CHANGING NEEDS OF ENGINEERS FOR SEISMIC DESIGN

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PERFORMANCE-BASED SEISMIC DESIGN OF STRUCTURES
INELASTIC RESPONSE OF STRUCTURES

Dynamic force-deformation hysteresis

Elasto-plastic model

Load reduction factor: \( R = \frac{F_{\text{elastic}}}{F_{\text{plastic}}} \)

Ductility: \( \mu = \frac{x_{\text{plastic}}}{x_{\text{yield}}} \)

Seismic load or moment

Limited damage

Life safety

No collapse

Displacement or rotation

No damage
## PERFORMANCE-BASED DESIGN

### ORDINARY APARTMENT BUILDING

<table>
<thead>
<tr>
<th>HAZARD LEVEL</th>
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### HOSPITAL BUILDING

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SENSITIVITY OF INELASTIC RESPONSE TO YIELD LEVEL AND YIELD TIME
ELASTO-PLASTIC RESPONSE OF A 2.0 Hz SDOF OSCILLATOR
ELASTO-PLASTIC RESPONSE OF A 2.0 Hz SDOF OSCILLATOR

GROUND ACCELERATIONS

ABSOLUTE-ACCELERATION RESPONSE

\[ \mu = \frac{\mu_{\text{max}}}{\mu_{\text{f}}} \]
FORCE-DEFORMATION PLOTS OF ELASTO-PLASTIC RESPONSE FOR DIFFERENT DUCTILITY LEVELS
(Note that the plots have the same axis limits)
SENSITIVITY OF INELASTIC RESPONSE TO INPUT AND YIELD LEVEL

ELASTIC RESPONSE

Yield times:
- t=4.95 s.
- t=6.75 s.
- t=6.76 s.

Yield level

GROUND ACCELERATION

Yield level
SENSITIVITY OF INELASTIC RESPONSE TO INPUT AND YIELD LEVEL: VARIATION OF FORCE AND DISPLACEMENT

TIME VARIATION OF DISPLACEMENTS

TIME VARIATION OF FORCE

SENSITIVITY OF INELASTIC RESPONSE TO INPUT AND YIELD LEVEL: VARIATION OF FORCE AND DISPLACEMENT
SENSITIVITY OF INELASTIC RESPONSE TO INPUT AND YIELD LEVEL: VARIATION OF FORCE-DISPLACEMENT HYSTERESIS

FORCE - DISPLACEMENT HYSTERESIS

Duct = 6.5258
Duct = 5.5109
Duct = 4.7354
IMPORTANCE OF SURFACE WAVES FOR LONG-PERIOD STRUCTURES
DISPLACEMENTS OF A 17-STOREY BUILDING IN LOS ANGELES DURING A M=4.9 EARTHQUAKE

**NS DISPLACEMENTS**

**EW DISPLACEMENTS**

End of the earthquake record from a triggered station.
EFFECTS OF SURFACE WAVES ON BUILDING RESPONSE

YORBA LINDA E-W ACCELERATIONS AND DISPLACEMENTS AT USGS, PASADENA

ACCELERATION RESPONSE SPECTRA

DISPLACEMENT RESPONSE SPECTRA
EFFECTS OF SURFACE WAVES ON BUILDING RESPONSE

RECORDED ACCELERATIONS

RESPONSE OF ELASTO-PLASTIC OSCILLATOR

FORCE-DISPLACEMENT HYSTERESIS

$\mu = 2.75$

$\mu = 6.63$
ROTATIONAL EXCITATION DUE TO SURFACE WAVES
\[ \theta(x,t) = \frac{\partial v(x,t)}{\partial x} \]

FORCES ON A TALL BUILDING SUBJECTED TO SURFACE WAVES
RAYLEIGH WAVES ON THE SURFACE OF UNIFORM HALF SPACE

\[ u(x,t) = A \left( -ik + \frac{2iqsk}{s^2 + k^2} \right) e^{i(\omega t - kx)} \]

\[ v(x,t) = A \left( \frac{2qk^2}{s^2 + k^2} - q \right) e^{i(\omega t - kx)} \]

with

\[ k = \frac{\omega}{v}, \quad q = k^2 - \frac{\omega^2}{v^2}, \quad s = k^2 - \frac{\omega^2}{v^2} \]

\[ \theta(x,t) = \frac{\partial v(x,t)}{\partial x} = -ik \cdot v(x,t) \]
HORIZONTAL AND VERTICAL DISPLACEMENTS AND ROTATIONS DUE TO RAYLEIGH WAVES

(Note that horizontal and rotational motions are in phase)

Uniform half space with $f = 0.5\, \text{Hz}$, $V_r = 500\, \text{m/s}$, $\nu = 0.25$, $V_z = V_r / 0.92$, $V_p = \sqrt{3} \, V_z$
P-Δ EFFECTS DUE TO BASE ROTATION

P-Δ Effects

M = P \cdot \Delta

\Sigma H_{P\Delta}

\Sigma \Delta

\Sigma P

\Sigma H
IMPORTANCE OF HIGH-PASS FILTER CORNER ON LONG-PERIOD STRUCTURAL RESPONSE

(From: Becky, R., K. Buyco, and T. Heaton (2017). Filtered data is less likely to introduce collapse in tall buildings than raw records, SSA Annual Meeting in Denver, CO, 18-20 April 2017)

"The data processing method used in NGA database (i.e., 10 sec. non-causal, zero-phase Butterworth filter) removes the tilt effects from the record and may cause under-estimation of P-Δ effects and collapse probability in long-period structures".
SOFT-FIRST-STORY BUILDINGS AND P-Δ RESPONSE SPECTRA
DAMAGE TO A TYPICAL APARTMENT BUILDING WITH SOFT FIRST STORY DURING THE M=7.4, 1999 KOCaelI, TURKEY EARTHQUAKE
P-Δ EFFECTS ON SOFT-FIRST-STORY BUILDINGS

P-Δ Effects due to soft 1st story

Failure

M = P·Δ

P-Δ Effects due to soft 1st story
RESPONSE SPECTRA WITH P-Δ EFFECTS

No soft story  Soft story  SDOF model for P-Δ effects
REDUCTION OF NATURAL FREQUENCY DUE TO P-Δ EFFECTS

\[
\ddot{x}(t) + 2\xi_0 \omega_0 \dot{x}(t) + \omega_0^2 \left[ 1 - \frac{P}{P_{cr}} \left( 1 - \frac{\ddot{v}(t)}{g} \right) \right] \cdot x(t) = -\ddot{y}(t)
\]

\[
\omega_{eff} = \omega_0 \cdot \left[ 1 - \frac{P}{P_{cr}} \left( 1 - \frac{\ddot{v}(t)}{g} \right) \right]^{1/2}
\]

Additional parameters needed for response spectra: \( P/P_{cr} \) and vertical accelerations.
DISPLACEMENT RESPONSE SPECTRA WITH P-Δ EFFECTS

STATION YPT

STATION IZT

STATION SKR

STATION DZC
TALL BUILDING RESPONSE TO LARGE DISTANT EARTHQUAKES
M=7.8; 16 April 2013

≈900 km
SOME OF THE BUILDINGS WITH STRUCTURAL HEALTH MONITORING SYSTEMS IN ABU DHABI
RECORDED GROUND ACCELERATIONS

BASEMENT ACCELS. IN X (LONG) DIRECTION

BASEMENT ACCELS. IN Y (SHORT) DIRECTION
TOP FLOOR ACCELE. IN X (LONG) DIRECTION

$T_x = 3.85$ sec.

TOP FLOOR DISPL. IN X (LONG) DIRECTION

5 min. 10 min. 15 min.
62-story Sapphire Tower
The tallest building in Istanbul
SOUTH-SIDE, NORTH-DIRECTION ACCELERATIONS

$T_x = 4.54 \text{ sec}$

3.33 min.

SOUTH-SIDE, NORTH-DIRECTION DISPLACEMENTS

$T_x = 4.54 \text{ sec}$

3.33 min.
$T_x = 6.20 \text{ sec}$

3.33 min.
CALCULATED DAMPING RATIOS

NORTH–SIDE, EAST–DIRECTION, FIRST–MODE DISPLACEMENTS

\[ \zeta_1 = 0.006 \]

NORTH–SIDE, NORTH–DIRECTION, SECOND–MODE DISPLACEMENTS

\[ \zeta_2 = 0.007 \]

NORTH–SIDE, EAST–DIRECTION, THIRD–MODE (TORSION) DISPLACEMENTS

\[ \zeta_3 = 0.008 \]
Measured damping ratio vs building height

From Satake at.al, 2003
SOME SUGGESTIONS FOR NEW APPROACHES:

- Utilize data from dense urban networks to supplement GMPEs
- Use a probabilistic approach to calculate response spectra
- Use energy and energy flux for ground motion description and structural response
CAN WE UTILIZE DATA FROM DENSE URBAN NETWORKS TO LOCALIZE GMPEs?

Example: Istanbul

- 100+ real-time strong-motion stations (700 more are currently being installed)
- Over 7,000 records from M>3.00 earthquakes
- Well known fault path
- Topography seems to be important in shaking distribution
- Can a calibrated 3D seismic model be an alternative to GMPEs?
Relative displacement with respect to ground

\( \omega_0, \zeta_0 \)

\( x(t) \)

\( a(t) \)

PROBABILISTIC APPROACH TO CALCULATE RESPONSE SPECTRA:
DISTRIBUTION OF PEAKS OF A SDOF OSCILLATOR

Distribution of peaks (Rayleigh distribution)

\[
p(x) = \frac{x}{\sigma_x^2} \cdot \exp \left( -\frac{x^2}{2\sigma_x^2} \right)
\]

\[
E(x) = 1.25\sigma_x \quad \text{Var}(x) = 0.43\sigma_x^2
\]
The rate of decay of amplitudes with increasing peak number gives a measure of duration.
INFORMATION THAT CAN BE EXTRACTED FROM PROBABILISTIC RESPONSE SPECTRA

Given: Distribution of peak displacements relative to base.

1. Number of crossings of level $\eta$ per unit time: $N(\eta) = 2f \cdot \exp\left(-\frac{\eta^2}{2\sigma_y^2}\right)$

2. Number of cycles (i.e., zero crossings) per unit time: $N(0) = 2f$

3. Probability of exceeding a specified displacement level $\eta$: $F(\eta) = \int_0^\eta p(\eta) \cdot d\eta$

4. Displacement level corresponding to a specified probability of exceedance: $\eta = \text{inv} \left[ \int_0^\eta p(\eta) \cdot d\eta \right]$
RANDOM VIBRATION APPROACH TO STRUCTURAL RESPONSE

Power Spectral Density of ground accelerations: \( S_a(\omega) = \lim_{T \to \infty} \frac{\pi}{T} \cdot E \left[ \left| F_a(\omega) \right|^2 \right] \) where \( \int_{-\infty}^{\infty} S_a(\omega) \cdot d\omega = \sigma_a^2 \)

\[
\sigma_a^2 = \int_{-\infty}^{\infty} S_a(\omega) \cdot d\omega = S_0 \cdot (\omega_2 - \omega_1)
\]

\[
\Rightarrow S_0 = \frac{\sigma_a^2}{\omega_2 - \omega_1}
\]

\( S_0 \) is the best single parameter to characterize ground shaking for engineering purposes.
ENERGY-BASED FORMULATION OF RESPONSE

\[ m \cdot \ddot{x}(t) + c \cdot \dot{x}(t) + k \cdot x(t) = -m \cdot a(t) \]

Dividing by \( m \) and denoting: \( k/m = \omega_0^2 \) and \( c/m = 2\xi_0 \omega_0 \):

\[ \dot{x}(t) + 2\xi_0 \omega_0 \cdot \dot{x}(t) + \omega_0^2 \cdot x(t) = -a(t) \]

(\( \xi_0 \) and \( \omega_0 \) vary with \( x \) and \( t \) if nonlinear)

By integrating over the relative displacement with respect to base:

\[
\int \dot{x}(t) \cdot dx + \int 2\xi_0 \omega_0 \cdot \dot{x}(t) \cdot dx + \int \omega_0^2 \cdot x(t) \cdot dx = -\int a(t) \cdot dx
\]

where \( E_K \), \( E_D \), \( E_A \) includes energies absorbed due to elastic and inelastic behaviors.

Energy response spectrum is the plot of \( (E_I)_{max} \) against \( T_0 = 2\pi / \omega_0 \) for given \( a(t) \) and \( \xi_0 \).
ENERGY FLUX

“Amount of energy transmitted through a cross section per unit time.”

\[ E(t) = \frac{1}{2} \cdot \rho \cdot [v(t)]^2 \cdot V \]
U_j(t) = A_j^2(f) \cdot [\alpha_j(f) \cdot D_j(t-\tau_j) + \beta_j(f) \cdot U_{j-1}(t-\tau_j)]

D_j(t) = A_j^2(f) \cdot [\alpha_j(f) \cdot U_j(t-\tau_j) + \beta_j(f) \cdot D_{j+1}(t-\tau_j)]

\alpha, \beta = \text{Energy reflection and transmission coefficients}

\tau = \text{Wave travel time in the layer}

A(f) = \exp\left(-\frac{\pi \tau f}{Q}\right) - \text{Energy loss due to damping}
EXAMPLE: Energy flux in a 10-story building on two-layer soil media

Parameters required:

$E_I$: Upgoing input energy (or velocity) from ground

$\tau$: Wave travel times in layers.

$r$: Wave reflection coefficients at layer interfaces.

$Q$: Damping in each layer.
References:


SOME CONCLUSIONS:

- Performance-based design requires the control of inelastic deformations, which are very sensitive to the initial build-up of ground accelerations and the yield point of the structure.

- Surface waves from distant large earthquakes can be critical for long-period structures because of rotational excitations and P-Δ effects.

- Duration of vibration of a structure is related to its natural frequency and damping, and does not always correlate with the duration of earthquake.

- Collapse of soft-first-story structures is also controlled by P-Δ effects and vertical ground accelerations.

- Damping in tall buildings decrease with increasing height, and can be as low as 1%.

- Probabilistic response spectra provide much more information than standard response spectra.

- Energy-based representation of ground shaking and structural response can be a powerful alternative to current seismic design methods.