EVALUATING ACCURACY OF THE MOTEMS AND ASCE/COPRI 61-14 SUBSTITUTE STRUCTURE METHOD

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ABSTRACT

This paper evaluates the substitute structure method (SSM) in MOTEMS and ASCE/COPRI 61-14 by comparing seismic displacement from the SSM with results from the nonlinear response history analysis (NLRHA). It is found that the SSM over-predicts displacement demand for short-period systems and under-predicts displacement demand for long-period systems. The over-prediction tends to be excessive for very-short period systems and under-prediction for long period systems may lead to unconservative design. Therefore, it is recommended that the SSM should not be used for very-short or long period systems. The SSM was found to provide results (within 20% of results from the NLRHA) for systems with periods in the constant spectral acceleration region of the design spectrum.

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\textbf{ABSTRACT}

This paper evaluates the substitute structure method (SSM) in MOTEMS and ASCE/COPRI 61-by comparing seismic displacement from the SSM with results from the nonlinear response history analysis (NLRHA). It is found that the SSM over-predicts displacement demand for short-period systems and under-predicts displacement demand for long-period systems. The over-prediction tends to be excessive for very-short period systems and under-prediction for long period systems may lead to unconservative design. Therefore, it is recommended that the SSM should not be used for very-short or long period systems. The SSM was found to provide results (within 20\% of results from the NLRHA) for systems with periods in the constant spectral acceleration region of the design spectrum.

\textbf{Introduction}

The substitute structure method (SSM) was originally developed as a design tool to determine seismic design forces \cite{1,2}. With recognition of the importance of displacements, this method received renewed attention for displacement-based design \cite{3-5} and Priestley et al. \cite{6} proposed several versions of the SSM for displacement-based design of bridges. These methods involve replacing the inelastic system with a substitute linear-elastic model. The stiffness and damping of the substitute structure is calibrated with the expectation that the displacement of the original nonlinear system will be the same as that of the substitute system. The substitute structure will generally have a period longer than and a damping higher than that of the initial elastic structure (Figure 1).

Other variations of the SSM, such as nonlinear static procedure (NSP) in the ATC-40 and FEMA-273 documents \cite{7,8} or the capacity spectrum method \cite{9,10}, have also been proposed. These methods share with the SSM the basic concept of an elongated period and increased, as shown in Figure 1, to represent a nonlinear system with an equivalent linear elastic system. However, the procedure to compute equivalent damping varies among these methods.

The NSP method in ATC-40 and FEMA-273 documents was evaluated in a study by

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Chopra and Goel [11]. It was found that the NSP may significantly over- or under-estimate the
deformation with errors approaching 50%. Hutchinson et al. [12] also evaluated these methods for
extended pile shaft supported bridge structures and found that the SSM overestimated demands by
about 40%. These studies indicate that the SSM may not always provide reasonable estimate of
seismic displacement demand.

More recently, the SSM has been adopted in MOTEMS [13] and in ASCE/COPRI Standard
61-14 [14] for estimating seismic demands in piers and wharves. Both these methods share the
general characteristics of the SSM, i.e., elongation of period and increased damping. However,
MOTEMS restricts use of the SSM for systems with period less than the period where constant
acceleration and constant velocity regions of the design spectrum intersect; the displacement
demand in the nonlinear system is taken as that of the initial elastic system for longer periods. The
ASCE/COPRI 61-14 does not put such restriction on use of the SSM. The SSM has been adopted
in MOTEMS and ASCE/COPRI 61-14 even though its ability, when compared against the
NLRHA, in predicting the peak seismic displacement demand has been found to be questionable
[11,12].

It is clear from the discussion so far that there is a need to re-examine the ability of the
MOTEMS and ASCE/COPRI 61-14 SSM for estimating seismic displacement demands in marine
oil terminals and other piers and wharves. This investigation is aimed at filling this need. For this
purpose, seismic displacement demands from the SSM are compared against those obtained from
the NLRHA using a suite of 20 ground motions developed for SAC study [15]. Since results from
the MOTEMS SSM, when convergence is achieved, were found to be the same as those from the
ASCE/COPRI 61-14 [16], only the ASCE/COPRI 61-14 SSM is considered in rest of this
investigation.

Figure 1. Period elongation and increased damping in the SSM (adopted from Goel and Goel, 2017).
Following is a summary of the SSM in ASCE/COPRI 61-14 standard:

1. Idealize the pushover curve from nonlinear pushover analysis (Figure 2) and estimate the yield force, $F_y$, and yield displacement, $\Delta_y$.

![Figure 2. Idealization of nonlinear pushover curve (adopted from [16]).](image)

2. Compute the effective linear-elastic lateral stiffness, $k_e$, as the yield force, $F_y$, divided by the yield displacement, $\Delta_y$.

3. Compute the effective linear-elastic structural period in the direction under consideration from

$$ T_e = 2\pi \sqrt{\frac{m}{k_e}} $$

(1)

4. Determine displacement, $\Delta_d$, of the effective linear-elastic system from

$$ \Delta_d = S_d \frac{T_e^2}{4\pi^2} $$

(2)

where $S_d$ is the 5%-damped spectral acceleration corresponding to the linear elastic structural period, $T_e$.

5. Select initial estimate of the displacement demand in the SSM as

$$ \Delta_{d,j} = \Delta_d $$

(3)

6. Compute the ductility, $\mu_{\Delta,j}$,

$$ \mu_{\Delta,j} = \frac{\Delta_{d,j}}{\Delta_y} $$

(4)
7. Use the appropriate relationship between ductility and damping for the component undergoing inelastic deformation to estimate the effective structural damping, $\xi_{\text{eff},j}$. In lieu of more detailed analysis, use the following the relationship for concrete and steel piles connected to the deck through dowels embedded in the concrete:

$$
\xi_{\text{eff},j} = 0.05 + \frac{1}{\pi} \left( 1 - \frac{1 - \alpha}{\sqrt{\mu_{\Delta,j}}} - \alpha \sqrt{\mu_{\Delta,j}} \right)
$$

(6)

where $\alpha$ is ratio of the post-yield stiffness and the initial elastic stiffness (see Figure 2).

8. Compute the force, $F_{d,j}$, on the force-deformation relationship associated with the estimated displacement, $\Delta_{d,j}$ (Figure 3).

![Figure 3. Solution strategy and effective stiffness in the SSM (adopted from [16]).](image)

9. Compute the effective stiffness, $k_{\text{eff},j}$, as the secant stiffness from

$$
k_{\text{eff},j} = \frac{F_{d,j}}{\Delta_{d,j}}
$$

(7)

10. Compute the effective period, $T_{\text{eff},j}$, from

$$
T_{\text{eff},j} = 2\pi \sqrt{\frac{m}{k_{\text{eff},j}}}
$$

(8)

11. For the effective structural period, $T_{\text{eff},j}$, and the effective structural damping, $\xi_{\text{eff},j}$, compute the spectral acceleration $S_A(T_{\text{eff},j}, \xi_{\text{eff},j})$ from an appropriately damped design acceleration response spectrum.

12. Compute the new estimate of the displacement, $\Delta_{d,j}$, from:

$$
\Delta_{d,j} = \frac{T_{\text{eff},j}^2}{4\pi^2} S_A(T_{\text{eff},j}, \xi_{\text{eff},j})
$$

(9)
13. Repeat steps 6 to 12 with $\Delta_{d,j} = \Delta_{d,j}$ until displacement, $\Delta_{d,j}$, computed in step 12 is sufficiently close to the starting displacement $\Delta_{d,0}$ in step 6 (Figure 3).

**Evaluation Approach**

The SSM is evaluated by examining the ratio of $\Delta_{SSM}$ and $\Delta_{NLRHA}$, which are the peak displacement demands of single-degree-of-freedom (SDF) system from the SSM and NLRHA, respectively. To assess the effects of level of system nonlinearity, four different values of $R_y = 2, 4, 8$ and 10 were considered, where $R_y$ is defined as the ratio of the system strength required for the system to remain linear elastic and the yield strength. The system nonlinearity is characterized by bilinear force-deformation relationship with 5% post-yield stiffness. The NLRHA of the SDF system is implemented in OpenSees [17] using Takeda hysteresis material model [18]. The ASCE/COPRI 61-14 SSM, described in the preceding section, is implemented in MATLAB [19]. In this implementation, peak displacement demands in steps 2 and 9 are computed from linear response history analysis of the system with appropriate vibration period and damping; the “original” method in ASCE/COPRI 61-14 estimates these demands from a design spectrum.

**Selected Ground Motions**

A suite of 20 ground motions developed for 10% probability of exceedance in 50 years for a site in Los Angeles, California for the SAC study [15] are used in this investigation. The elastic response spectra for individual ground motions and median for the selected set are shown in Figure 4.

![Figure 4. Response spectrum for SAC ground motions.](image-url)
Evaluation of the ASCE/COPRI 61-14 SSM

The results presented in Figure 5 indicate that the SSM over-predicts the displacement demand for systems with short periods and under-predicts the displacement demand for systems with long periods. This is apparent from the median of $\Delta^*$ being larger than one for systems with short periods and smaller than one for systems with long periods. The over-prediction tends to be very large for very-short period systems, with the over-prediction in many cases exceeding 50%. The significant over-prediction for very-short period system occurs because the SSM errs on the side of longer period [20]. The very-short period region is defined as the region between zero period and period where the design spectrum transitions from linearly increasing spectral acceleration to the constant spectral acceleration. For the SAC median spectrum, periods in this region are less than 0.3 sec.

Figure 5. Ratio of peak displacement demand from the SSM and the NLRHA for SAC ground motions.

For systems with periods in the constant spectral region of the spectrum, the SSM over-predicts displacement demand but by no more than 20%. Therefore, the SSM is expected to provide reasonable results, although there may still be some over-prediction, in this region of the spectrum. For the SAC median spectrum, this region is between 0.3 sec and 1 sec.

The SSM has the tendency to under-predict displacement demand for longer period systems that fall in the velocity- and displacement-sensitive regions. For such systems, the displacement of the nonlinear system should be approximately equal to that of the linear elastic
system irrespective of the level of nonlinearity. The tendency of the SSM to “err” on the side of higher damping dominates and leads to lower displacement and thus under-prediction of displacement demand [20]. Periods longer than 1 sec fall these regions for the SAC median spectrum.

The under-prediction of displacement demand by the SSM for periods beyond the constant spectral acceleration region may lead to unconservative design. Therefore, it may not be appropriate to use the SSM to estimate displacement demand for longer period systems. While MOTEMS precludes use of the SSM beyond the constant spectral acceleration region, the ASCE/COPRI 61-14 does not. Therefore, it is recommended that ASCE/COPRI 61-41 also preclude use of the SSM beyond the constant spectral acceleration region of design spectrum; displacement demand of nonlinear systems with periods longer than those beyond the constant spectral acceleration region may simply be estimated as that of the corresponding linear elastic systems.

These observations are consistent, in general, for different values of \( R_y \) for systems beyond the very-short period region. However, the over-prediction by the SSM for systems with period in the very-short period region, in some cases, may increase with increasing values of \( R_y \).

The discussion so far indicates the SSM should not be used to estimate displacement demand for very-short period systems because this method significantly over-predicts the displacement, with over-prediction exceeding 50% in many cases. The SSM should also not be used for longer period systems because it under-predicts the displacement demand and thus may lead to unconservative design. Finally, the SSM may be used for systems which fall in the constant spectral acceleration region of the design spectrum where the SSM provides reasonable results (within 20% of the value from the NLRHA).

**Conclusions and Recommendations**

This investigation demonstrates that the MOTEMS and ASCE/COPRI 61-14 SSM over-predicts the displacement demands of short-period systems and under-predicts the displacement demand for longer period systems. The over-prediction for very-short period systems may be excessive with the SSM providing displacement estimates that exceed the values from the NLRHA by more than 50%. The SSM provides reasonable results only in constant spectral acceleration region of the earthquake design spectrum.

It is recommended that the ASCE/COPRI 61-14 and MOTEMS SSM should not be used for systems with very-short periods or for systems with periods beyond the constant acceleration region of the earthquake design spectrum. This method may be used for systems in the constant spectral acceleration region of the earthquake design spectrum. The engineer should be aware that the SSM may over-predict the displacement demand by 20% for such systems.

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