g for reference rock ( m/s). The GEM 2023 model reports a PGA of 0.98 g for the same conditions, representing a 45.9% higher value than that used by ATC/W.

A benchmark ergodic, nonlinear site-response analysis performed at the TSF coordinates indicates also that peak ground acceleration (PGA) values for softer soils (Site Class D) are approximately 40% lower than those computed for rock conditions (Site Class BC). The differences become more pronounced at longer return periods. These results indicate significant nonlinear amplification effects at the TSF location for alluvial soils and larger (SEE/MCE) seismic events.

## Rupture Size

**ATC/W response:** *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.*

The differences in computed ground accelerations between the Ghasemi et al. ([2016](#ref-Ghasemi2016)) and DIM–ASIA ([2016](#ref-DimasGibson2016)) area‐source models cannot be attributed solely to variations in maximum magnitude (). While higher values generally lead to larger accelerations, seismic hazard outcomes are also strongly influenced by recurrence parameters (, ), source geometry and segmentation, rupture characteristics, and especially by the selection and weighting of Ground Motion Prediction Equations (GMPEs) ([McGuire 2004](#ref-McGuire2004); [Bommer et al. 2015](#ref-Bommer2015)). In subduction‐dominated regions such as Papua New Guinea, these modelling choices can equal or exceed the influence of on hazard estimates ([Norman A. Abrahamson, Gregor, and Addo 2020](#ref-Abrahamson2020)).

It is also relevant that ATC/W’s comparison used the 2016 Ghasemi et al. model ([H. Ghasemi et al. 2016](#ref-Ghasemi2016)), whereas the current GEM PNG hazard model is based on an updated 2020 version by the same lead author ([Hadi Ghasemi et al. 2020](#ref-Ghasemi2020)), in which many values and other key source parameters have been revised. Consequently, conclusions drawn from the 2016–DIM–ASIA comparison may not reflect differences between DIM–ASIA and the most up‐to‐date Ghasemi model currently underpinning GEM PNG.

## DSHA Ground Motions. Maximum Credible Earthquake

The ATC/W dynamic deformation analysis considered two seismic loading levels: the Operating Basis Earthquake (OBE) and the Safety Evaluation Earthquake (SEE/SSE). The OBE was defined from the site‐specific PSHA as the 2{,}000‐year return period event, with a bedrock PGA of approximately at , spectrally matched to the corresponding uniform hazard spectrum. The SEE/SSE was defined as the 10,000‐year return period event, with a PGA of approximately at , also spectrally matched to its target spectrum. These two levels were used to evaluate the potential dynamic deformation of the TSF under both operational and extreme seismic conditions.

The deterministic maximum credible earthquake (MCE) scenario adopted by ATC/W yields a mean peak ground acceleration (PGA) of at , effectively when rounded. This value is essentially the same as the PGA from the probabilistic seismic hazard analysis (PSHA) for a 10,000‐year return period, .

Given that the ATC/W deterministic MCE at is (effectively ) and essentially matches the project’s 10{,}000-year PSHA PGA of ([Dimas 2020](#ref-ATCW2020)), a modest downward bias in the MCE is plausible but is not expected to approach the larger discrepancy observed at the 1/475 PSHA level between ATC/W and GEM-based benchmarks ([Dimas 2020](#ref-ATCW2020); [H. Ghasemi et al. 2023](#ref-GEM2023PNG)). The reason is structural: the deterministic MCE is defined by a single controlling scenario that maximizes ground motion at the period of interest and is therefore not affected by 50/50 averaging across alternative seismotectonic models; any residual bias would primarily stem from the chosen GMPE suite and weights, which influence both DSHA and PSHA but act through ground-motion scaling rather than source omission effects ([McGuire 2004](#ref-McGuire2004); [Bommer et al. 2015](#ref-Bommer2015)). Consequently, if the GMPE set underpredicts motions for the controlling large-magnitude, short-to-moderate distance scenario, the MCE could be somewhat underestimated, but the effect would be expected to be materially smaller than the gap identified for the 1/475 PSHA comparison.

## Ground Motion Prediction Equations (GMPE)

**ATC/W response:** *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.*

ATC/W states that the seismic hazard analysis incorporates GMPEs for both shallow crustal (NGA-West2) and subduction-zone earthquakes (BC Hydro). Given the proximity of significant seismic sources—including the Ramu–Markham Fault System (RMFS) capable of large crustal earthquakes, and the New Britain subduction megathrust capable of producing Mw 8.0 events—it is critical to confirm that the weighting of these GMPE sets adequately represents regional seismic hazard conditions.

While NGA-West2 models have been extensively validated globally for active shallow crustal regions ([N. Abrahamson et al. 2014](#ref-Abrahamson2014); [Boore et al. 2014](#ref-Boore2014); [Campbell and Bozorgnia 2014](#ref-Campbell2014)), and the BC Hydro subduction GMPE is based on global subduction data ([N. A. Abrahamson, Gregor, and Addo 2016](#ref-Abrahamson2016); [Norman A. Abrahamson, Gregor, and Addo 2018](#ref-Abrahamson2018); [Parker et al. 2020](#ref-Parker2020)), explicit verification of their applicability to Papua New Guinea conditions through residual analyses using regional seismic records is recommended.

However, the author is unaware of the current availability of sufficient strong-motion records from bedrock conditions near these seismic sources, which may pose challenges for conducting such residual analyses. A practical first step could involve reviewing available studies, including those by Ghasemi et al. ([2020](#ref-Ghasemi2020)), to determine whether appropriate validation or calibration has already been performed or whether additional investigations are necessary.

## Source Models

Two complete alternative seismogenic source models have been applied in Papua New Guinea PSHA: (i) the Geoscience Australia PNG models developed by Ghasemi et al. ([H. Ghasemi et al. 2016](#ref-Ghasemi2016), [2023](#ref-GEM2023PNG); [Hadi Ghasemi et al. 2020](#ref-Ghasemi2020)), which underpin the GEM PNG hazard model and are generally regarded as state of practice, and (ii) the DIM–ASIA (ASIA‐1) model by Dimas and Gibson ([Dimas and Gibson 2016](#ref-DimasGibson2016)), a 3D representation of crustal, subduction‐interface, and intraslab sources. In the 2020 ATC/W study, these two full models were assigned equal weight (50% each) in the logic tree.

Epistemic uncertainty is typically addressed by branching on key parameters—– and –values, slip rates, segmentation, geometry, and —within a single comprehensive model ([McGuire 2004](#ref-McGuire2004); [U.S. Nuclear Regulatory Commission 2012](#ref-NRC2012); [Bommer 2012](#ref-Bommer2012)). Mean hazard is obtained by weighting exceedance rates or probabilities, not by averaging intensity measures such as PGA or . When a branch omits a physically credible source, its contribution to the mean is proportionally reduced, which can bias hazard estimates.

SSHAC guidance cautions that logic‐tree branches should represent complete alternative scientific interpretations; undisputed sources should not be alternately omitted in a competing full model but instead included in a comprehensive model with parameter‐level branching ([U.S. Nuclear Regulatory Commission 2012](#ref-NRC2012); [Bommer 2012](#ref-Bommer2012)). Assigning equal weight to two complete models where one omits a credible contributor effectively halves its influence on the mean hazard. A defensible approach for this site is to adopt one comprehensive PNG source model that includes all credible contributors and then represent lack of consensus on key parameters (e.g., , ‐values/recurrence) through logic‐tree branches. This approach aligns with recent PNG regional practice ([Hadi Ghasemi et al. 2020](#ref-Ghasemi2020); [Global Earthquake Model Foundation 2023](#ref-GEM2023)).

## Vertical Ground Motions

**ATC/W 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.*

Routine practice typically focuses dynamic deformation analyses on horizontal ground motions for earth and rockfill dams subjected to moderate-to-strong earthquakes ([Dams (USSD) 2022](#ref-USSD2022)). However, FEMA ([2015](#ref-FEMA2015)) guidelines indicate that vertical accelerations near active faults can be significant and may even exceed horizontal accelerations. Although neither ANCOLD nor USSD universally requires including vertical motions, both recommend explicitly evaluating vertical ground motions near large faults, either through sensitivity checks or as separate load cases ([Dams (USSD) 2022](#ref-USSD2022); [Australian National Committee on Large Dams 2019](#ref-ANCOLD2019)).

Considering the proximity of the RMFS, capable of producing earthquakes with , explicitly incorporating vertical ground motions into dynamic deformation analyses is appropriate for load cases associated specifically with RMFS seismic events. For these load cases, ensuring realistic vertical spectra and vertical-to-horizontal (V/H) ratios from the ATC/W seismic hazard analysis requires careful validation of the selected GMPEs and their weighting for vertical predictions. On the contrary, vertical ground motions unrelated with the RMFS scenario should not be included.

**ATC/W response:** *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).*

The Zipingpu Dam example cited by ATC/W represents only a single case history and is insufficient for drawing generalized conclusions regarding vertical shaking effects. The deformation response of dams under large events depends strongly on ground motion properties such as shaking duration and frequency content. Reliable assessments require analysis of multiple earthquake records relevant to the regional or tectonic context, including both vertical and horizontal accelerations. Consequently, the Zipingpu example alone does not substantiate ATC/W’s broader inference for dam performance predictions at other locations, such as the RMFS scenario.

# Summary

* The PGA values adopted by ATC/W for key design events are significantly lower compared to independent hazard analyses based on the GEM (2023) model. Specifically, ATC/W reports a PGA of 0.31 g for the 1/475-year event and 0.53 g for the 1/2000-year event, which represent reductions of approximately 50.8% and 45.9%, respectively, relative to GEM-based reference results (0.63 g and 0.98 g). These substantial differences suggest potential underestimation of seismic hazard at the TSF site and warrant further review ([Dimas 2020](#ref-ATCW2020); [H. Ghasemi et al. 2023](#ref-GEM2023PNG)).
* The observed discrepancies arise predominantly from methodological differences, including the selection and weighting of Ground Motion Prediction Equations (GMPEs), the equal weighting (50/50) of two complete alternative seismogenic source models—Ghasemi et al. ([2020](#ref-Ghasemi2020)) and DIM–ASIA ([2016](#ref-DimasGibson2016))—and the treatment of epistemic uncertainty predominantly at the model rather than at the parameter level. This approach deviates from established SSHAC guidelines and current regional practice, potentially suppressing credible seismic contributions included only in one model ([U.S. Nuclear Regulatory Commission 2012](#ref-NRC2012); [Bommer 2012](#ref-Bommer2012)).
* ATC/W’s deterministic Maximum Credible Earthquake (MCE) PGA (approximately 0.90 g) closely aligns with the 10,000-year return period PGA from their probabilistic analysis (0.89 g). However, any residual bias in this deterministic value is likely attributable to GMPE selection and weighting rather than model averaging effects, implying that potential underestimation at shorter return periods (such as 1/475) is structurally more significant ([Dimas 2020](#ref-ATCW2020); [McGuire 2004](#ref-McGuire2004); [Bommer et al. 2015](#ref-Bommer2015)).
* Given the site’s proximity to active fault systems such as the RMFS, explicit consideration of vertical ground motions is justified for seismic loading cases associated specifically with this fault. Major international guidelines (e.g., USSD, FEMA, ANCOLD) highlight that vertical accelerations near active faults can significantly influence dynamic performance, recommending verification through appropriate vertical-to-horizontal (V/H) ratios for near-fault scenarios ([Dams (USSD) 2022](#ref-USSD2022); [Federal Emergency Management Agency 2015](#ref-FEMA2015); [Australian National Committee on Large Dams 2019](#ref-ANCOLD2019)).
* ATC/W’s internal logic-tree parameters, including source-zone definitions, recurrence parameters, GMPE selections, and assigned weights, are not publicly disclosed, limiting transparency. In contrast, the GEM (2023) hazard model is both publicly available and peer-reviewed, incorporating updates to key parameters such as compared to earlier versions (e.g., Ghasemi et al., 2016). Greater alignment with transparent, regionally validated models would substantially reduce uncertainty and enhance the reliability of seismic hazard inputs for engineering design ([Dimas 2020](#ref-ATCW2020); [H. Ghasemi et al. 2023](#ref-GEM2023PNG); [Hadi Ghasemi et al. 2020](#ref-Ghasemi2020)).
* The impact of nonlinear site-response effects on softer soils (Site Class D) significantly reduces PGA values relative to rock conditions (approximately 40% lower), with the effect becoming more pronounced at longer return periods. Explicitly accounting for these nonlinear amplification characteristics at the TSF location is critical for accurately evaluating dynamic response and seismic risk at higher seismic loading levels such as the SEE/MCE.

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