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ON LESS COMPUTATIONAL COSTS FOR ANALYSIS OF SILOS SEISMIC BEHAVIOR BY TIME INTEGRATION

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Abstract. *Time integration is the most versatile tool for analyzing semi-discretized equations of motion. Nevertheless, the associated computational costs are generally high and the computed responses are approximate. Integration step size is the main parameter affecting the computational cost and accuracy, in different ways; and hence, should be set equal to the largest value, acceptable from the point of view of accuracy. For practical cases, subjected to digitized excitations, an additional restriction, potentially increasing the computational costs, is the digitization size of the recorded excitations. Recently, a technique uses a convergence-based replacement of the digitized excitations with excitations digitized at larger steps, to arrive at time integration analyses in need of less computational cost. The good performance of the proposed technique regarding simple linear and nonlinear structural dynamic systems and shear frame structures has been displayed. Considering these, the importance of time history analysis in seismic analyses, the fact that the sizes and complicatedness of structural systems are in increase and the earthquakes are likely being recorded in smaller steps everyday, and meanwhile, the strategical role of silos in most of countries, the objective in this paper is to study the effectiveness of the new technique, when applied to analysis of silos seismic behaviors. After brief theoretical discussion, a steel silo designed based on existing codes, is once analyzed without implementing the technique, and then again, when implementing it, considering 80 percent of the mass of granular material inside silo as the effective mass. The numerical results clearly evidence the good performance of the technique.*

1 INTRODUCTION

Time integration is the most versatile tool to analyze the semi-discretized equation of motion, below:

$$\mathbf{M}\ddot{\mathbf{u}}(t)+\mathbf{f}_{\text{int}}(t)=\mathbf{f}(t) \tag{1}$$

$$\text{Initial conditions: } \left| \begin{array}{l} \mathbf{u}(t=0)=\mathbf{u}_0 \\ \dot{\mathbf{u}}(t=0)=\dot{\mathbf{u}}_0 \\ \mathbf{f}_{\text{int}}(t=0)=\mathbf{f}_{\text{int}_0} \end{array} \right.$$

Additional constraints: $\mathbf{Q}$

$$0 \le t < t_{end}$$

In equations (1) t and t_{end} imply the time and duration of dynamic behavior; $\mathbf{M}$ is the mass matrix; $\mathbf{f}_{\text{int}}(t)$ and $\mathbf{f}(t)$ represent the vectors of internal force and excitation; $\mathbf{u}(t)$, $\dot{\mathbf{u}}(t)$ and $\ddot{\mathbf{u}}(t)$ are the unknown vectors of displacement, velocity, and acceleration, $\mathbf{u}_0$, $\dot{\mathbf{u}}_0$, and $\mathbf{f}_{\text{int}_0}$ define the initial status of the model, and $\mathbf{Q}$ represents some restricting conditions, e.g. additional constraints in problems involved in impact or elastic-plastic behavior. In spite of the versatility, time integration analyses suffer from considerable computational cost and computational errors [1], both mainly depending on integration step size, Δt . Time integration initiates with selection of time step size or a criterion for adaptive time stepping, then considering the initial conditions, the analysis is being continued with marching along the time axis and computing the responses for distinct time stations. Typical arrangement of time steps and time stations in time integration analyses is shown in Figure 1.

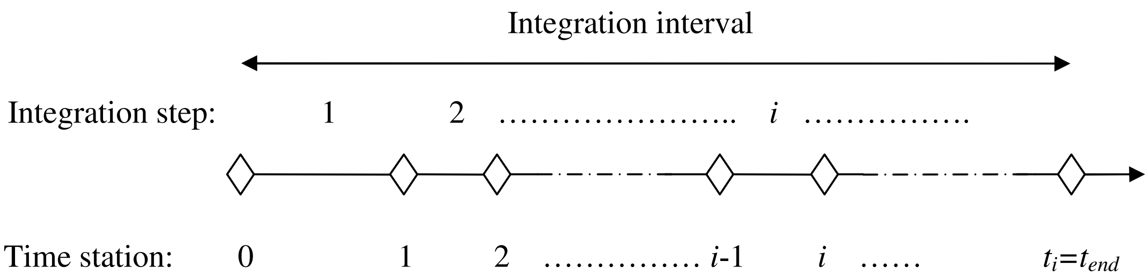


Figure 1. Typical arrangement of time steps and time stations in time integration analyses [2].

Due to the fact that smaller integration steps result in more precision and also more computational cost, it is mandatory to select time step sizes as small as acceptable from precision point of view. The existing proposed values for Δt in technical literature are presented below [3,4,5].

$$\Delta t = \text{Min}\left(h, \frac{T}{10}, {}_f\Delta t \right) \qquad \text{for linear systems}$$

$$\Delta t = \text{Min}\left(h, \frac{T}{100}, {}_f\Delta t \right) \qquad \text{for nonlinear systems} \tag{2}$$

In equations (2) h represents the requirements regarding response numerical stability and consistency, T is the dominating period of oscillations, not precisely known in advance, and ${}_f\Delta t$, representing an additional restriction for practical cases where the excitation $\mathbf{f}(t)$ is available as digitized record, implies the size by which the excitation is recorded. Reducing the effect of ${}_f\Delta t$ in equations (2) can decrease the computation cost considerably. Recently a technique is proposed [2], which replaces the digitized excitations with the step size equal to ${}_f\Delta t$ with excitations digitized at steps equal to $n\ {}_f\Delta t$, $n \in Z^+$, such that to preserve responses rate of convergence. The technique is implemented in simple linear and nonlinear systems analysis and also in a shear frame model analysis and led to considerable computational cost reduction with tolerable loss of accuracy [2,6]. In this paper the performance of this technique is investigated in the case of a steel silo.

2 THE RECENTLY PROPOSED TECHNIQUE [2]

In view of equations (2), considering the case when ${}_f\Delta t < \text{Min}(h, T/(10 \text{ or } 100))$ and taking into account the four assumptions mentioned below:

1- The excitation steps are equally sized, (see Figure 2)

$$\forall i, j \quad {}_f\Delta t_i = {}_f\Delta t_j = {}_f\Delta t > 0 \tag{3}$$

2- The integration steps are equally sized,

$$\forall i, j \quad \Delta t_i = \Delta t_j = \Delta t > 0 \tag{4}$$

3- The excitation steps are embedded by the integration steps (the first time station is a station for both excitation and integration),

$$\exists \quad n \in Z^+ \quad \frac{\Delta t}{{}_f\Delta t} = n < \infty \tag{5}$$

4- The $\mathbf{f}(t)$ in equations (1) is a digitized representation of an actual excitation $\mathbf{g}(t)$ which is smooth with respect to time,

$$\mathbf{f}(t) = \mathbf{g}(t)\delta(t-\alpha_i)$$
$$\mathbf{g}(t): \text{smooth with respect to time}$$
$$\alpha_i = i_f \Delta t \text{ , } i = 0,1,2,... \qquad (6)$$
$$\delta(t-\alpha_i) = \begin{cases} 1 & t = \alpha_i \\ 0 & t \neq \alpha_i \end{cases}$$

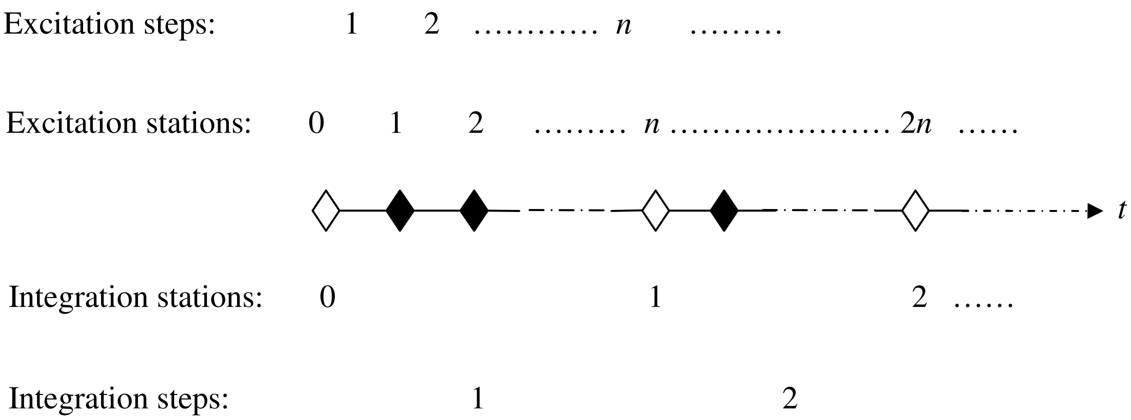


Figure 2. Typical distribution of excitation and integration stations in [2].

we can replace the original excitation with a new excitation defined by:

$$t_i = 0: \quad \tilde{\mathbf{f}}_i = \mathbf{f}(t_i),$$
$$0 < t_i < t_{end}: \tilde{\mathbf{f}}_i = \frac{1}{2}\mathbf{f}(t_i) + \frac{1}{4n'}\sum_{k=1}^{n'}[\mathbf{f}(t_{i+k/n}) + \mathbf{f}(t_{i-k/n})], \qquad (7)$$
$$t_i = t_{end}: \quad \tilde{\mathbf{f}}_i = \mathbf{f}(t_i),$$

where,

$$t = \Delta t \quad : \quad n' = n - 1$$
$$\Delta t < t < t_{end} - \Delta t \quad : \quad n' = \begin{cases} \frac{n}{2} & n = 2j \quad j \in Z^+ \\ \frac{n-1}{2} & n = 2j+1 \quad j \in Z^+ \end{cases} \qquad (8)$$
$$t = t_{end} - \Delta t \quad : \quad n' = n - 1$$

and Δt and n ($n \in Z^+$) are the largest values satisfying

$$\Delta t = n_f \Delta t \leq \text{Min}\left(h, \frac{T}{10}\right) \qquad \text{for linear systems}$$

$$\Delta t = n_f \Delta t \leq \text{Min}\left(h, \frac{T}{100}\right) \qquad \text{for nonlinear systems} \qquad (9)$$

$$\Delta t \leq t_{end}$$

and obtain responses from time integration with much less computational cost. Following the numerical examples already successfully examined in the literature [2,6], the technique is in the next section implemented in the analysis of a steel silo by time integration.

3 SEISMIC ANALYSIS OF A STEEL SILO

In this paper a steel silo subjected to an earthquake excitation is taken into account. The mass density of granular material inside silo is considered equal to 1500 kg/m^3. Dimensions of the silo model are presented in Table 1 [7]. ABAQUS finite element package [8] is used for finite element modeling. 4-noded shell element S4R is used for modeling the wall of silo. The modulus of elasticity of the wall of silo is considered equal to 2×10^5 MPa. For decreasing the computation time only half of silo is modeled and symmetric boundary conditions are used at the center of silo. Eurocode 8 Part 4 [9] has proposed that if more accurate evaluations are not undertaken, the global seismic response and the seismic action effects in the supporting structure may be calculated assuming that the particulate contents of the silo move together with the silo shell and modeling them with their effective mass, the contents of the silo may be taken to have an effective mass equal to 80 percent of their total mass, In common silo design in ACI 313 [10], 80 percent of granular material mass is proposed to be considered as effective mass for calculation of seismic loads. For modeling the silo, 80 percent of granular material mass is uniformly applied to the wall of the silo. The computed fundamental period, T, equals 0.2038 sec. The finite element mesh of the model is shown in Figure 3.

Silo height H (m)	Diameter D (m)	Silo wall thickness t (m)
20	10	0.03

Table 1. Dimensions of the silo model.

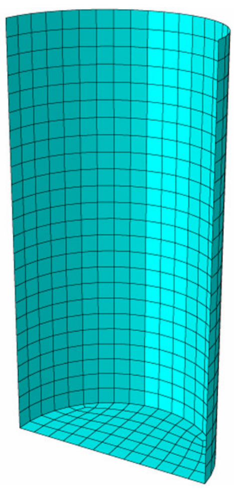


Figure 3. The finite element mesh of silo model (half of silo is considered).

The excitation which is a strong motion record, digitized at steps equal to ${}_f\Delta t = 0.005$ is shown in Figure 4. Generally in conventional time integration analyses using integration steps as small as ${}_f\Delta t$ is essential, but by using the technique described in Section 2, we can consider n =2,3,4 to perform time integration analyses by replacing the digitized excitation shown in Figure 4 with the step size of ${}_f\Delta t = 0.005$ with excitations digitized at steps equal to $n\ {}_f\Delta t = 0.01, 0.015, 0.02$ in consistence with equations (2), Hilber-Hughes-Taylor method [11] is implemented as the integration method, with a parameter, α, equal to -0.05. The base shear and top displacement histories of the silo structural system subjected to the original excitation and when considering the technique with n =2,3,4 are reported in Figures 5 and 6. As shown, the results obtained considering new excitations with n =2,3,4 have a good correlation with the results obtained from the conventional time integration by applying the earthquake excitation depicted in Figure 4 to the silo model. The computation time and the computation cost saved for each analysis are presented in Table 2. As shown in Table 2, the computation cost saved when integration steps are equal to $4\,{}_f\Delta t$ is 77.65 percent with a negligible loss of accuracy (see Figures 5-6). The obtained results clearly display that the recently proposed technique can be successful in time integration of silos structural system.

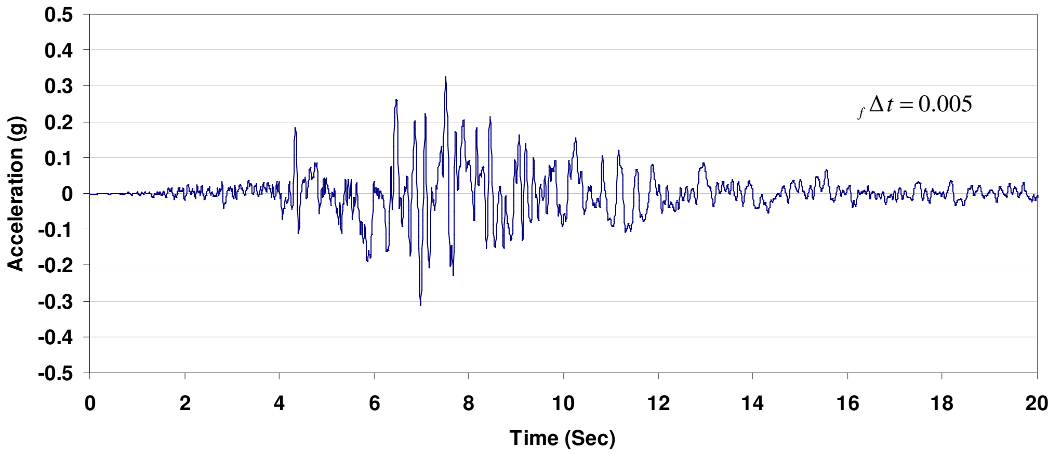


Figure 4. The earthquake excitation.

Type of analysis	Computation time (sec)	Computation cost saved (%)
Integration steps equal to ${}_f\Delta t$ (conventional)	1383	-------
Integration steps equal to $2\,{}_f\Delta t$	716	48.22
Integration steps equal to $3\,{}_f\Delta t$	468	66.16
Integration steps equal to $4\,{}_f\Delta t$	309	77.65

Table 2. Computational costs when implementing the technique with different values of *n*.

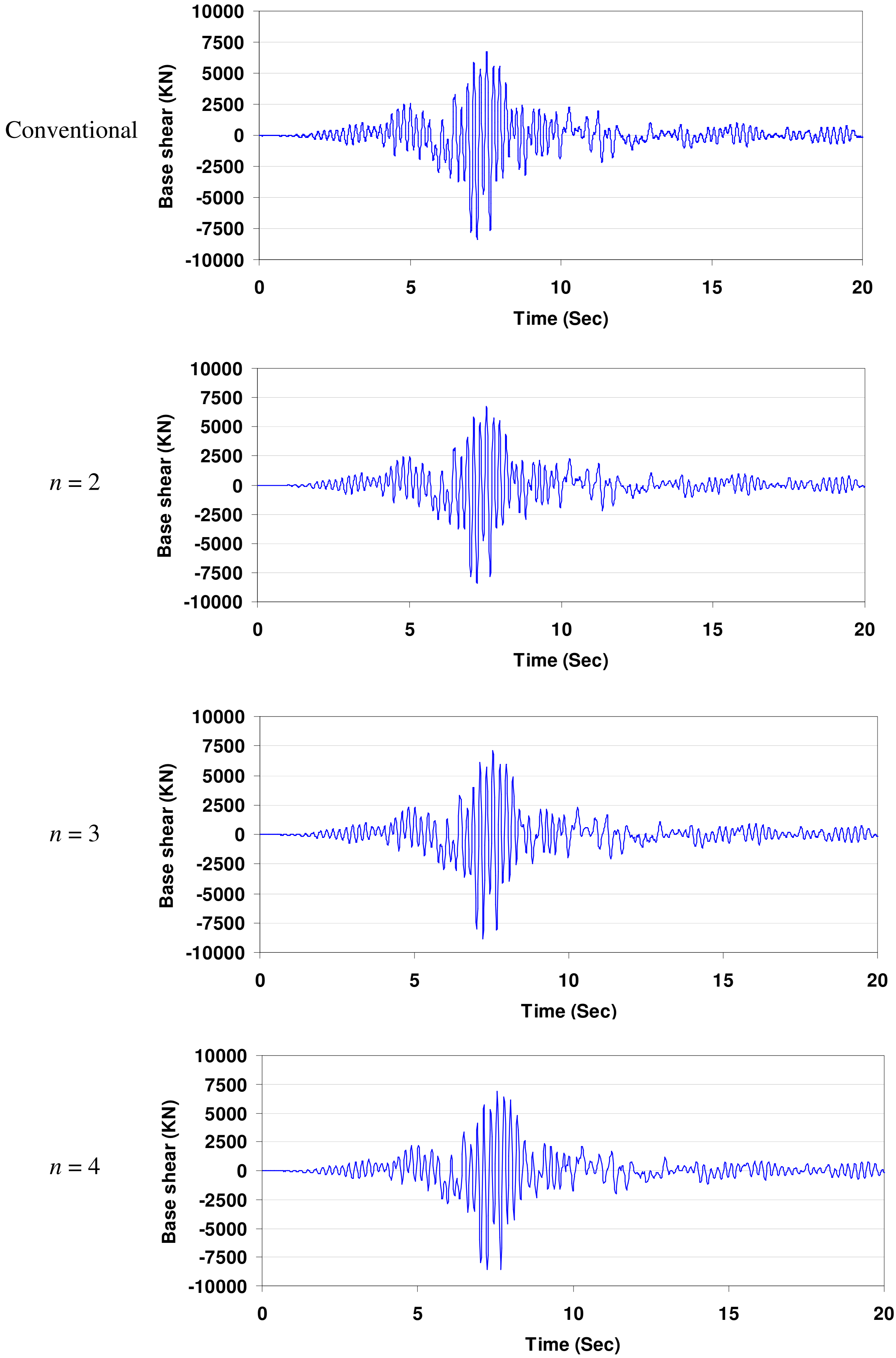
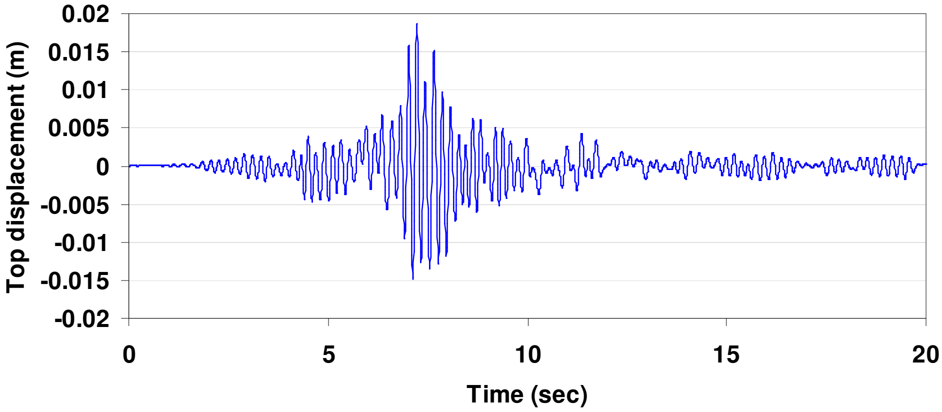
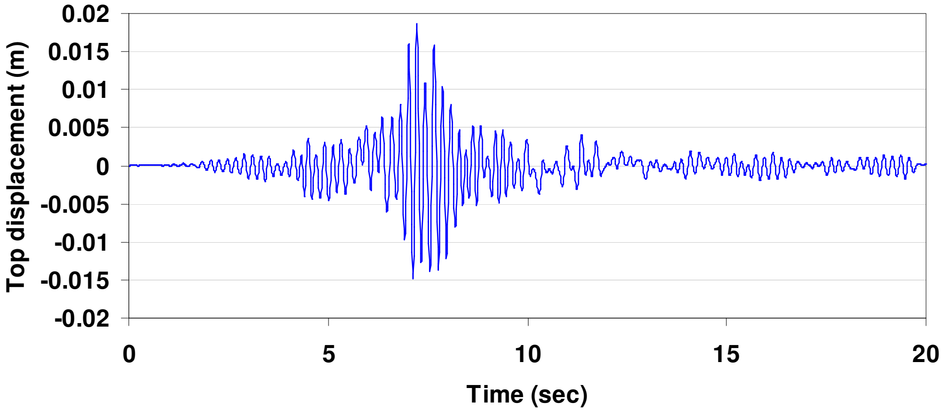


Figure 5. Comparison between base shear time histories for different values of *n*.

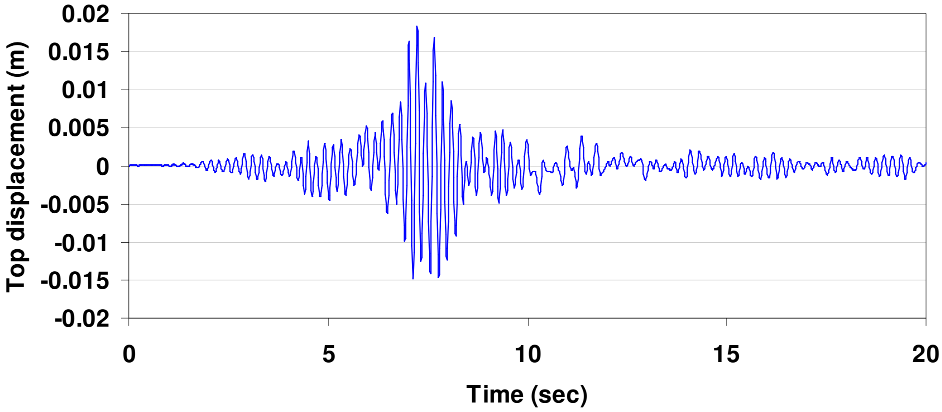
Conventional



$n = 2$



$n = 3$



$n = 4$

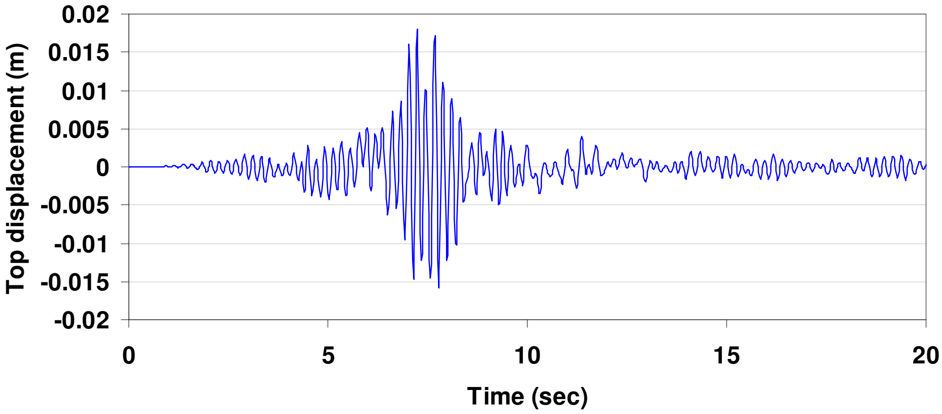


Figure 6. Comparison between top displacement time histories for different values of *n*.

4 CONCLUSIONS

In this paper, the performance of a new technique recently proposed for decreasing the computational cost of time integration analysis is investigated in the case of seismic analysis of a steel silo. The results show that using the new technique leads to significant computational cost reduction with negligible loss of accuracy. Further study in this regard, especially with different silos, different strong motion records and different integration methods is recommended.

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