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EARTH SCIENCE CONSULTANTS

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From: Ivan Wong

To: Victoria Peacey

**SUBJECT: Response to Action Item GS-16 and Follow-up from FMEA Workshop: Induced Earthquakes at the Resolution Copper Mine and TSF**

In response to GS-16, I have evaluated two potential issues that have been raised as part of the EIS process and risk assessment for the proposed Resolution Copper Mine and tailings storage facility (TSF). The first issue described in the letter to Ms. Peacey from Neil Bosworth, U.S. Forest Service dated 14 February 2020 is what is the level of ground shaking that could be produced by caving-induced fault-slip events (earthquakes) at the proposed Resolution Copper Mine as described in Itasca (2019). The second issue raised during the risk assessment hold by the U.S. Forest Service on 5-6 February 2020 is what is the potential for induced seismicity, as observed in water impoundment dams, due to development of the proposed TSF. The following describes my evaluation of these two issues.

## Caving-Induced Earthquake Ground Motions

Itasca (2019) assessed the potential for mining-induced fault-slip seismicity at the proposed Resolution Copper Mine. They assumed that the induced seismicity due to the caving process would occur along pre-existing zones of weakness (faults) rather than the other form of rockbursting which is associated with the crushing of highly stressed volumes of rock. The former produces the largest earthquakes (moment magnitude [**M**] > 3) (e.g., Wong, 1992; 1993). Using the FLAC3D model, Itasca (2019) predicted that 19 of 31 faults observed in the mine area would experience seismicity during the lifetime of the mine. The largest predicted earthquake would have a **M** 2.9. As stated in their report, a key assumption is that all the seismic moment is released in a single event rather than several smaller slip events distributed over time. We believe this is a very conservative assumption. In their Table 2 which is reproduced below, we estimated the ground motions from two scenario events: a **M** 2.9 earthquake at a depth of 1500 m along the Anxiety fault and a **M** 2.6 earthquake at a depth of 1300 m on the Camp fault. The latter, although a smaller event, is shallower and is located approximately 240 m above the uppermost portion of the ore body that will be mined. We calculated the ground motions directly above the events to provide the maximum ground shaking that would be produced at the ground surface. We understand that the ground surface is on rock. We also calculated the ground motions at Apache Leap at an epicentral distance of 1.9 km from the mine also assuming rock site conditions.

**Caving-Induced Seismicity Due to Fault-slip at Resolution Mine**

| Fault | Initial Period | Final Period | Maximum Moment Magnitude | Depth (m) |
|---|---|---|---|---|
| MP 3 | YR 1 | YR 3 | 2.1 | 1950 |
| MP 1 | YR 2 | YR 40 | 2.6 | 1900 |
| MP 2 | YR 2 | YR 2 | 1.9 | 1900 |
| Manske | YR 3 | YR 3 | 2.6 | 1900 |
| Paul | YR 3 | YR 15 | 2.6 | 1900 |
| Camp | YR 4 | YR 4 | 2.6 | 1300 |
| Peterson | YR 4 | YR 5 | 2.1 | 1800 |
| Superior | YR 5 | YR 6 | 2.6 | 1600 |
| Hammer N | YR 6 | YR 6 | 2.4 | 1750 |
| Hammer S | YR 7 | YR 23 | 2.8 | 1600 |
| Anxiety | YR 7 | YR 7 | 2.9 | 1500 |
| Andesite | YR 8 | YR 15 | 2.1 | 1950 |
| Gant E | YR 8 | YR 10 | 2.9 | 1550 |
| Paul S | YR 8 | YR 10 | 2.8 | 1680 |
| Hammer SW | YR 15 | YR 18 | 2.4 | 1850 |
| Gant W | YR 21 | YR 26 | 2.6 | 1400 |
| S Boundary | YR 22 | YR 41 | 2.9 | 1700 |
| W Boundary | YR 28 | YR 41 | 1.5 | 1100 |
| Rancho Rio | YR 33 | YR 41 | 1.9 | 1450 |

To estimate the ground motions from the two scenario earthquakes, ground motion models (GMMs) are required. Obviously there is no model that is specific to this potential case at the mine so GMMs from observed cases of induced seismicity are required. There are two published models that might be applicable to this situation: Atkinson (2015) and McGarr and Fletcher (2005). Besides magnitude and distance as inputs into the GMMs, site condition is generally required unless the GMM is for a specific site condition as it is the case for these two models. We understand that the ground surface above Resolution Mine and at Apache Leap is firm rock which would indicate a time-averaged shear-wave velocity in the top 30 m (Vs30) of approximately 760 m/sec.

The Atkinson (2015) GMM was developed using a subset of strong motion records from the Next Generation of Attenuation (NGA)-West2 database for California earthquakes of **M** 3 to 6 at hypocentral distances less than 40 km. None of the earthquakes in the subset of strong motion records were induced. The stochastic point-source GMM was used to help constrain the scaling in both magnitude and distance space. Because induced earthquakes are shallow and hence potentially closer to a site, the ground motion amplitudes can be larger from an induced event than a deeper tectonic earthquake of the same magnitude. A key difference between this model and other GMMs is that the distance-saturation model (represented by parameter $h_{eff}$) was keyed to the shallow depths and short distances as compared to deeper tectonic earthquakes. One potential disadvantage of the Atkinson (2015) model is that because it is based on tectonic earthquakes, if induced earthquakes have different seismic source properties (such as stress drop), the scaling may be different for induced events as compared to tectonic earthquakes. The Atkinson (2015) model has become the most widely-used GMM for injection-induced seismicity in the U.S. and western Canada although new GMMs for injection-induced earthquakes have become available in the past two years that are site-specific e.g., Oklahoma.

In the postulated case of induced seismicity at the proposed mine, the question is raised on whether the Atkinson (2015) model is appropriate for caving-induced earthquakes. For the purpose of this analysis, we assume that is the case. The Itasca (2019) study assumed that the caving-induced fault-slip events were analogous to typical tectonic earthquakes and thus the Atkinson (2015) GMM should be applicable. The model assumes a firm rock site condition (Vs30 760 m/sec). Note, because the minimum magnitude included in the Atkinson (2015) is **M** 3.0, we are extrapolating the model downwards to **M** 2.6. Such limited extrapolation is common in the use of GMMs.

A possibly more appropriate GMM would be a model derived from data from mining-induced earthquakes. The only GMM for mining-induced earthquakes in the western U.S. is the model by McGarr and Fletcher (2005) which is based on a limited dataset of mining-induced earthquakes at the Trail Mountain coal mine in the Book Cliffs of east-central Utah. McGarr and Fletcher (2005) regressed on recordings of 12 mining-induced earthquakes up to Richter local magnitude ($M_L$) 4.2. $M_L$ was assumed to be equivalent to **M.** The recordings were made on hard rock whose Vs probably exceeds 1,500 m/sec. It should be noted that mine seismicity is uncommon in the western U.S. (Wong, 1992; 1993). To my knowledge, the only significant cases in the western U.S. where induced earthquakes have magnitudes exceeding **M** 3 are associated with the silver, lead, and zinc mining in the Coeur d'Alene district in the Idaho Panhandle and the coal-mining induced earthquakes in the Book Cliffs and western Colorado.

Based on the Atkinson (2015) model, the resulting median peak horizontal ground acceleration (PGA), which is the most commonly used ground motion parameter in engineering, for the two earthquake scenarios, **M** 2.9 at 1550 m and the **M** 2.6 at 1300 m are 0.024 g and 0.013 g, respectively. Using the McGarr and Fletcher (2005) GMM, the PGA values are 0.028 g and 0.021 g, respectively. The PGAs between the two GMMs are rather similar despite the two different databases, tectonic versus mining-induced events. This is not surprising given the observations that mining-induced and tectonic earthquakes can be quite similar (e.g., Wong, 1993).

The Atkinson (2015) GMM gives PGA values at Apache Leap of 0.015 g and 0.008 g, respectively, for the **M** 2.9 event (hypocentral distance 2.48 km) and **M** 2.6 event (hypocentral distance 2.33 km). Based on the McGarr and Fletcher (2005) GMM, the estimated PGAs are 0.011g and 0.007 g, respectively.

These ground motions on rock are low as expected for earthquakes smaller than **M** 3.0. Ground motions at these levels are extremely unlikely to produce structural damage. To put these ground motions into context, the following table from the U.S. Geological Survey correlates PGA and peak horizontal ground velocity (PGV) to Modified Mercalli intensities.

| Perceived Shaking | Not felt | Weak | Light | Moderate | Strong | Very Strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| **Potential Damage** | None | None | None | Very light | Light | Moderate | Moderate/ Heavy | Heavy | Very Heavy |
| **PGA (g)** | 0.0017 | 0.0017 to 0.014 | 0.014 to 0.039 | 0.039 to 0.092 | 0.092 to 0.18 | 0.18 to 0.34 | 0.34 to 0.65 | 0.65 to 1.24 | >1.24 |
| **PGV (cm/s)** | <0.1 | 0.1-1.1 | 1.1-3.4 | 3.4-8.1 | 8.1-16 | 16-31 | 31-60 | 60-116 | >116 |
| **Instrumental Intensity** | I | II-III | IV | V | VI | VII | VIII | IX | X |

The highest PGA value from either of the two GMMs for a site above the mine is 0.028 g which corresponds to Modified Mercalli (MM) intensity IV or "light" ground shaking and no potential damage. The ground shaking at Apache Leap is even lower corresponding to MM II to III or "weak" shaking and of course no potential damage. Atkinson (2020) estimated that induced earthquakes have to be at least **M** 4.0 in size to have damage potential within 5 km of the hypocenter. The threshold for damage is estimated to be about a MM intensity VI which is roughly equivalent to a median PGA of 0.11 g (Worden *et al*., 2012). This PGA is a factor of four higher than the estimated ground motions for the mine. (Above table indicates a lower end of the range of 0.09 g).

It should be noted again that the estimates provided by Itasca (2019) are very conservative because they assume that all the seismic moment will occur in a single earthquake. Also as stated earlier, I am unaware of any significant induced seismicity associated with mining in the western U.S. outside of the coal mines in Utah and Colorado and the heavy metal mines in the Coeur d' Alene.

**TSF Induced Seismicity Potential**

The following is taken from Wong *et al*. (2019). Reservoir-induced or more appropriately reservoir-triggered seismicity (RTS) is due to one of two possible mechanisms. The effects of the reservoir itself does not produce earthquakes but instead they can trigger the release of pre-existing tectonic stresses in the form of earthquakes (e.g., Simpson, 1976; WCC, 1977). The presence of the reservoir is able to accelerate the process of stress release, promoting earthquakes to occur that otherwise would have occurred naturally and sometime in the future. This acceleration process is especially important in areas of relatively low seismicity, where the natural rate of strain accumulation is slow and the earth's crust may remain at stress levels near failure for long periods of time.

Although a disproportionately large percentage of the largest and deepest reservoirs (depth ≥ 92 m and/or capacity ≥ 10,000 x $10^6$ $m^3$ [8.1 million acre-feet]) have been associated with reported cases of RTS, increased earthquake activity has also been correlated with small reservoirs such as Lake Mendocino in Californa with depths less than 60 m and capacities less than 1 x $10^8$ $m^3$ (81,000 acre-feet) (Packer *et al*., 1979). Cases of RTS can be divided into two general categories (Simpson *et al*., 1988):

Rapid response: At many reservoirs, increased seismicity rapidly follows the initial filling of the reservoir and the level of seismicity is closely correlated with subsequent changes in the water level of the reservoir. The seismicity at these reservoirs tends to be of relatively small magnitude, commonly swarm-like in nature and concentrated in the immediate reservoir area. The seismicity at these reservoirs may be related to the direct influence of the load of the reservoir acting to both increase the elastic stress in the reservoir area and, through the elastic load, increase the pore pressure in saturated cracks and fissures. This type of response is not limited to but is most common in reservoirs with small volume-to-height ratios where rapid changes in water level are common. The influence of the reservoir in most of these cases is confined to the immediate vicinity of the reservoir.

Delayed response: At some reservoirs there is a considerable delay between the initial filling of the reservoir and the period of significant seismicity. Examples include Kariba, Koyna, and Aswan. In these cases, the influence of the reservoir may reach to greater distances or depths by the diffusion of pore-water pressure along permeable fault zones. By this mechanism, the influence of the reservoir can extend beyond the immediate reservoir area, creating a larger seismically active region.

Whereas at some reservoirs it is possible to categorize the associated seismicity as belonging to one of these two categories (for example, Manic-3 and Monticello appear to be purely cases of immediate response), both types of response may exist at any one reservoir (Simpson *et al*., 1988). It is reasonable to expect that cases showing a delayed response may have a component of immediate response as well.

To my knowledge, there has never been a report of induced seismicity associated with a TSF with one possible exception: the Samarco Mine in southeastern Brazil. Agurto-Detzel *et al*. (2015) raised the issue of the seismicity being induced by the Fundao dam impoundment but they stated that it was impossible to prove because there was no pre-impoundment seismic monitoring.

The process of developing a TSF is unlike the impoundment of water behind a dam. The water content of tailings also varies considerably. The proposed TSF will impound unsaturated tailings. Also for dams, the process of reservoir filling is performed over a period of weeks to months while the development of a TSF takes months to years. The longer the crustal loading process takes due to the accumulation of tailings, the more time the underlying crustal volume has to adjust in terms of its stress changes. The potential increase in pore pressures due to either crustal loading or fluid migration would seem to be quite different between reservoir impoundment and the accumulation of tailings.

In summary, it is extremely unlikely that the development of the proposed Resolution Mine TSF will result in induced seismicity similar to what is sometimes observed for large and deep reservoirs impounded by water retention dams. The process of developing a TSF and its physical impacts on the underlying crust are very different than they are for RTS.

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**Subject: Resolution Copper Mining, LLC – Mine Plan of Operations and Land Exchange – Response to Action Item GS-16 (Geology, Subsidence, Seismicity) and Follow-up Action from the Failure Modes and Effects Analysis (FMEA) Workshop**

Dear Ms. Rasmussen,

Enclosed for your review and consideration and in response to Geo-Subsidence/Seismicity Action Item # GS-16 and a follow up question from the FMEA Workshop (February 5-6, 2020) please see the information below:

1. Response to Action Item GS-16: *Provide additional information that may be available on induced seismicity or land instability related to the block cave operations, potentially including: site-specific analysis of induced fault motion; propagation of these effects; pertinent experiences when constructing Shaft 10; and any analysis of noise and vibration, if that analysis exists. These effects should be focused on the movement of the block cave itself*.
    a. Attachment 1: Technical memorandum by Itasca (2020) titled "*Assessment of Potential for Caving-Induced Fault Slip Seismicity at Resolution Copper Mine*."
    b. Attachment 2: Technical memorandum by Lettis Consultants International, Inc. (2020) titled "*Response to Action Item GS-16 and Follow-up from FMEA Workshop: Induced Earthquakes at the Resolution Copper Mine and TSF* assessing the level of ground shaking that could be produced by caving-induced fault-slip events (earthquakes) at the proposed Resolution Copper Mine as described in Itasca (2019).
    c. There have been no instances of induced seismicity related to the construction Shaft 10.

2. A follow up action item from the Failure Modes and Effects Workshop (February 5-6, 2020).
    a. Technical memorandum by Lettis Consultants International, Inc. (2020) titled "*Response to Action Item GS-16 and Follow-up from FMEA Workshop: Induced Earthquakes at the Resolution Copper Mine and TSF*" assessing the potential for induced seismicity as observed in water impoundment dams, due to the development of the proposed TSF.

Should you have any questions or require further information please do not hesitate to contact me.

Sincerely,

Vicky Peacey
Senior Manager, Permitting and Approvals; Resolution Copper Company, as Manager of Resolution Copper Mining LLC

Attachments:

Attachment 1 – Itasca (2020), Assessment of Potential for Caving-Induced Fault Slip Seismicity at Resolution Copper Mine

Attachment 2 - Lettis Consultants International, Inc. (2020), Response to Action Item GS-16 and Follow-up from FMEA Workshop: Induced Earthquakes at the Resolution Copper Mine and TSF