TECHNICAL MEMORANDUM

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TO Andrew Evers
Ministry of Environment and Climate Change

FROM Alan Hull, Paul Smolkin

POTENTIAL EFFECTS OF EARTHQUAKE SHAKING ON THE PROPOSED CRRRC LANDFILL

This technical memorandum provides additional information on the potential effects of earthquake shaking on the landfill component of the proposed CRRRC. In particular, this memorandum addresses the potential effects on the landfill during an extreme earthquake event. Contingency measures are also discussed.

Earthquake Shaking Assessment

As part of the assessment of the proposed CRRRC project on the Boundary Road Site, Golder analyzed the seismic stability and potential deformation of the landfill component from earthquake shaking using a 2,475-year return period. The analysis results are presented in Volume III of the EA package. An overview of the results and additional information on this subject was prepared by Golder and provided to the MOECC in the June 2015 and March 2016 response documents. The seismic design approach for the CRRRC landfill component is consistent with both the accepted level of seismic design in Canada for buildings as set out in the National Building Code of Canada (NBCC) and for landfills as regulated in the USA. In the NBCC and the USA Federal Landfill regulations, the design earthquake ground motion has a return period of 2,475 years and represents the level of ground shaking calculated to have a 2% probability of being exceeded in the next 50 years.

The ground shaking to be used at a site for seismic design as stipulated in the NBCC is based on a national hazard model for Canada developed by the Geological Survey of Canada (GSC). The GSC provides 2,475-year ground shaking values for sites in Canada, including an estimate of the magnitude and distance to the earthquakes that make the largest contribution to the hazard at the site. The GSC model shows that the earthquake shaking with a 2,475 year return period at the CRRRC site is contributed mostly by earthquakes with magnitudes, (**M**[1]), between **M** 6 and **M** 7 located between 25 and 72 km from the CRRRC site. Accordingly, actual and synthetic earthquake records that represent these types of earthquake magnitudes and distances were used to assess the seismic stability of the CRRRC landfill slopes. The CRRRC landfill slopes were found to be stable during the shaking estimated from these earthquakes. The predicted lateral deformation of the toe of the landfill was small (less than about 350 mm) under the modelled 2,475-year earthquake design loads. Neither the effects of earthquake

[1] Moment earthquake magnitude.

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shaking, nor the expected ground settlements from the waste loading, were predicted to have an adverse effect on the performance of the landfill during or after its "contaminating lifespan."

The location of the Boundary Road Site relative to Holocene-active faults (faults that have experienced activity in the past 11,700 years) also satisfies the regulatory requirements for landfill siting in British Columbia and the USA (in the absence of such standards in Ontario). Golder's assessment is that there are no Holocene-active faults in the vicinity of the proposed CRRRC, and certainly not within either the 60 m (the US standard) or 100 m (the BC standard) setback required for landfills from Holocene-active faults in those jurisdictions. This conclusion appears to be shared by the experts at the Ontario Geological Survey, who note in their comments of September 7, 2016 that the available information "*suggests that bedrock faults in the vicinity of the CRRRC have not moved significantly since at least the last glaciation, more than 12,000 years ago*."

Additional "Extreme Earthquake" Assessment

The July 21, 2016 letter from Mr. David Williams, the person responsible for the inferred bedrock geology depicted on OGS bedrock geology map MRD 219, indicates that Mr. Williams has updated his interpretation. He now infers a fault about 2.2 km farther north than shown on map MRD 219, and roughly the same distance north of the northern limit of the proposed CRRRC landfill. Golder's interpretation of the updated geological information does not support the existence of this inferred fault. However, because a fault has been inferred by Mr. Williams, additional seismic stability analyses were undertaken to consider the potential earthquake shaking effects on the proposed CRRRC landfill should this inferred fault move and generate an earthquake in the future.

An assumed large magnitude earthquake occurring on an inactive fault located very close (2.2.km) to the proposed CRRRC landfill represents an extreme event earthquake scenario for the CRRRC site because the assumed earthquake essentially occurs directly beneath the site. Ground motions from a large earthquake generated on an inactive fault directly under a site can be expected to be much larger than the **M** 6 to **M**7 earthquake occurring 25 to 70 km away from the site corresponding to the 2,475 year return period design earthquake ground motion for landfill seismic analysis and design specified in the US Federal landfill regulations and in the NBCC for building design in Canada.

For the extreme event analysis, it was assumed that an earthquake will be generated by future movement along the fault now inferred by Mr. Williams some 2.2 km north of the landfill component of the CRRRC. This fault was assumed to be an oblique strike-slip fault, about 35 km long (as per other inferred faults shown on map MRD 219), and dipping north at 60°. Consistent with the earthquake locations in eastern Canada, the hypocenter of the earthquake was inferred to occur with the Precambrian basement rock, at a depth of 10 km.

The earthquake magnitude for the fault movement was estimated using the Nuttli (1983) earthquake magnitude, fault length scaling relationship. The Nuttli (1983) relation was selected because it was developed to estimate earthquake magnitudes in stable continental regions of eastern North America. The estimated median earthquake magnitude developed on the 35 km long fault is about **M**[2] 7.06. The magnitude has a standard deviation of ± 0.26 magnitude units according to Anderson et al. (2006). Accordingly, an earthquake magnitude of **M** 7.3 (i.e., the median plus one standard deviation) was used to estimate the horizontal peak ground acceleration (PGA) and peak ground velocity (PGV) from this earthquake at the CRRRC site.

PGA and PGV estimates were developed using a number of published relationships to estimate the ground earthquake shaking as a function of earthquake magnitude and distance. The estimated PGA from an **M** 7.3 earthquake generated 10 km deep within the basement rock and extending along a fault to the ground surface located 2.2 km from the landfill site is about 2.5 g[3]. The estimated PGV is about 0.5 m/s for this extreme earthquake scenario. The conservative nature of this analysis is reinforced by the observation that these estimates are very high when compared to earthquake ground shaking recorded close to similarly large earthquakes in western North America, which rarely exceed 1 g. This extreme earthquake scenario produces a level of ground shaking with a return period longer than 100,000 years based on the 5th Generation National Seismic Hazard Model for Canada developed by the GSC. This return period is equivalent to an annual exceedance probability of 0.00001 or approximately equivalent to a 0.05% probability of being exceeded in the next 50 years. The long return period and low annual exceedance probability confirm the very low probability of occurrence for ground shaking associated with an **M** 7.3 earthquake so close to the CRRRC site. The very low probability of the extreme earthquake is significantly lower than the 2,475 year return period (2% probability of exceedance in 50 years) that is accepted for building life safety design and for landfill design at the CRRRC site.

The FLAC model used for the original seismic stability analysis in the EA was again used to assess the potential shaking effects from the extreme earthquake at the CRRRC landfill component. Because the estimated PGA for the design earthquake shaking (0.24 g) is about one-tenth of the estimated PGA for the extreme earthquake (2.5 g), the extreme earthquake analysis used the earthquake acceleration records from the 2,475-year return period design earthquake and multiplied them by 10. The 10 times increase reflects earthquake shaking from the extreme earthquake that is 10 times greater than the earthquake shaking used for the seismic stability of the design earthquake.

The results of the analysis indicate that the landfill remains stable under this very extreme and low probability earthquake scenario; however, the very large applied PGA and PGV (compared to the 2,475 year return period event) predicts lateral deformations of 5 to 6 metres at the toe of the landfill. The landfill itself, however, remains as a largely intact mass. While these computed displacements are about 15 to 20 times greater than the displacements computed previously for the 2,475 year return period ground motions, the analysis indicates that the landfill will remain stable even under extreme earthquake loads with a very low probability of occurrence (i.e., only a 0.05% chance of occurring in the next 50 years).

Under such an extreme and low probability earthquake and associated ground motions, the toe and portions of the sideslopes of the CRRRC landfill could be damaged, but as described above and further described below the damage to the landfill would be localized and readily capable of being repaired.

Potential Effects of Earthquake Shaking on the Proposed CRRRC Landfill

While the principles of engineering design for earthquake loads are well established, the true test of the earthquake design of a landfill is its performance during large earthquakes. This section of the memorandum provides information on the observed performance of landfills subjected to earthquake shaking. We are not aware of reports from modern, engineered Canadian landfills that have experienced strong earthquake shaking, probably because strong earthquakes are rare in Canada, and in particular in eastern Canada. In the western USA, however, and California in particular, strong earthquakes are relatively frequent, and occur in areas with large populations and many landfills.

[3] 1 g is the acceleration due to gravity at the Earth's surface at about 9.8 m/s^2

California Landfills

As described by Matasovic et al (1998)[4], active and closed landfills in California have proven to be very stable during large earthquake shaking. Post-earthquake evaluations of landfills up to 75 m high undertaken from the late 1960s to the mid-1990s, for earthquakes ranging from magnitude (M) 5.6 to 7.3 in the Los Angeles and San Francisco areas, indicate that landfill slopes and landfill leachate collection systems performed very well during earthquake shaking for all the landfills assessed. The solid waste landfills evaluated in California were both unlined and lined with geomembrane liner systems. At the time of the earthquakes, the landfills had relatively steep sideslopes of 2 Horizontal to 1 Vertical (2H:1V) to 3H:1V, which is significant when compared to the much flatter 14H:1V slopes proposed for the CRRRC landfill. The observed post-earthquake shaking effects on the landfills studied ranged from no noticeable effects to small cracks in the landfill soil cover, and minor downslope movement of areas of the cover soil. For those landfills with bottom liner systems, the geomembranes were generally undamaged. At one landfill a tear in a geomembrane was observed on a steep canyon liner above the disposed waste; the underlying soil liner remained intact. In no case was instability of the waste mass observed, nor was there a release of leachate. The observed cracking and other damage was easily and quickly repaired by conventional methods and earth moving equipment. The landfill cover, when damaged, was easy to reinstate. Studies showed that although the waste locally amplified the ground shaking, the relatively high internal strength of the waste limits its movement, even under very strong shaking.

Proposed CRRRC Landfill

Design and Operational Features: At the proposed CRRRC landfill, as noted above, the landfill sideslopes are designed to be at a very low angle of 14H:1V, and to reach to a height of about 12 m, and then flatten even further to top slopes with 20H:1V. The CRRRC landfill has a peak height of only 25 m. There is also a 3.5 m high perimeter stability berm proposed around the landfill. The berm has a top width of 36 m and relatively flat outside sideslopes at 7H:1V. Perimeter leachate containment is assisted by a flexible geosynthetic clay (GCL) liner on the interior of the perimeter berm. The leachate collection system (LCS) overlies a 30 m thick, low permeability silty clay deposit that provides natural, low permeability containment.

The LCS is designed to maintain a maximum leachate level of 0.3 m above the base of the landfill, which is greater than 1 m below the original ground level and about 4.5 m below the top of the perimeter berm. The CRRRC landfill component is designed to ensure that the leachate drains towards the pumped extraction locations within the interior of the landfill. The extraction locations are a minimum of some 125 to 200 m inside the waste footprint. To maintain this low leachate head, the site operations include the continuous removal of leachate from the landfill for treatment; as such, there will only be a limited quantity of pooled leachate within the landfill (and in particular around the exterior portion of the landfill) available at any time for release from the waste footprint in the very unlikely event that an earthquake resulted in a breach in the leachate containment provided by the perimeter GCL and berm. There is also a minimum 100 m buffer width between the waste footprint area and the property boundary, thereby providing ample separation to contain on-site any potential effects from a severe earthquake on the landfill.

As already noted above, the proposed CRRRC landfill has much shallower slopes and is lower in height than the California landfills that had little or no damage during strong earthquake shaking. As also described above, analyses undertaken for the proposed CRRRC landfill demonstrate that the slopes and leachate collection system for the proposed landfill will be stable under the design seismic loads. Even under an extreme earthquake and

[4] Matasovic, N., Kavazanjian, Jr., E. and Anderson, R.L., Performance of Solid waste Landfill sin Earthquakes, Earthquake Spectra, Volume 14, No.2, May 1998.

very low probability scenario, the predicted damage to the landfill would be observable and contained on-site and, as described below, readily remediable.

Contingency Measures: Based on the California experience and taking into account the conservative design features of the CRRRC landfill (flat side slope slopes, internal leachate system) as described above, under the design seismic loading the most likely effects of earthquake shaking would be the opening of cracks in the CRRRC landfill soil cover. Under this design shaking, some localized slumping of the soil cover may also occur, although unlikely considering the very flat 14H:1V sideslopes and low maximum height of the landfill. Under the more severe, extreme and very low probability case shaking conditions assessed above, the much larger deformations may result in some cracking of the landfill cover that could extend down into the underlying waste and outward lateral shifting of portions of the perimeter berm and lower portion of the landfill sideslopes. The GCL on the inside of the perimeter berm is very flexible because of its components (geotextiles and a swelling clay mineral) and can tolerate large movements without tearing. As such, even under these large deformations along a section of the landfill perimeter, the GCL is expected to remain largely intact. In addition, even if localized damage to the GCL occurred, and if there was leachate present in the exterior portion of the landfill area because it had not been removed by the leachate collection system, the leachate would migrate slowly through the approximately 50 metre width of the perimeter berm soil before it seeped out of the berm. Therefore, post-earthquake uncontrolled release of leachate present within the landfill is not predicted or expected, nor is it predicted or expected that any movements of landfill soil cover or shifting of the toe area would extend beyond 5 to 10 metres, which is well within and removed from the CRRRC site boundary. We have not identified a plausible scenario under which even an extreme and very low probability earthquake event could result in off-site adverse impacts associated with the landfill component of the proposed CRRRC.

The CRRRC will of course be carefully inspected in the event of any seismic activity during its operating life and post-closure monitoring period. Any earthquake-related damage to the landfill will be readily observable and could be repaired by standard earthworks to fill any cracks in the soil cover and/or regrade any deformed and/or slumped areas of the landfill and/or perimeter berm. Similarly, if the deformations affected the adjacent stormwater management system components (ponds, ditches), they could be easily reinstated. If the deformations affected the leachate forcemain or landfill gas header located within the perimeter berm, the affected sections of pipe would be isolated and repaired. A release of leachate from the landfill footprint is very unlikely for the reasons discussed above. If it is observed that damage has been caused by a large earthquake event that might result in a leachate release from the landfill footprint, the backup leachate containment provided to the perimeter GCL by the wide perimeter berm provides ample time to implement contingency measures, such as closing the outlet control structures in the perimeter stormwater management system or setting up temporary leachate containment (such as earth dykes or shallow ditches) within the on-site buffer area. Any affected pond or ditches and any temporary leachate control features would be emptied through a temporary pumping operation that would be combined with the landfill leachate for subsequent treatment.

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