EFFECTIVE INCREMENTAL GROUND VELOCITY: AN IM TO ESTIMATE SLIDING ISOLATION DISPLACEMENT

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Traditional low-rise light-frame structures:

are vulnerable to costly earthquake damage\(^1\)

• $20 Billion in Northridge EQ

• 100,000 in Northridge EQ


Challenges for Isolating Houses

Isolation made expensive by:

• Isolators, moat, pipes, required component testing, peer review, limited payoff in superstructure design forces

How can we reduce the cost?

• Use common, inexpensive materials
• Reduce the anticipated isolation displacements
• Tailor isolator characteristics to the superstructure
High Friction Isolation vs. Conventional Isolation

**Conventional**
- Heavy structures
- Low base shear in moderate events
- High base shear in rare events

**High Friction**
- Proposed for Light frame structures
- The same base shear in all events

Reduces MCE\(_R\) Displacement by 50%
Approaches for Estimating Isolation $\Delta$

**Equivalent Linear Procedure**

\[ \Delta = \frac{g S_{M1} T_M}{4\pi^2 B_M} \]

use iteration

**Response History Analysis**

GMs selected using linear-elastic response spectrum

**Risk-Based Approach**

GMs selected using Conditional Spectrum, integrate analysis results with hazard curves

\[ \Delta = \text{Factor} \times \text{Spectral Disp(assumed period)} \]

\[ \Delta = \text{mean(peak responses)} \]

\[ \Delta \text{ based on target acceptable } P(\text{exceedance}) \]
Difference in Response Between Equivalent Linear and Nonlinear System

Response is dominated by sliding excursions

Notion of an effective period for a system whose behavior is highly nonlinear is not applicable
Problems with Response Spectrum-Based Approaches

Different Pulses Excite Linear and Nonlinear Systems

Even with Conditional Spectrum record selection, $\beta$ is 0.8 to 1.5 for high-friction sliding systems.
One dominant pulse that causes a large sliding excursion
Large Excursions in High PGV Records

75 Records with PGV > 50 cm/s
Response of Block to a Half-Sine Pulse

Subject rigid block to half-sine acceleration pulse

Friction and inertial force only
Pulse has peak acceleration, $a_p$
Pulse has duration, $T_p$
Simplifying the Closed-Form Solution

\[ \Delta_{\text{max}} = \frac{a_p^2 T_p^2}{\mu g} \left[ 1 + \frac{1 - \left( \frac{\mu g}{a_p} \right)^2}{\pi^2} \right] + \left( \frac{\mu g}{a_p} \right) \frac{\sin^{-1}\left( \frac{\mu g}{a_p} \right)}{\pi} - \frac{1}{\pi} + \mu g T_p^2 \left[ \frac{1}{2\pi^2} \right] \]

\[ \Delta_{\text{max}} \approx C_1 \frac{a_p^2 T_p^2}{\mu g} + C_2 a_p T_p^2 + C_3 \mu g T_p^2 \]

\[ \Delta_{\text{max}} \approx C_4 \mu g \left[ \left( \frac{a_p}{\mu g} - 1 \right) T_p \right]^2 \]

Can find \( C_4 = \frac{1}{4} \)

Where:

\[ \eta = \left( \frac{a_p}{\mu g} - 1 \right) T_p \]
Effect of Pulse Shape

Peak displacement is similar as long as the pulse duration and incremental ground velocity are the same.

Can derive similar expressions for $\eta$ using any simple pulse shape.
What is $\eta$: Effective Incremental Ground Velocity (EIGV)

$\eta = \frac{V_{gi} - V_{s0}}{V_{s0}}$  

$\eta$ is the ratio of the “extra” incremental ground velocity beyond what it takes to yield the system to the incremental ground velocity it takes to yield the system, times the pulse duration.

$\eta = \left(\frac{a_p - \mu g}{\mu g}\right)T_p$  

$\eta = \left(\frac{V_{gi} - V_{s0}}{V_{s0}}\right)T_p$
Why is $\eta$ effective in ground motions?

One direction of shaking

- Ground acceleration
- Incremental Ground Velocity
- EIGV
- Sliding Displacement
Why is EIGV effective in ground motions?

Peak Displacement $\approx$ Peak Excursion

$\rightarrow$ Peak excursion caused by a single pulse because of ratcheting-type behavior

$\rightarrow$ Pulse intensity measure EIGV can predict displacement from single pulses
Peak Displacement as a function of $\eta$ and $\mu$

Max. direction value of $\eta$ and bi-directional application of ground motion recordings

\[ \ln \Delta_{max} = c_1 \mu + c_2 \ln \eta_{max} \]

Dispersion:
\[ \beta_\Delta = 0.46 \]

Same functional form as the pulse closed-form solution

Works for systems with a restoring force too!
Ground Motion Prediction Equations for EIGV

Existing GMPEs to find $P(\eta > 0) = P(\text{PGA} > \mu)$

**New GMPE for $\eta$ given $\eta > 0$**

$$\ln(\eta) = b_1 + b_2 (M_n - 8)^2 + b_3 \left( \frac{V_{830,n}}{1600} \right)^{-0.1} + \ln(\eta_{jb,n} + b_4) + \varepsilon_r + \varepsilon_e$$

**Dispersion, $\beta \sim 0.8$**

$\mu = 0.2, V_{830} = 300$ [m/s]

**PSHA to compute MAF of $\eta$**

$$\lambda(\eta > x) = \lambda(M > m_{\text{min}}) \sum_{j=1}^{n_{\text{nu}}} \sum_{k=1}^{n_{\text{ns}}} P(\eta > x | m_j, r_k, \mu, \text{PGA} > \mu) P(\text{PGA} > \mu | m_j, r_k, \mu) P(M = m_j) P(R = r_k)$$

Integrate with prediction equations for displacement, given $\eta$ and $\mu$ to calculate a displacement demand curve
Comparison of Displacement Predictions

Stanford, CA

Using Equivalent Linear Procedure: 1-2% in 50 year displacement

Using Response History Procedure: 3-4% in 50 year displacement

\[ \lambda(\Delta > \delta) = \sum_{all\ IM} P(\Delta > \delta|\eta) \frac{d\lambda}{d\eta} d\eta \]

\( \Delta \) and \( \delta \) are displacement variables.
Major Findings

• High friction sliding systems are well-suited for light frame structures.

• Using response spectrum as an intensity measure for systems that behave entirely inelastically can result in excessive dispersion in EDPs.

• An alternative ground motion intensity measure is developed for predicting isolation displacements, based on what causes large sliding excursions.
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