# A METHOD FOR GENERATING SPECTRUM-COMPATIBLE EARTHQUAKE GROUND MOTION TIME HISTORIES WITH PERMANENT DISPLACEMENT

Jeff Bayless (PhD)[1]
Norm Abrahamson (PhD, NAE)[2]

## ABSTRACT

For engineering projects in which dynamic analyses are performed, ground-motion time histories are required as input. In circumstances where both ground shaking and dynamic displacement are critical seismic load conditions, ground-motion time histories may be required which simultaneously match a target response spectrum and contain a permanent displacement (fling-step) with a specified duration and amplitude. In practice, there is no standardized procedure for developing earthquake time histories containing both features. This paper proposes such a procedure which maintains the physically important features of the fling-step. The procedure begins with the standard selection of recorded or simulated (seed) time histories with appropriate source-site geometry, style of faulting, earthquake magnitude, and spectral shape, but without a pre-existing fling-step. These time histories are spectrally matched to the target response spectrum. The fling-step pulse period and amplitudes on either side of the fault, for three orthogonal ground motion components, are determined using empirical models such as those in Kamai et al. (2014). The matched time history is modified to include the fling-step consistent with the target earthquake scenario by superimposing a one-cycle sine wave in the acceleration time history. The target response spectrum is then slightly modified by scaling it with the period-dependent ratio of the response spectra of the matched time history before and after adding the fling-step. The original time history is spectrally matched to the modified spectrum and should have no permanent displacement after matching. The matched time history is again modified to include the target fling-step. The resulting time history should be checked for compatibility with the target response spectrum and the target permanent displacement. This paper provides an example application of this procedure as applied to a dam seismic retrofit project in California, which includes the construction of new outlet works consisting of two new intake and outlet systems. Limitations of the method, including the potential for destructive interference of the fling-step in the time domain, are addressed.

## INTRODUCTION

In earthquake engineering, dynamic (time history) response analysis involves solving the dynamic equation of motion throughout the duration of the ground shaking (or ground displacement) and the subsequent system vibration. This is usually done by simultaneous application of the earthquake ground motions in three orthogonal directions to a finite-element model of the system to obtain time history excitations of the system, including stresses, strains, and reaction forces (Bai and Bai, 2014). In most applications, a suite of input ground-motion time histories is required. The time histories are scaled or modified

[1] AECOM, Engineering Seismologist, Los Angeles, California, jeff.bayless@aecom.com
[2] University of California, Berkeley, Adjunct Professor, Berkeley, California, abrahamson@berkeley.edu

to represent a 5%-damped, pseudo-spectral acceleration (PSA) spectrum established from the seismic hazard analysis. In some circumstances, such as for infrastructure near or crossing active faults, both ground shaking and dynamic displacement are critical seismic load conditions. In this case, the ground-motion time histories should match both the target response spectrum and contain a permanent displacement (fling-step) with a specified duration and amplitude.

Fling-step is the engineering term for the effects of the permanent tectonic offset of a rupturing fault in the recorded ground motions near the fault, expressed by a single-cycle acceleration pulse, manifested as a one-sided pulse in ground velocity and a nonzero final displacement at the end of shaking (Kamai et al., 2014). The permanent ground displacements in near-fault ground motions are caused by the relative movement of the two sides of the fault on which the earthquake occurs and consist of a discontinuity in displacement on the fault itself, with a gradual decrease in this displacement away from the fault on either side of the fault (Somerville, 2002; IAEA, 2015). Near-fault ground motions also contain rupture directivity effects (Somerville et al., 1997; Bayless et al., 2020). Somerville (2002) describes the orientation of both rupture directivity effects and fling-step in near-fault ground motions, but this paper addresses only fling-step.

(a)

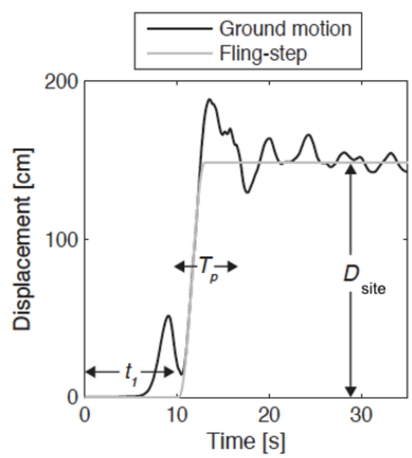


*Figure modified from Burks and Baker (2016)*

(b)

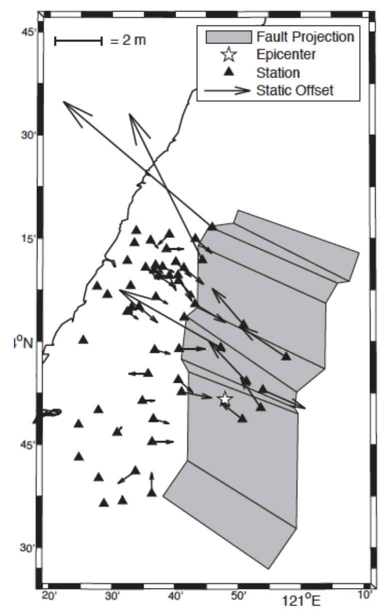


*Figure source: Burks and Baker (2016)*

Figure 1. (a) A ground motion displacement from the 1999 Kocaeli, Turkey earthquake showing fling-step, where $D_{site}$ is the displacement amplitude, $T_p$ is the period or duration, and $t_1$ is the arrival time. (b) Permanent displacements of the ground following the 1999 Chi-Chi, Taiwan earthquake, where the length of arrows indicates relative displacement amplitude.

Figure 1 shows an example of the fling-step recorded in the 1999 Kocaeli, Turkey earthquake and the spatial distribution of the permanent displacements following the 1999 Chi-Chi, Taiwan earthquake (Burks and Baker, 2016). State of the art methods for evaluating distributed fault displacements from future earthquakes are under way, including advances in the probabilistic fault displacement hazard analysis methodology, collection of new data, and development of ground motions models for fault displacement (e.g. Dalguer et al., 2021).

Empirical methods have been proposed to evaluate and implement the fling-step, e.g., Abrahamson (2002), Kamai et al. (2014), and Burks and Baker (2016). These three studies developed empirical parametric models for adding the fling-step by superimposing the expected fling step on a processed time history. Kamai et al. (2014) and Burks and Baker (2016) recognized that standard ground-motion processing procedures (filtering and baseline correction) typically remove some of the fling effects, and the former focused on methods to reconstruct the fling in recorded ground motions without double-counting of the intermediate periods that were not removed in the processing. Others have used numerical (Dreger et al., 2011) and theoretical methods (e.g. Wu et al., 2021; Hisada and Bielak, 2003; Hisada and Tanaka, 2021) to evaluate the fling-step. These studies all primarily focused on accurately characterizing and implementing the fling-step, and none of them address methods to developing earthquake time histories for engineering applications which simultaneously match a target response spectrum and contain a fling-step with a specified duration and amplitude, while maintaining the physically important features of the fling-step. This paper proposes such a methodology.

In this paper, the Kamai et al., (2014) notation is adopted for three key parameters:

- $D_{fault}$ is the mean fault slip (displacement) over the rupture plane in units of centimeters. This is derived from the definition of the seismic moment.
- $D_{site}$ is the component-specific amplitude of the tectonic displacement (fling-step) observed or modeled at a site, in centimeters.
- $T_p$ is the period in seconds of the single-cycle acceleration sine wave used to model $D_{site}$.

## Scaling and Matching of Time Histories with Fling in Practice

Design codes and guidelines vary individually, but generally speaking, they require that the mean PSA of a suite of time histories be consistent with the target spectrum (often the uniform hazard spectrum or conditional mean spectrum). This requirement should be done over the broad range of 0.01 – 10 seconds, or else a more focused period range relevant to the analysis may be selected. Two modification procedures are broadly permissible: linear scaling and spectral matching. Time-domain spectral-matching methods such as Al Atik and Abrahamson (2010) add wavelet functions to the acceleration time histories to obtain spectrum compatibility. The use of spectrally matched motions reduces the variability in the structural response and consequently decreases the total number of response history analysis runs required for a given level of uncertainty in the mean response; this is particularly true of the most common approach employed in practice, referred to as *tight* spectral matching (Zengin and Abrahamson, 2021).

When spectral matching is applied, and for sites near active faults, generally these same guidelines require that the pulse-like characteristics of time histories be retained after matching (e.g. ASCE, 2022; IAEA, 2015); however, in most guidelines, any reference to pulse-like characteristics refers to rupture directivity effects (Somerville et al., 1997; Bayless et al., 2020), which is a separate long-period phenomenon associated with pulses, and limited (if any) guidance is provided on how to preserve or implement the fling-step in the time histories. The International Atomic Energy Agency (IAEA, 2015) recommends that:

> *…it is important to preserve the pulse-like characteristic of the time history after matching. This can be done using a qualitative visual check on the acceleration, velocity, and displacement time history and the normalized energy summation curve, or by using methods that quantify the parameters of directivity pulses.*

But IAEA (2015) offers no additional recommendations relating to the fling-step, besides stating that the permanent ground displacements occur at about the same time as the large dynamic motions, indicating that the static and dynamic displacements need to be treated as coincident loads.

Zengin and Abrahamson (2021) introduced an approach to modify time series to simultaneously match a target response spectrum and the Instantaneous Power (IP) spectrum. In this approach, IP is used to capture effects of a velocity pulse in ground-motion selection. This approach has not yet seen widespread adoption in practice, and although it has significant capacity for ground-motion selection and modification for near-fault ground motions because it preserves the component-to-component variability while capturing the damaging features of velocity pulses, it does not address the fling-step.

## Description of the Dilemma

The difficulty in prescribing both a fling-step (with a specified duration and amplitude) and a match to a target response spectrum arises due to the inherent relationship between the response spectrum and the acceleration time history.

Consider a ground-motion time history with a pre-existing fling-step, such as the TCU049 recording of the 1999 Chi-Chi, Taiwan earthquake shown in Figure 2. Using simple scaling, it is straightforward to control the response spectrum amplitude at a given spectral period, or to control the fling-step amplitude ($D_{site}$); both scale linearly with linear scaling of the acceleration time history (e.g. Figure 2). If, for example, a scale factor of 2 is required to meet the target response spectrum at the period of interest, T=3 sec, a factor of 2 will also be applied to the fling-step amplitude. This is unlikely to meet the acceptance criteria for both seismic loading conditions of fling and spectral acceleration at other periods. Figure 2 also shows the effect of scaling to the target peak ground acceleration (PGA), which requires a scale factor of 4.7 in this example, and which would be unlikely to match either the long period response spectrum or the target

$D_{site}$. Additionally, with the simple scaling approach it is impossible to modify the period (duration) of the fling-step or the spectral shape of the time history.

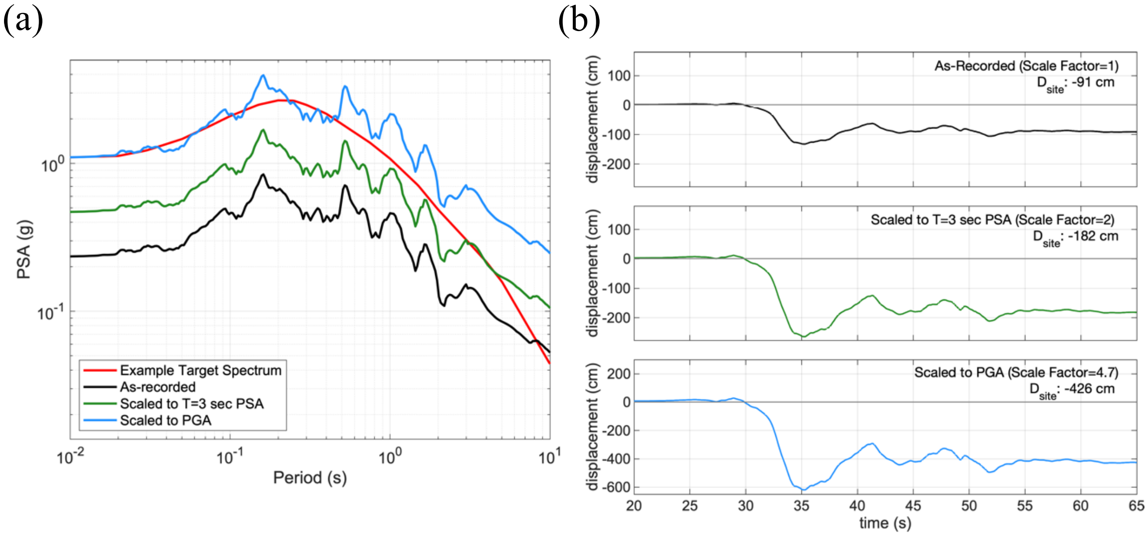


Figure 2. (a) Response spectra derived from the fault-normal component recording at station TCU049 of the 1999 Chi-Chi, Taiwan earthquake (located approximately 3 km distance from the rupture surface). The as recorded spectrum is in black, and the response spectra from linearly scaling to the example target spectrum at 3 seconds period (green) and at peak ground acceleration (approximately 0.01 seconds period, blue). (b) Displacement time series for the same three scale factors with the same color scheme.

Continuing the same example, one might reasonably recommend specifying the fling-step amplitude (through simple scaling by application of a scale factor) followed by spectral matching to achieve an acceptable match to the target spectrum in the desired period range, but this approach does not lend itself to specifying the fling-step duration. This method may work in some instances, but it has high potential to be problematic because time-domain spectral matching modifies the time history by adding wavelet functions with periods in the range of the matching, which can interfere with both amplitude and period of the fling-step or significantly alter the non-stationary characteristics of the time series if the required modifications are large, or both.

In summary, the period and amplitude of a pulse is related to the response spectrum amplitude in that period range, and modification to one will affect the other. This is the overestimation caused by the fling-step superposition process described in Kamai et al., (2014). Below, we introduce a conceptually simple procedure which matches a time history to a target response spectrum, removes the double-counting of the intermediate to long spectral periods introduced by the addition of the fling-step, and incorporates the target fling-step and its physically important features.

## TIME HISTORY MODIFICATION PROCEDURE

The proposed procedure for generating earthquake ground-motion time histories with a target permanent displacement ($D_{site}$) and with a broadband match to a target response spectrum ($Target$) is summarized in Steps 1-7:

1. Select recorded or simulated (seed) ground-motion time histories with appropriate source-site geometry, style of faulting, earthquake magnitude, and spectral shape. These seed time histories should not have a fling-step. The response spectral acceleration misfit (the difference between the response spectra of the seed time histories and the target) should be minimized through the selection process, including linear scaling as necessary.

For each orthogonal ground-motion component and for each seed time history:

2. Spectrally match the seed time history to the target spectrum ($Target$) using the Al Atik and Abrahamson (2010) method or another similar method which preserves the non-stationary characteristics of the time series. This match should be broadband, e.g., for spectral periods $T = 0.01 – 10$ sec.

3. Determine the fling-step pulse period ($T_p$) and component-specific permanent displacement ($D_{site}$).* Add the fling step following the Kamai et al. (2014) procedure, which is to add a single-cycle sine wave to the spectrally matched acceleration time series. The amplitude ($A$) of the acceleration sine wave can be determined from the fling-step pulse period ($T_p$) and displacement ($D_{site}$) using Equation 1, which shows that the sine wave with amplitude $A$ integrated twice over the pulse period duration yields the total displacement. The fling-step arrival is approximately equal to the s-wave arrival time.

$$D_{site} = \int_0^{T_p} \int_0^{y} A \sin\left(\frac{2\pi}{T_p} x\right) dx dy \; = \frac{A\, T_p^2}{2\pi} \tag{1}$$

4. Calculate a period-dependent adjustment factor $F(T)$, which is the ratio of the response spectra (PSA) of the spectrally matched time histories before and after adding the fling-step (Equation 2). Scale the $Target$ response spectrum by $F(T)$ to develop a modified spectral matching target (Equation 3).

$$F(T) = \frac{PSA_{NoFling}(T)}{PSA_{WithFling}(T)} \tag{2}$$

$$Target_{mod}(T) = Target(T) \times F(T) \tag{3}$$

5. Spectrally match the seed time history to the modified spectrum ($Target_{mod}$). The spectrally matched time history should have no permanent displacement after matching.

6. Add the fling step (as in Step 3) to the spectrally matched time history from Step 5.

7. Check the resulting time history for its non-stationary characteristics and for compatibility with the target response spectrum ($Target$) and the target permanent displacement ($D_{site}$). If the misfit to the target response spectrum is too large, start over at Step 4 with a new modified target response spectrum, based on the misfit.

*In step 3, the Kamai et al. (2014) model is recommended for determining $D_{site}$ because it has individual models for the hanging-wall (HW) and footwall (FW) sides of the fault, for horizontal and vertical components, and for strike-slip and thrust faulting earthquakes. This allows for fling-step predictions directly on either side of a fault, and for three orthogonal ground-motion components oriented in the fault-normal, fault-parallel, and vertical directions. These components, and the sign convention taken for them, are shown for a hypothetical dipping fault in Figure 3. Additional fling-step models may be utilized in addition to this model (e.g., Abrahamson, 2002; Burks and Baker, 2016) to address the fling-step epistemic uncertainty.

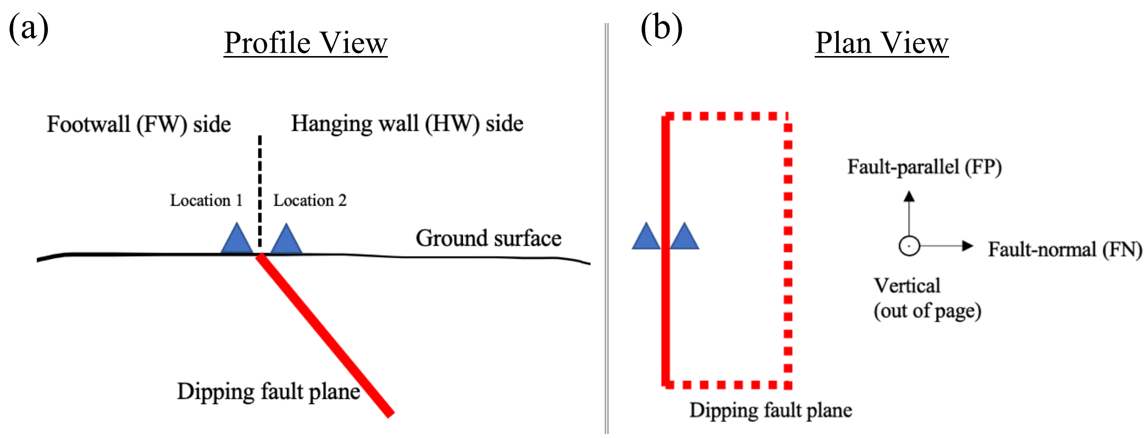


Figure 3. A sketch illustrating two locations on the ground surface and the sign convention for their ground-motion components, for a hypothetical dipping fault, in profile view (a) and plan view (b). Figure 5 provides a 3-dimensional view of $D_{site}$ for the example application described below.

## EXAMPLE APPLICATION

### Project-Specific Requirements

This procedure was developed as part of a dam retrofit project located in California. The subject project includes the construction of new outlet works that will meet current California Department of Water Resources Division of Safety of Dams (DSOD) criteria. The outlet works consists of two new intake and outlet systems: a low-level outlet works (LLOW) for normal operations, and a high-level outlet works to improve high-level evacuation capabilities. The LLOW consists of the upstream sloping intake structure, the downstream outlet control structure, the 1.98 m diameter primary outlet pipe, the 83.8 cm bypass pipe, and the low-level outlet tunnel; a reinforced concrete tunnel through which these pipes are routed. Within the tunnel, the outlet pipe cradles, cradle supports, and support spacing will allow the 1.98 m outlet pipe to respond elastically to 1.21 m of oblique reverse thrust, or 0.61 m of lateral offset at faults crossing the tunnel alignment.

The below example application uses a mean target fault displacement ($D_{fault}$) of 1.21 m in an oblique direction (rake angle of 45 degrees), corresponding to a **M**6.6 scenario earthquake on the Coyote Creek fault with 70-degree dip angle. This scenario and the target displacement were one combination of several considered for the subject project. Future applications of this methodology will require the description of project-specific scenario earthquakes, target ground-motion response spectra, and target fault displacements.

**Example Modification Procedure**

Step 1: Select time histories with appropriate source-site geometry, style of faulting, and earthquake magnitude. In this example, the target scenario is the Coyote Creek fault earthquake scenario described above, and the target response spectrum is from the seismic hazard assessment for the project. Four candidate recorded time histories, collected from the NGA-West2 database (Ancheta et al., 2014), are listed in Table 1.

Table 1. Candidate Recorded Time Histories and their Properties

| Earthquake Name, Year | Moment Magnitude, M | Recording Station Name | Earthquake Style of Faulting | Rupture Distance, $R_{rup}$ (km) | Lowest Usable Frequency (Hz) |
|---|---|---|---|---|---|
| San Fernando 1971 | 6.61 | Pacoima Dam | Reverse | 1.8 | 0.0875 |
| Loma Prieta 1989 | 6.93 | Saratoga – Aloha Ave | Reverse Oblique | 7.6 | 0.125 |
| Chi-Chi #3 1999 | 6.2 | TCU074 | Reverse | 14.2 | 0.04 |
| Christchurch 2011 | 6.2 | Canterbury Aero Club | Reverse Oblique | 14.4 | 0.0625 |

Note this procedure requires that these seed time histories do not have a fling-step, or that any fling-step should be removed at the initial stages. The NGA-West2 database project mostly removed the fling step from the time histories in their standardized processing of strong motion data, including band-pass filtering and baseline correction (Kamai and Abrahamson, 2015), therefore time histories from this database are excellent candidates. The remainder of this example utilizes the Loma Prieta earthquake recording listed in Table 1.

Step 2: Spectrally match the seed time history to the target spectrum ($Target$) over the period range $T = 0.01 - 10$ sec. Panel (a) of Figure 4 illustrates this process, where the top sub-panel shows the response spectrum of the seed time history matched to $Target$ in black. Below that, the acceleration, velocity, and displacement time series are also shown in black.

(a) (b)

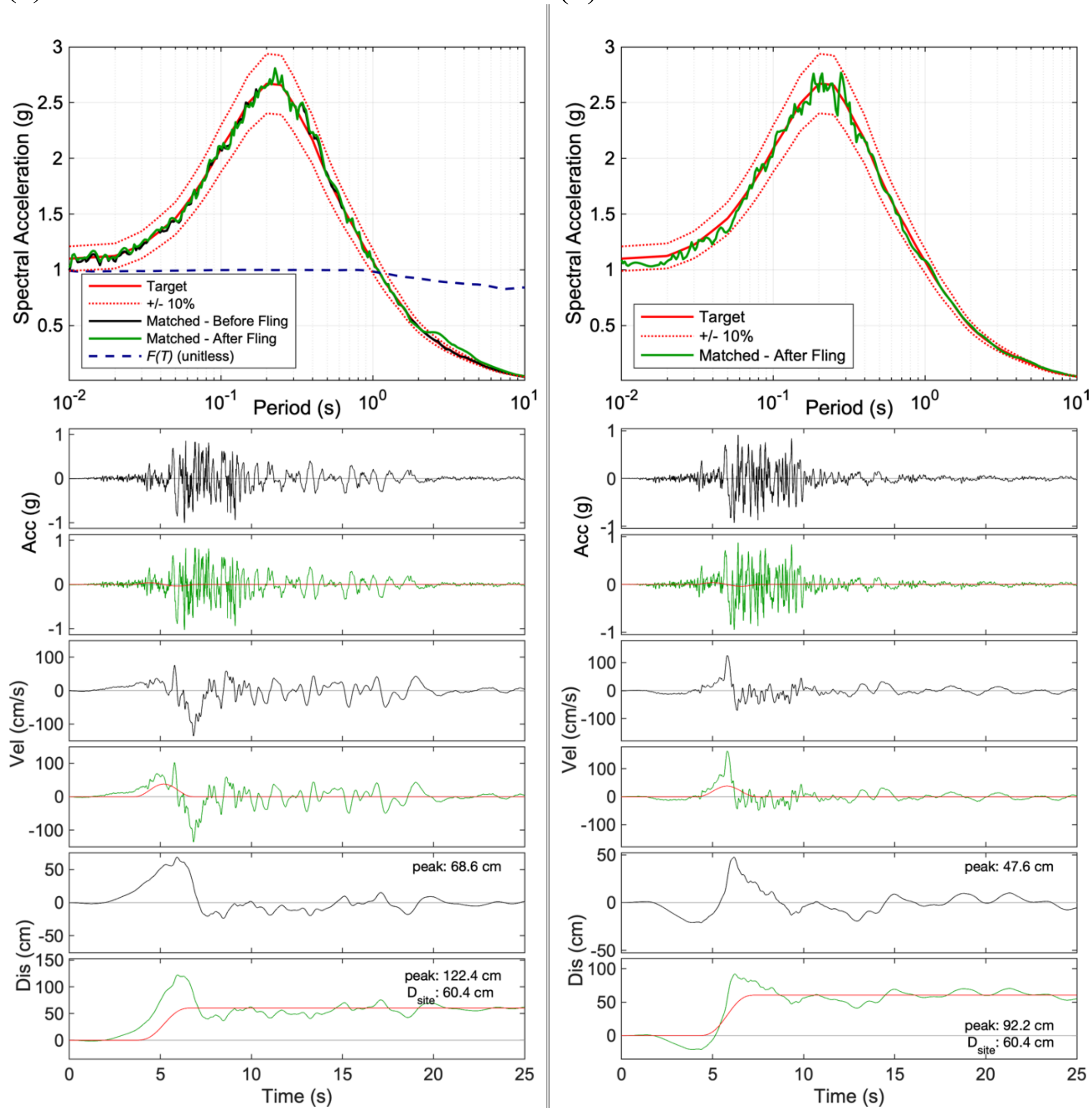


Figure 4. Spectral matching summary figures for Step 2 (a) and Steps 5-7 (b). For each, the top sub-panel shows the ground-motion response spectra compared with the target spectrum, shown in red. The bottom six sub-panels show pairs of acceleration, velocity, and displacement time histories before (black) and after (green) adding the fling-step. In the time histories, the red lines illustrate the effect of adding the fling-step as a single-cycle sine wave in acceleration.

Table 2. The $T_p$ and $D_{site}$ for two locations and three ground motion components.

| **Scenario Name** | **Dip Angle (deg)** | $T_p$ **(sec)** | **HW or FW location** | $D_{site}$**, FN Component (cm)** | $D_{site}$**, FP Component (cm)** | $D_{site}$**, Vertical Component (cm)** |
|---|---|---|---|---|---|---|
| Coyote Creek Oblique | 70 | 3.19 | HW | $HW_{FN}$ = -3.4 | $HW_{FP}$ = 60.4 | $HW_{V}$ = 76.5 |
| | | | FW | $FW_{FN}$ = 47.5 | $FW_{FP}$ = -34.4 | $FW_{V}$ = -23.5 |

Step 3: Determine the fling-step pulse period ($T_p$) and displacement ($D_{site}$). Depending on the application, it may be necessary to specify the $D_{site}$ on either side of the fault, and for three orthogonal ground-motion components: fault-normal, fault-parallel, and vertical (e.g., Figure 3).

In this example, 1.21 m of fault displacement ($D_{fault}$) is specified in an oblique direction (45-degree rake angle), which is equivalent to 0.86 m in the along-strike and up-dip directions. By decomposing the oblique displacement into reverse and strike-slip components based on the rake angle, the Kamai et al. (2014) models for strike-slip faulting and thrust faulting can be used together. The $D_{site}$ for both locations (HW and FW) and three ground-motion components are listed in Table 2 and shown in Figure 5.

The signs of the values listed in Table 2 are the result of the sign convention selected (shown in Figure 3a). On the FW side of the fault, the vertical component $D_{site}$ value is negative because the upwards direction is taken as positive, and the FW moves downward for reverse faulting. Similarly, for the HW side, the FN horizontal component $D_{site}$ is negative because the positive FN direction is oriented 90° clockwise from the strike direction, and by definition, the HW moves upwards and towards the FW in reverse-oblique faulting.

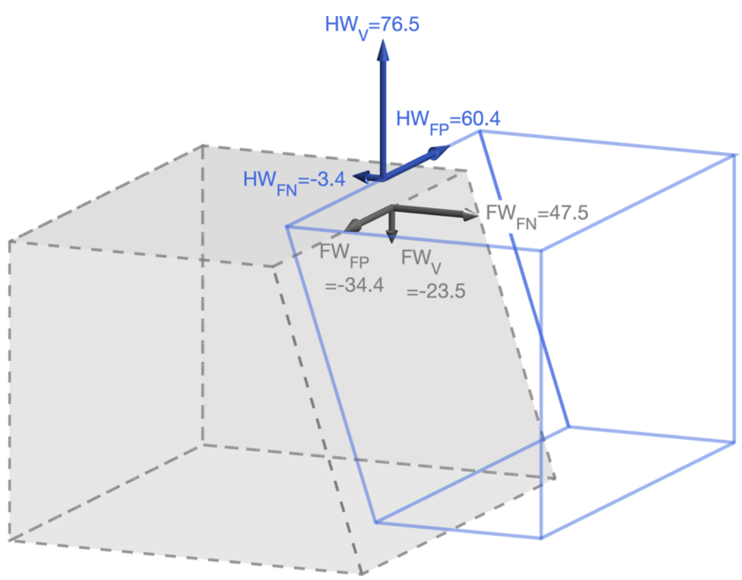


Figure 5. An illustration of the $D_{site}$ components (signed magnitudes and directions) from Table 2. For this reverse-oblique scenario with 70-degree dip, the HW, shown by the white colored volume with blue edges, moves up and in the along-strike direction. The FW, shown by the gray colored volume with dashed gray edges, moves downward and in the anti-strike direction.

The fling step is added to the matched time history following the Kamai et al. (2014) procedure. For this example, one horizontal component recorded from the Loma Prieta earthquake (Table 1) is shown, applied to the HW location and the FP component.

Therefore, the target $D_{site}$ is 60.4 cm (Table 2), which corresponds to $A = 37.3$ cm/s$^2$ (0.038 g) using Equation 1 with $T_p = 3.19$ sec. This procedure is illustrated in Figure 4a, where the response spectrum, acceleration, velocity, and displacement after adding the fling-step are shown in green. In the acceleration, velocity, and displacement panels, the impact of the fling-step superimposed as a sine-wave pulse in acceleration is shown in red.

Step 4: Calculate a period-dependent adjustment factor $F(T)$, which is the ratio of the response spectra before and after adding the fling-step. The $F(T)$, is shown in Figure 4a with a dashed blue line. The target response spectrum is scaled by $F(T)$ to develop the modified spectral matching target ($Target_{mod}$).

Steps 5-7: Spectrally match the seed time history to $Target_{mod}$, add the fling-step, and check performance. Steps 5 and 6 are shown in Figure 4b using the same color scheme (black before the addition of the fling-step, and green afterwards). Step 7 is a check on the performance, and Figure 4b shows (in green) that the response spectrum adequately matches the $Target$ spectrum, including the long periods, and that the $D_{site}$ of 60.4 cm is reached, while preserving the non-stationary characteristics of the time history and maintaining the physically important features of the fling-step.

## LIMITATIONS OF THE PROCEDURE

The main limitation to the proposed modification procedure is that it is not guaranteed to work in every instance or without careful consideration of the time history which is being modified. There is potential for the addition of the fling-step (sine wave in acceleration) to destructively interfere with the vibratory ground motion, leading to the spectrum of the final time history falling below the target at long periods. The easiest visualization of this effect is with the addition of the velocity pulse, which is one sided. In the most extreme case, a positively signed velocity pulse added to a velocity time series with a predominantly negatively signed velocity over the duration of the pulse will result in destructive interference (e.g., Figure 6a where the one-sided velocity pulse in red corresponds primarily to a negatively signed velocity time history in black).

This is another way of saying that the response spectrum of the sum of two time series (the fling-step sine wave and the ground acceleration in our case) is not the sum of the individual response spectra (Boore, 2001).

The reason for performing spectral matching (Step 2) before adding the fling-step and calculating the period-dependent adjustment factor $F(T)$ (Steps 3-4) is to reduce the potential for destructive interference. If instead the $F(T)$ is calculated from the un-matched time history with and without addition of the fling-step (which is appealing because it eliminates Step 2 from the procedure) the potential for destructive interference is high. This is because changes in the phasing and amplitudes introduced by spectral matching make the addition of the fling-step less likely to be constructive. By performing spectral matching first (Step 2) the likelihood of destructive interference is reduced, but users of the method will still need to be cognizant of the effect each step of the procedure has on the time history.

While the polarity of the fling-step is determined by the location of the site relative to the fault, the polarity of the seed time histories is often arbitrary. The polarity of the seed time histories can be selected such that the S-wave polarity is consistent with the polarity of the fling step to avoid significant destructive interference.

(a) (b)

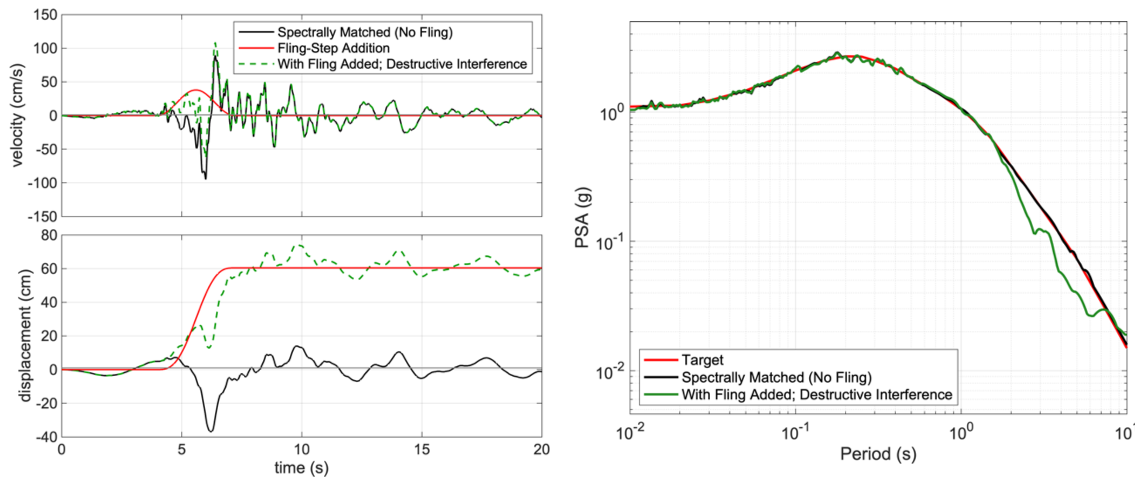


Figure 6. (a) Spectrally matched velocity and displacement time histories before addition of the fling-step (black) and after superimposing the fling step (green). The fling-step itself is shown in red. (b) Response spectra of the time histories, with the target spectrum in red. The addition of the fling step destructively interferes, causing the spectrum of the final time history to fall below the target at long periods.

## SUMMARY

For engineering projects in which dynamic analyses are performed, ground-motion time histories are required as input. In circumstances where both ground shaking and dynamic displacement are critical seismic load conditions, ground-motion time histories may be required which simultaneously match a target response spectrum and contain a permanent displacement (fling-step) with a specified duration and amplitude. This paper proposes a straightforward procedure for developing earthquake time histories containing both features while maintaining the physically important features of the fling-step. An example application of this procedure as applied to a dam seismic retrofit project in California. The main limitation to the proposed procedure is that it is not guaranteed to work in every instance or without careful consideration of the time history which is being modified, because there is potential for the addition of the fling-step to destructively interfere with the vibratory ground motion. Users of the method will need to be cognizant of the effect each step of the procedure has on the time history.

**ACKNOWLEDGEMENTS**

Thanks to C.B. Crouse for providing the Chi-Chi TCU049 record with a fling-step, to Ronnie Kamai for the numerous helpful discussions, and to Paul Somerville and Scott Condon for their review and suggestions.

## REFERENCES

Abrahamson, N.A. (2002) Velocity pulses in near-fault ground motions. In: Proceedings of the UC Berkeley - CUREE Symposium in Honor of Ray Clough and Joseph Penzien. Berkeley, California; 2002, p. 40-1

Al Atik, L., and N.A. Abrahamson (2010). An Improved Method for Nonstationary Spectral Matching. *Earthquake Spectra.* 26(3):601-617. doi:10.1193/1.3459159

Ancheta, T.D., R.B. Darragh, J.P. Stewart, E. Seyhan, W.J. Silva, B.S. Chiou, K.E. Wooddell, R.W. Graves, A.R. Kottke, D.M. Boore, T. Kishida, J.L. Donahue (2014). NGA-West2 Database. *Earthquake Spectra.* 30(3):989-1005. doi:10.1193/070913EQS197M

ASCE (2022). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE 7-22. Reston, VA: American Society of Civil Engineers/Structural Engineering Institute

Bai, Q., and Y. Bai (2014). *Subsea Pipeline Design, Analysis, and Installation.* Gulf Professional Publishing. https://doi.org/10.1016/C2010-0-67706-6

Bayless J, Somerville P and Skarlatoudis A (2020) "A Rupture Directivity Adjustment Model Applicable to the NGA West2 Ground Motion Models and Complex Fault Geometries", Final Technical Report, USGS Award G18AP0092, USGS, California

Boore, D.M. (2001). Effect of Baseline Corrections on Displacements and Response Spectra for Several Recordings of the 1999 Chi-Chi, Taiwan, Earthquake. *Bull. Seismol. Soc. Am.*; 91 (5): 1199–1211. doi: https://doi.org/10.1785/0120000703

Burks, L.S, and J.W. Baker (2016). A predictive model for fling-step in near-fault ground motions based on recordings and simulations. *Soil Dynamics and Earthquake Engineering*, vol. 80, pp. 119-26, 2016.

Dalguer, L.A, S.M. Day, G.M. Atkinson, R. Chen (2021). Introduction to the Special Section on Fault Displacement and Near-Source Ground-Motion Models. *Bull. Seismol. Soc. Am.*; 111 (5): 2271–2274. doi: https://doi.org/10.1785/0120210204

Dreger, D., G. Hurtado, A. Chopra, and S. Larsen (2011). Near-field across-fault seismic ground motions, *Bull. Seismol. Soc. Am*. 101, no. 1, 202–221

Hisada, Y., and J. Bielak (2003). A theoretical method for computing near-fault ground motions in layered half-space considering static offset due to surface faulting, with a physical interpretation of fling step and rupture directivity, *Bull. Seismol. Soc. Am*. 93, no. 3, 1154–1168.

Hisada, Y., and S. Tanaka (2021). What is fling step? Its theory, simulation method, and applications to strong ground motion near surface fault rupture, *Bull. Seismol. Soc. Am.* doi: 10.1785/0120210046.

IAEA (2015). *Ground Motion Simulation Based on Fault Rupture Modelling for Seismic Hazard Assessment in Site Evaluation for Nuclear Installations.* Vienna, Austria: International Atomic Energy Agency, IAEA Safety Reports Series No. 85

Kamai, R., N.A Abrahamson, R.W Graves (2014). Adding Fling Effects to Processed Ground-Motion Time Histories. *Bulletin of the Seismological Society of America;* 104 (4): 1914–1929. doi: https://doi.org/10.1785/0120130272

Somerville, P.G., N.F. Smith, R.W. Graves, and N.A. Abrahamson (1997). Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity, *Seismological Research Letters*.68, 180-203

Somerville, P. (2002). Characterizing Near Fault Ground Motion For The Design And Evaluation Of Bridges. Third National Seismic Conference & Workshop on Bridges & Highways, Portland, Oregon, April 29 – May 1, 2002

Wu, S. L., A. Nozu, and Y. Nagasaka (2021). Accuracy of near-fault fling-step displacements estimated using the discrete wavenumber method, *Bull. Seismol. Soc. Am.* 111, no. 1, 309–320.

Zengin, E., N.A. Abrahamson (2021). A procedure for matching the near-fault ground motions based on spectral accelerations and instantaneous power. *Earthquake Spectra*; 37(4):2545-2561. doi:10.1177/87552930211014540