Stochastic Response Comparison between Base Isolated and Fixed-Base Structures

B. Palazzo, M. EERI, and L. Petti

Random response of linear Base Isolated Systems, mounted on elastomeric bearings, subject to horizontal random excitations, is analyzed in comparison with the one of the fixed-base structures. Considering the superstructure motion described by its first modal contribution, a two-degree-of-freedom equivalent linear model, under stationary Gaussian excitations modelled by the modified Kanai-Tajimi power density spectrum, has been used in the analysis. The response sensitivity to design parameters for the superstructure and the isolators have been evaluated for a wide range of parameters. Optimum viscous damping and isolation degree values which minimize structural response are also obtained. Some implications of these results for the design and code requirements are discussed.

INTRODUCTION

The objective of this study is to compare the seismic random response of Base Isolated Systems (BIS) with the one of the conventional Fixed-Base Structures (FBS).

As known, base isolation is a mean of protecting buildings against earthquakes which mainly consists in reducing the transmission of horizontal ground motion to the buildings by using special support devices interposed between the foundations and the superstructure. The effectiveness of Base Isolated System (BIS) depends on the interface low-pass filtering capacities of the excitations entering the superstructure. The filtering effect is stronger if the isolation layer supporting the superstructure presents a fundamental vibration frequency much lower than both the superstructure and ground motion predominant frequencies.

The filtering concept generally requires some knowledge of the input signal which might occur during the life time. However, the exact characteristics of the earthquake ground motion that may occur at a given site cannot be predicted. Seismic excitations dramatically differ from each other being characterized by a high randomness. Consequently, the filtering action has to be applied to an unpredictable excitation having an aleatory frequency content.

Design of FB structures for seismic loads is mainly based on experienced performance of constructions in past earthquakes.

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Current design codes for FB structures have been developed with the aim of ensuring life safety during major earthquakes accepting extensive damage in the constructions.

Seismically-Isolated buildings need different design criteria in order to provide an acceptable protection level against both potentially seismic damaging and collapse.

Considering the young state of the art of Base Isolation, the small number of systems effectively tested by severe earthquakes and the particular sensitivity of these systems to the seismic motion, random vibration approach should have a central role in establishing the general design criteria and code requirements. However, not much work has been carried out in the field of Base Isolated System random response. Constantinou and Tadjbaknsh (Constantinou 1985) have investigated the optimum fundamental BIS period under random excitations. Lin et al. (1989-1990) used the Clough-Penzien model of stochastic input to study the response of various isolation systems in a way similar to the approach followed in this paper. Optimum damping has been recently investigated by Inaudi and Kelly (Inaudi 1992) and by Ahmadi et al. (Ahmadi 1993) using different approaches. Pinto and Vanzi (Pinto 1992) presented a probabilistic analysis in which a critical sensitivity to the superstructure strength factor has been pointed out. Warburton (Warburton 1992) presented an interesting review on several vibration reduction strategies.

In this investigation, the response of Base Isolated Systems with elastomeric bearings, subject to a stationary Gaussian random process is analyzed. The stationary filtered white noise modelled by Kanai (Kanai 1957) and Tajimi (Tajimi 1960) and modified by Clough and Penzien (Clough 1975) has been used as the stochastic model of seismic excitation.

The analysis was focused on a response comparison between isolated and non isolated structures. The investigation was carried out by analyzing a two-degree-of-freedom equivalent linear model, considered as the simplest general isolated building model when the superstructure is represented by its 1st modal contribution. The probabilistic characteristics of the response (mean, covariance and power spectral density) of Base Isolated linear systems have been evaluated to explore the sensitivity of the response to the design parameters. The parametric study is focused on three particular points whose consequences are particularly relevant in establishing the design criteria and code requirements:

- the influence of the isolating degree as defined by Palazzo 1991;
- the influence of the equivalent viscous damping at the isolation interface;
- the influence of the fundamental non isolated structure period.

The first two points are relevant in establishing the optimum isolating degree and damping factor to choose the appropriate isolation system to be applied to the structures. Further considerations are also derived in order to establish the favorable applicability range of the isolation strategy.

STOCHASTIC MODEL OF SEISMIC EXCITATIONS

In this study, the horizontal ground acceleration $a_g(t)$ is modelled as a stationary Gaussian filtered white noise random process with a zero mean and characterized by its Power Spectral Density (PSD) $S_{ag}(\omega)$.

As known, PSD is the Fourier transform of the autocorrelation function $R(\tau)$:

$$S_{ag}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} R_{ag}(\tau)\exp(-i\omega\tau)\,d\tau \qquad (1)$$

The mean square value or variance of the ground acceleration is given by:

$$\sigma_{ag}^2 = E[a_g(t)\cdot a_g(t)] = R_{ag}(0) = \int_{-\infty}^{+\infty} S_{ag}(\omega)\,d\omega \qquad (2)$$

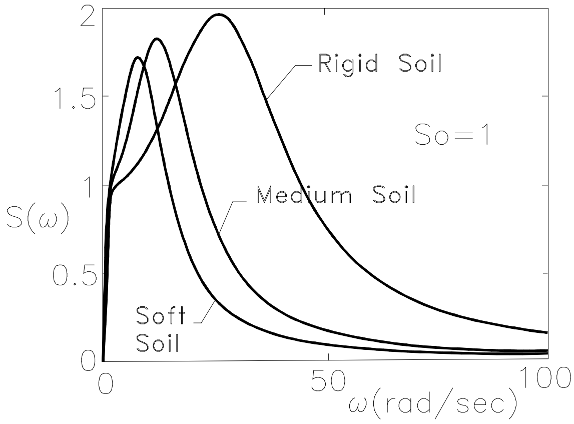


Fig. 1: Modified Kanai-Tajimi Power Spectral Density

The formulation of Power Density Spectrum of the absolute ground accelerations (fig.1), proposed by Kanai and Tajimi (Kanai 1957, Tajimi 1960) and later modified by Clough and Penzien (Clough 1975), by applying a low frequency filter, is used in this study:

$$S_{ag}(\omega) = H_{CP}^2(\omega)\cdot H_{KT}^2(\omega)\cdot So \qquad (3)$$

where $H_{CP}(\omega)$ is the Clough & Penzien low band frequency filter given by:

$$H_{CP}(\omega) = \frac{\dfrac{\omega^2}{\omega_1^2}}{(1-\dfrac{\omega^2}{\omega_1^2}) + 2i\xi_1\dfrac{\omega}{\omega_1}} \qquad (4)$$

$H_{KT}(\omega)$ is the Kanai and Tajimi filter given by:

$$H_{KT}(\omega) = \frac{1+2i\xi_g\dfrac{\omega}{\omega_g}}{(1-\dfrac{\omega^2}{\omega_g^2}) + 2i\xi_g\dfrac{\omega}{\omega_g}} \qquad (5)$$

So is the white noise power density considered in the Kanai-Tajimi model.

In this model ω_g and ξ_g are respectively the natural frequency and damping ratio describing the soil deposit characteristics, ω_1 and ξ_1 describe the low band filter introduced by Clough-Penzien. Three types of soils were considered in the analysis by assuming the following in the spectrum model:

Firm soil : ω_g = 31.4 rad/sec; ξ_g = 0.55

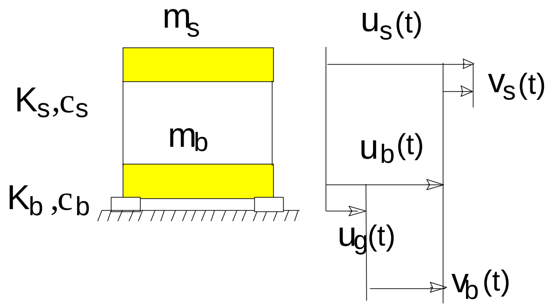
Medium soil : ω_g = 15.6 rad/sec; ξ_g = 0.6
Soft soil : ω_g = 10.5 rad/sec; ξ_g = 0.65

For all cases the Clough-Penzien modification low-band frequency filter characteristics are assumed as $\omega_1 = 1$ and $\xi_1 = 0.7$.

EQUIVALENT LINEAR MODEL OF BASE ISOLATED SYSTEMS

Consider the two-degree-of-freedom equivalent linear model represented in fig.2, which can be considered as the simplest model to represent a more general isolated multi-storey building if the superstructure is represented by its 1st natural vibration mode.

As shown by Kelly (Kelly, 1996) by retaining only one mode of the fixed-base structure the approximate 2-DOF model gives results that are very close to the ones obtained considering a M-DOF model.



$x = m_s/(m_s + m_b)$ mass ratio

$I_d = \omega_s/\omega_b$ isolating degree

Fig. 2 : Base Isolated model

As known, while the isolator behaviour is generally non linear the superstructure should be generally designed to remain in the linear range under the strongest design excitation (Pinto 1992, Palazzo 1993). Several equivalent linear models for the isolator behaviour using effective stiffness and viscous damping have been carried out and used by isolation design guidelines (Fuller 1991 ; Hwang 1993 ; SEAOC -Tentative 1986 ; General 1989 ; Partial Draft 1994 ; UBC 1991 ; AASHTO 1991 ; JPWRI, 1992 ; NZMWD 1983) .

By using such type of equivalence criteria the system behaviour is described by the coupled linear second-order differential equations:

$$
\begin{aligned}
& m_s\ddot{u}_s + c_s(\dot{u}_s - \dot{u}_b) + k_s v_s = 0 \\
& m_b\ddot{u}_b + m_s\ddot{u}_s + c_b(\dot{u}_b - \dot{u}_g) + k_b v_b = 0
\end{aligned}
\qquad (6)
$$

where u_g is the ground displacement; m_b, c_b, k_b, respectively represent the mass, the equivalent damping and stiffness referred to the isolating base; m_s, c_s, k_s, respectively are the 1st modal mass, damping and stiffness of the superstructure; u and v respectively represent the absolute and relative displacement. It has been shown (Kelly 1990, Palazzo 1991) that, if ω_s and ω_b indicate the superstructure and isolated system fundamental frequencies, parameter $I_d = \omega_s/\omega_b$, defined as isolating degree, regulates the behaviour of an isolated system. The mentioned authors showed that I_d influences the decoupling capacity of the superstructure motion in respect to the ground horizontal movement.

Equation (6) can also be represented in the state-space form :

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u_g \qquad (7)$$

where $\mathbf{x}$ represents the four-dimensional state vector and $\mathbf{u}$, $\mathbf{v}$ respectively indicate the absolute and relative displacement vectors given by :

$$\mathbf{x} = \left[\mathbf{v}^T, \dot{\mathbf{u}}^T\right]^T \; ; \; \mathbf{u} = \begin{bmatrix} u_s \\ u_b \end{bmatrix}; \; \mathbf{v} = \begin{bmatrix} v_s \\ v_b \end{bmatrix}$$

The following matrices :

$$\mathbf{A} = \begin{bmatrix} \mathbf{O} & \mathbf{I}^* \\ -\mathbf{\Omega} & -\mathbf{\Sigma} \end{bmatrix}; \mathbf{B} = \begin{bmatrix} \mathbf{I}_1 \\ -\mathbf{\Sigma I} \end{bmatrix}; \mathbf{I}^* = \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix}; \mathbf{I}_1 = \begin{bmatrix} 0 \\ -1 \end{bmatrix}; \mathbf{I} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

represent the system in the state-space representation, while the followings matrices

$$\mathbf{\Sigma} = \begin{bmatrix} m_s & 0 \\ m_s & m_b \end{bmatrix}^{-1} \cdot \begin{bmatrix} c_s & -c_s \\ 0 & c_b \end{bmatrix} ; \quad \mathbf{\Omega} = \begin{bmatrix} m_s & 0 \\ m_s & m_b \end{bmatrix}^{-1} \cdot \begin{bmatrix} k_s & 0 \\ 0 & k_b \end{bmatrix}$$

respectively represent the damping factor matrix Σ and the frequency matrix $\mathbf{\Omega}$.

The transfer functions of the system (7) are obtained by applying the Fourier transform assuming the initial conditions to be zero:

$$\mathbf{H}(\omega) = \frac{\mathbf{X}(\omega)}{U_g(\omega)} = i\omega(\mathbf{I}i\omega - \mathbf{A})^{-1}\mathbf{B} \qquad (8)$$

where $\mathbf{X}(\omega)$ and $U_g(\omega)$ respectively represent the Fourier transform of $\mathbf{x}(t)$ and $u_g(t)$.

The complex frequency response $\mathbf{H}(\omega)$ relates the system response to the ground motion. Therefore the response spectral density vector $\mathbf{S_{out}}(\omega)$ is related to the acceleration spectral density $S_{ag}(\omega)$ by :

$$\mathbf{S}_{out}(\omega) = \mathbf{H}(\omega)^* \cdot S_{ag}(\omega) \cdot \mathbf{H}(\omega)^T / \omega^4 \qquad (9)$$

Some background information regarding the procedure can be found in Soong (Soong, 1993). Therefore, the mean square of the response is given by:

$$\boldsymbol{\sigma}_{out}^2 = \int_{-\infty}^{\infty} \mathbf{S}_{out}(\omega) d\omega \qquad (10)$$

COMPARATIVE RESULTS

Using the power density spectrum described above, the root mean square or "rms" response of the model with and without isolation, has been evaluated for several values of main parameters. The calculated rms response values of the base isolated model are normalized with respect to those of the correspondent fixed-base model. The analysis has been focused on the evaluation of the influence of the isolating parameters (I_d, ξ_b) on the seismic response for several values of fixed-base structural periods T_s.

In all cases a standard 2% damping factor has been considered in the superstructure.
Figures 3-10 show the influence of T_s and ξ_b on relative displacements, absolute velocities and accelerations. Results show that the isolator damping plays a significant role in reducing the isolator relative displacement, absolute acceleration and velocity (Figg. 5-6).
Diagrams clearly show that by increasing the isolation damping factor ξ_b, the base response is always reduced while the superstructure response reaches minimum values for particular damping factors (Figg. 3-4,7-10). Therefore there are optimum values of isolation damping factors which minimize the superstructure response, varying with the superstructure main period T_s, as shown in the two-dimensional diagrams. The optimum damping factor ξ_b mainly influences relative displacements, absolute velocities and absolute accelerations. Results show that the optimum damping factor which minimizes both the superstructure acceleration and relative displacement slightly varies by about 25 % of critical damping for usual cases. Optimum damping levels can be defined as those which minimize the relative displacements of the superstructure. The optimum value of the isolation damping factor increases quite linearly with the superstructure main period varying from 20% for T_s=0.10 sec. to 50% for T_s=2.70 sec.. Figures 11-18 show the influence of both the isolating degree I_d and fixed-base period T_s on the system response. Results show that by increasing the isolation degree, positive effects on the superstructure response are always produced. However, for most cases of interest having original fixed-base periods in the range 0.4 to 1 sec. by choosing I_d values greater than 3-4 doesn't produce any other significant benefit. On the other hand base relative displacements strongly increase with the I_d increment, particularly for superstructures having a long natural vibration period. With respect to superstructure accelerations greater benefits occur when isolating low period structures than long period ones. The almost flat dependence of the base displacement response in the range of high values of isolating degree and original period T_s would have been less predictable.As shown in figures 13-14, the rms isolated base displacement ratio to the non isolated structure strongly increases with the isolating degree in the range of small damping values.The rms base relative displacement can significantly be larger than the one of the non isolated structure, but its ratio significantly decreases by increasing the damping factor ξ_b. The same ratio tends to be lower for structures having an elevated original T_s period. For a given isolation damping factor, the superstructure relative displacement is already substantially reduced for isolation degrees greater than 2.5-3 and $T_s > 2\pi / \omega_g$. It is important to notice that in all investigated cases the superstructure response is always more favorable than the one of non isolated structures.The influence of both I_d and ξ_b isolation parameters, plotted in figures 19-20, confirm the results described above. From these figures it is possible to notice that the influence of the damping factor in the isolating system is greater for long period structures than for short period ones. Therefore, in these cases the choice of a value close to the optimum damping is more important. The study of the results allows the evaluation of the reduction effects on the superstructure response produced by a well isolation system by about 70%-80% respect to the non isolated seismic response. The influence of the foundation soil on the stochastic response is represented in figures 21-25. In the case of soft soil results indicates that the benefits on the superstructure response due to the isolation are lightly reduced but the base displacements are strongly increased respect to

the case of firm or medium soil. Figure 25 shows the rms response ratios of BIS compared to the one of non-isolated structures versus the χ mass ratio and the original T_S period. Observing the diagram the χ mass ratio does not have a significant effect on the seismic response.

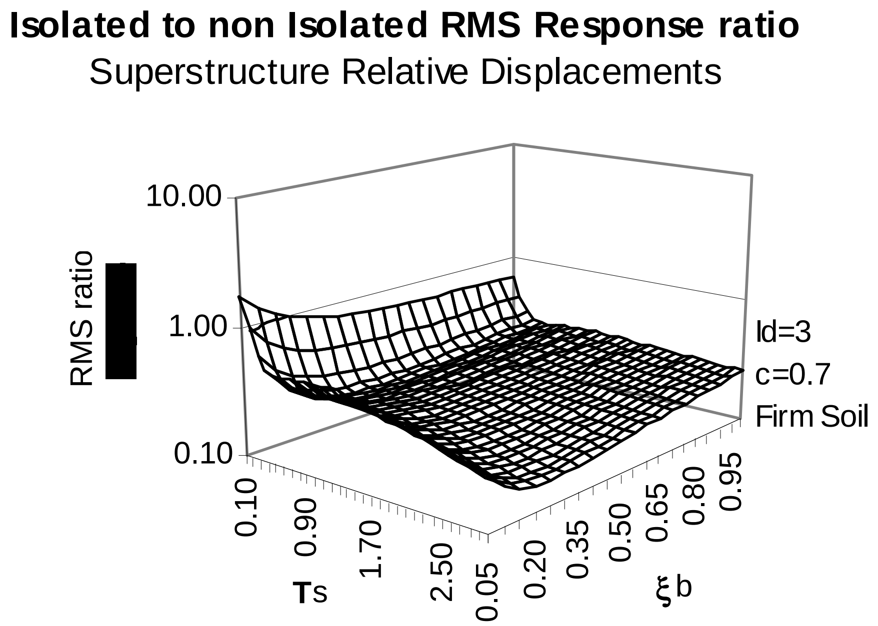


Fig. 3

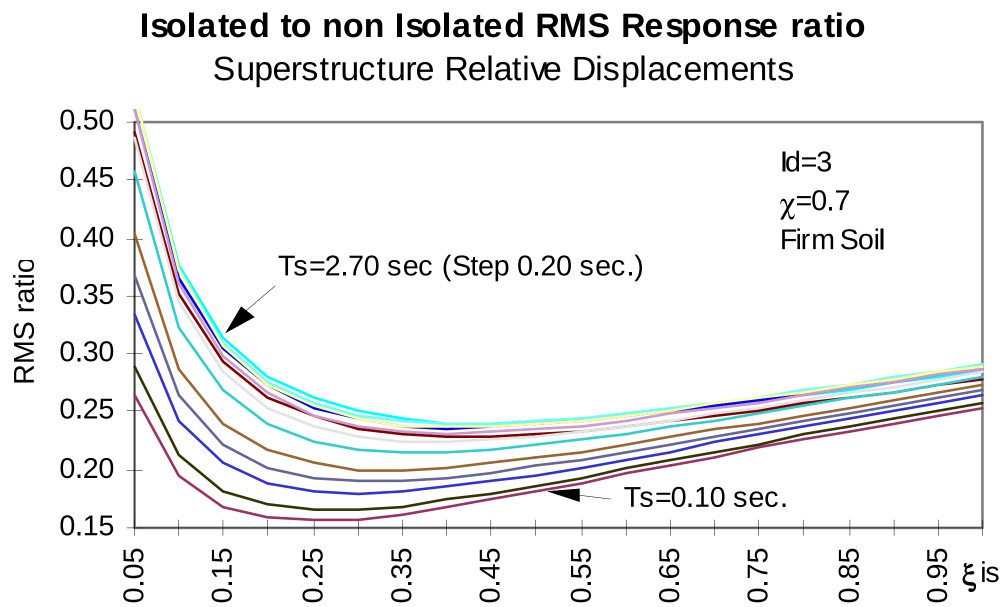
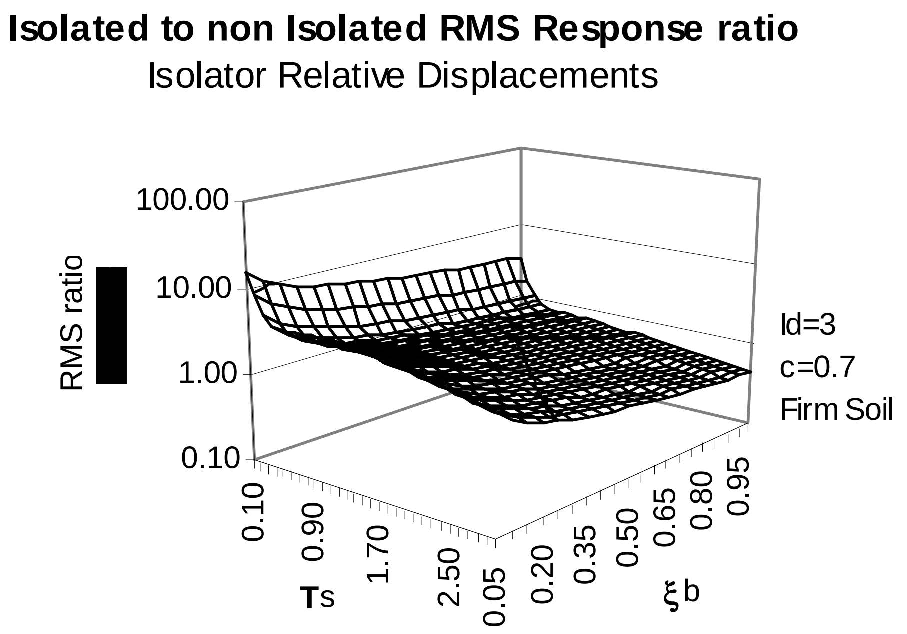
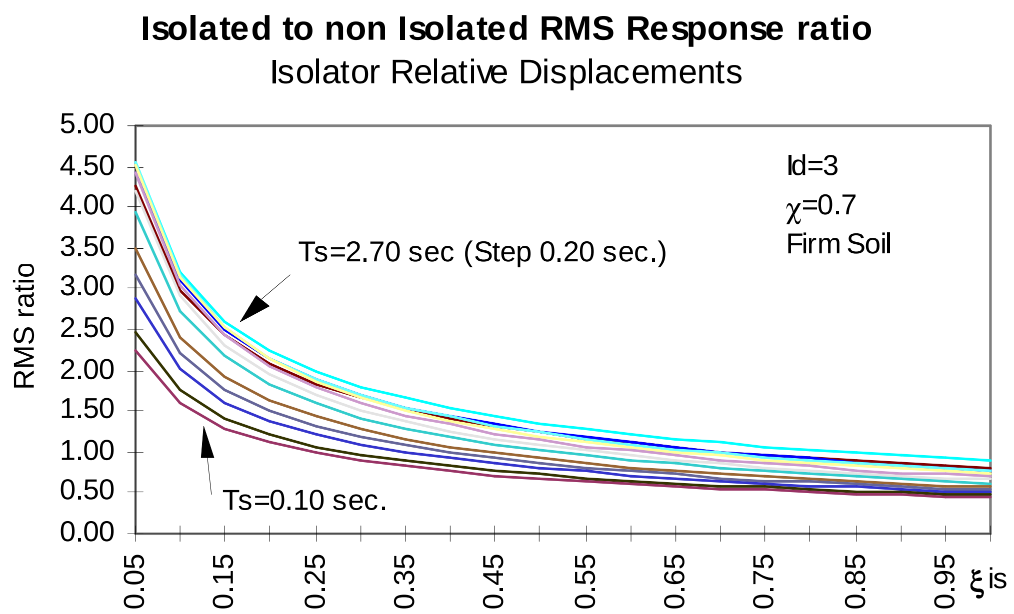


Fig. 4



Isolated to non Isolated RMS Response ratio
Isolator Relative Displacements
100.00
10.00
1.00
0.10
RMS ratio
0.10
0.90
1.70
2.50
Ts
0.05
0.20
0.35
0.50
0.65
0.80
0.95
ξ b
Id=3
c=0.7
Firm Soil

Fig. 5



Isolated to non Isolated RMS Response ratio
Isolator Relative Displacements
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
RMS ratio
Ts=2.70 sec (Step 0.20 sec.)
Ts=0.10 sec.
Id=3
χ=0.7
Firm Soil
0.05
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
ξ is

Fig. 6

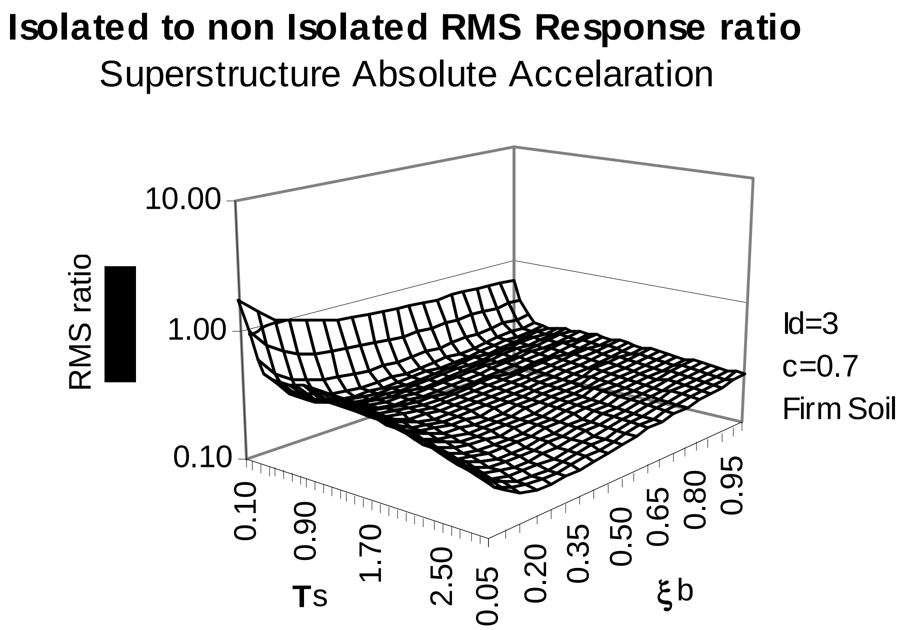

Isolated to non Isolated RMS Response ratio
Superstructure Absolute Accelaration
RMS ratio
10.00
1.00
0.10
0.10
0.90
1.70
2.50
Ts
0.05
0.20
0.35
0.50
0.65
0.80
0.95
ξb
Id=3
c=0.7
Firm Soil

Fig. 7

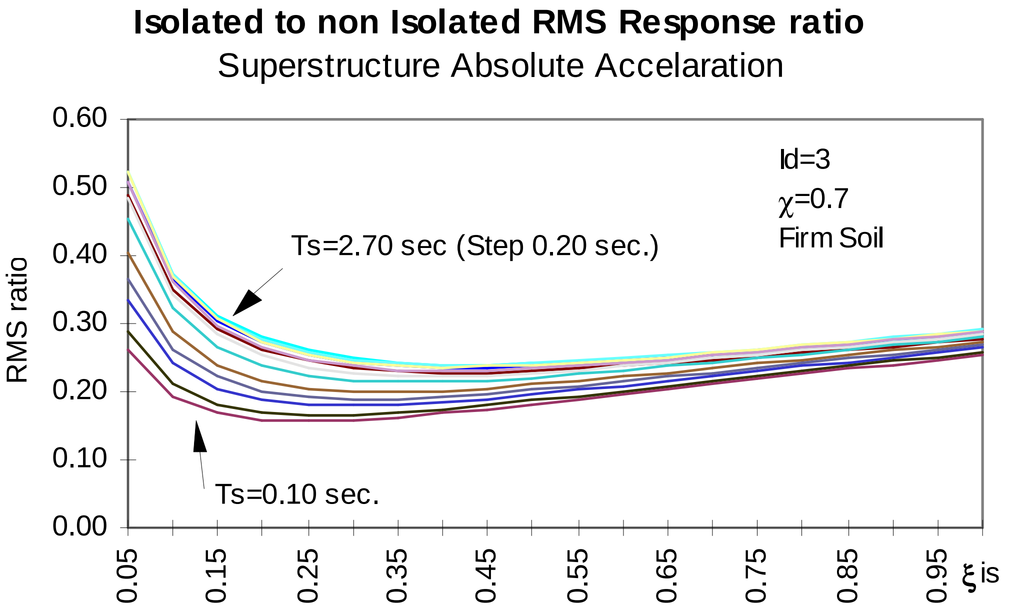

Isolated to non Isolated RMS Response ratio
Superstructure Absolute Accelaration
RMS ratio
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Id=3
χ=0.7
Firm Soil
Ts=2.70 sec (Step 0.20 sec.)
Ts=0.10 sec.
0.05
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
ξ is

Fig. 8

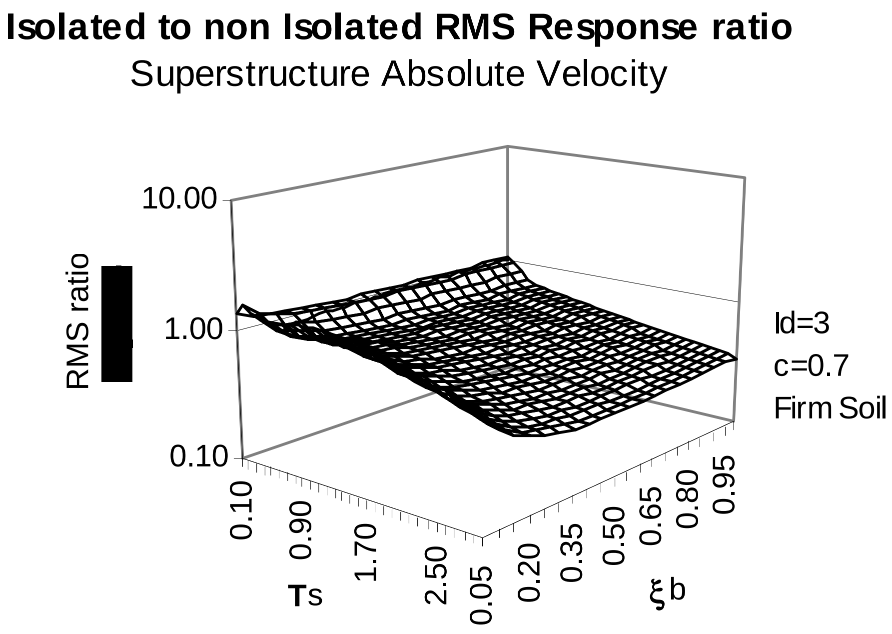

Isolated to non Isolated RMS Response ratio
Superstructure Absolute Velocity
RMS ratio
10.00
1.00
0.10
Id=3
c=0.7
Firm Soil
0.10
0.90
1.70
2.50
Ts
0.05
0.20
0.35
0.50
0.65
0.80
0.95
ξ b

Fig. 9

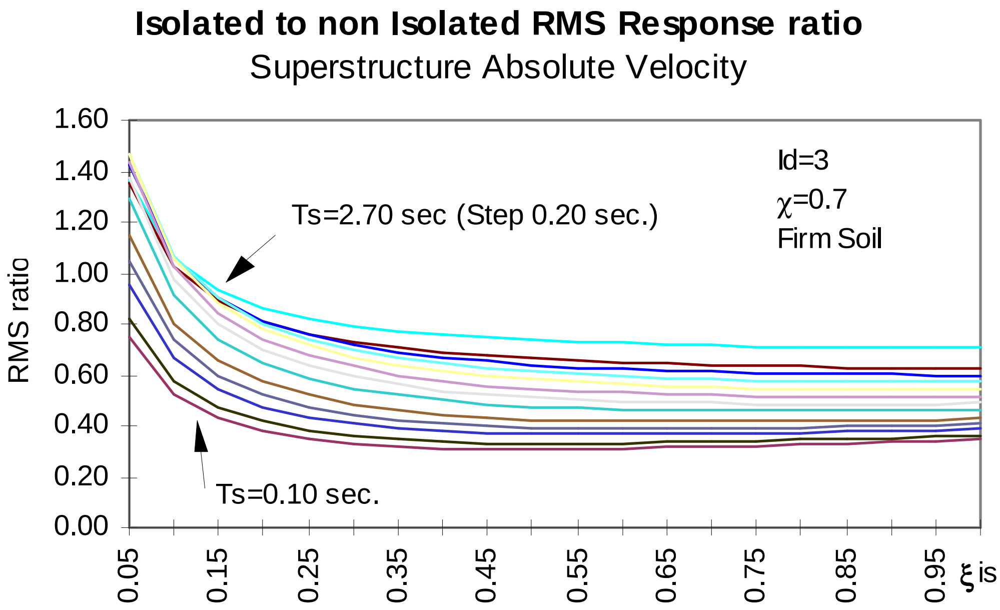

Isolated to non Isolated RMS Response ratio
Superstructure Absolute Velocity
RMS ratio
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.05
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
ξis
Ts=2.70 sec (Step 0.20 sec.)
Ts=0.10 sec.
Id=3
χ=0.7
Firm Soil

Fig. 10

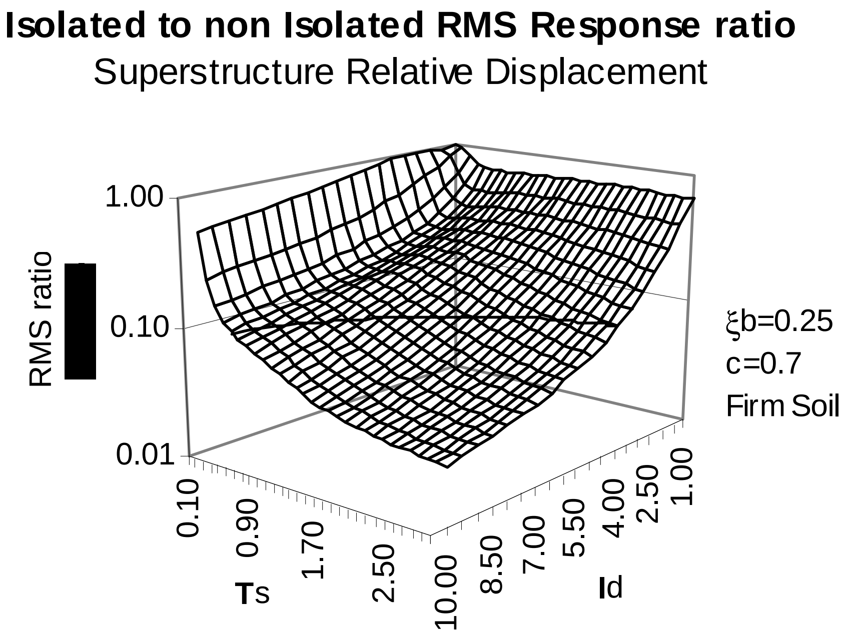

Isolated to non Isolated RMS Response ratio
Superstructure Relative Displacement
RMS ratio
1.00
0.10
0.01
0.10
0.90
1.70
2.50
Ts
10.00
8.50
7.00
5.50
4.00
2.50
1.00
Id
ξb=0.25
c=0.7
Firm Soil

Fig. 11

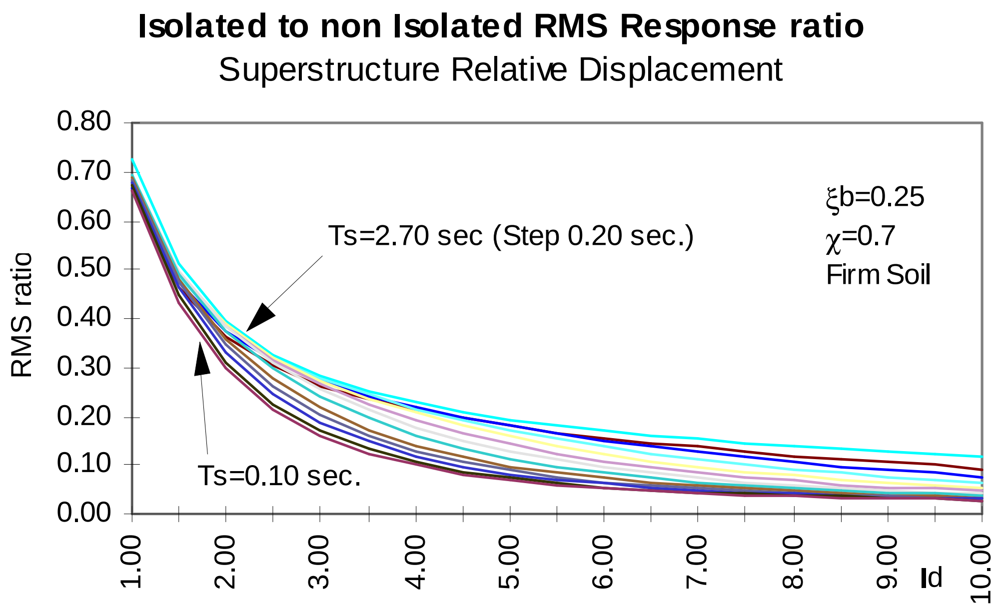

Isolated to non Isolated RMS Response ratio
Superstructure Relative Displacement
RMS ratio
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Ts=2.70 sec (Step 0.20 sec.)
Ts=0.10 sec.
ξb=0.25
χ=0.7
Firm Soil
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
Id
10.00

Fig. 12

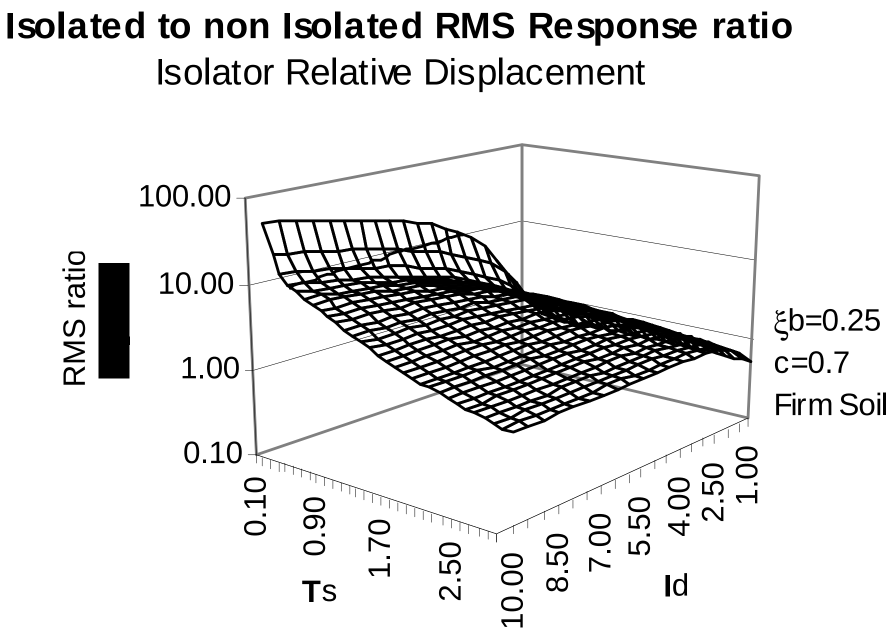

Isolated to non Isolated RMS Response ratio
Isolator Relative Displacement
RMS ratio
100.00
10.00
1.00
0.10
ξb=0.25
c=0.7
Firm Soil
0.10
0.90
1.70
2.50
Ts
10.00
8.50
7.00
5.50
4.00
2.50
1.00
Id

Fig. 13

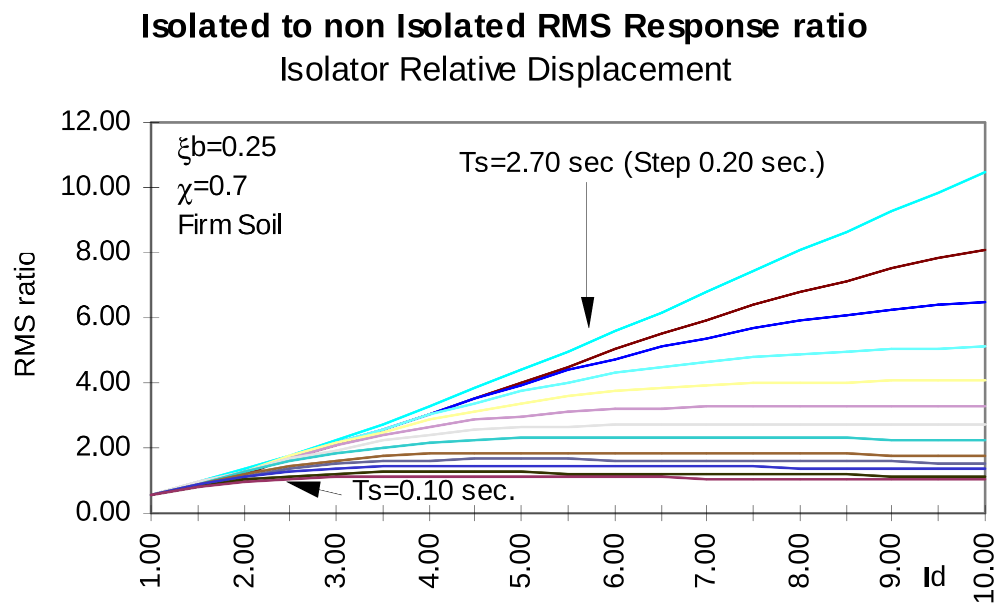

Isolated to non Isolated RMS Response ratio
Isolator Relative Displacement
ξb=0.25
χ=0.7
Firm Soil
Ts=2.70 sec (Step 0.20 sec.)
Ts=0.10 sec.
RMS ratio
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
Id
10.00

Fig. 14

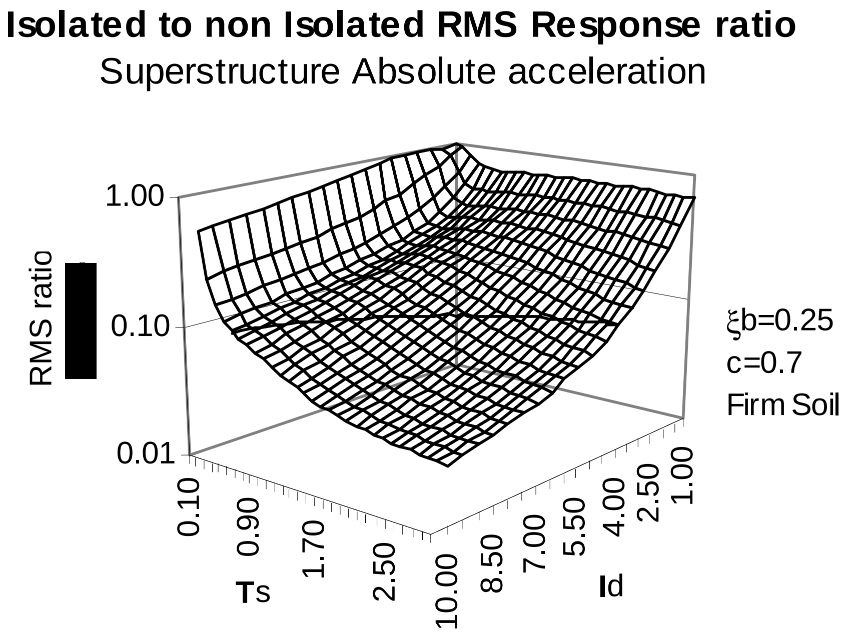

Isolated to non Isolated RMS Response ratio
Superstructure Absolute acceleration
RMS ratio
1.00
0.10
0.01
0.10
0.90
1.70
2.50
Ts
10.00
8.50
7.00
5.50
4.00
2.50
1.00
Id
ξb=0.25
c=0.7
Firm Soil

Fig. 15

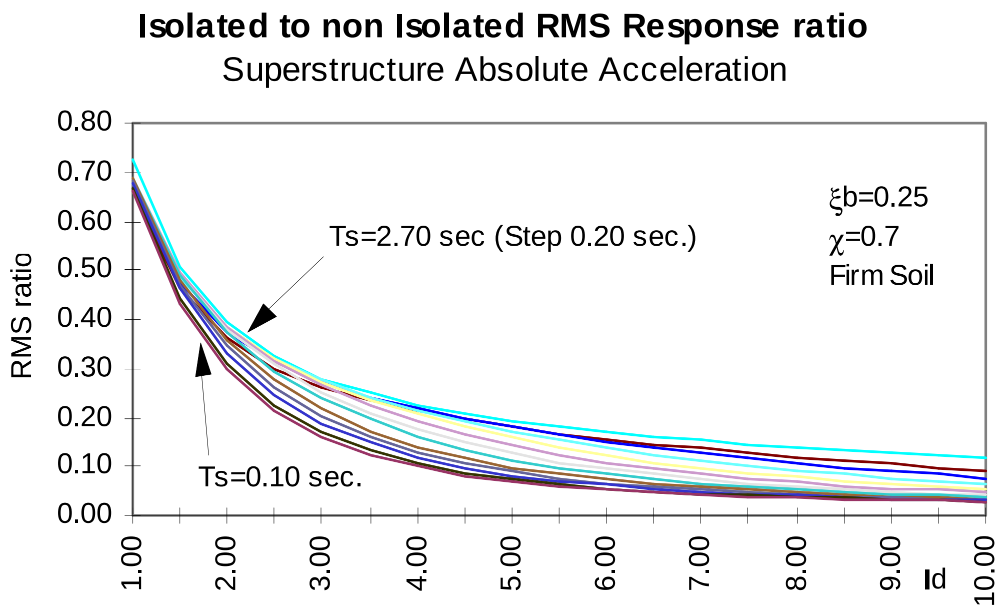

Isolated to non Isolated RMS Response ratio
Superstructure Absolute Acceleration
RMS ratio
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Ts=2.70 sec (Step 0.20 sec.)
Ts=0.10 sec.
ξb=0.25
χ=0.7
Firm Soil
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
Id
10.00

Fig. 16

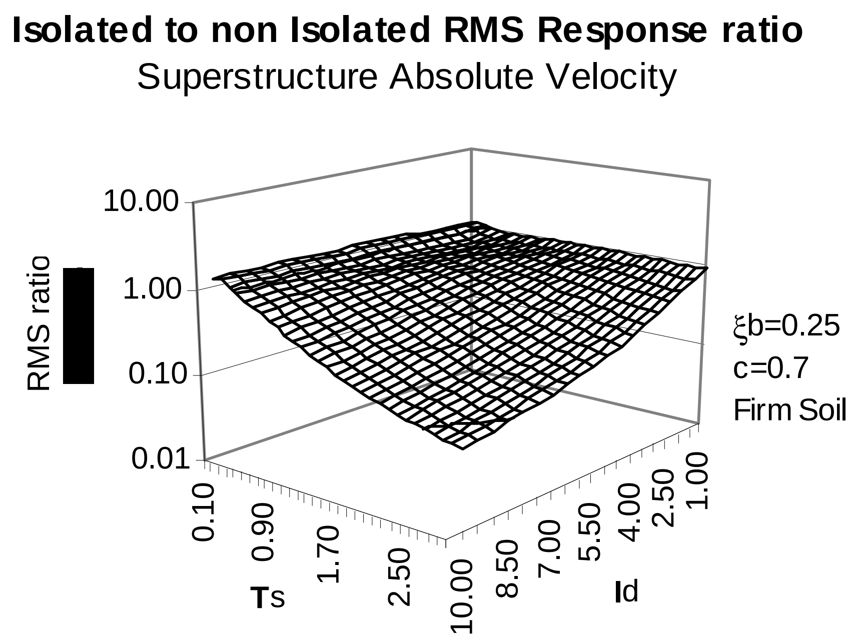

Isolated to non Isolated RMS Response ratio
Superstructure Absolute Velocity
RMS ratio
10.00
1.00
0.10
0.01
ξb=0.25
c=0.7
Firm Soil
0.10
0.90
1.70
2.50
Ts
10.00
8.50
7.00
5.50
4.00
2.50
1.00
Id

Fig. 17

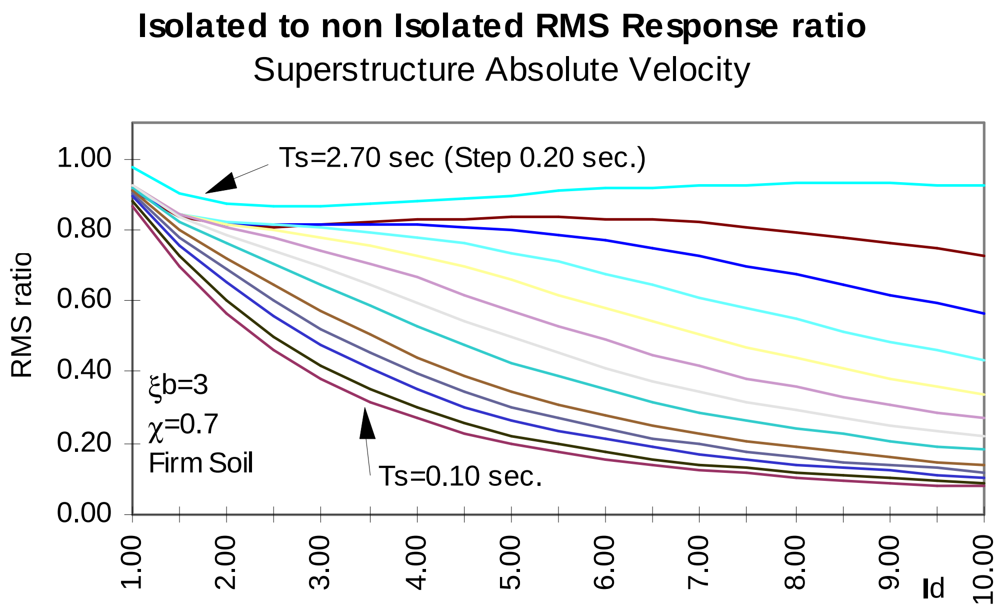

Isolated to non Isolated RMS Response ratio
Superstructure Absolute Velocity
Ts=2.70 sec (Step 0.20 sec.)
RMS ratio
ξb=3
χ=0.7
Firm Soil
Ts=0.10 sec.
Id
1.00
0.80
0.60
0.40
0.20
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00

Fig. 18

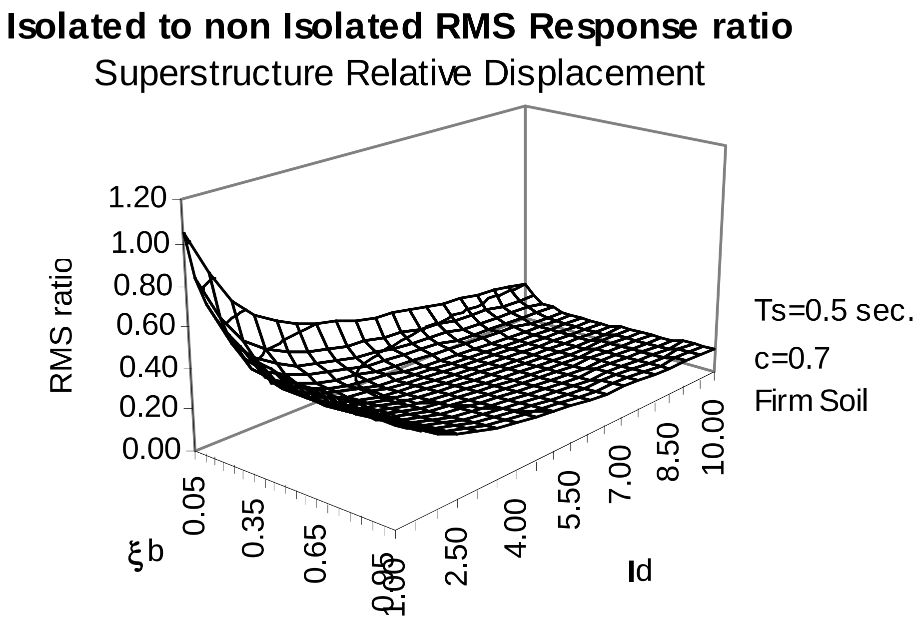

Isolated to non Isolated RMS Response ratio
Superstructure Relative Displacement
RMS ratio
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Ts=0.5 sec.
c=0.7
Firm Soil
ξb
0.05
0.35
0.65
0.95
1.00
2.50
4.00
5.50
7.00
8.50
10.00
Id

Fig. 19

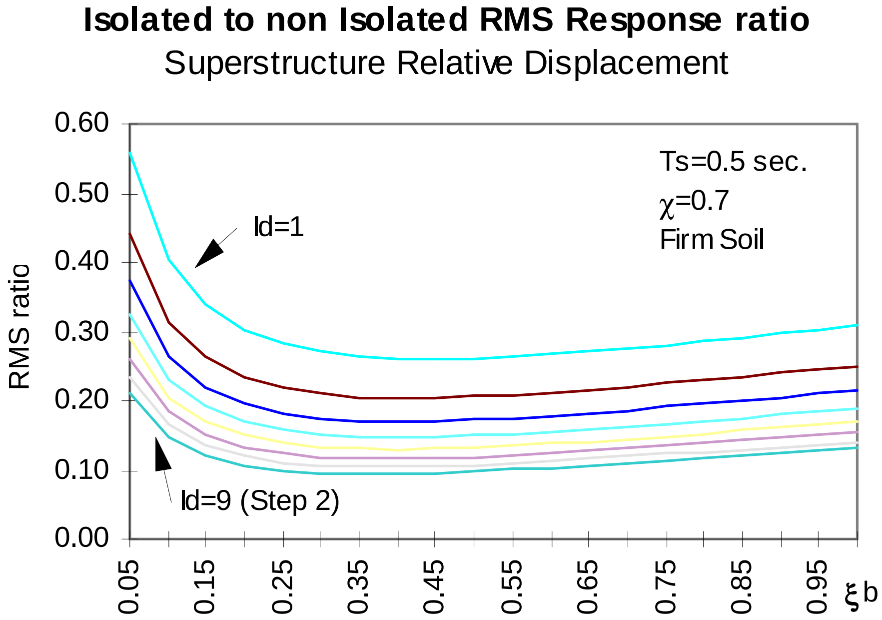

Isolated to non Isolated RMS Response ratio
Superstructure Relative Displacement
RMS ratio
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Ts=0.5 sec.
χ=0.7
Firm Soil
Id=1
Id=9 (Step 2)
0.05
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95
ξb

Fig. 20

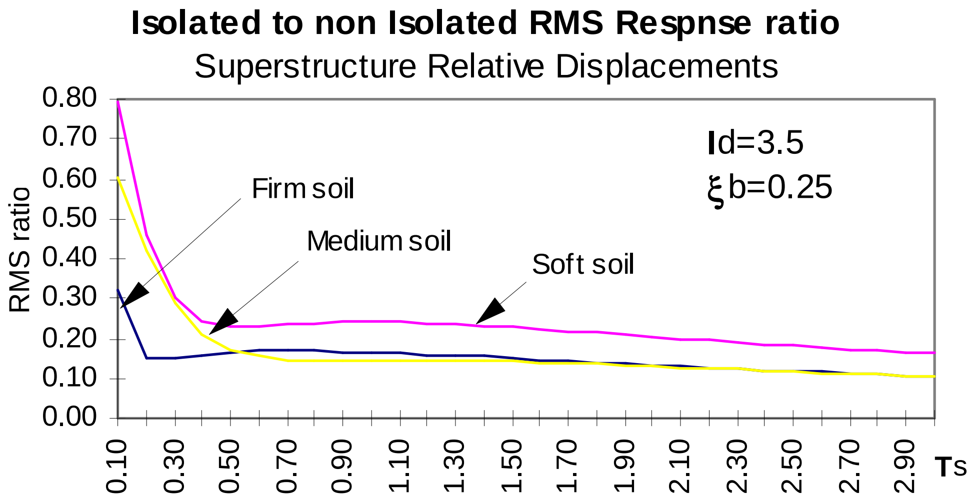

Isolated to non Isolated RMS Respnse ratio
Superstructure Relative Displacements
RMS ratio
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Id=3.5
ξb=0.25
Firm soil
Medium soil
Soft soil
0.10
0.30
0.50
0.70
0.90
1.10
1.30
1.50
1.70
1.90
2.10
2.30
2.50
2.70
2.90
Ts

Fig. 21

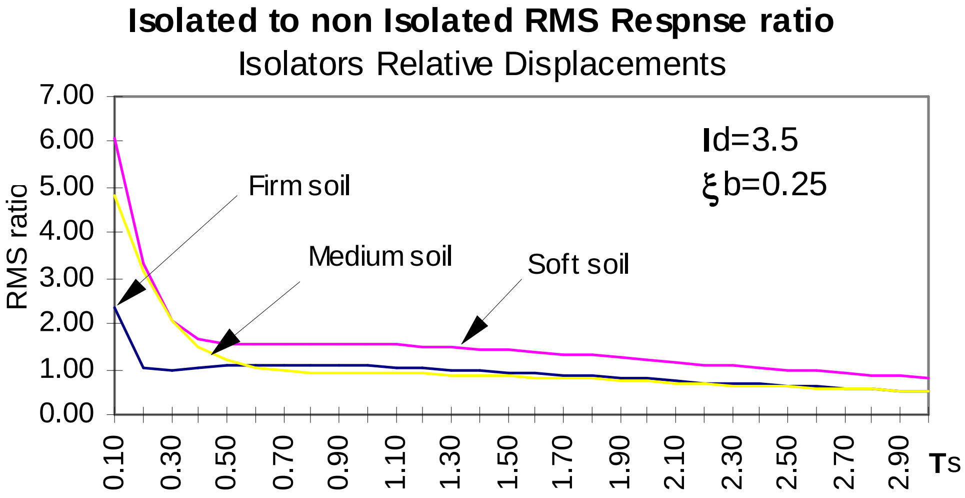


Fig. 22

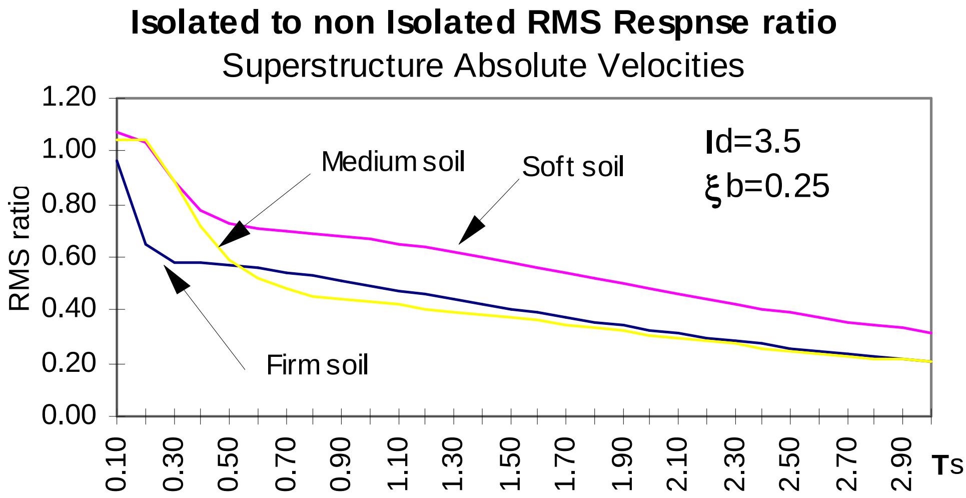


Fig. 23

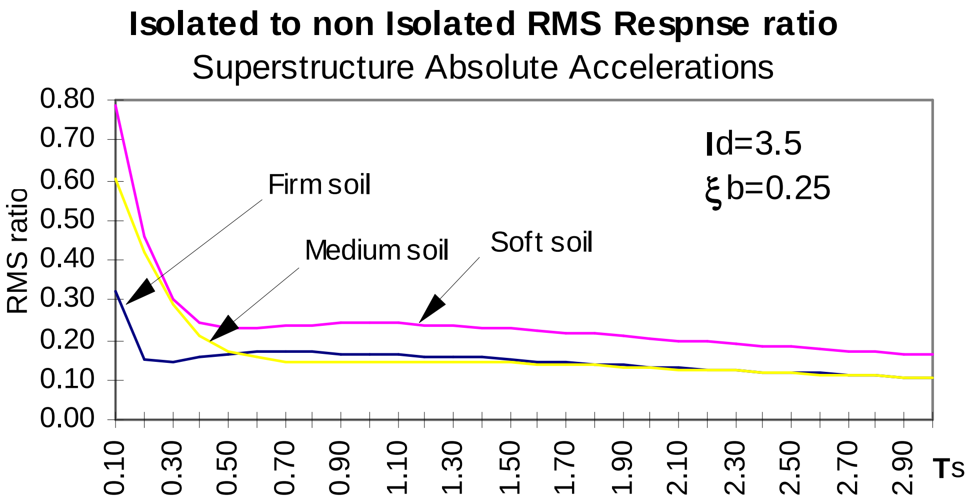


Fig. 24

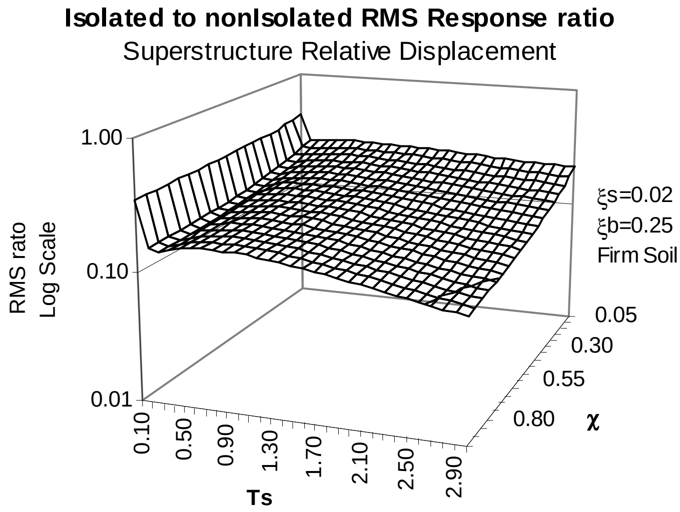


Fig. 25

CONCLUSION

Results regarding the response comparison between base isolated systems and fixed-base structures subject to a stationary Gaussian process, modelled according to the modified Kanai-Tajimi power density spectrum, lead to the following conclusions:

1 - The linear base isolated system random response expressed in term of ratio to the correspondent non isolated system has been evaluated and plotted for a wide range of parameters in order to be used as a preliminary design chart. Since isolators exhibit a significant hysteretic behaviour, the presentes results have some limitations having replaced the governing set of non-linear differential equations by an equivalent linear one.

2 - Results have shown a great influence on the BIS random response of the isolation damping factor and the isolating degree.

3 - Optimum damping factors of the isolation system, which minimize relative displacements depend on the original period and the isolating degree. The optimum equivalent viscous damping factor increases with the superstructure fixed-base period varying from 20% to 50%.

4 - The optimum values are greater than those generally considered and used in the applications. From a technological point of view, it seems extremely hard to reach optimum damping values by only using rubber bearings at the isolating interface eventhough high-damping rubber is used. Therefore, in order to realize optimum damping factors, it seems to be more convenient to combine isolators in parallel with other damping devices. Therefore supplementary hysteretic or viscous dampers should be added to the isolators in order to reduce the isolation interface displacements.

5 - The evaluated effect of an isolation damping greater than 5% doesn't correspond to the scaling procedure considered for damping by the UBC 1991.

6 - Structures having fundamental non isolated periods less than the ones where the spectral amplitude is maximum, need a higher value of isolating degree in order to obtain significant advantages from the isolation and therefore shift out the frequency range where the spectral amplitude is high.

7 - For structures having non isolated periods greater than ones where the power density spectra have maximal amplitudes, an isolating degree of the order of 3-4 is generally sufficient to reduce the superstructure response by about 70%-80%.

8 - Long period structures can also be favorably isolated with a low isolating degree and optimum damping.

9 - In all isolated cases, the superstructure response is always more favorable than the correspondent non isolated structure. Therefore the isolating degree should be designed as high as the isolator displacement limit allows.

10 - Soft soil effect generally leads to double the base displacement response of the BIS placed on firm soil.

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