# SEISMIC PROTECTION OF STRUCTURES WITH MODERN TECHNOLOGIES

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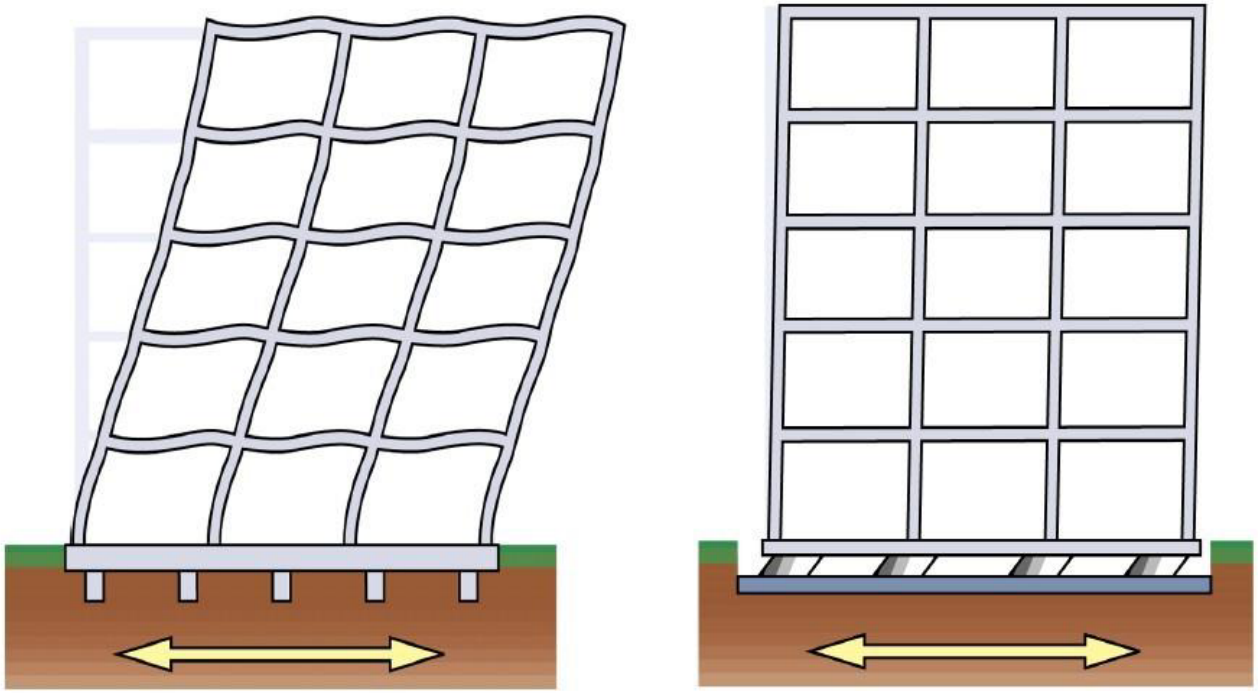
# Seismic Isolation

A flexible interface between the superstructure and the foundation that consists of well engineered devices (Isolation Bearings) which decouple the motion at the expense of large displacements; therefore, reducing the inertia forces that develop in the superstructure.



Conventional Structure  Base-Isolated Structure

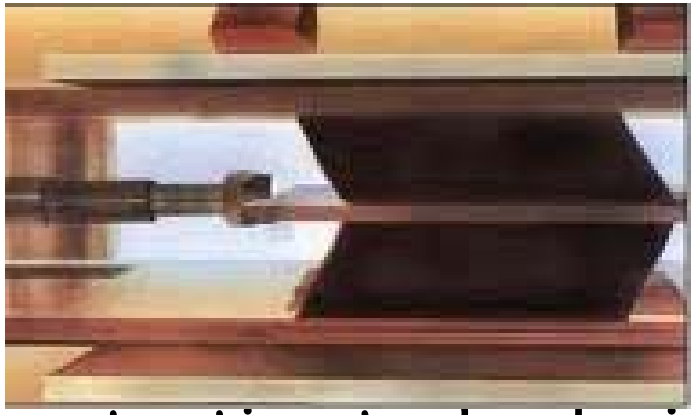
# Seismic Design and Retrofit with Isolation Bearings

Seismic Retrofit of Richmond San Rafael Bridge, CA

Seismic Retrofit of American River Bridge, CA

# Seismic Design and Retrofit with Fluid Dampers

## Prototype and production testing of bearings and dampers


Modern seismic protection technologies consist of well engineered devices that have been tested extensively and when properly installed may lead to sustainable engineering.

Sustainable Engineering: The design and construction of structures that meet acceptable performance levels at present and in the years to come without compromising the ability of future generations to use them, maintain them and benefit from them.

# Outline

The Concept of Seismic Isolation
Accommodating Forces and Displacements
Examples from the Implementation of Seismic Protection Systems in Bridges
Isolation Bearings

- Elastomeric Bearings (NRB, HDRB, LRB)
- Sliding Bearings (FPS)

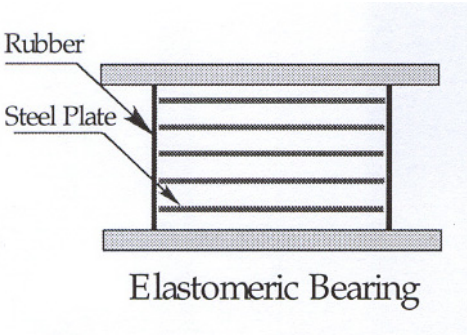
Definition of the Isolation Period
The Linear Viscoelastic Behavior
The Bilinear Behavior
Fluid Dampers
Nonlinear Viscous Behavior

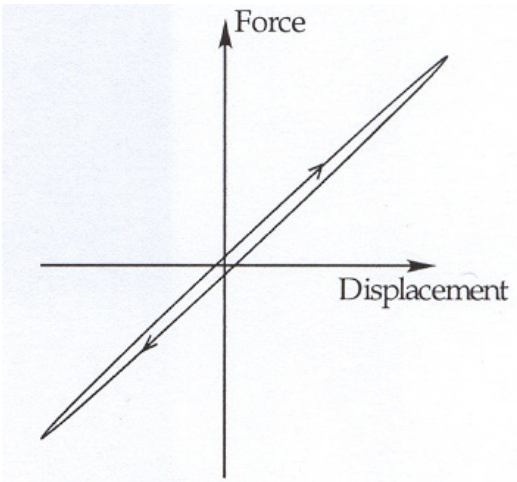
# The Concept of Seismic Isolation

- Use some type of support that uncouples the motion of the super-structure from the ground
- Basic Properties of an Isolation System
  - Horizontal Flexibility: to increase structural period and reduce spectral demands
  - Energy Dissipation: to reduce displacements
  - Sufficient Stiffness/Rigidity at Small Displacements

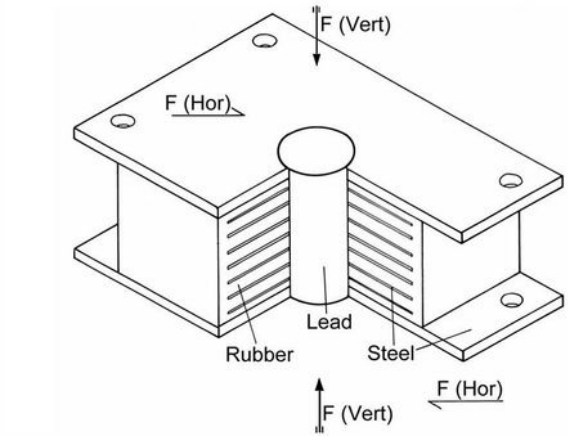
# Types of Isolation Bearings

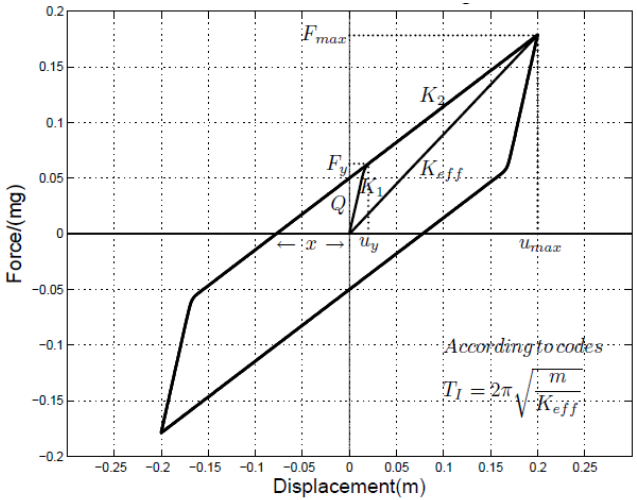
Laminated Elastomeric Bearings
Natural Rubber Bearings (NRB)
High Damping Bearing (HDRB)



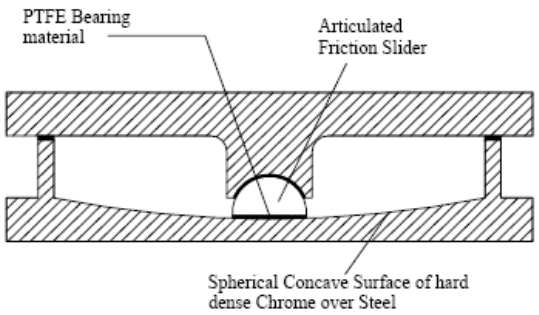

Lead Rubber Bearings (LRB)
(lead diameter 60 to 150 mm)

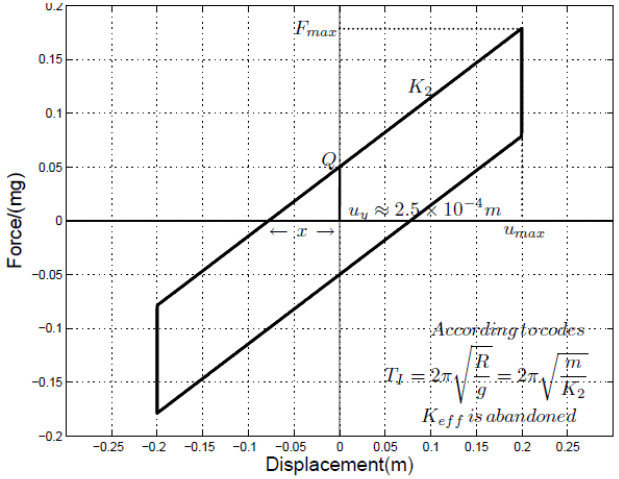



$u_y \approx 2cm$

Sliding Bearing




$u_y \approx 0.2mm$


# Egnatia Highway
# Northern Greece

# 91/5 overcrossing
# Orange County in Southern California

**View of 91/5 overcrossing located in Orange County in Southern California. The deck is supported at mid-span by an outrigger prestressed beam, while at each abutment it rests on four elastomeric pads and is attached with four fluid dampers.**

# 91/5 overcrossing
# Orange County in Southern California

**View of 91/5 overcrossing located in Orange County, Southern California.**

# 91/5 overcrossing
# Orange County in Southern California

# 91/5 overcrossing
# Orange County in Southern California

**Photo showing four dampers installed at the south end of the 91/I5 overpass.**

# Seismic Isolation: Examples of Retrofitted Bridges

**I-40 Mississippi River Bridge**
**Memphis, Tennessee**

**It was retrofitted with Friction PendulumTM isolation bearings designed to withstand a magnitude 7 earthquake occurring on the New Madrid fault.**

**Use of Friction PendulumTM bearings allows the 40 year old bridge to remain operational after an extreme earthquake event.**

# Seismic Isolation: Examples of Retrofitted Buildings

**U.S. Court of Appeals**
**San Francisco, California**

***Friction PendulumTM seismic isolation saves $7.6 million and wins National Award***

# Seismic Isolation: Examples of New Projects

**San Francisco Airport International Terminal**

***World's Largest Isolated Building***

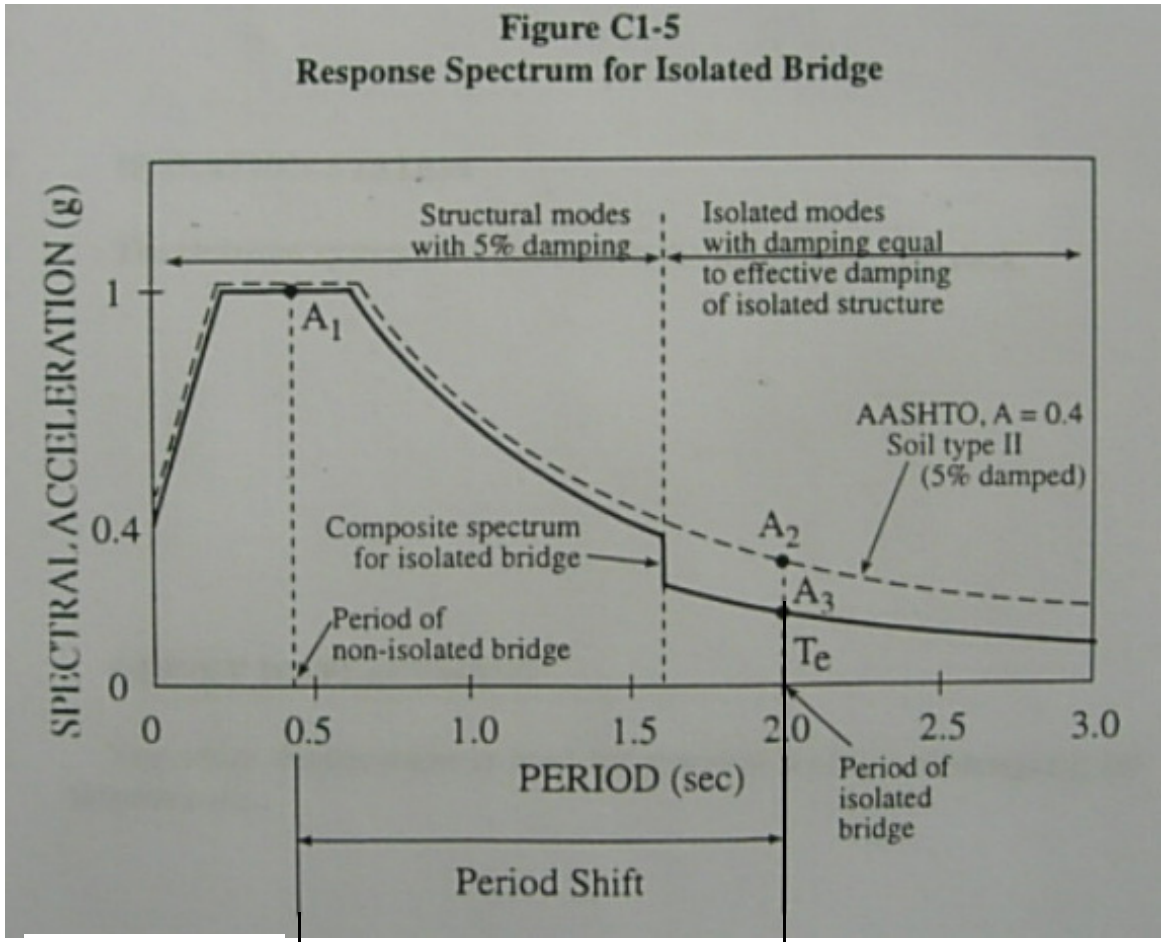

**The Friction PendulumTM bearings provide a 3 sec. isolated period.**

**Each bearing can displace up to 20 inches in any horizontal direction**
**while supporting buildings and seismic loads of up to 6 million pounds**

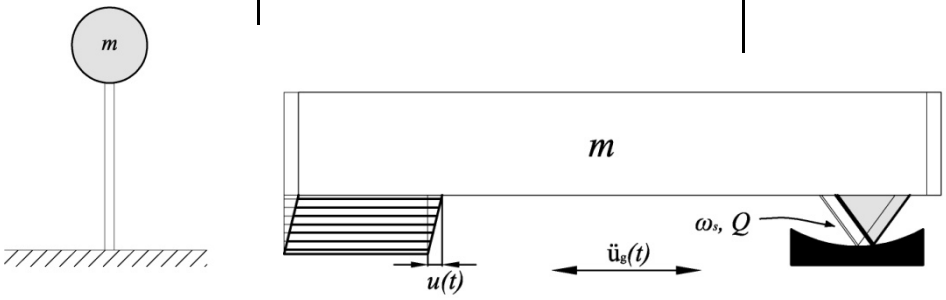
# Seismic Isolation: Examples of New Projects

**Tokyo Rinkai Hospital**
**Tokyo, Japan**

# The Concept of Seismic Isolation




Reduce forces at the expense of accommodating large displacements



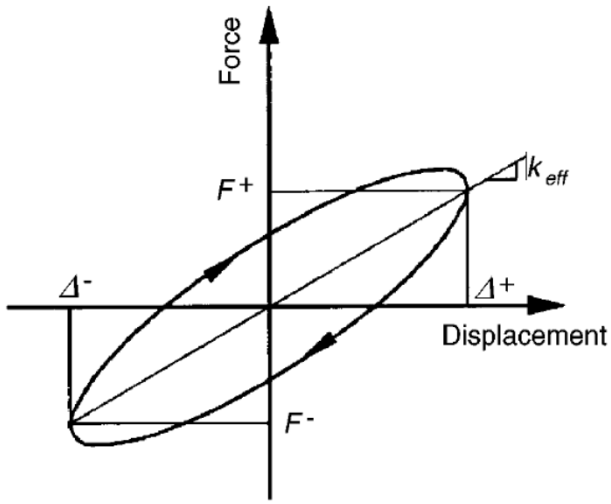

Various types of isolation bearings

How is the isolation period $T_I$, $T_0$ defined ?

# The Confusion!

**Offered by established Design Codes (see ASSHTO 1998, FEMA-274 1997)**

## Nearly Viscoelastic



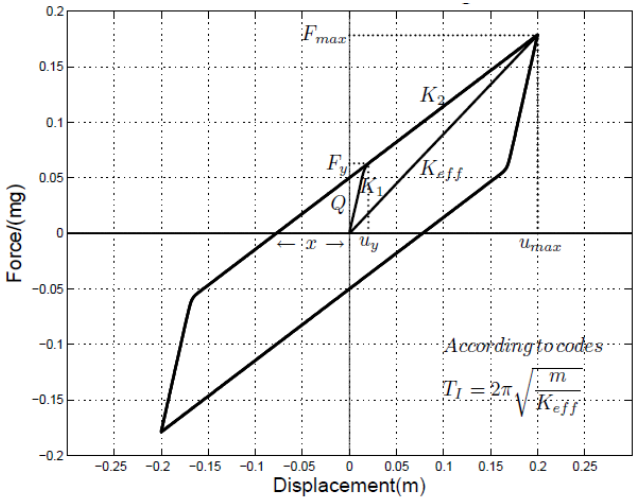

$$K_{eff} = \frac{|F^+| + |F^-|}{|\Delta^+| + |\Delta^-|}$$

$$T_I = T_{eff} = 2\pi\sqrt{\frac{m}{K_{eff}}}$$

**Theoretically correct!**

**Why?**

## Bilinear Behavior

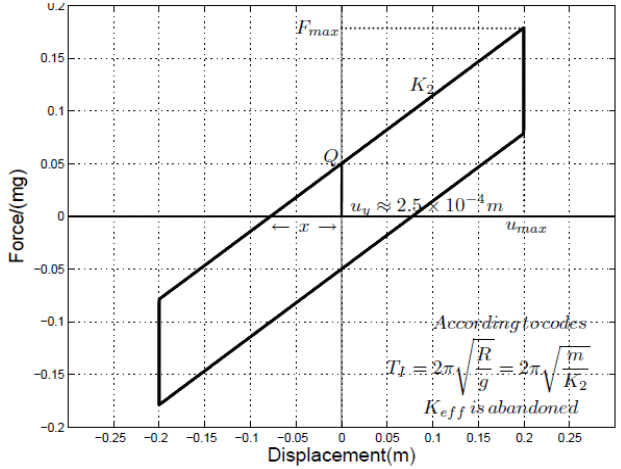



$K_{eff}$ What most seismic codes use

$$T_I = T_{eff} = 2\pi\sqrt{\frac{m}{K_{eff}}}$$

**Theoretically Unsubstantiated!**

## Rigid Elastic Behavior




$$K_2 = \frac{mg}{R} = \frac{W}{R}$$

There exists a very small uy=0.025cm

$$T_I = 2\pi\sqrt{\frac{R}{g}}$$

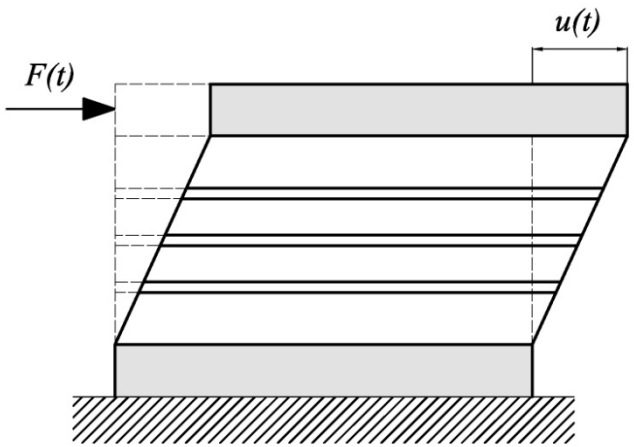
(R= radius of curvature of spherical surface)

The concept of Teff is abandoned

**Theoretically Correct!**

**Why?**

# The Linear Viscoelastic Behavior



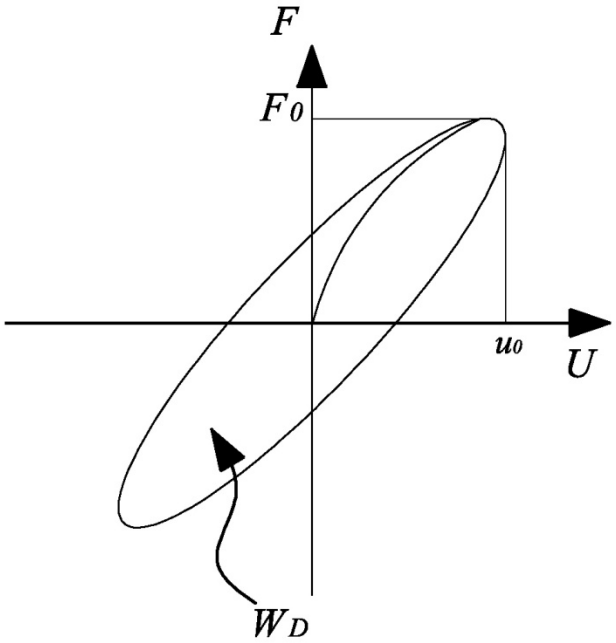

**Cyclic loading with frequency Ω**

**Imposed Displacement**

$$u(t) = u_0 \sin(\Omega t)$$
$$\dot{u}(t) = \Omega u_o \cos(\Omega t)$$

**Recorded Force**
(force needed to support the motion)

$$F(t) = F_0 \sin(\Omega t + \varphi)$$




**Expansion of the argument**

$$F(t) = F_0 \sin(\Omega t)\cos\varphi + F_o \cos(\Omega t)\sin\varphi$$

$$F(t) = \frac{F_o}{u_0} u_0 \sin(\Omega t)\cos\varphi + \frac{F_0}{u_0}\frac{1}{\Omega}\Omega\cos\ (\Omega t)\sin\varphi$$

$$\boxed{F(t) = \frac{F_0}{u_0}\cos(\varphi)\, u(t) + \frac{F_0}{u_0}\frac{1}{\Omega}\cdot\sin(\varphi)\, \dot{u}(t)} \quad (1)$$

# The Linear Viscoelastic Behavior cont'

$$\boxed{F(t) = \underbrace{\frac{F_0}{u_0}\cos(\varphi)\, u(t)} + \underbrace{\frac{F_0}{u_0}\frac{1}{\Omega}\cdot\sin(\varphi)\, \dot{u}(t)}}$$

$$K_1(\Omega) = \frac{F_0}{u_0}\cos\varphi = \text{ storage stiffness}$$

$$C(\Omega) = \frac{F_o}{u_o}\frac{1}{\Omega}\sin\varphi = \text{damping coefficient}$$

$$K_2(\Omega) = \Omega C(\Omega) = \frac{F_0}{u_0}\sin\varphi = \text{loss stiffness}$$

note that :

$$K_1^2(\Omega) + K_2^2(\Omega) = \left(\frac{F_o}{u_o}\right)^2\left[\cos^2\varphi + \sin^2\varphi\right] = \left(\frac{F_o}{u_o}\right)^2$$

so :

$$K_o(\Omega) = \sqrt{K_1^2(\Omega) + K_2^2(\Omega)} = \frac{F_o}{u_o} \quad \text{:total stiffness}$$

Returning to equation *(1)*:

$$\boxed{F(t) = K_1(\Omega)\, u(t) + C(\Omega)\, \dot{u}(t)}$$

$$\begin{cases} 1.\ \text{A single frequency } \Omega \\ 2.\ \text{Steady State Motion.} \end{cases}$$

# The Linear Viscoelastic Behavior cont'

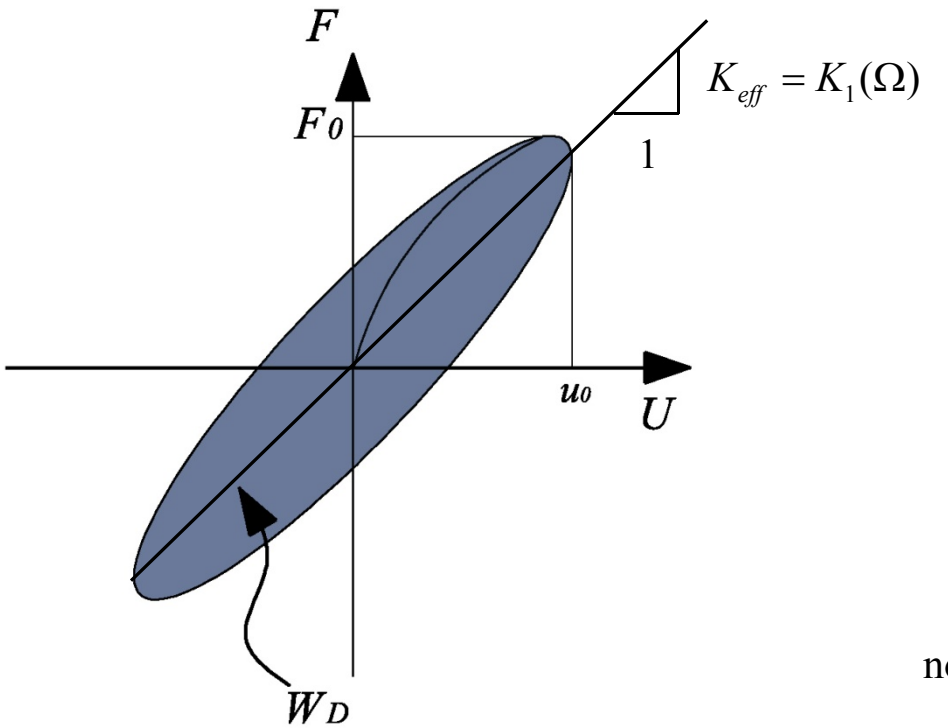
**Work done per cycle:**

$$\left.\begin{aligned} W_D &= \int_o^T F(t)\frac{du}{dt}dt \\ F(t) &= K_1(\Omega)u(t) + C(\Omega)u(t) \end{aligned}\right\} \Rightarrow W_D = \int_o^T F(t)\dot{u}(t)dt \ldots\ldots\ldots$$

$$\ldots\ldots\ldots \Rightarrow W_D = \pi C(\Omega)\Omega u_o^2$$

$$\boxed{C(\Omega) = \frac{W_D}{\pi \Omega u_o^2}}$$

# Evaluation of Mechanical Properties from Experiments




$$K_{eff} = K_1(\Omega)$$

$$C(\Omega) = \frac{W_D}{\pi \Omega u_o^2}$$

$$K_2(\Omega) = \Omega C(\Omega) = \frac{W_D}{\pi u_o^2}$$

$$K_o = \frac{P_o}{u_o}$$

$$K_1(\Omega) = \sqrt{K_o^2 - K_2^2} = \sqrt{\left(\frac{F_o}{u_o}\right)^2 - \left(\frac{W_D}{\pi u_o^2}\right)^2}$$

$$\text{now}: K_I = K_1(\Omega)$$

$$\text{and}: T_I = 2\pi\sqrt{\frac{m}{K_1}}$$

$$\text{We measure three quantities} \begin{cases} F_o \\ u_o \\ W_D \end{cases}$$

# Equivalent Damping Coefficient and Viscous Damping Ratio

$$\textit{Equivalent Damping Coefficient} = \beta = \left[\begin{array}{l}\textbf{a measure for the ability}\\ \textbf{of a bearing or any structural}\\ \textbf{components to dissipate energy}\end{array}\right.$$

$$\omega_I = \frac{2\pi}{T_I}$$

$$T_I = 2\pi\sqrt{\frac{m}{K_1}}$$

$$\beta = \frac{1}{2}\frac{K_2(\Omega)}{K_1(\Omega)} = \frac{1}{2}\frac{W_D(\Omega)}{\pi K_1 u_o^2}$$

Viscous Damping ratio $= \xi_I =$ modal damping of an isolated mass

$$2\xi_I m\omega_I = C(\Omega) = \frac{\sum_i W_{D_i}}{\pi\Omega u_o^2}$$

$$\Rightarrow \xi_I = \frac{\sum_i W_D}{2\pi m\omega_I \Omega u_o^2} \Rightarrow \qquad \xi_I = \frac{1}{2\pi}\frac{\omega_I}{\Omega}\frac{\sum_i W_{D_i}(\Omega)}{\sum_i K_1 u_o^2}$$

$$\xi_I = \frac{1}{2\pi}\frac{\omega_I}{\Omega}\frac{\sum_i W_{D_i}(\Omega)}{\sum_i K_1 u_0^2} = \frac{\omega_I}{\Omega}\beta$$

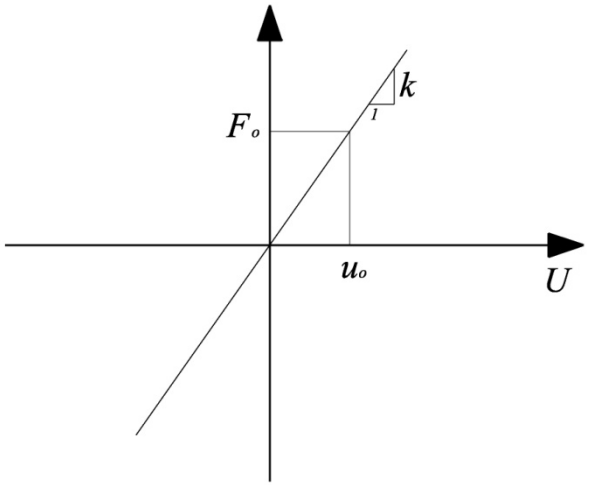
# What the Code Offers as Effective Damping Ratio

$$\xi_{eff} = \xi_I = \frac{1}{2\pi} \frac{\sum_i W_D(\Omega)}{K_{eff} u_o^2} \qquad \left( \text{indeed } \frac{\omega_I}{\Omega} = 1 \right)$$

In this case the areas $W_{Di}$ need to be taken from experiments performed at $\Omega = \omega_I \left( \text{say } \omega_I = 2\,\text{sec} \right)$

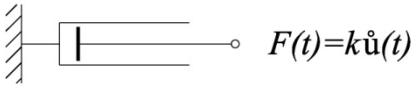
# Examples

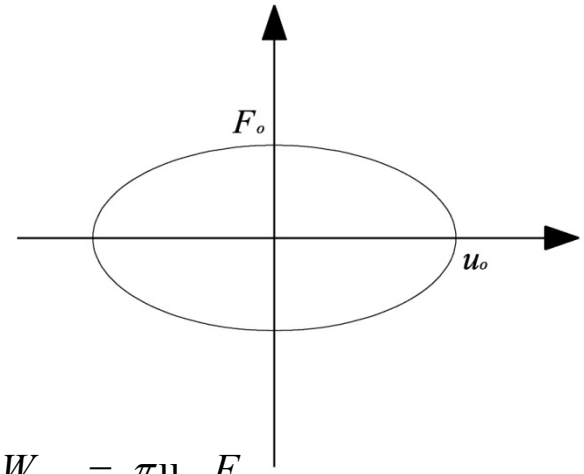
## Elastic Springs


$$C(\Omega)=0$$
$$K_2(\Omega)=0$$
$$K_1(\Omega)=\sqrt{\left(\frac{F_o}{u_o}\right)^2-0}=\frac{F_o}{u_o}=K_0$$

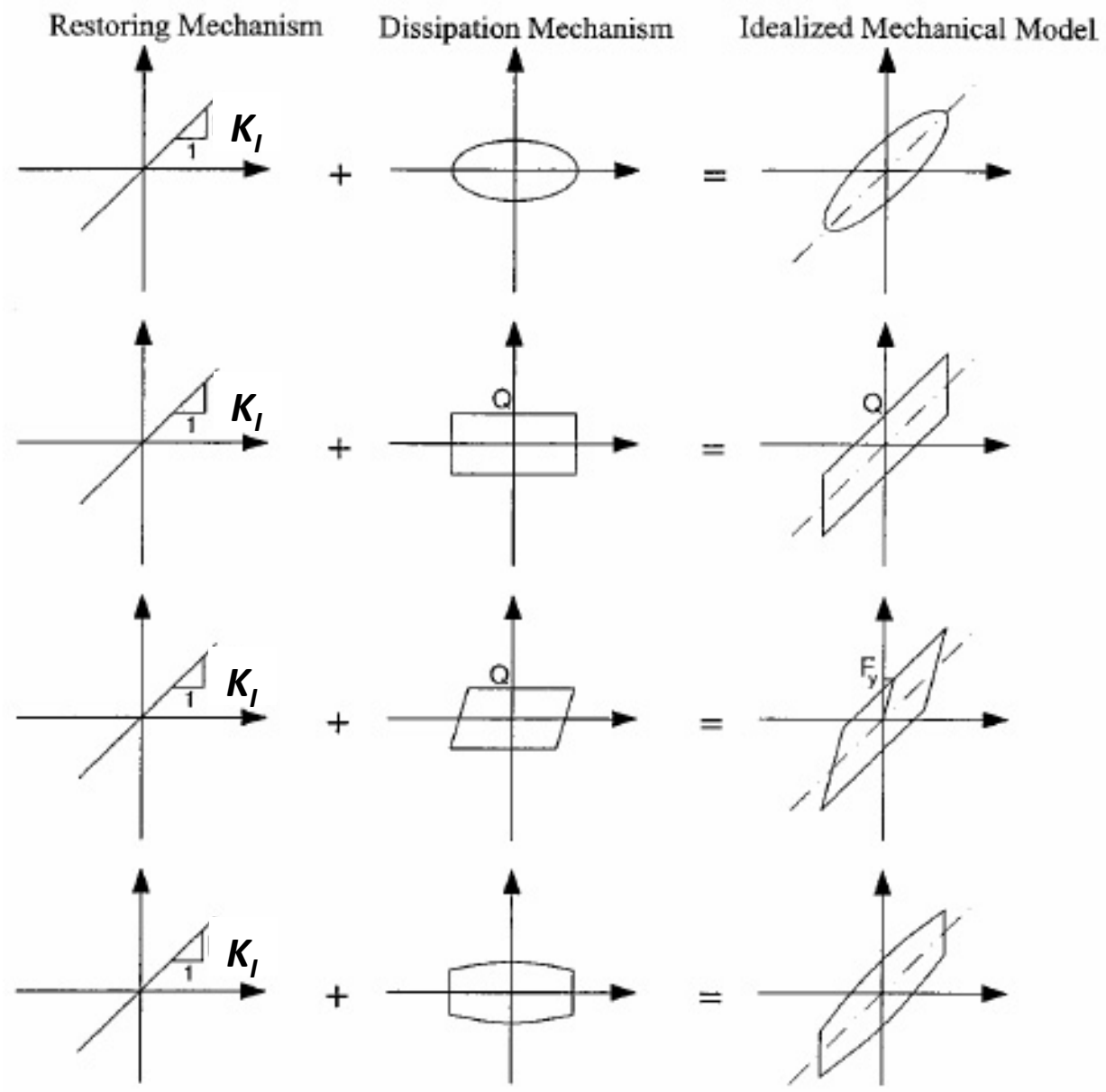
## Viscous Dashpot

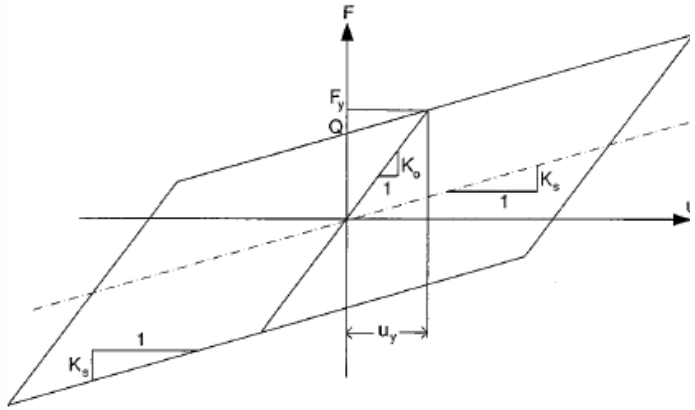


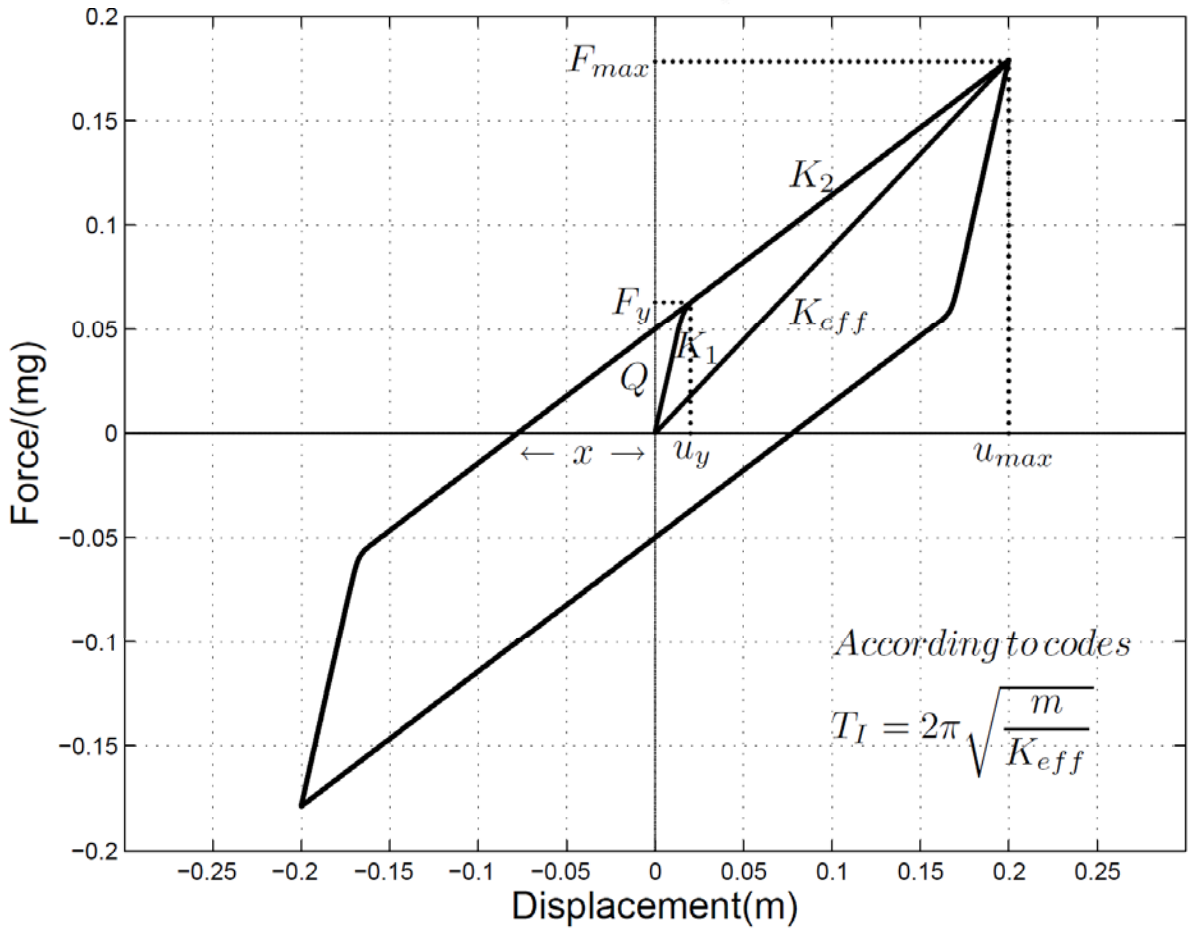

$$W_D = \pi u_o F_o$$
$$C(\Omega)=\frac{W_D}{\pi\Omega u_o^2} \Rightarrow C(\Omega)=\frac{F_o}{\Omega u_o}$$
$$K_2(\Omega)=\frac{F_o}{u_o}$$
$$K_1(\Omega)=\sqrt{\left(\frac{F_o}{u_o}\right)^2-\left(\frac{F_o}{u_o}\right)^2}=K_1(\Omega)=0!$$
$$K_o=\frac{F_o}{u_o}\rightarrow \text{no physical meaning}$$

# Restoring and Dissipation Mechanisms of Isolation Bearings



$$\alpha = K_2/K_1$$




$$\frac{F_{max}}{F_y} = \frac{u_{max}+x}{u_y+x}$$

$$K_{eff} = K_1 \frac{u_y}{u_{max}} \frac{u_{max}/u_y + Q/K_2 u_y}{1+(Q/K_2 u_y)}$$

$$K_{eff} = K_1 \frac{1+\alpha(\mu-1)}{\mu}$$

$$T_{eff} = T_1 \sqrt{\frac{\mu}{1+\alpha(\mu-1)}}$$

Question: Is Teff indeed the time needed for a bilinear oscillator to complete one cycle?

## Small to Moderate ductility values

Iwan and Gates (1979) → $T_{eff} = [1 + 0.121(\mu - 1)^{0.939}]T_1, \quad \mu \le 8$

Guyader and Iwan (2006) →

$$T_{eff} = [1 + 0.1145(\mu - 1)^2 - 0.0178(\mu - 1)^3]T_1, \text{ for } \mu < 4.0$$

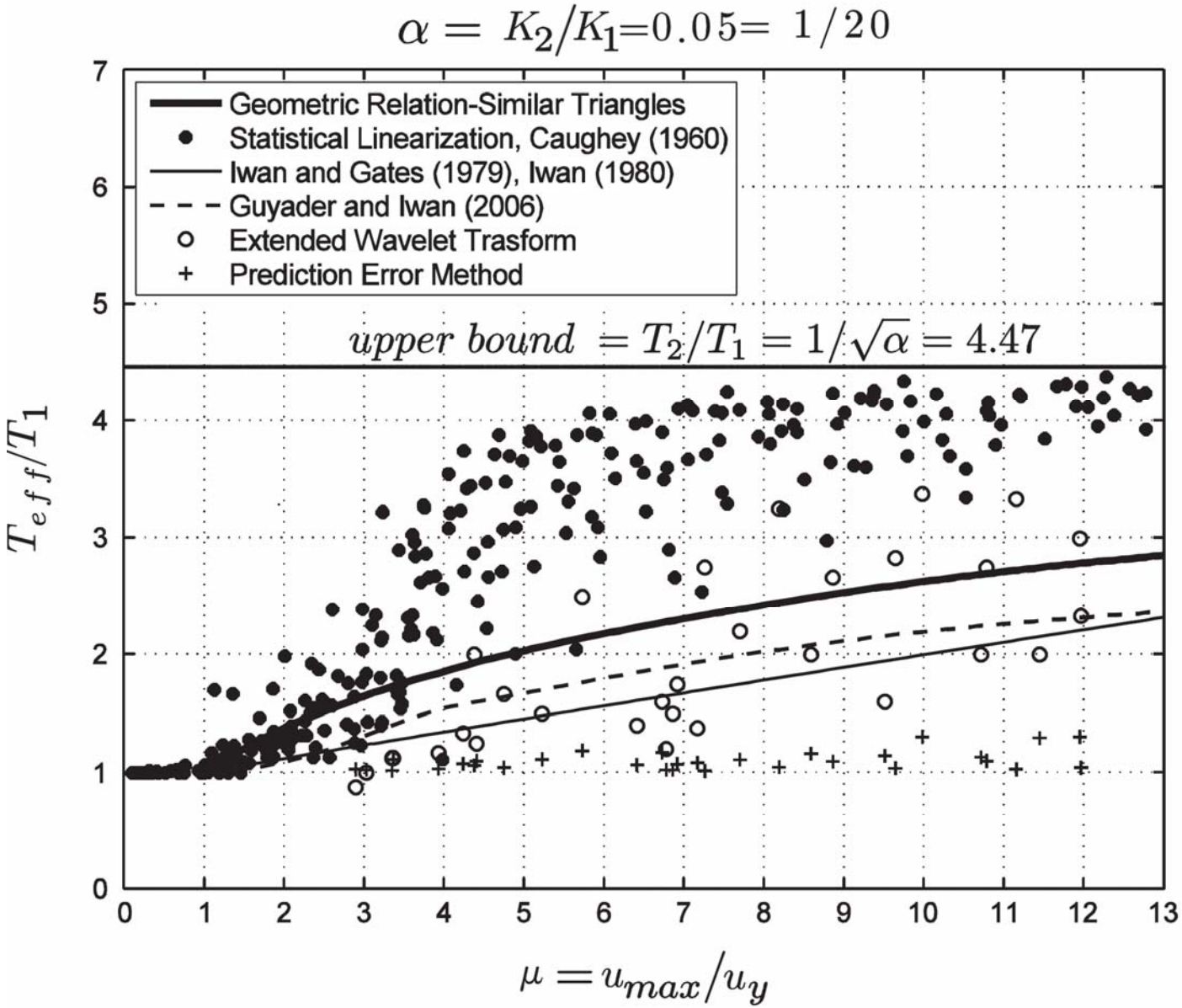
$$T_{eff} = [1 + 0.1777 + 0.1240(\mu - 1)]T_1, \text{ for } 4.0 \le \mu \le 6.5$$

## Large ductility values

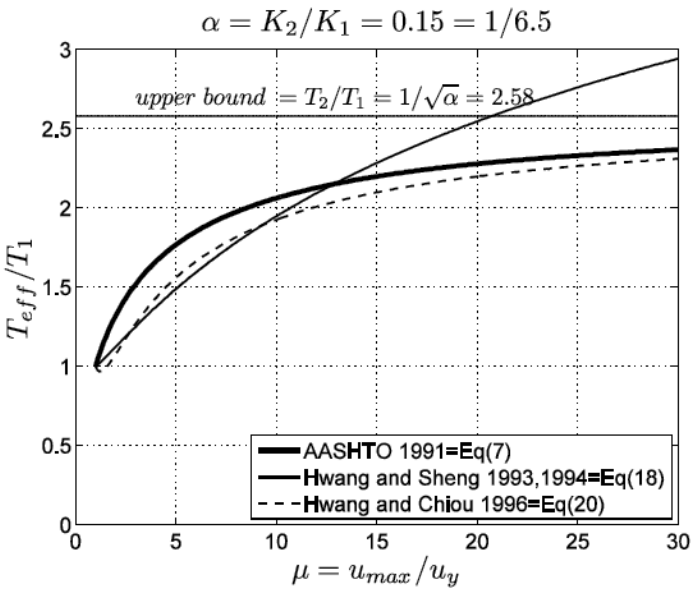
Hwang and Sheng (1993, 1994) → $T_{eff} = \{1 + \ln[1 + 0.13(\mu - 1)^{1.137}]\}T_I$

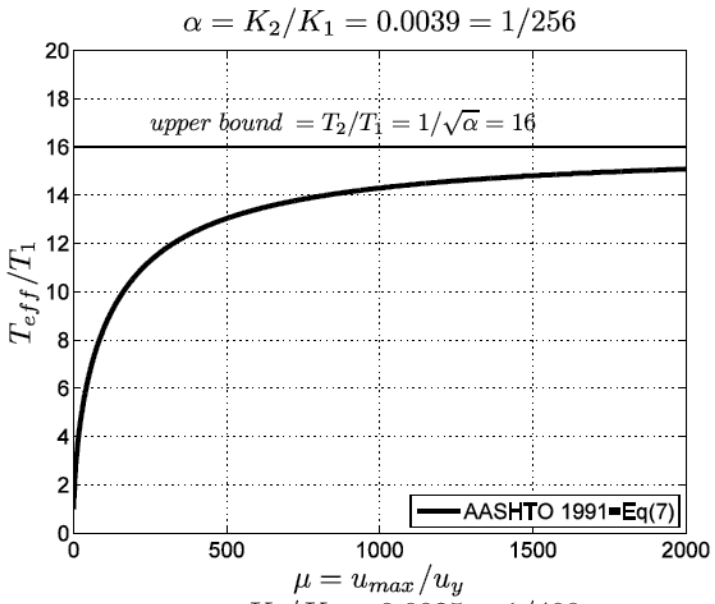
Hwang and Chiou (1996) → $T_{eff} = \sqrt{\dfrac{\mu}{1 + \alpha(\mu - 1)}}\left(1 - 0.737\dfrac{\mu - 1}{\mu^2}\right)T_1$

# Bilinear System: Small to Moderate ductility values




Makris N., and G. Kampas, "Estimating the "Effective period" of Bilinear Systems with Linearization Methods, Wavelet and Time-Domain Analysis", *Journal of Soil Dynamics and Earthquake Engineering*, 2012, Vol. 45, pp. 80-88.

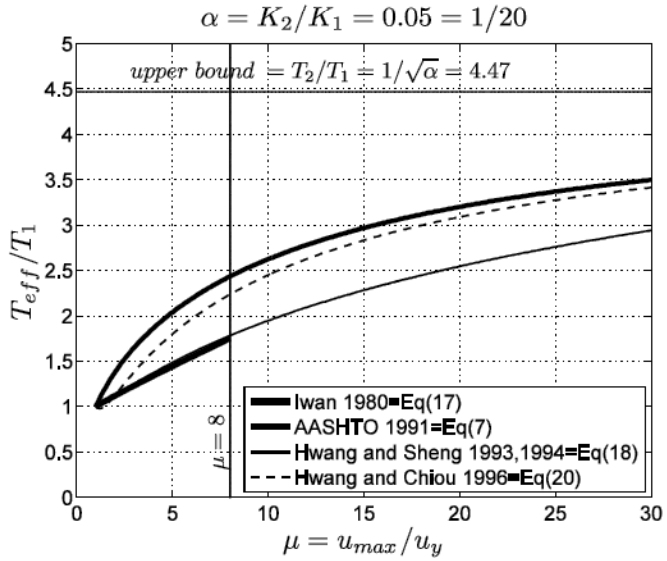


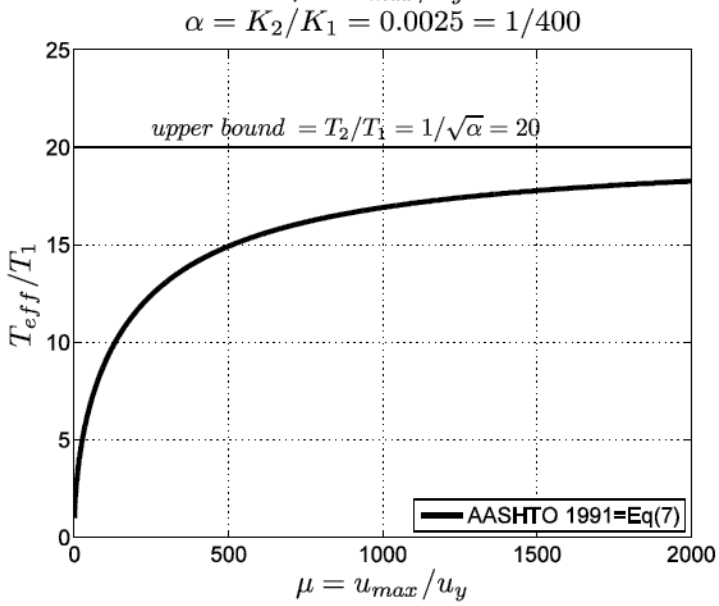




$$K_2 = \alpha K_1$$

$$K_{eff} = K_2 \frac{1+\alpha(\mu-1)}{\alpha\mu}$$

$$T_{eff} = T_2 \sqrt{\frac{\alpha\mu}{1+\alpha(\mu-1)}}$$



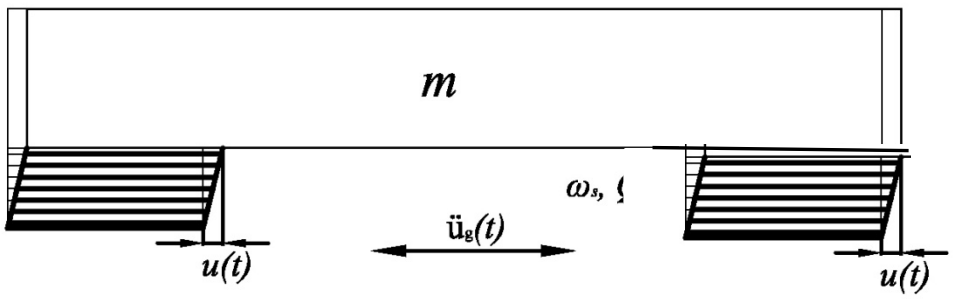



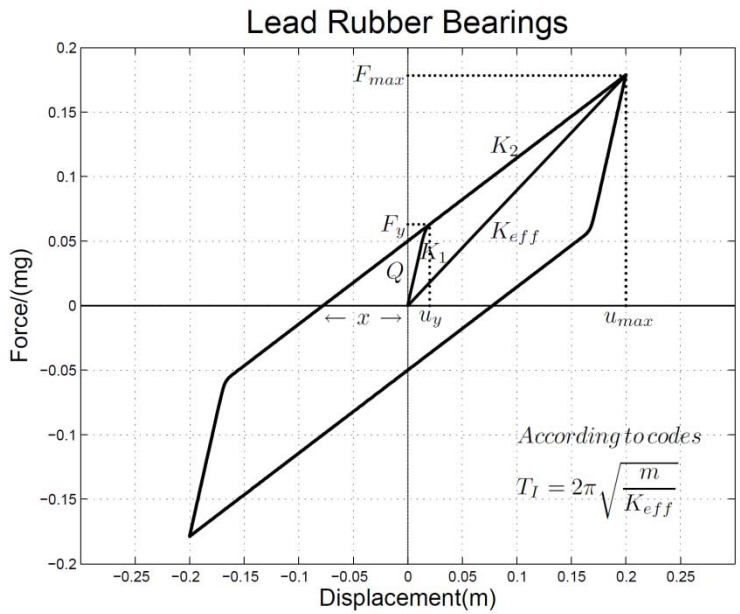
# Geometric relation for large μ gives

$$T_{\substack{eff \\ for\ large\ \mu}} = \frac{1}{\sqrt{1+\frac{Q}{K_2 u_{\max}}}} T_2$$

$$\frac{T_{eff}}{T_2} = 1 - \frac{1}{2}\frac{Q}{K_2 u_{\max}} + \frac{3}{8}\left(\frac{Q}{K_2 u_{\max}}\right)^2 + \cdots$$

# Free-Vibration Period of a Bilinear System

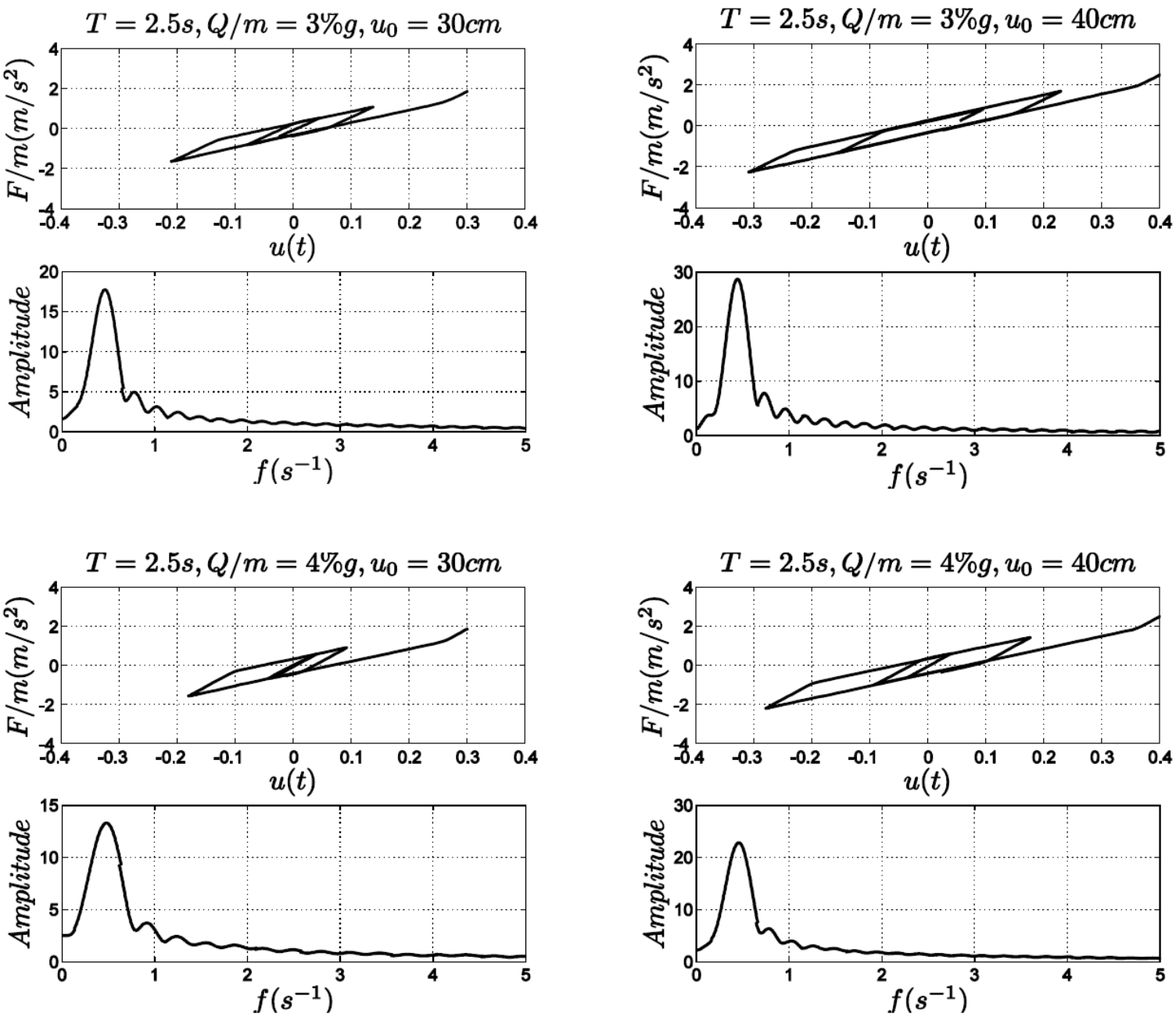



$$T_I = f\left(\frac{Q}{m}, u_y, \frac{K_2}{m}\right)$$

$$\frac{T_I}{2\pi\sqrt{\frac{m}{K_2}}} = \varphi\left(\frac{Q}{K_2 u_y}\right) \Rightarrow T_I = \varphi\left(\frac{Q}{K_2 u_y}\right) T_2$$

# Free-Vibration Period of a Bilinear System



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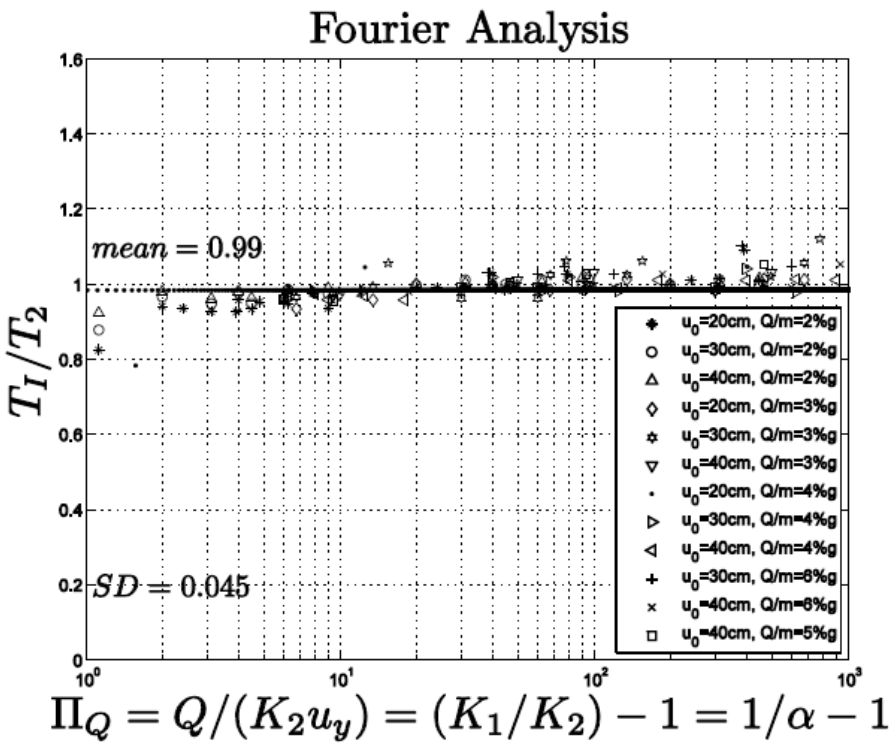
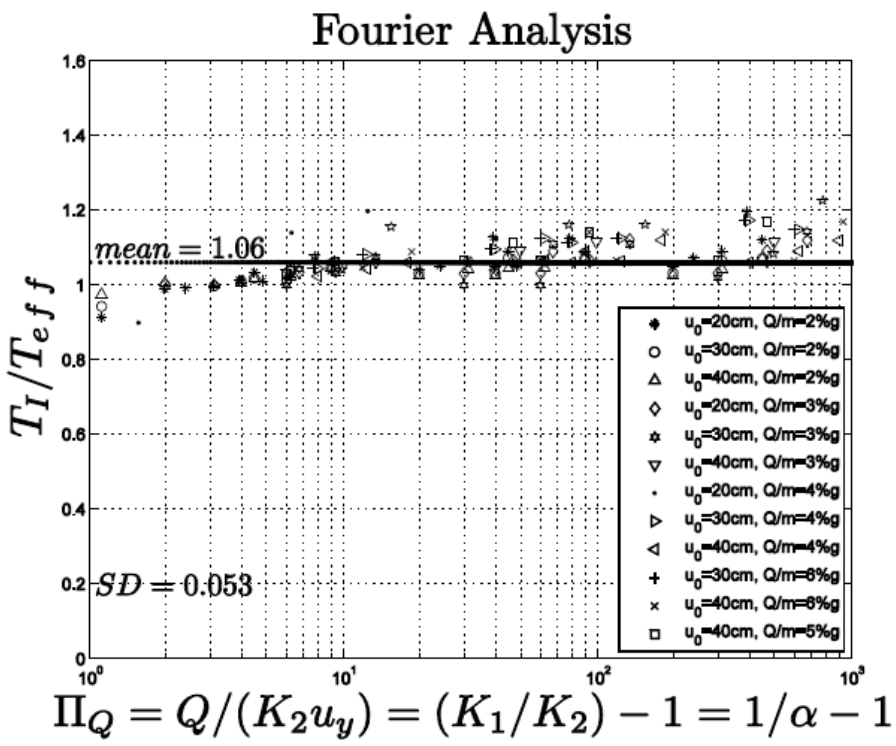
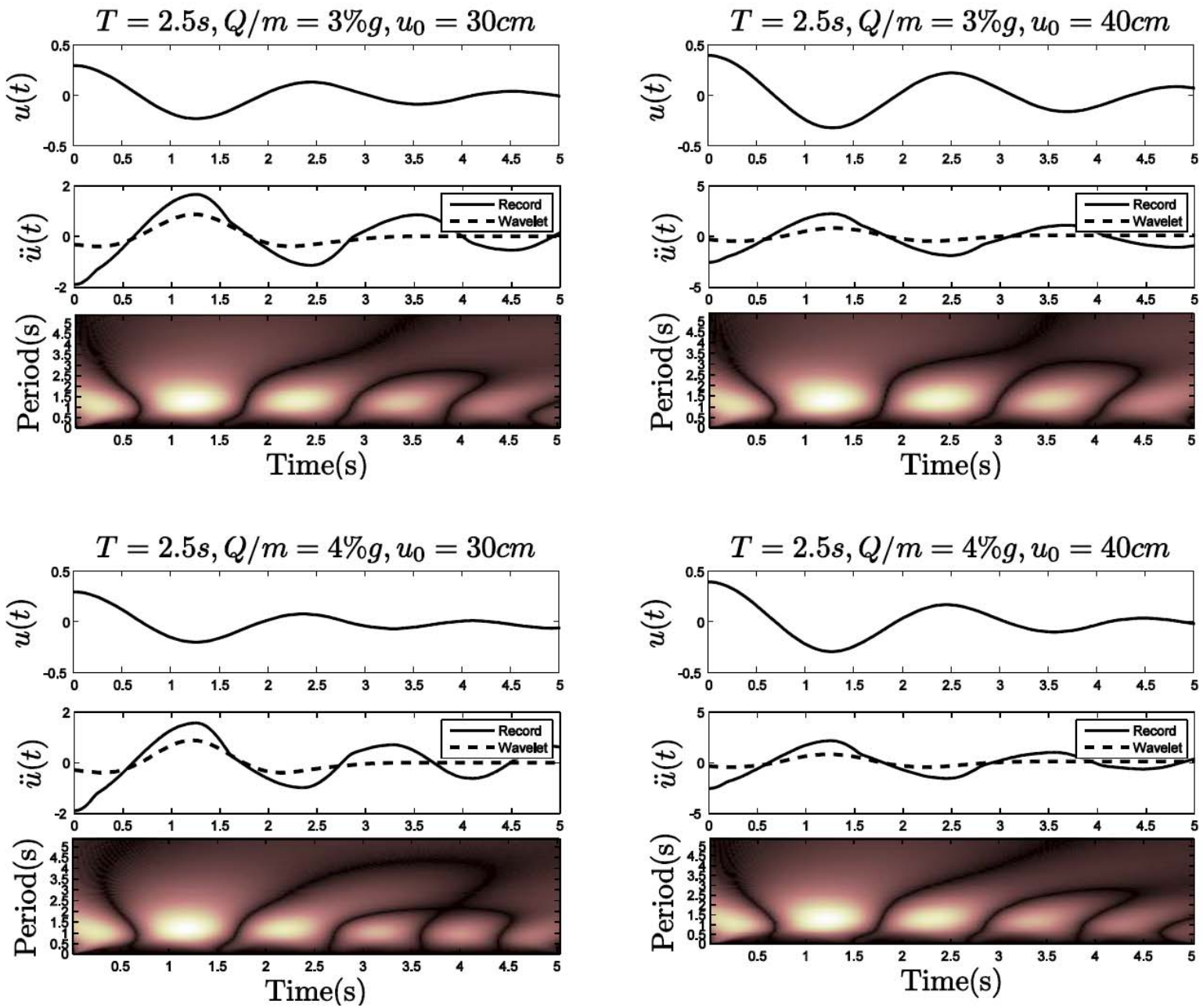
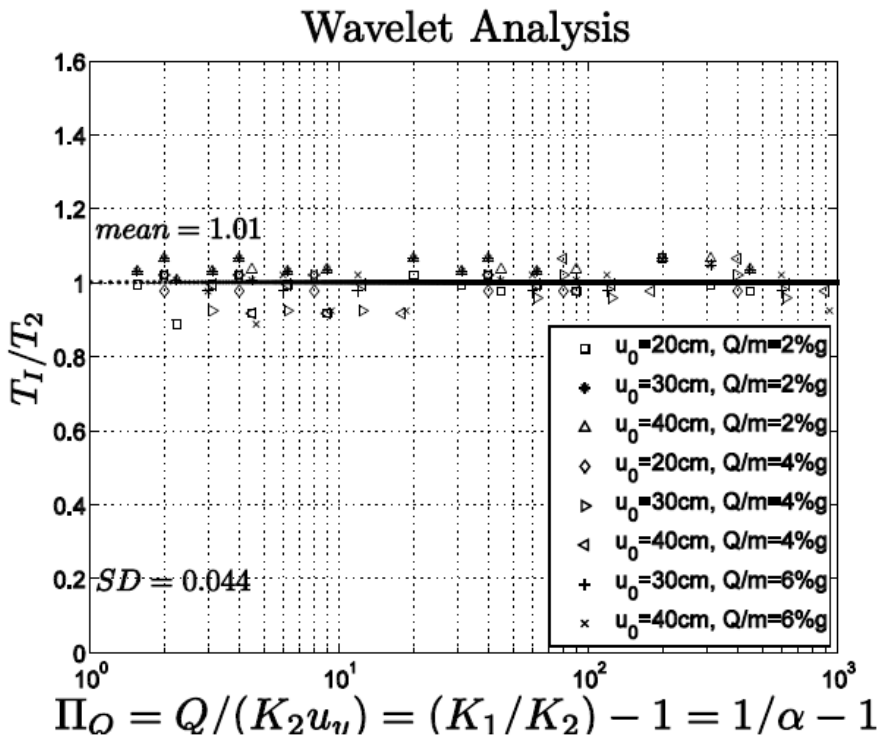


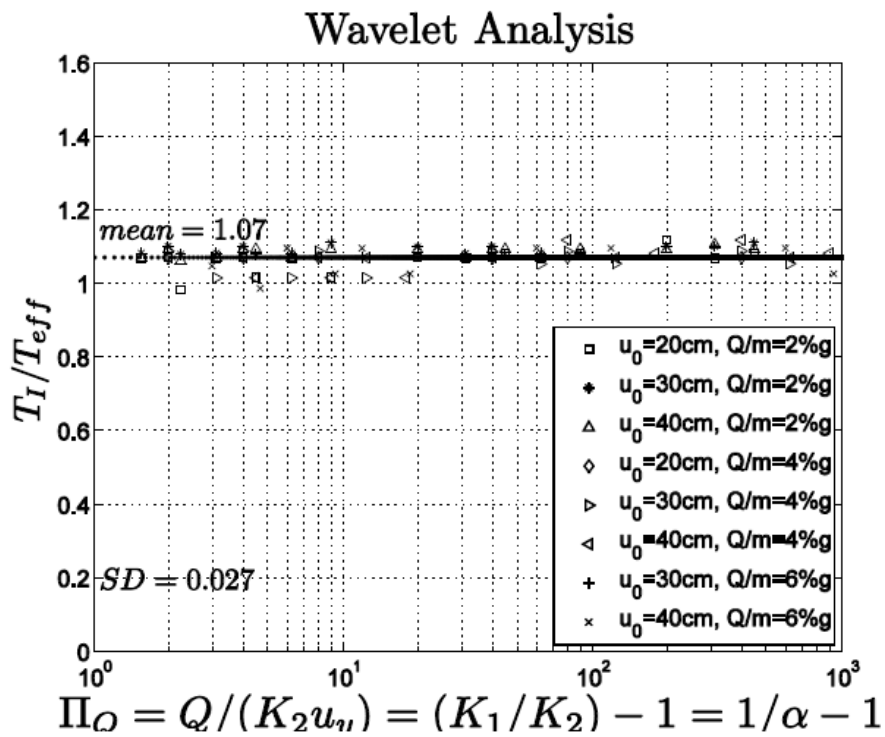



# Free-Vibration Period of a Bilinear System



# Free-Vibration Period of a Bilinear System




Makris, N. and G. Kampas, "The Engineering Merit of the "Effective Period" of Bilinear Isolation Systems", *Earthquakes and Structures*, 2013, Vol. 4(4), pp. 397-428.

# Conclusions

When the response history of the bilinear system exhibits a coherent oscillatory trace with a narrow frequency band as in the case of free vibration of forced vibrations from most pulselike excitations, the talk shows that the "effective period"= Teff of the bilinear isolation system is a dependable estimate of its vibration period.

At the same time the talk concludes that the period associated with the second slope of the bilinear system = T2 is an even better approximation of the —vibration period regardless of the value of the dimensionless strength $Q/(K_2 u_y) = \frac{1}{a} - 1$ of the system. Consequently, this talk concludes that whenever the concept of associating a vibration period is meaningful the "effective" period, Teff can be replaced with $T_2$ which is a period that is known a priori (no iterations are needed) and offers in general superior results.

# Conclusions

This finding serves both simplicity and a more rational estimation of maximum displacement. Simplicity is served because instead of looking for Teff – a quantity that derives from the non-existing Keff, for which iterations are needed to be approximated, the paper shows that the period associated with the second slope of the bilinear system = $T_2$ (that is known a priori – no iterations are needed) is a better single-value descriptor of the frequency content of the dynamic response of a bi-linear isolation system. Given that $T_2$ is always longer than Teff the peak inelastic displacement does no run the risk to be underestimated.