AN EVALUATION OF THE AASHTO UNIFORM LOAD METHOD FOR ESTIMATING FORCES AND DEFORMATIONS IN SEISMICALLY ISOLATED BRIDGE SYSTEMS

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SUMMARY

The AASHTO *Guide Specification for Seismic Isolation Design* contains simplified procedures for estimating the design displacement and force demand imposed on a bridge designed to be seismically isolated. The Uniform Load Method in this document, based on the secant method, involves several assumption and approximations, and essentially utilizes the same procedures contained in building codes for design of isolated buildings. The equivalent linear system is defined based upon an energy equivalence assumed at a resonant harmonic frequency defined by the secant stiffness of the system responding at its maximum displacement. Methods based on harmonic response, such as these, are known to be not as accurate as those based on random response. In addition, the procedures for design of substructure components contained in the *Guide Specification* assume optimum reliability on average in the methods used, so that Response Modification Factors for structural component design have been reduced such that their ductility based portions are assumed to be equal to or nearly unity. The efficacy of the Uniform Load Method in estimating response - forces and deformations - in seismically isolated bridge systems on average over a range of design spectrum compatible ground motions is evaluated in this paper by two methods. The peak forces and deformations of seismically isolated systems determined by the Uniform Load Method are found to be most inaccurate for structures with periods shorter than the characteristic period of the excitation. For records representative of near fault pulse motions, the method consistently underestimates forces and deformations by overestimating the effectiveness of damping in the equivalent system. Further studies utilizing these methods over a broader range of system parameters and ground motion inputs are needed to establish the general reliability of these design procedures to achieve system performance objectives on average for a broader database of spectrum compatible ground motion inputs.

INTRODUCTION

Although the basic intent of seismic isolation of buildings and bridges is similar, i.e. to increase the seismic performance of the structural system by reducing forces and component deformation demands thus limiting damage, the dynamic response of seismically isolated bridges differs in several fundamental ways from that of seismically isolated buildings. For example, the flexibility of the bridge substructure below the isolation interface in an isolated bridge system may alter the effectiveness of the isolation system or cause significant force redistributions that need to be considered. Relatively rigid foundation systems within seismically isolated buildings inhibit this substructure flexibility, limiting this concern. In addition, higher mode response contributed by in-plane deck flexibility, or interactions between several bridge components seperated along expansion joints,

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in relatively long bridge deck spans may contribute significantly to local deformation responses within an isolated bridge system, unlike in more compact isolated building structures.

The AASHTO *Guide Specification for Seismic Isolation Design* [AASHTO, 1999] was developed based on information available at the time for buildings and bridges, and borrows essentially the same substitute structure approach, or equivalent linear analytical model, with damping characterized using a frequency-dependent equivalent viscous model, derived from the building code formulation for isolation system design. But with the aforementioned fundamental differences in dynamic response apparent between buildings and isolated bridge systems, the efficacy of this new bridge design formulation in its ability to reliably meet specified target performance objectives in seismically isolated bridge systems needs to be verified.

Furthermore, it is an inherent assumption in the formulation of the AASHTO *Guide Specification* that the application of seismic isolation design in bridge structures based upon the prescribed design procedures is fundamentally reliable. This is based on a presumed assumption of reliability in the design formulation and an inherent assumption of system reliability enforced by stringent inspection and testing requirements prescribed by the code on the isolation systems themselves. This reliability is presumed in the design specification as it relates to the prescribed Response Modification Factors (R-Factors) utilized to establish component design forces. In seismic isolation design, these R-Factors are prescribed to be half of those given for standard, non-isolated, bridge design. The AASHTO Guide Specification commentary states:

> "*The specified R-Factors are in the range of 1.5 to 2.5, of which the ductility based portion is near unity and the remainder accounts for material overstrength and structural redundancy inherent in most structures. That is, the lower R-Factors ensure, on the average, essentially elastic substructure behavior in the design-basis earthquake. It should be noted that the calculated response by the procedures described in this document represents an average value, which may be exceeded given the inherent variability in the characteristics of the design basis earthquake* [AASHTO, 1999]."

In this respect the *Guide Specification* assumes both reliability in the system performance and code design methodology to "ensure" on average "essentially elastic substructure behavior", which would be considered an optimum performance level for the mean spectrum compatible earthquake event. Optimizing performance in this manner is not without its risks. For a stipulation of "essentially elastic" behavior on average, would imply inelastic substructure behavior for 50% of representative spectrum compatible motions. However, no further guidance is given within the *Guide Specification* on how to incorporate the effect of substructure yielding into the procedure nor on how to estimate substructure deformation demands in the event of seismic motions producing response above the mean.

In this respect, it is deemed the purpose of this study to systematically evaluate the efficacy of this new code formulation in its ability to reliably predict demands - forces and deformations - imposed by earthquake motions representative of design basis seismic events. And, further to validate the code prediction on ensured reliability in meeting specified target performance objectives for a broad range of seismically isolated bridge systems.

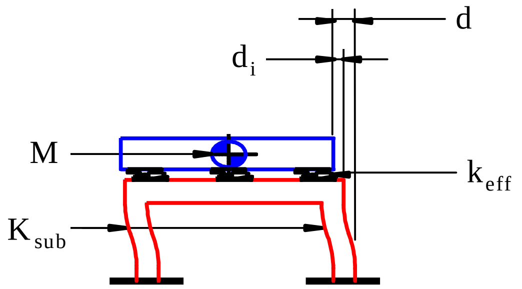
EQUIVALENT LINEAR PROCEDURES

Approximate analytical methods for estimating the earthquake response of inelastic systems have been postulated on the basis of replacing the nonlinear system with an "equivalent linear system". Generally speaking, these procedures include methods either based on harmonic response or on random response [Chopra and Goel, 1999]. It has been shown by others that methods proposed based on harmonic response considerably overestimate the period shift, whereas the methods derived considering random response give much more realistic estimates of the effective period [Iwan and Gates, 1979b]. Currently there has been renewed interest in applications of these procedures to the design of inelastic structures. Two methods based upon harmonic response have been adapted for this purpose. The "substitute structure method" [Shibata and Sozen, 1976], has been popularized by some for displacement-based design [Gulkan and Sozen, 1974; Shibata and Sozen, 1976; Moehle, 1992; Kowalsky et al., 1995; Wallace, 1995]. The "secant stiffness method" [Jennings, 1968] has been adapted to formulate the "nonlinear static procedure" in the ATC-40 [Applied Technology Council, 1996] and FEMA-274 report [FEMA, 1997]. The Uniform Load Method contained in the 1999 AASHTO *Guide Specification for Seismic Isolation Design* [AASHTO, 1999] has essentially adapted this "secant stiffness" procedure for estimating forces and deformations in seismically isolated bridge systems.

AASHTO UNIFORM LOAD METHOD

The Uniform Load Method is a design procedure prescribed in the AASHTO *Guide Specifications* for estimating the response - forces and deformations - along each of two separate orthogonal axes of an isolated bridge system. Total response is evaluated by either of two methods: the Single Mode Spectral Method and the Multi-Mode Spectral Method, as stipulated in the code. In either case the results from the Uniform Load Method for response in each of the two perpendicular axes of the bridge are combined in specified ratios to obtain the total bi-directional design response estimates for the isolated bridge system.

A typical structural model of an isolated bridge bent responding uni-directionally in its isolated mode is presented in Fig. 1. The force-deformation hysteretic response of typical isolation bearings is generally broad and relatively stable. The AASHTO *Guide Specification* allows a bilinear simplification to be utilized to characterize isolation bearings for purposes of the design procedures (Fig. 2a). The total force-deformation response of the isolated bridge system defined at the level of the bridge deck for a system with negligible substructure mass or substructure damping, defined in the parameters identified in the AASHTO code, is shown in Figure 2b.



k_{eff}= effective isolator stiffness
K_{sub}= linear substructure stiffness
M = lumped deck mass
d_i = isolator displacement
d_{sub} = substructure displacement
d = total displacement = $d_i + d_{sub}$

Figure 1- Structural idealization of isolated bridge bent

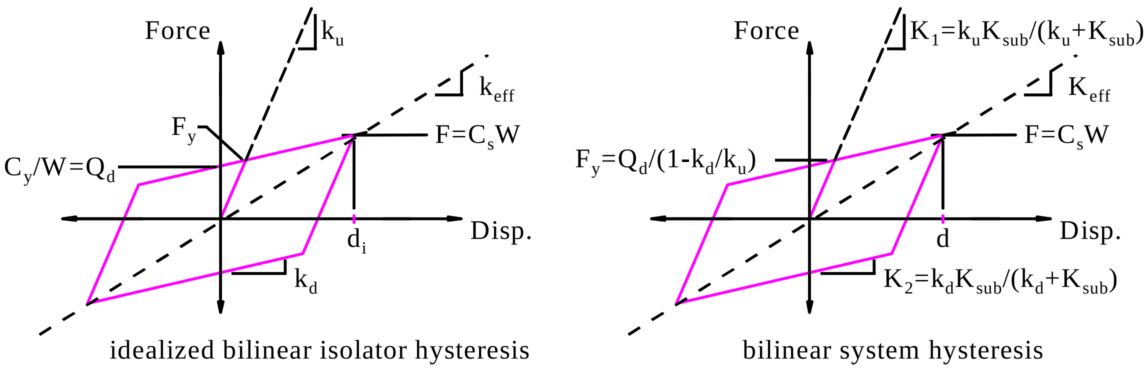


Figure 2- Bilinear idealization of isolation bearings and overall bridge system

The code stipulates linearized characteristics for the isolated bridge system based upon secant stiffness properties defined at the maximum displacement of the bridge derived from the earthquake response analysis. These "equivalent" properties are postulated by equating the energy dissipated per cycle in the isolated bridge system to that of an "equivalent" linear visco-elastic damping component oscillating harmonically at the same maximum amplitude, and a frequency characterized by the systems secant stiffness [Chopra, 1995]. The "effective" properties are defined as:

$$T_{eff} = 2\pi\sqrt{\frac{M}{Keff}}$$ - effective secant period at maximum system displacement (1)

$$\beta_{eff} = \frac{2\sum Q_d(d_i - d_y)}{\pi\sum K_{eff}d^2}$$ - effective damping ratio, excluding contributions from substructure (2)

Total design displacement is then prescribed, assuming system response in the constant velocity region of the design spectrum, as

$$d = \frac{10 A S_i T_{eff}}{B} \tag{3}$$

where the frequency independent factor B (as function of the damping ratio, β_{eff}) accounts for reduction in response due "effective" damping in the system. Force response is similarly prescribed at the effective period and damping values, where the force coefficient,

$$C_s = \frac{A S_i}{T_{eff} B} \tag{4}$$

but limited to $C_s \leq 2.5A$ to account for the peak in the psuedo-acceleration spectrum. The equivalent seismic force at the level of the bridge deck is then computed as $F = C_s W$.

With these linearized parameters defined, and iterative procedure for computing the system forces and deformations using this method is outlined in the following steps:

1. Estimate the system effective period and damping ratio, where rational first estimates may be taken as $T_{eff} = 2\pi\sqrt{M/K_2}$ and β_{eff} = 0.05,
2. Compute d and C_s from equations (3) and (4), with B established from the code values relating to β_{eff} ,
3. Compute equivalent static force at the deck level of the bridge, $F = C_s W$,
4. Determine maximum displacement, d_i, across the isolation bearing due to the application of force F,
5. Update system effective stiffness as K_{eff} = F/d, and effective damping ratio, β_{eff} , using equation (2),
6. Repeat steps 2 through 5 until the difference in effective system properties varies negligibly between subsequent iterations,
7. Report final design displacement, d and d_i, and equivalent static force estimates, F= K_{eff} d.

Two limitations on the method are stipulated: 1) T_{eff} < 3, and 2) β_{eff} <= 0.30 (except if B = 1.7 is utilized for β_{eff} >= 0.3, then the method is still allowed). The code further stipulates bounding analyses to be performed to account for probable maximum and minimum variations of the isolator properties Q_d and K_d.

The basis of this method on an assumption of harmonic response suggests it is not as accurate as methods based on random response, as mentioned previously [Iwan and Gates, 1979a,b]. The poorest correlation would presumably be expected for the most strongly impulsive motions (such as those characteristic of near-fault shocks) where the dissipation provided by viscous damping is rendered relatively ineffective. In addition, the stipulation is that "on average" the method "ensures" essentially elastic substructure response. Presumably moderate ductility demands in substructure components would be realized for response above the mean, such that typical design details would account for the level of ductility demand expected.

These presumptions and limitations render the need for validation of the method. In this respect, it is the purpose of this study to perform a systematic evaluation of this method to establish the reliability of the procedure in proportioning systems to meet the stipulated performance objectives. The general procedures for this evaluation are outlined in the following section.

EVALUATION PROCEDURE

Two methods of evaluation are proposed for this study. The basic procedure for each are outlined below:

Method A: Design Spectrum

For purposes of this evaluation method, a suite of twenty ground motion records representative of seismic events in the Los Angeles basin have been compiled. These motions have been amplitude and frequency scaled such that the mean 5% damped elastic spectrum for the set matches the USGS target spectrum corresponding to a probability of exceedence of 10% in 50 years [SAC, 1997]. They are intended to be representative of stiff soil sites (NEHRP site type D). Utilizing an acceleration coefficient, A = 0.4 (representative of a probability of exceedence of 10% in 50 years in the San Fernando region [AASHTO, 1999]), and a site soil coefficient, S_i = 1.5675 (representing approximately AASHTO soil type II), the ground motion records in the database were linearly scaled such that their mean spectrum matched the AASTHO design spectrum for this set of parameters with minimum absolute error, particularly in the constant velocity range (see Fig. 3). Evaluating the AASHTO Uniform Load Method procedure utilizing this set of scaled ground motion records thus provides a rational basis for establishing the ability of the method to produce calculated responses representative of the average over a range of spectrum compatible design basis earthquake records.

Using this database of ground motions, Method A computes the design response of an isolated bridge system defined by its characteristic parameters (Fig. 1,2), utilizing the AASHTO design spectrum (with A=0.4 and Si = 1.5675), and the iterative procedures outlined in Section 3 above. Results are compared to the average response obtained directly from nonlinear analysis of the same isolated bridge system subjected to the suite of ground motion records. Nonlinear analysis of the isolated bridge systems are performed by familiar nonlinear numerical time-stepping algorithms utilizing the properties of the linear substructure and bilinear characteristics of the

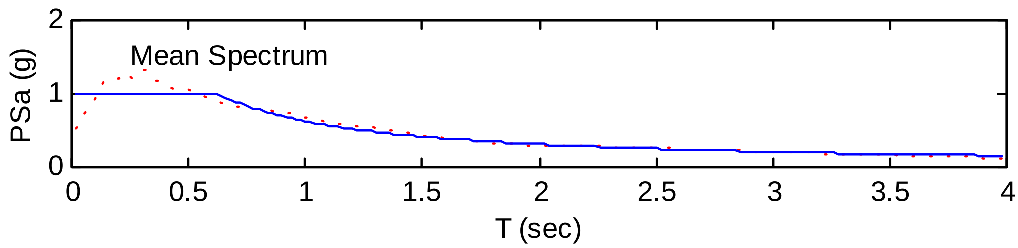


Figure 3 - AASHTO design spectrum and mean spectra of database motions

Method B: Specified Ground Motion

In this evaluation method, the underlying linearization procedures defined in the Uniform Load Method are applied directly to the response spectrum obtained for a specified ground motion record. Steps in this procedure are outlined as follows:

1. Estimate the system effective period and damping ratio, where rational first estimates may be taken as $T_{eff} = 2\pi\sqrt{M/K_2}$ and β_{eff} = 0.05, as before.
2. Compute the system response quantities, d and C_s, using classical linear analysis methods for the specified ground motion input and effective system parameters.
3. Compute equivalent static force at the deck level of the bridge, F = C_sW.
4. Determine maximum displacement, d_i, across the isolation bearing due to the application of force F.
5. Update system effective stiffness as K_{eff} = F/d, and effective damping ratio, β_{eff} , using equation (2),
6. Repeat steps 2 through 5 until the difference in effective system properties varies negligibly between subsequent iterations.
7. Report final design displacement, d and d_i, and equivalent static force estimates, F= K_{eff} d.

The results of this evaluation for given isolated bridge systems are again compared to the results of direct nonlinear analysis of the system to the specified ground motion.
For this method, two sets of ground motion records are utilized: 1) the database suite of 20 spectrum compatible earthquake records used in evaluation Method A above, and 2) pure pulse records representative of near-fault ground motions (fault-normal and fault-parallel, see Fig. 4a). For purposes of this study, the pulse records were chosen with amplitude $\ddot{u}_{g\,\max}$ (g) = A(g) = 0.4, and duration T_p = 1.0 second (representing the mid-range of non-isolated bridge systems evaluated in the study, T_{sub} = 0 to 2 seconds, see Section 5). Response spectra for the stipulated near-fault pulses are shown in Figure 4b.

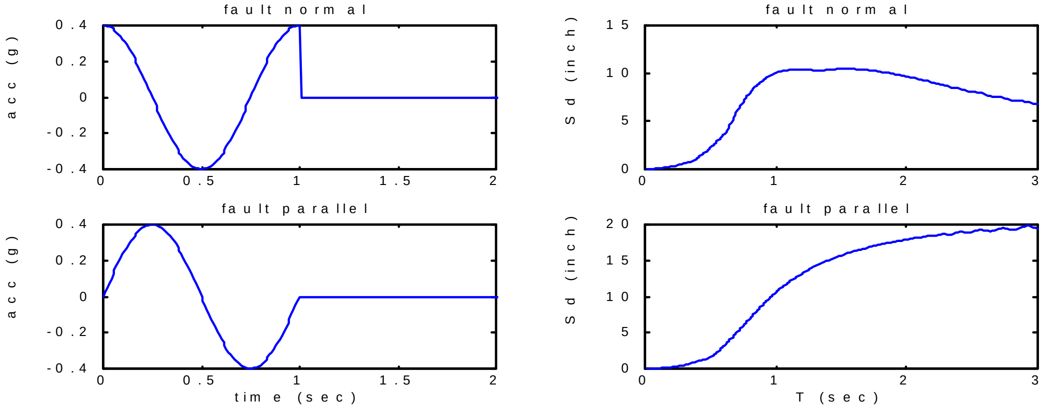


Figure 4 - Near-fault pulse motions and response spectra (5% damping)

EVALUATION OF AASHTO PROCEDURE

Evaluation of the AASHTO Uniform Load Method was performed utilizing the above outlined Method A and Method B for systems characterized over a broad range of parameters representative of the general range of potential seismically isolated bridge systems. Ranges of system parameters utilized were:

- Substructure characteristic period, $T_{sub} = 2\pi\sqrt{M/K_{sub}}$ = 0 to 2 seconds (where contribution of substructure damping is presumed to be zero in these initial studies).
- Characteristic isolator strength ratio, $C_y = Q_d/W$ = 0.03 to 0.12.
- Characteristic isolation period, $T_i = 2\pi\sqrt{M/k_d}$ = 1 to 6 .
- A range of isolator first to second slope stiffness ratios, alpha = k_d/k_u , representative of rigid-plastic (alpha = 0) to linear isolator behavior (alpha = 1).
- Isolation system parameters, Q_d, k_u, and k_d are assumed known uniquely, precluding the requirement for bounding analysis.

Summaries of the general results obtained thus far in this evaluation are presented below:

Method A: Design Spectrum

In general, the total displacement is seen to increase and forces are seen to decrease with increasing characteristic structural period, T_{sub}. The AASHTO Uniform Load Method significantly overestimates system forces and displacements, particularly for structures having characteristic periods, T_{sub}, below the peak in the pseudo-acceleration design spectrum (Fig. 5). This could be interpreted as providing a conservative estimate of system deformations and forces on average, at least for the database motions utilized to establish the mean ground motion responses.

Method B: Specified Ground Motion

Database Motion: El Centro

In general, the Method B evaluation procedure does not generally improve the prediction of forces and displacements determined by the Uniform Load Method significantly over (Fig. 6). Again, the AASHTO Uniform Load Method significantly seems to overestimate system forces and displacements, particularly for structures having characteristic periods, T_{sub}, below the peak in the pseudo-acceleration design spectrum. This could be interpreted as providing a conservative estimate of these response quantities for design.

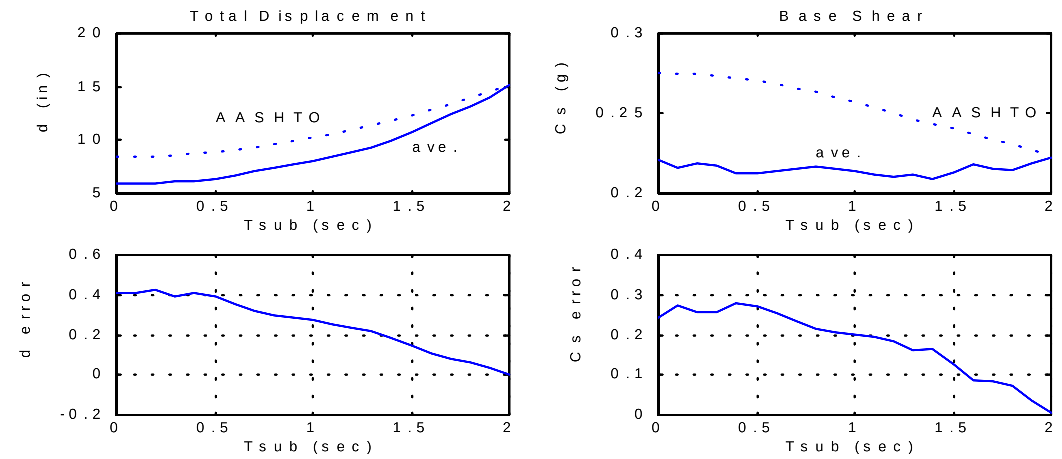


Figure 5 - Results from Method A: averaged response, Cy=.06,Ti=2sec,alpha=0

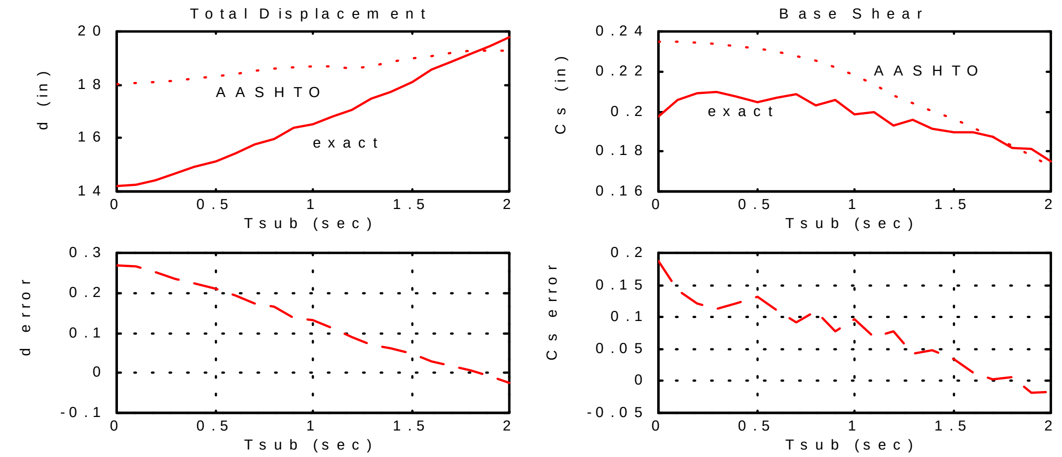


Figure 6 - Results from Method B: El Centro, Cy=.03,Ti=3sec,alpha=0

Pulse Motion: Fault-normal

In general, the Uniform Load Method applied directly to pulse type motions representative of near-fault shock records generally underestimates system forces and displacements, over the range of system parameters studied (Fig. 7). This would be anticipated based on the assumptions of the equivalent linear procedure utilized in the method, where the linear parameters would tend to systematically over-estimate the effect of damping in the system for these type of non-harmonic motions.

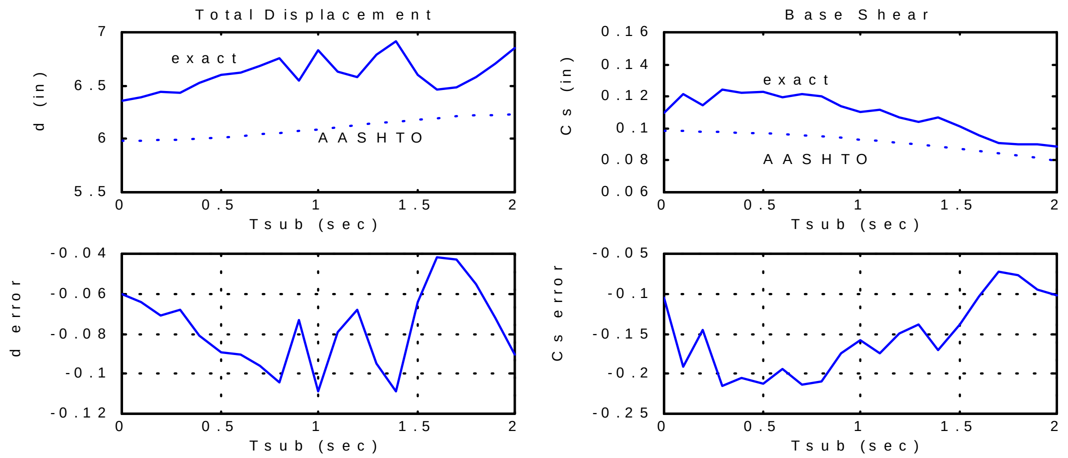


Figure 7 - Results from Method B: Fault-normal, Cy=.06,Ti=4sec,alpha=0

CONCLUSIONS

The peak forces and deformations of seismically isolated systems determined by the Uniform Load Method are found to be most innacurate for structures with periods shorter than the characteristic period of the excitation. For records representative of near fault pulse motions, the method consistently underestimates forces and deformations by overestimating the effectiveness of damping in the equivalent system. For these types of ground motion inputs, Response Modification Factors utilized in the code procedures may prove to be inadequate to reliably enforce the stipulated performance objective of "essentially elastic substructure behavior" on average. Further studies utilizing these methods over a broader range of system parameters and ground motion inputs are needed to establish the general reliability of these design procedures to achieve system performance objectives. Alternate displacement-based design methods may be warranted to improve the reliability of these current code design procedures.

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