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GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8950

# Sixth-generation seismic hazard model of Canada: grid values of mean hazard to be used with the 2020 National Building Code of Canada

Version 1.0

M. Kolaj, S. Halchuk, and J. Adams

2023

Canada

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# CONTENTS

# 1. ABSTRACT

Canada's 6th Generation seismic hazard model is the basis for the seismic design provisions in the 2020 National Building Code of Canada. The 2020 code uses mean ground motions of spectral acceleration at 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0 second periods, peak acceleration and peak velocity for a variety of site conditions. Users of the 2020 code access seismic hazard values by using the 2020 National Building Code of Canada Seismic Hazard Tool which provides values for any site located in Canada. The online tool accomplishes this through the interpolation of a pre-calculated dataset. This Open File provides that dataset for users who may wish to access those values directly, and describes the interpolation methods used.


# 2. INTRODUCTION

Natural Resources Canada (NRCan) has released a new national seismic hazard model, the 6th Generation Seismic Hazard Model of Canada (CanadaSHM6 or CSHM6 for short). Seismic hazard values generated from CanadaSHM6 form the basis for the seismic provisions in the 2020 edition of the National Building Code of Canada (NBCC 2020). Seismic hazard values from CanadaSHM6 and for NBCC 2020 are delivered to users through the NBCC 2020 seismic hazard tool (SHT; NRCan, 2022). The online tool provides the spectral acceleration, peak ground acceleration and peak ground velocity values for the probabilities of 2%, 5% and 10% in 50 years, as prescribed in the NBCC. Other probabilities between 2% in 50 years and 40% in 50 years are also provided as additional information. The tool is able to provide these values for any location in Canada and most site conditions (i.e., those with a $V_{s30}$, the time-averaged shear wave velocity to a depth of 30 m, value from 140 – 3000 m/s or Site Classes E-A) by interpolating a pre-calculated dataset of seismic hazard values. This Open File provides and describes that dataset, and describes the interpolation process.

Readers interested in more detailed information on the CanadaSHM6 seismic hazard model or on the calculation of seismic hazard are referred to Kolaj et al. (2020; 2023a).

Note that this Open File does not include the other, non-NBCC versions of the model (e.g., non-collapsed model) that will be released as a subsequent series of Open Files. In general, when referring to CanadaSHM6, we are either referring to the 6th Generation national seismic hazard mapping project as a whole, or are referencing the version which forms the basis of NBCC 2020.

# 3. THE CanadaSHM6 GRID

For NBCC 2015 and CanadaSHM5, seismic hazard values were provided (and interpolated from) a grid of more than 200,000 points across Canada and surrounding areas (Halchuk et al., 2015). However, for NBCC 2020 the number of different products has increased by more than an order of magnitude due to the move from a single reference site condition to a wide range of reference conditions based on $V_{s30}$ and Site Class. As a result of the increased computational load, the fact that hazard values are generally spatially smooth, and that for large regions within Canada the gradient of hazard is low, it is neither efficient nor computationally practical to use such a dense fixed grid.

As such, for CanadaSHM6 we implemented an optimized unstructured triangular grid with 34,732 vertices creating a grid of 69,430 triangles. Each triangle vertex, referred to as a grid point in this document, is associated with a set of seismic hazard parameters which are used for spatial interpolation. Grid points are on average roughly 20 km apart, with 99.7% of distances being between 3 to 150 km (the increased density being in regions with a higher seismic hazard gradient). It is worth noting that roughly 13% of the distances are less than 10 km (i.e., the CanadaSHM5 grid spacing). The grid covers all of Canada and surrounding areas. The same grid was used for all CanadaSHM6 hazard parameters. An example of the grid for south-eastern Canada is shown in Figure 1. Interested readers are referred to Kolaj (2023) for more information on how the grid was devised.

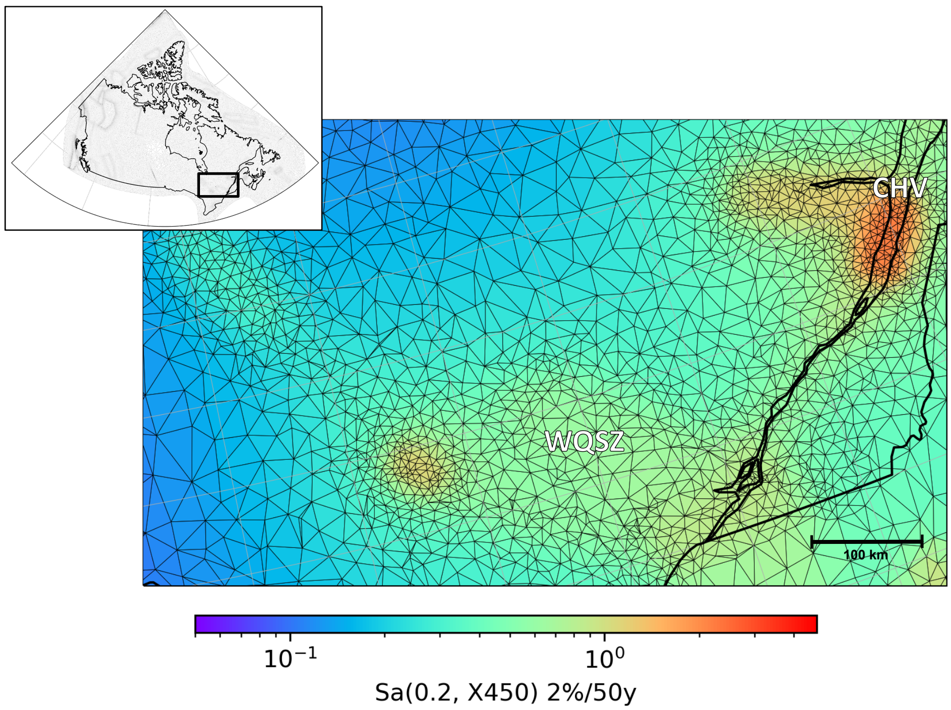


*Figure 1. An example of the CanadaSHM6 triangular grid (black lines) in southeastern Canada. Seismic hazard values (Section 4; Sa(0.2, X450) in this case) are provided for each grid point (vertex). Seismic hazard values for any other point can be solved for via interpolation of the bounding triangle (Section 5). Note the higher density of the grid in regions with larger hazard gradients (e.g., Charlevoix, CHV, and the edges of the west Quebec seismic zone, WQSZ).*

# 4. SEISMIC HAZARD VALUES

Seismic hazard was calculated for each grid point using the model and procedure outlined in Kolaj et al. (2023a). The resultant hazard curves (i.e., exceedance probability versus ground motion amplitude) for the required NBCC 2020 and NBCC 2020 Commentary seismic hazard parameters, were then interpolated using log-log interpolation to provide values for the NBCC exceedance probabilities and for several additional probabilities that may be of use for various engineering or non-engineering projects. The complete list of seismic hazard values provided is given below.

- Site designations (X). Site designation is a new term introduced in NBCC 2020 to describe the site condition. It can be defined via a $V_{s30}$ value ($X_V$ where V is the $V_{s30}$ value) or with a Site Class ($X_S$ where S is the Site Class):
  - Site Classes ($X_S$): A, B, C, D, E

- $V_{s30}$ ($X_V$): 140, 160, 180, 250, 300, 360, 450, 580, 760, 910, 1100, 1500, 1600, 2000, and 3000 m/s
- Ground motion intensity measures:
  - Spectral Accelerations (5% damping): 0.05, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 5.0, 10.0 s.
  - Peak Ground Acceleration (PGA)
  - Peak Ground Velocity (PGV)
- Exceedance probabilities:
  - Percent exceedance in 50 years: 2, 2.5, 3.5, 5, 7, 10, 14, 20, 30, and 40 (see Appendix A for the corresponding annual frequency and return period).

The seismic hazard values for each grid point in the CanadaSHM6 grid are provided in comma-separated-values (CSV) format and are described further in Appendix B. The seismic hazard maps in Kolaj et al. (2023b) may be useful for providing a national and regional context to the individual grid values.

This dataset of values forms the basis for seismic hazard values for the NBCC 2020 and the NBCC 2020 seismic hazard tool. As values are required for arbitrary locations in Canada (which may be some distance from a grid node) and for an arbitrary $V_{s30}$ value (in the range of 140 – 3000 m/s), interpolation is required. Spatial interpolation is described in Section 5 and $V_{s30}$ interpolation is described in Section 6.

# 5. SPATIAL INTERPOLATION

In order to provide hazard values for an arbitrary location in Canada, spatial interpolation of the CanadaSHM6 grid is required. The spatial interpolation algorithm can be divided into two steps: 1) determining which triangle the requested location falls into and 2) linear barycentric interpolation.

Determining which triangle the coordinate falls into can be found using a variety of methods. Our implementation is performed using functions that are part of the MongoDB package (MongoDB Inc., 2022) which forms the basis of our seismic hazard database.

Linear barycentric interpolation on a triangular grid is performed by solving for:

$$\mathbf{r} \approx w_1\mathbf{r}_1 + w_2\mathbf{r}_2 + w_3\mathbf{r}_3$$

Where $\mathbf{r}_{1,2,3}$ are the hazard values at the three vertices of the triangle, $\mathbf{r}$ is the desired interpolated value for the point within the triangle, and $w$ are the associated barycentric coordinates of $\mathbf{r}$. The barycentric coordinates can be calculated a variety of ways using simple arithmetic (not described herein, see "Barycentric coordinate system", 2022).

Our selected projection is the Lambert Conformal Conic projection (EPSG 3978) with standard parallels of 77º and 49º and a central meridian of -95º. This projection was selected as it is a commonly used projection for national scale maps in Canada where direction, angles and shape are maintained across the entire region.

The grid (a description of the connection of the triangle vertices) is provided in the comma-separated-values (CSV) format and is described in Appendix C.

# 6. $V_{s30}$ INTERPOLATION

Once the values for the exact spatial coordinates are available (Section 5), and a site designation using $X_V$ is required (i.e., the user is using $V_{s30}$), interpolation of the hazard value for the specific $V_{s30}$ value is performed. The NBCC 2020 (and CanadaSHM6) Seismic Hazard Tool calculates this using log-log interpolation (i.e., linear interpolation using the log of $V_{s30}$ and the log of the hazard value) of the fifteen pre-calculated $V_{s30}$ values.

An example of a log-log interpolation (using the natural log) to calculate $PGA(X_{400})$ is:

$$PGA(X_{400}) = e^{\left(\log(PGA(X_{360})) + \frac{\log(400)-\log(360)}{\log(450)-\log(360)}[\log(PGA(X_{450}))-\log(PGA(X_{360}))]\right)}$$

# 7. VALIDATION OF THE INTERPOLATION

The reliability of the grid and the spatial interpolation (Section 5) can be determined by comparing interpolated and directly-calculated values. An example of the performance of spatial interpolation is shown in Figure 2. Figure 2 shows the cumulative distribution functions of the percent difference between a range of seismic hazard values calculated for 680 representative Canadian cities and those obtained via interpolation of the CanadaSHM6 grid. A key design component of the grid was for most (e.g., >98%) of the interpolated values to be within 2% of the directly calculated value (Kolaj, 2023). This cut-off corresponds to the intersection of the dashed black line along the y-axis and the maximum ("2.00") percent difference value on the x-axis in Figure 2. All intensity measures meet or exceed this requirement. For a $V_{s30}$ of 160 m/s (top panel), there is a maximum of a 1.0 percent difference for 98% of the cities for all hazard values. For a $V_{s30}$ of 3000 m/s (bottom panel), the percent difference is 1.75% for the same 98% cut-off. In general, long-periods and lower $V_{s30}$ values reach the 98% cumulative proportion faster and this is likely due to the smaller gradients of these hazard parameters. It is important to note that an error of 2% is well below the inherent uncertainty present in the mean hazard values (i.e., roughly a factor of 2 in eastern Canada, Kolaj et al., 2020).

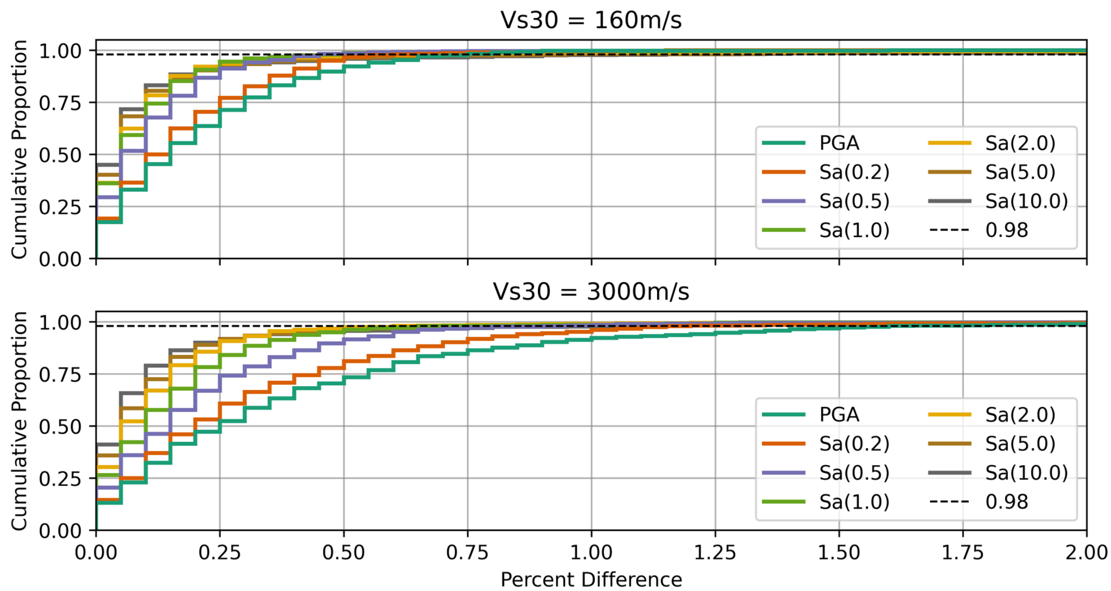


*Figure 2. The cumulative distribution of the percent difference between interpolated and calculated values for 680 representative cities in Canada. Shown for various seismic hazard values at 160 m/s (top) and 3000 m/s (bottom).*

# 8. DISCUSSION

In our view, an appropriate level of precision for seismic hazard values is two significant figures. However, in order to avoid imprecision and rounding errors during various calculations, the hazard values in the NBCC 2020 are provided to end-users with a precision of three significant figures. As such, in order to provide three significant figures of precision for the interpolated (spatially and by $V_{s30}$) values, our database of values is stored with 4 significant figures.

Appendix D contains the latitude and longitude coordinates of the Canadian territory. Seismic hazard at grid points beyond the Canadian territory is likely to be inaccurate (underestimated) because they extend towards regions (e.g. northeastern United States) where the seismic hazard source zones included in CanadaSHM6 represent an incomplete account of the seismicity that is contributing ground motions. While these values are provided in this Open File for completeness and to ensure reliable interpolation along the Canadian border, the NBCC 2020 online webtool does not provide any values outside of Canadian territory. It is not recommended that these distal grid values are used and/or interpreted beyond the intended use (i.e., for improving interpolation). Also, the model does not include stable oceanic crust sources that lie farther offshore than higher-activity offshore sources because such stable oceanic sources would not change the onshore hazard for NBCC. Therefore the hazard for distal points within Canadian territory but offshore of higher-activity oceanic sources are somewhat underestimated. This is most obvious for the region of the Arctic Ocean north of ~80°-85° N that extends to the North Pole, and where the hazard values drop below the stable craton values onshore. Appendix D includes a description of the region in the high-Arctic where caution should be taken in the interpretation of the seismic hazard values.

Hazard gradients, defined as the change in hazard value with distance, are very steep in close proximity to modelled onshore fault(s) in northwestern British Columbia and western Yukon. These regions are indicated in Appendix D. For these regions, further considerations may be required. Some guidance is provided within the NBCC Structural Commentary J (expected to be released by the end of 2023).

The high-probability ground motions (e.g., 40% in 50 year probability) may underestimate actual ground motions due to the lower-magnitude ("$M_{min}$") cut-off used in the seismic hazard calculation. For most areal sources, the lower-magnitude cut-off is $M_W$ 4.8, so contributions from earthquakes smaller than 4.8 are not considered. While shaking from these earthquakes may not be of engineering concern (e.g., due to their lower duration of shaking), they may be a significant contributor to the total seismic hazard value at high probabilities (Halchuk and Adams, 2010).

NBCC 2020 and CanadaSHM6 do not provide values for probabilities below 2% in 50 years. The determination of 1/5,000 or 1/10,000 year (i.e., 0.0002 or 0.0001 per annum) seismic hazard is normally required only for special facilities such as nuclear power plants or dams which have a large consequence if they were to fail. These low probabilities are beyond the scope of the NBCC 2020. Extrapolation of the hazard model to lower probability results is possible, but represents an uncertain extrapolation of the model, and may be unreliable due to (for example) the crudeness of the seismic source zones used in the national NBCC model. Some guidance on possible approaches are provided in "Low probability hazard and the National Building Code of Canada" (2021).

Lastly, as NBCC 2020 and CanadaSHM6 were developed using the open source OpenQuake platform (see Kolaj et al., 2023a), users are encouraged to perform their own seismic hazard calculations to a) reproduce our seismic hazard products and b) then develop new seismic hazard products.

# 8. API

In lieu of the online tool or this Open File, hazard values can also be requested (in json format) through a webservice using the GraphQL Application Programming Interface (API). The webservice address is: https://www.earthquakescanada.nrcan.gc.ca/api/canshm/graphql and is described further in Appendix E.

# 9. ACKNOWLEDGEMENTS

The creation of a new hazard model is a complex undertaking, and has involved many of our colleagues over and above those whose names appear as authors on this and the related Open Files. In particular, we would like to acknowledge the members of the Standing Committee on Earthquake Design and of its the Seismicity and site amplification Task Group. We also thank Philip LeSueur for his review of the Open File which improved this document.

We would also like to especially thank Charles Blais (IT specialist in CHIS) for his work in implementing the NBCC 2020 seismic hazard tool.

# 10. REFERENCES

Please also see the earthquake hazard related publications available at: https://www.earthquakescanada.nrcan.gc.ca/hazard-alea/recpubs-en.php (website address correct as of May 2022).

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# Appendix A: Return period calculation

The probability of exceedance and return period can be expressed through the Poisson relation as:

$$p(T) = 1 - e^{-\lambda T}$$

$$R = 1/\lambda$$

where $p$ is the probability of exceedance in $T$ years, $\lambda$ is the frequency (rate) of exceedance and $R$ is the return period. The CanadaSHM6 pre-calculated values can be seen in Table 1.

*Table 1. Comparison of various quantities to describe the probability of exceedance. Numbers are rounded to standard values. NBCC 2020-defined probabilities are in bold (i.e., 2, 5 and 10%).*

| Probability of exceedance in 50 years (in %) | Annual probability of exceedance | Annual frequency of exceedance | Return Period (years) |
|---|---|---|---|
| **2** | **0.000404** | **0.000404** | **2475** |
| 2.5 | 0.000506 | 0.000506 | 1975 |
| 3.5 | 0.000712 | 0.000713 | 1403 |
| **5** | **0.00103** | **0.00103** | **975** |
| 7 | 0.00145 | 0.00145 | 689 |
| **10** | **0.00210** | **0.00211** | **475** |
| 14 | 0.00301 | 0.00302 | 332 |
| 20 | 0.00445 | 0.00446 | 224 |
| 30 | 0.00711 | 0.00713 | 140 |
| 40 | 0.0102 | 0.0102 | 98 |

# Appendix B: Seismic hazard values

Comma-separated values (CSV) format of the NBCC 2020 and CanadaSHM6 seismic hazard values at the grid points are provided in *Appendices/AppendixB/*. The values are organized into an individual file per site designation where the file names follow the *NBCC_CanadaSHM6_X.csv* convention where *X* is the site designation (e.g., $X_{450}$ or $X_C$).

A description of the fields contained in the csv is provided below:

| Column | Description |
|---|---|
| Index | Unique identifier for the grid node |
| Longitude | Longitude |
| Latitude | Latitude |
| LCC_projected_x | The Lambert conformal conic projected easting (see Section 5) |
| LCC_projected_y | The Lambert conformal conic projected northing (see Section 5) |
| siteDesignation | Site designation |
| poe-in-50-y | Probability of exceedance in 50 years (in %); see also Appendix A |
| Sa(T) | 5%-damped spectral acceleration with a period of T (units: g) |
| PGA | Peak ground acceleration (units: g) |
| PGV | Peak ground velocity (units: m/s) |

# Appendix C: CanadaSHM6 triangular grid

Comma-separated values (CSV) format of the NBCC 2020 and CanadaSHM6 triangular grid points structure is provided in *Appendices/AppendixC/*. This file contains the unique index identifier of each of the vertices of the triangular grid. The triangular grid can be reconstructed by joining the tables in Appendix C with Appendix B on the corresponding index.

A description of the fields contained in the table is provided below:

| Column | Description |
|---|---|
| Triangle_Index | Unique identifier for the triangle |
| Vertex1_Index | Unique identifier for the 1$^{st}$ vertex of the triangle (corresponds to Index in Appendix B) |
| Vertex2_Index | Unique identifier for the 2$^{nd}$ vertex of the triangle (corresponds to Index in Appendix B) |
| Vertex3_Index | Unique identifier for the 3$^{rd}$ vertex of the triangle (corresponds to Index in Appendix B) |

## Appendix D: Seismic hazard zone warnings

*Appendices/AppendixD/* contains geoJSON format files with 4 polygons that describe various warnings used by the NBCC 2020 seismic hazard tool that should also be considered if using the seismic hazard values within this Open File. The warning zones are:

1. *NBC_CNB2020_Canada*: This polygon provides the coordinates for the region within which hazard values are provided (i.e., the Canadian territory). Values outside of this region are only provided in order to improve the interpolation near the edge of the Canadian territory.

2. *NBC_CNB2020_High-Arctic-Warning_Haut-Arctique-Avis*: Within this polygon hazard values may be underestimated due to not considering hazard contributions from sources outside of Canada in the high Arctic.

3. *NBC_CNB2020_NW-Fault-Warning_NO-Faille-Avis_1*: Within 15 km of the East Denali and/or Duke River onshore faults, special considerations may be required to accurately determine the fault-to-site distance and various near-fault effects which may strongly impact ground motions.

4. *NBC_CNB2020_NW-Fault-Warning_NO-Faille-Avis_2*: Same note as #3 above.

# Appendix E: API

In lieu of the online tool or this Open File, hazard values can also be requested (in json format) through a webservice using the GraphQL Application Programming Interface (API). The webservice address is: https://www.earthquakescanada.nrcan.gc.ca/api/canshm/graphql.

A description of the GraphQL API can be found at: https://graphql.org/

The schema for the API can be found in json format in *Appendices/AppendixE/ NBCC2020_schema.json*. Of note are the following fields or functions:

| Field/Function | Description |
|---|---|
| sa0p05 ... sa10p0 | 5% damped spectral acceleration for various periods (see Section 4 for supported periods). Note the use of a "p" in place of a "decimal". |
| poe50 | Probability of exceedance in 50 years (in %) |
| foe | Annual probability of exceedance (fraction) |
| vs30 | $V_{s30}$ of the site designation. Note that when a Site Class is used it will return the $V_{s30}$ range of the Site Class. |

Four examples of API calls can be found below. The Appendix E directory (*Appendices/AppendixE/*) includes the json file that the API returns.

## A. Example 1

Request for PGA, Sa(0.2) and Sa(0.5) for a site designation $X_{760}$ ($V_{s30}$ value of 760 m/s) for probabilities of exceedance of 2%, 5% and 10% in 50 years for a site located at 45.421, -75.697:

```
query{
  NBC2020(latitude: 45.421, longitude: -75.697){
    X760: siteDesignationsXv(vs30: 760, poe50: [2.0, 5.0, 10.0]){
      sa0p2
      sa0p5
    }
  }
}
```

## B. Example 2

Same as example 1 but for a site designation of $X_C$.

```
query{
  NBC2020(latitude: 45.421, longitude: -75.697){
    XC: siteDesignationsXs(siteClass: C, poe50: [2.0, 5.0, 10.0]){
      sa0p2
      sa0p5
    }
  }
}
```

### C. Example 3

Request seismic hazard values for a probability of exceedance of 2% in 50 years for two sites, two site designations $X_V$ ($V_{s30}$'s) and for a larger range of parameters.

```
query{
  Ottawa: NBC2020(latitude: 45.42, longitude: -75.69){
    X250: siteDesignationsXv(vs30: 250, poe50: [2.0]){
      ...groundMotions
    }
    X450: siteDesignationsXv(vs30: 450, poe50: [2.0]){
      ...groundMotions
    }
  }
  Vancouver: NBC2020(latitude: 49.25, longitude: -123.12){
    X250: siteDesignationsXv(vs30: 250, poe50: [2.0]){
      ...groundMotions
    }
    X450: siteDesignationsXv(vs30: 450, poe50: [2.0]){
      ...groundMotions
    }
  }
}

fragment groundMotions on CanSHM6SiteDesignation {
  sa0p2
  sa0p5
  sa1p0
  sa2p0
  sa5p0
  sa10p0
  pga
}
```

### D. Example 4

The API can also return information on whether the requested site is: (1) close proximity to the East Denali and Duke River faults in northwestern British Columbia and western Yukon; (2) in the high-Arctic or (3) in Canada. Refer to the Commentary entitled Design for Seismic Effects in the Structural Commentaries (User's Guide – NBC 2020: Part 4 of Division B) for guidance on these cases. See Appendix D for further information on these zones.

```
query{
  NBC2020(latitude: lat, longitude: lon) {
    ...point
  }
}

fragment point on CanSHM6Point {
  metadata: metadata {
      zones
  }
  X450: siteDesignationsXv(vs30: 450, poe50: [2.0]){
```

```
    sa0p2
  }
}
```

For the appropriate latitude (*lat*) and longitude (*lon*) the API will return a Zones object which will contain 'NBC_CNB2020_NW-Fault-Warning_NO-Faille-Avis' for case 1; 'NBC_CNB2020_High-Arctic-Warning_Haut-Arctique-Avis' for case 2; and/or 'NBC_CNB2020_Canada' for case 3. *Example4.json* includes an example for case 1 and 3 (latitude and longitude of 61.252 and -138.804, respectively).