WINSTON-BATAN: A SEISMOLOGICAL GROUND-MOTION ANALYSIS CODE

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Abstract. A thorough understanding of an earthquake is very important to provide a descriptive knowledge and in the same time as a prescriptive knowledge for the future development. In particular, it is essential for site selection and structural design development of nuclear reactor and other critical facilities. Ground motion acceleration time history is an important raw information to understand the earthquake and specific geological condition of where the data is recorded. This paper presented the development of strong-motion analysis code, called Winston-BATAN, which able to interpret ground motion time history. The analysis scope of the code including the ground motion parameters such as peak ground acceleration, several additional seismic intensity parameters, strong motion duration, its frequency content via Fast Fourier Transformation and response spectra analysis. Being developed based on an open source Python programming language, Winston-BATAN is flexible for exploratory study to exploit the ground motion time history and easily improve to accommodate additional features. This code able to read input from PEER NGA type file or a simple time and acceleration data type of ground motion. Analysis results of Winston-BATAN shows a very good agreement compare to the results from the standard tools Seismosignal® 2018 Software, in addition flexibility of this code, in particular, to explore the response spectra from the ground motion time history is demonstrated.

Keywords: ground motion analysis, seismological, response spectra analysis, python code.

I INTRODUCTION

A thorough understanding of a natural event which might cause a huge impact, such as earthquake, is very important. This understanding can be used descriptively to explained past events, and in the same time become an accumulated prescriptive knowledge for future development. By the help of fast and reliable communication technology, the knowledge gain from such understanding is very strategic to prepare efficient mitigation plan, loss estimation and communication to public [1]. In particular, construction of critical infrastructure, such as nuclear reactor, required a comprehensive knowledge of past and predicted future earthquake is very important. This knowledge is needed to choose the appropriate site for the construction and the structural and safety design of the nuclear reactor. Civil design of critical infrastructure required the site specific response spectra analysis which incorporate the site characteristics and dynamic analysis of certain input motion. According to Boomer and Acevedo (2004), quoted from Iervolino (2008), “the signals that can be used for the seismic structural analysis consists of artificial waveforms, simulated accelerograms and natural records”[2][3]. The most basic information of an earthquake, or input motion in general, is the ground motion acceleration time history data which recorded by an accelerometer instrument or artificially created. Ground motion time histories intrinsically provide a specific geological condition and particular earthquake parameters [4]. Establishment of strong motion seismograph network is growing to provide, among others, an acceleration time history. Access to commercial software for ground-motion analysis is limited. Moreover, available software tends to be developed in a partial step rather than a comprehensive tool covering all aspect and step of ground motion analysis. As noted by Pagani (2014), open and reproducible software is one of the central tenets of scientific process. It is of importance to develop an open scientific code for strong motion. This paper’s objective is to elaborate the development of strong-motion analysis code which based on open source Python 3 coding language called Winston-BATAN. Furthermore, it is
expected to develop this code into a more comprehensive tool, which have the capability covering both strong-motion analysis, spectral matching analysis and non-linear dynamic analysis of the site. In the following, the calculation model used in the code is presented along with the code structures. In order to understand the performance of the code, input motion based on different site classes were simulated. The resulted calculations were then compared to commercial software of Seismosignal\textsuperscript{®} which developed by Seismosoft as a standard tools in ground motion analysis [6].

II METHODOLOGY

One of the Winston-BATAN code feature is the extraction of ground motion parameters for the input seed record. Ground motion parameters calculation are performed using the formulas used as shown in Table 1. Integration of acceleration time history can be performed to have the velocity and displacement time series. This also include the peak parameter of peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD). These parameters are very important in seismic analysis. PGA in general represent the seismic impact of the strong motion to the structure. These parameters can also be used as a measure of the frequency content of the ground motion including the use of PGV/PGA and PGD/PGV in estimating the respective corner periods at which the constant acceleration plateau and the constant displacement plateau begins. PGV can be used to correlate with earthquake damage to buried pipelines. In fact, fragility relationships for buried pipelines expressed in terms of PGV are included in the manuals of the American Lifelines Alliance (ALA, 2001) and in HAZUS (FEMA, 2003) [7]. PGV has also been included as a parameter in some recent methods for estimating the potential for soil liquefaction [7]. Despite its simplicity in being the amplitude of a single peak in the velocity trace, PGV has also been shown to be a robust indicator of the potential of the ground motion to cause structural damage[7].

Winston-BATAN also calculate the root-mean-square of the acceleration, velocity, and displacement. The root mean square of the acceleration provides an approximation to the standard deviation and also can be taken as an average constant intensity acting during the total duration \( T_d \) of the motion [8]. For the transformation from time domain to frequency domain, the time history can be written as Eqs. (1).

\[
x(t) = c_0 + \sum_{n=1}^{\infty} c_n \sin(\omega_n t + \varphi_n)
\]

where \( c_n \) and \( \varphi_n \) are the amplitude and phase angle, respectively, of the \( n \)th harmonic in the Fourier series. The Fourier amplitude spectrum is a plot of \( c_n \) versus \( \omega_n \), which shows the frequency content of the ground motion. In Winston-BATAN, the transformation is performed by computing the one-dimensional \( n \)-point discrete Fourier Transform (DFT) with the efficient (FFT) algorithm applying the \texttt{numpy.fft.fft} module in the Numpy [9]. In addition, Winston-BATAN provides several ground motion intensity parameters including Arias Intensity (AI), Cumulative Absolute Velocity (CAV), and Characteristics Intensity. These parameters which based on ground motion duration, describe the cumulative damage potential due to ground shaking and liquefaction also correlate well with observed building damage, particularly for structures that are susceptible to long-duration ground motion [10]. Two types of strong motion duration are included in Winston-BATAN namely bracketed and significant duration. Bracketed duration is the time between the first and last crossing of a threshold acceleration [11]. Bolt method with 0.05 g criteria is applied when calculating the bracketed duration [11]. Meanwhile, significant duration is the interval of time over which a proportion (percentage) of the total Arias Intensity is accumulated [6, 11].

Trifunac-Brady method which applied a range of 5% to 95% of AI accumulation is implemented for the significant duration type. For a stiff structure such as those in nuclear reactor the limit from Trifunac-Brady is considered too long, a limit of 5% to 75% which based on NUREG/CR-5347 is added in Winston-BATAN [11]. Shock response spectrum (SRS) analysis is another feature of Winston-BATAN. For a system as shown in Figure 1 in which a substructure mounted to a based structure with flexibility described by stiffness and damping parameter. SRS provides a peak response on a substructure due to a vibration caused. Calculation of response spectra implement a digital recursive filter to measure the response of single-degree-of-freedom (SDOF) shown in Figure 1 can be described by Eqs. (1) and (2). The \( c \) and \( k \) constants in Eqs. (1) and (2) are damping parameter and stiffness[16], and can be expressed by Eqs. (3) and (4).
Table 1: Ground Motion Calculation Formulas [12][13][14]

<table>
<thead>
<tr>
<th>Ground motion Parameters</th>
<th>Formulas</th>
</tr>
</thead>
</table>
| Max. Acceleration (g)            | \( p_{ga} = \max |a(t)| \)  
  \( a(t) \) is acceleration time series |
| Max. Velocity (cm/sec)           | \( p_{ga} = \max |v(t)| \)  
  \( v(t) \) is velocity time series |
| Max. Displacement (cm)           | \( p_{ga} = \max |d(t)| \)  
  \( v(t) \) is velocity time series |
| Acceleration RMS (g)             | \( a_{rms} = \sqrt{\frac{1}{t_{dur}} \int_0^{t_{dur}} a(t)^2 dt} \)  
  \( t_{dur} \) is time duration which is equal to the multiplication of time interval (dt) and acceleration series number. |
| Velocity RMS (cm/sec)            | \( v_{rms} = \sqrt{\frac{1}{t_{dur}} \int_0^{t_{dur}} v(t)^2 dt} \) |
| Displacement RMS (cm)            | \( d_{rms} = \sqrt{\frac{1}{t_{dur}} \int_0^{t_{dur}} d(t)^2 dt} \) |
| Arias Intensity (m/sec)          | \( AI = \frac{\pi}{2g} \int_0^{t_{dur}} a(t)^2 dt \)  
  \( g \) is gravity constant in m/sec\(^2\) |
| Characteristic Intensity         | \( I_c = a_{rms}^{3/2} \sqrt{t_{dur}} \) |
| Specific Energy Density (cm\(^2\)/sec) | \( sed = \int_0^{t_{dur}} |v(t)|^2 dt \) |
| Cumulative Absolute Velocity (cm/sec) | \( cav = \int_0^{t_{dur}} |a(t)|^2 dt \) |
| Acceleration Spectrum Intensity (g*sec) | \( asi = \int_{0.1}^{0.5} s_a(\xi = 0.005, T) dt \)  
  \( S_a \) is acceleration spectrum at damping level, \( \xi \), of 5% |
| Velocity Spectrum Intensity (cm)  | \( vsi = \int_{0.1}^{0.5} s_v(\xi = 0.005, T) dt \)  
  \( S_v \) is velocity spectrum at damping level, \( \xi \), of 5% |
| Housner Intensity (cm)            | \( hi = \int_{0.1}^{2.5} PS_v(\xi = 0.005, T) dt \)  
  \( PS_v \) is pseudo-spectral velocity at damping level, \( \xi \), of 5% |
Figure 1 Single-Degree-of-Freedom System [15]

Nigam-Jennings (1968) explained that the digital computation of response spectra requires the repeated numerical solution of the response of a simple oscillator to a component of recorded ground acceleration [17].

\[
m\left(\ddot{u} + \dddot{u}_g\right) + cu + ku = 0 \quad (2)
\]

\[
mi\dddot{u} + cu + ku = -m\dddot{u}_g \quad (3)
\]

\[
c = 2\zeta\omega_0 \quad (4)
\]

\[
k = \omega_0^2 \quad (5)
\]

Where \(u(t)\) is the ground motion, while \(u(t)\) is the motion of the mass relative to ground and \(\omega_0\) is natural frequency of a SDOF linear oscillator. Winston-BATAN code provides two methods to construct response spectra, namely Nigam Jennings and Smallwood. Smallwood proposed the algorithm back in 1981. The algorithm was based on recursive formula to calculate the shock response spectra which has a good result over a band frequency range including natural frequencies [18]. Smallwood algorithm required the user to have an input waveform band less than the Nyquist frequency. Nigam-Jennings algorithm provide estimation of the spectra at frequency higher than that of the sampling frequency. Nigam-Jennings algorithm was originally proposed in 1968 [17]. Instead of using a third order Runge-Kutta method on the numerical integration, Nigam-Jennings introduced an exact analytical solution to the governing differential equation for the successive linear segments of the excitation. Subsequently, by using this solution to compute response at discrete time intervals in an arithmetical method [17]. Acceleration, velocity and displacement response spectra were calculated using iterative process of Eqs. (6), (7) and (8), respectively.

\[
\ddot{y}_m = b_0\ddot{x}_m + b_1\ddot{x}_{m-1} + b_2\ddot{x}_{m-2} - a_1\dot{y}_{m+1} - a_2\dot{y}_{m+2} \quad (6)
\]

with,

\[
E = e^{i\omega_d t}
\]

\[
A = \omega_0\sqrt{1 - \zeta^2}
\]

\[
K = T_{wd}
\]

\[
C = E \cos K
\]

\[
S = E \sin K
\]

\[
S' = \frac{S}{K} = \frac{E \sin K}{K}
\]

\[
h_0 = 1 - S
\]

\[
h_1 = 2(S' - C)
\]

\[
b_2 = E^2 - S'
\]

\[
x = (k \cdot g_1) + (l \cdot g_2) + z_3 - z_2 - z_4 \quad (7)
\]

\[
\dot{x} = (k \cdot h_1) - (l - h_2) - z_4 \quad (8)
\]

\[
\ddot{x} = (-f_6 \cdot \dot{x}) - (\omega_0^2 \cdot x) \quad (9)
\]

with,

\[
l = z_2 - z_3
\]

\[
k = f_3 \cdot b - f_4 \cdot z_4
\]

\[
z_1 = f_2 \cdot (a_{i+1} - a_i)
\]

\[
z_2 = f_2 \cdot (a_i)
\]

\[
z_3 = f_1 \cdot (a_{i+1} - a_i)
\]

\[
z_4 = \frac{z_4}{dt}
\]

\[
f_1 = \frac{2\zeta}{\omega_0^3} \cdot \frac{dt}{dt}
\]

\[
f_2 = \frac{1}{\omega_0^2}
\]

\[
f_3 = \frac{\zeta}{\sigma_0}
\]

\[
f_4 = \frac{1}{\sigma_d}
\]

\[
f_5 = f_3 \cdot f_4
\]

\[
f_6 = 2 \cdot f_3
\]

\[
g_1 = e^{-f_1 \cdot dt} \left(\sin(\omega_d \cdot dt)\right)
\]

\[
g_2 = e^{-f_1 \cdot dt} \left(\sin(\omega_d \cdot dt)\right)
\]

\[
h_1 = (\omega_d \cdot g_2) - (f_3 \cdot g_1)
\]

\[
h_2 = (\omega_d \cdot g_1) - (f_3 \cdot g_2)
\]
Winston-Batan: A Seismological Ground-Motion Analysis Code,
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**Code Structure**
Winston-BATAN code consisted of following items:

a) Input file processing which allow user to use the strong-motion data format file acquired from PEER Strong Motion database or a two-column data input of time and acceleration. Output consisted of both numbers and graphs. User can adjust the graphics display by setting-up the minimum and minimum axis number.

b) Ground motion parameters calculation which comprised of PGA, PGV, PGD, Acceleration RMS, Velocity RMS, and Displacement RMS. Intensity measurement including the Arias Intensity, Characteristic Intensity, Specific Energy Density, Cumulative Absolute Velocity, Acceleration Spectrum Intensity, Velocity Spectrum Intensity and Housner Intensity.

c) Fourier Spectrum analysis which has the ability to extract wave characteristics of the strong-motion data inter alia frequency, period, Fourier amplitude and phase.

d) Strong motion duration calculation.

e) Response spectra evaluation which yield acceleration response, velocity response and displacement response.

**III RESULT AND DISCUSSION**
Three different ground motions taken from PEER Ground Motion Database NGAWEST-2 were used in this study. The three ground motions were chosen to represent far field, near field-pulse like, and near field-no pulse like earthquake motions. Table 2 shows the selected ground motions. The magnitudes of the selected events range from M6.5 to M7.4 with an average magnitude of M6.98.

### Table 2 Selected Ground Motions

<table>
<thead>
<tr>
<th>Earthquake name/Year</th>
<th>Magnitude</th>
<th>Recording Station/Component</th>
<th>PGA</th>
<th>Site Class /Vs30 (m/s)</th>
<th>Source Distance</th>
<th>Ground Motion Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landers /1992</td>
<td>7.28</td>
<td>Yermo Fire Station/Component 270</td>
<td>0.25</td>
<td>C/523</td>
<td>23.6</td>
<td>Far Field</td>
</tr>
<tr>
<td>Imperial Valley-06</td>
<td>6.5</td>
<td>El Centro Array#6/Component140</td>
<td>0.41</td>
<td>D/203</td>
<td>1.4</td>
<td>Near Field Pulse</td>
</tr>
<tr>
<td>/1979</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loma Prieta /1989</td>
<td>6.9</td>
<td>BRAN/Component 000</td>
<td>0.48</td>
<td>C/376</td>
<td>10.7</td>
<td>Near Field No-Pulse</td>
</tr>
</tbody>
</table>

### Table 3. Calculated Ground Motion Parameters

<table>
<thead>
<tr>
<th>Ground motion Parameters</th>
<th>Landers</th>
<th>Imperial Valley earthquake</th>
<th>Loma Prieta</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winston-BATAN code</td>
<td>SEISMO-SIGNAL</td>
<td>Winston-BATAN code</td>
</tr>
<tr>
<td>Max. Acceleration (g)</td>
<td>0.2445</td>
<td>0.2445</td>
<td>0.4473</td>
</tr>
<tr>
<td>Max. Velocity (cm/sec)</td>
<td>51.1248</td>
<td>51.1248</td>
<td>67.0193</td>
</tr>
<tr>
<td>Max. Displacement (cm)</td>
<td>41.7106</td>
<td>41.7165</td>
<td>27.8956</td>
</tr>
<tr>
<td>Acceleration RMS (g)</td>
<td>0.0369</td>
<td>0.0369</td>
<td>0.0506</td>
</tr>
<tr>
<td>Velocity RMS (cm/sec)</td>
<td>10.6884</td>
<td>10.6884</td>
<td>11.4346</td>
</tr>
<tr>
<td>Displacement RMS (cm)</td>
<td>11.3538</td>
<td>11.3542</td>
<td>6.4978</td>
</tr>
<tr>
<td>Characteristic Intensity</td>
<td>0.0470</td>
<td>0.0470</td>
<td>0.0711</td>
</tr>
<tr>
<td>Specific Energy Density (cm²/sec)</td>
<td>5024.3663</td>
<td>5024.3663</td>
<td>5109.6706</td>
</tr>
<tr>
<td>Cumulative Absolute Velocity (cm/sec)</td>
<td>964.2085</td>
<td>964.5541</td>
<td>979.9443</td>
</tr>
<tr>
<td>Acceleration Spectrum Intensity (g/sec)</td>
<td>0.1751</td>
<td>0.1771</td>
<td>0.2744</td>
</tr>
<tr>
<td>Velocity Spectrum Intensity (cm)</td>
<td>149.2335</td>
<td>150.4239</td>
<td>187.0313</td>
</tr>
<tr>
<td>Housner Intensity (cm)</td>
<td>148.3892</td>
<td>149.3651</td>
<td>193.6201</td>
</tr>
</tbody>
</table>
The variation of soil conditions and shear wave velocity (Vs30) were also considered in selecting the ground motions. The Peak Ground Acceleration (PGA) of the selected ground motions range from 0.13-0.98 g with an average of 0.45 g. Velocity and displacement time histories resulted from Winston-BATAN, including the PGA, PGV, and PGA for three different ground motions show a good agreement with the results from Seismosignal® as can be seen in Figure 2, and Table 3. Each of the selected ground motion were calculated. The resulted calculation using Winston-BATAN were compared to the calculation result using Seismosignal® as shown in Table 3. For thirteen ground motion parameters, Winston-BATAN resulted in less than 7% different compare to Seismosignal®. Further discussions and comparisons between Winston-BATAN and Seismosignal® are subjected to Landers ground motion data. Results of AI calculation from Winston-BATAN and Seismosignal® are shown in Figure 3 where both results show a very good agreement and gives a total AI value of 0.923 m/s as shown in Table 3.

Figure 2 Landers Acceleration, Velocity and Displacement time series comparison.
Figure 3 Arias Intensity Comparison.

Figure 4 Fourier Spectra Comparison.

Figure 5 Response Spectra Comparison.
From this AI, significant strong motion duration of the ground motion based on Trifunac and Brady method is calculated which also have the same results with Seismosignal® of 17.58 s. While, the bracketed duration based on Bolt method using acceleration level of 0.05 g is 20.22 s and 20.14 s for Seismosignal® and Winston-BATAN, respectively. Ground motion Fourier spectra analysis is important at spectral matching analysis. Thus, Winston-BATAN provide the tool to extract ground motion characteristic using Fourier transform. Fourier spectra comparison as shown in Figure 4 yield slightly different values for Fourier amplitude at the range frequency of 0.07–0.4 Hz. Acceleration, velocity, and displacement response spectra for Landers ground motion from Winston-BATAN and Seismosignal® are shown in Figure 5, again the results show a very good agreement. In addition, predominant period calculated in both code is exactly the same at 0.68 s. Flexibility of Winston-BATAN to explore comprehensively the response acceleration due to certain ground motion is shown in Figure 6. A detail information on the response acceleration at any time, as shown in Figure 6 (a) for 10 s, 20 s, and 40 s, and the response acceleration with each Period (or Frequency), as shown in Figure 6 (b) for 24.4 Hz, 6.7 Hz, and 0.6 Hz, can provide a thorough understanding on the impact of certain ground motion on particular structure.

CONCLUSION

Development of a seismological ground motion analysis code, called Winston-BATAN, is presented in this paper. The code able to extract information from a ground motion acceleration time history to achieve ground motion parameters such as PGA, several seismic intensity measures including arias intensity, and the strong motion duration. Frequency content via Fast Fourier Transform of the ground motion and the detail response spectra analysis are another important features of the code. Results from this code show a good agreement with the standard commercial tools Seismosignal® 2018.
Flexibility of the code, in particular, to explore the response spectra of the ground motion is demonstrated.

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REFERENCE


