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Research Article

On the limitations of simplified kinematic interaction models for embedded foundations

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ABSTRACT

Kinematic interaction (KI) effects arising from foundation embedment alter the motion transmitted from the free field to the foundation level and can therefore influence the seismic demands imposed on structures. Although several analytical formulations and guideline-based procedures exist to represent these effects, their accuracy when used directly to modify design and response spectra has not been thoroughly validated against real ground-motion data. This study provides a systematic evaluation of two widely used KI approaches; (i) the analytical transfer functions of Elsabee and Morray (1977) and (ii) the spectral-modification procedure of FEMA-440 (2005). Using a large suite of recorded motions, free-field and foundation input motions are computed through frequency-domain modification, and corresponding acceleration response spectra are obtained to form computed spectral ratios. These computed ratios serve as a benchmark for assessing the predictive performance of the simplified KI procedures across a range of embedment-to-stiffness conditions. The results show that analytical KI factors substantially underestimate short-period spectral ordinates, whereas FEMA-440 captures overall trends more effectively but loses accuracy for larger embedment depths. The study defines practical ranges in which simplified KI procedures remain reliable and identifies conditions that require more refined soil-structure interaction modelling. The findings provide engineers with clearer guidance for incorporating KI effects in seismic analysis and design.

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1. Introduction

Soil-structure interaction (SSI) is one of the most extensively investigated yet still not fully understood topics in earthquake engineering (Kramer 1996; Kausel 2010). Simply stated, SSI refers to the mutual influence between a structure and the underlying soil deposit. The presence of soil alters the expected behavior of the structure, particularly under dynamic loading; conversely, the presence of the structure modifies the response of the soil beneath it. This bidirectional interaction may lead to either reduced or increased structural demands, depending on factors such as the dynamic characteristics of the structure, the mechanical properties of the supporting soil, and the geometric configuration of the foundation (Gazetas 1991). The literature contains numerous and sometimes contradictory findings concerning whether SSI effects are ultimately beneficial or detrimental to a structure (Mylonakis and Gazetas 2000; Bapir et al. 2023).

From a design perspective, it is critical to determine whether SSI has a favorable or unfavorable influence on structural response. The Turkish Building Earthquake Code (TBDY-2018) includes a dedicated section on the modeling of SSI effects in earthquake-resistant design. In that section, it is stated that if SSI effects reduce seismic demand-that is, if they prove beneficial-the designer must neglect them. In contrast, when performing detailed

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structural analyses, it is essential to model the system as closely as possible to its true physical conditions to improve accuracy. Therefore, incorporating SSI effects, regardless of whether they increase or decrease seismic demands, is of critical importance. Different levels of modeling fidelity are available for representing SSI, which can significantly improve analytical accuracy; however, these advanced modeling approaches fall outside the scope of the present study.

SSI is commonly divided into two distinct components: (i) kinematic interaction (KI) effects and (ii) inertial interaction effects. Kinematic interaction refers to the modification of free-field ground motion due solely to the presence of a rigid, massless foundation (Veletsos and Meek 1974). Free-field motion (FFM) is defined as the ground motion that would be recorded at the top of the soil deposit if the foundation were absent. The presence of a foundation may alter this motion through three primary mechanisms which together constitute the foundation input motion (FIM). First, base-slab averaging may occur due to the high stiffness contrast between the foundation and the supporting soil, effectively filtering out high-frequency components. Second, incident seismic waves may scatter when encountering the foundation's edges and corners (Brandenberg et al. 2015). Third, embedment causes the lower portions of the foundation to experience reduced excitation amplitudes, since ground motion intensity typically decreases with depth. As a result, a structure with an embedded foundation may be subjected to a lower level of seismic excitation relative to a structure with a surface foundation.

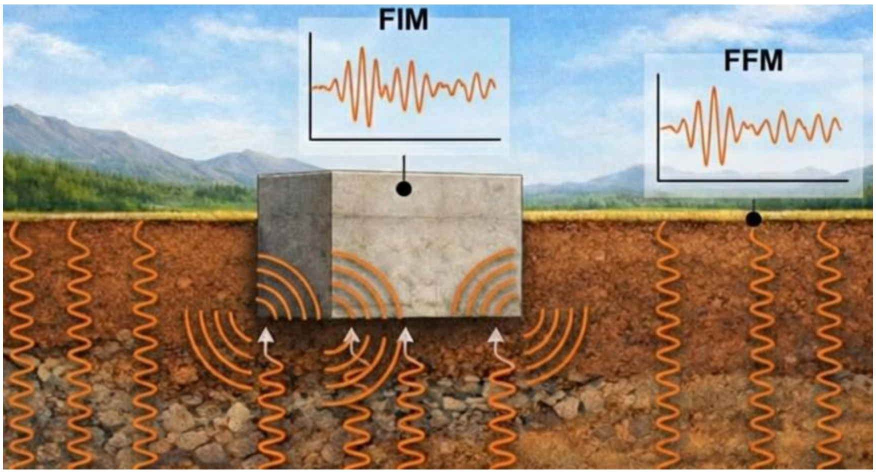

Fig. 1. Schematic representation of the investigated problem.

Inertial interaction effects, on the other hand, refer to the changes in the dynamic characteristics of a structure when it is coupled with a deformable soil. Two primary manifestations are observed: (i) elongation of the fundamental period due to soil compliance, and (ii) an increase in the overall damping ratio due to radiation damping. A structure can be represented by two key dynamic parameters: its fundamental period (or frequency) and damping ratio. When the supporting soil is deformable, the structural period elongates relative to its fixed-base period, producing what is commonly referred to as the effective fundamental period (Avilés and Pérez-Rocha 1998). Meanwhile, seismic waves traveling through the structure reflect from the upper stories and radiate away from the foundation. These waves interact with the soil, causing energy dissipation through both radiation damping and soil hysteresis (Wolf 1985). The combination of these mechanisms is termed foundation damping, which is additive to the inherent structural damping (Wolf and Deeks 2004). Although increased damping is always beneficial and reduces seismic demand, the effect of period elongation depends on the location of the fixed-base period relative to the response spectrum. When foundation damping is not dominant and the fixed-base period lies in the pre-plateau region, elongation may shift the period into the constant-acceleration region, thereby increasing seismic demand.

For structures supported by rigid foundations on homogeneous soil deposits, design and assessment should be based on the foundation input motion rather than the free-field motion observed on the ground surface in the absence of the foundation. Foundation input motion can be determined from the free-field motion when the geometric properties of the foundation and the mechanical properties of the soil are known. The relationship between foundation input motion and free-field motion is expressed by a frequency-domain transfer function, often referred to as kinematic interaction factors. When this transfer function is available, it can be applied to the Fourier amplitude spectrum of the free-field motion to obtain the foundation input motion in the frequency domain (Kim and Stewart 2003; Zogh et al. 2021). However, this requires access to ground-motion time histories, which are often unavailable in routine design practice. Designers typically rely on response/design spectra rather than full time series. Consequently, approximate methods have been proposed in the literature that use KI factors to directly modify design/response spectra. This approximation is exact only for structures with negligible damping ($\xi \approx 0\%$). For structures with higher damping, the approach systematically reduces spectral ordinates at the foundation level. The extent of this reduction depends on the geometric and mechanical properties of the soil-foundation system and may be significant.

Although several analytical expressions and guideline recommendations exist for estimating foundation input motions, their practical applicability in modern seismic design and evaluation remains uncertain, particularly in situations where only design spectra are available. Many of the classical formulations were originally developed for frequency-domain analyses involving full ground-motion time histories. In contemporary engineering practice, however, structural models commonly incorporate elevated effective damping ratios due to radiation damping and soil hysteresis. Applying traditional KI factors directly to design spectra may therefore introduce non-negligible biases, and these biases have not been comprehensively assessed using recorded ground motions.

Motivated by this gap, the present study focuses on quantifying the accuracy and limitations of commonly used KI procedures, specifically the analytical KI factors of Elsabee and Morray (1977) and the spectral-modification recommendations in FEMA-440 (2005). The analysis is restricted to translational KI effects for embedded rigid foundations in homogeneous, elastic soil. By comparing predicted spectral ratios against computed ratios calculated from a large set of recorded strong motion accelerograms, the study provides a direct and objective evaluation of how effectively these simplified methods capture realistic KI behavior across a range of soil stiffnesses and embedment depths.

The primary contribution of this work is to establish practical bounds on the reliability of simplified KI procedures and to identify conditions under which they tend to underestimate foundation-level demands. The findings offer clearer guidance to practicing engineers regarding when FEMA-440 or classical KI factors can be safely applied and when more detailed SSI analyses are warranted. By grounding the evaluation in observed ground motion data rather than purely idealized assumptions, the study strengthens the empirical foundation for incorporating KI effects into modern seismic design and assessment frameworks. It is also important to note that other aspects of kinematic SSI, such as base slab averaging and contributions from rotational degrees of freedom, are intentionally set aside for future research.

2. Kinematic Interaction Factors

For a foundation embedded within an elastic, homogeneous half-space, several researchers have derived analytical expressions that relate foundation input motion, namely, foundation translation and foundation rocking to free-field motion in the frequency domain. Among these formulations, one of the most widely known is that of Elsabee and Morray (1977), presented in Eq. (1) (Cavalieri et al. 2021; Conti et al. 2016). In their expression, the transfer function is defined as a piecewise function: it maintains a constant amplitude at frequencies higher than a certain threshold, while its amplitude gradually converges to 1.0 as the frequency of the input motion decreases. The corresponding expression that relates foundation rocking to free-field motion is not included here, as the present study focuses exclusively on translational foundation input motions.

$$I_u(\omega) = \frac{u_{FIM}}{u_{FF}} = \begin{cases} \cos\left(\frac{\omega D}{V_s}\right), & \omega \le 0.35\pi \frac{V_s}{D} \\ 0.453, & \omega > 0.35\pi \frac{V_s}{D} \end{cases} \tag{1}$$

In the above equation, u_{FF} and u_{FIM} denote the free-field ground motion and the translational foundation input motion in the frequency domain, respectively. $I_u(\omega)$ represents frequency-dependent KI factors which relate foundation input motion to free-field motion. The embedment depth of the foundation, measured from the ground surface to the foundation bottom, is represented by D. And the representative shear-wave velocity of the elastic half-space is denoted by V_s. The term ω corresponds to the radial frequency of the input motion, expressed in units of rad/s.

A very similar expression was also proposed by Mylonakis et al. (2006) to relate translational foundation input motions to free-field motions. In their work, the transfer function was presented as a piecewise formulation expressed in terms of cyclic frequency rather than radial frequency. For consistency and compatibility with the current study, the expression of Mylonakis et al. (2006) has been rewritten in terms of radial frequency and is provided in Eq. (2). All terms appearing in the equation below are identical to those defined previously.

$$I_u(\omega) = \frac{u_{FIM}}{u_{FF}} = \begin{cases} \cos\left(\frac{\omega D}{V_s}\right), & \omega \le \frac{\pi}{3}\frac{V_s}{D} \\ 0.5, & \omega > \frac{\pi}{3}\frac{V_s}{D} \end{cases} \tag{2}$$

Although the above relationship expresses the foundation input motion in terms of the free-field motion in the frequency domain, Mylonakis et al. (2006) stated that it could also be used to modify a design or response spectrum in an approximate manner. A similar approach is recommended in FEMA-440 (2005), where the design spectrum is modified to incorporate kinematic interaction effects resulting from foundation embedment. The corresponding expression is formulated as a function of the fundamental period of the structure and is given in Eq. (3). In this equation, RRS_e is the spectral factor used to modify the design spectrum to account for kinematic interaction effects associated with embedment. $S_{a,FIM}$ and $S_{a,FF}$ denote the acceleration design spectrum ordinates for the foundation input motion and the free-field motion, respectively. The fundamental period of the structure is represented by T, and nV_s corresponds to a representative shear-wave velocity reduced by a factor n to account for potential stiffness degradation due to the severity of the considered earthquake. The factor n may be taken as 1.0 to maintain compatibility with the previously defined expressions, in which the soil deposit is assumed to remain elastic. For practical values of D and V_s, the expression recommended in FEMA-440 (2005) is essentially identical to that of Elsabee and Morray (1977), except for the threshold frequency (or period) adopted in the formulation.

$$RRS_e(T) = \frac{S_{a,FIM}}{S_{a,FF}} = \cos\left(\frac{2\pi D}{TnV_s}\right) \ge \max\left(\cos\left(\frac{2\pi D}{0.2nV_s}\right), 0.453\right) \tag{3}$$

A small correction to the above expression should be introduced. For some short-period values T near the numerical value of D/V_s (or D/nV_s), the cosine term may become equal or very close to unity. In such cases, fluctuations appear in the spectral ratios for periods below the threshold period. To address this numerical issue, one should first determine the threshold period and the corresponding spectral ratio. Then, all periods smaller than the threshold period should be assigned the spectral ratio at the threshold period. This correction is applied consistently throughout the calculations performed in this study.

As explained above, the approach suggested by several researchers relies on using frequency-domain transfer-function amplitudes as multiplicative factors applied to the design or response spectra of the free-field motion to obtain the design or response spectra of the foundation input motion. However, this approximation is strictly valid only for very small damping ratios. It is also important to emphasize that the design or response spectra of the foundation input motion are intended for use in subsequent structural analyses that incorporate inertial interaction. In that stage of the analysis, the effective damping ratios are generally relatively high due to the contributions of radiation damping and soil hysteretic damping. Consequently, the approximation described above is not practically feasible.

One possible remedy for the aforementioned issue would be to convert the frequency-domain transfer functions into equivalent factors that can be applied directly to the ordinates of a design spectrum. However, this conversion is not straightforward, as it is highly dependent on the frequency content of the expected earthquake ground motion. The Random Vibration Theory may serve as a useful tool for this conversion (Rathje et al. 2005; Rathje and Ozbey 2006), but it is beyond the scope of this paper. Moreover, because the design spectrum serves only as an envelope of anticipated seismic demands, it is not sufficient by itself to infer the Fourier amplitude spectrum of the design earthquake. In this study, a suite of recorded ground motions is employed to compute mean spectral ratios between foundation input motions and free-field motions. It is, of course, almost impossible for an expected future earthquake to exhibit frequency content identical to that of any previously recorded motion. Nevertheless, using a set of records and averaging over them yields a reasonable and representative estimate.

3. Numerical Analyses and Results

In this section, a comparison of the spectral ratios commonly employed in practice is presented. There are two primary approaches for estimating these ratios: (i) using frequency-domain KI factors directly as spectral ratios, and (ii) using the spectral ratio expression recommended by FEMA-440 (2005). To enable a meaningful comparison of these approaches, a large number of recorded ground motion histories are utilized. First, acceleration response spectrum ordinates of the selected recordings are computed, representing the spectral ordinates of the free-field ground motion. Second, each recording is modified in the frequency domain using the KI factors proposed by Elsabee and Morray (1977) to obtain the corresponding foundation input motions. Acceleration response spectrum ordinates of these foundation input motions are then calculated. Finally, the ratio between the foundation input motion spectra and the free-field motion spectra is determined (Lin and Miranda 2008). The performance of the expressions used in practice are then evaluated against the calculated spectral ratios.

The ground motion dataset used in this study was assembled from the PEER NGA-West2 (Ancheta et al. 2014) database, selecting recordings representative of strong crustal earthquakes. To ensure that the motions reflect near-field conditions without introducing complications associated with extremely small source-to-site distances, only records with Joyner-Boore distances between 10 km and 20 km were included. This selection captures motions with sufficiently rich frequency content across the engineering-relevant range while avoiding strong directivity pulses that would otherwise skew the analysis. The resulting dataset provides a balanced representation of strong-shaking environments in which kinematic interaction effects are expected to be significant. In the PEER NGA-West2 database (Ancheta et al. 2014), each ground motion record is assigned a unique Resource Sequence Number (RSN); the RSNs corresponding to the ground motions employed in this study are provided in Table 1.

Table 1. RSNs for the employed ground motion recordings.

Resource Sequence Number (RSN)							
RSN174	RSN175	RSN192	RSN718	RSN721	RSN728	RSN4284	RSN2703
RSN3934	RSN5992	RSN6888	RSN6889	RSN31	RSN162	RSN2739	RSN4129
RSN167	RSN172	RSN266	RSN456	RSN458	RSN719	RSN3907	RSN1633
RSN1101	RSN1104	RSN1116	RSN1158	RSN4072	RSN4125	RSN3964	RSN1787
RSN5823	RSN5827	RSN5829	RSN5831	RSN5837	RSN5975	RSN4124	
RSN5991	RSN6886	RSN6890	RSN6952	RSN6961	RSN187	RSN33	
RSN457	RSN460	RSN549	RSN725	RSN848	RSN864	RSN550	
RSN881	RSN3933	RSN4085	RSN4106	RSN4137	RSN6874	RSN553	
RSN6893	RSN28	RSN164	RSN265	RSN1614	RSN2699	RSN554	

The stations associated with these recordings span a wide range of $V_{S,30}$ values, from approximately 138 m/s to 730 m/s, covering site classes ranging from soft soil to stiff soil. Because the objective of this study is also to examine how soil stiffness influences kinematic interaction effects, this natural variability in $V_{S,30}$ is essential. Prior to binning the records by site stiffness, the $V_{S,30}$ values were adjusted using the shear-modulus-reduction recommendations of FEMA-440 to approximate the effective small-strain shear wave velocity corresponding to the severity of each ground motion. This adjustment ensures better compatibility between the soil conditions implicitly represented in the recordings and the elastic half-space assumptions underpinning the KI formulations examined in this study.

No amplitude scaling was applied to the ground motions. Because the analysis focuses on spectral ratios, i.e. the ratio between the spectra of foundation input motions and free-field motions, amplitude scaling is unnecessary. These spectral ratios are dimensionless and primarily reflect differences in frequency content and wave propagation mechanisms, rather than absolute shaking intensity. Furthermore, all response spectra were computed assuming 5% damping in a linear-elastic framework. Using unscaled, recorded motions therefore preserves realistic variability in frequency content and ensures that the evaluation of KI procedures remains grounded in actual strong motion characteristics rather than artificially modified ones.

For the spectral ratio comparison, a total of 133 ground motion recordings are utilized. The recordings are classified into four bins, with representative shear wave velocities falling within the ranges 100-200 m/s, 200-300 m/s, 300-400 m/s, and 400-500 m/s. Records from sites with shear wave velocities greater than 500 m/s are excluded, as KI effects are not expected to be significant for such stiff soil conditions. The distributions of representative shear-wave velocities before and after applying the FEMA-440 modification are plotted in Fig. 2. As illustrated in the figure, all sites have reduced shear wave velocities between 100 m/s and 500 m/s, whereas the original $V_{S,30}$ values span a broader range, from approximately 100 m/s to 800 m/s.

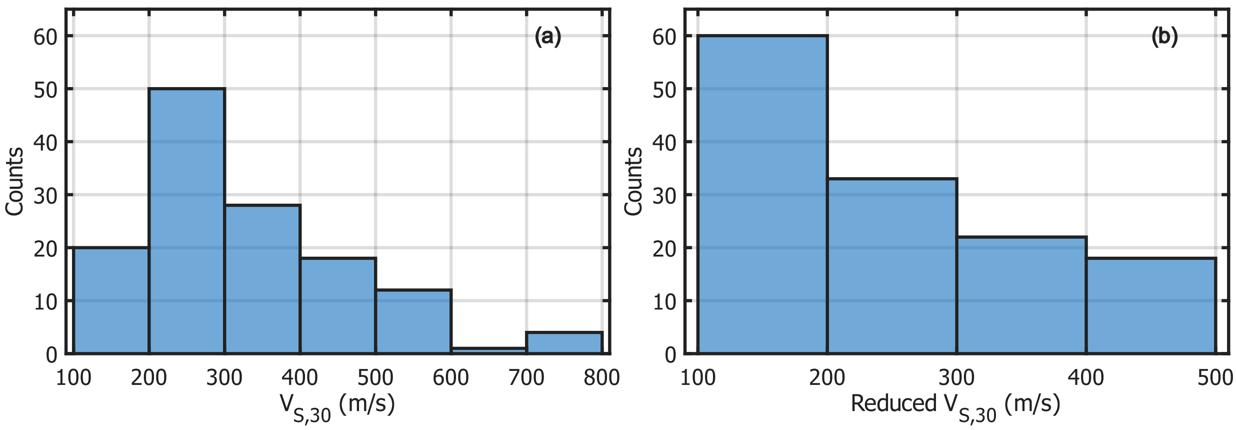

Fig. 2. Distribution of original and reduced shear wave velocities.

Spectral ratios for the first and last reduced shear wave velocity bins (i.e., $100\,\mathrm{m/s} \le V_s < 200\,\mathrm{m/s}$ and $400\,\mathrm{m/s} \le V_s < 500\,\mathrm{m/s}$) are calculated and plotted in Fig. 3. In this figure, two embedment depth cases are considered, 10 m for the first bin and 2.5 m for the last bin to obtain representative extreme values of D/V_s. Because each bin contains multiple recordings from different sites, the mean shear wave velocity within each bin is used in the calculation of the corresponding D/V_s values. As observed in the figure, when D/V_s is small, the resulting spectral ratios are large, indicating that KI effects are minor. Conversely, when D/V_s is large, the spectral ratios decrease substantially, demonstrating that KI effects become increasingly significant.

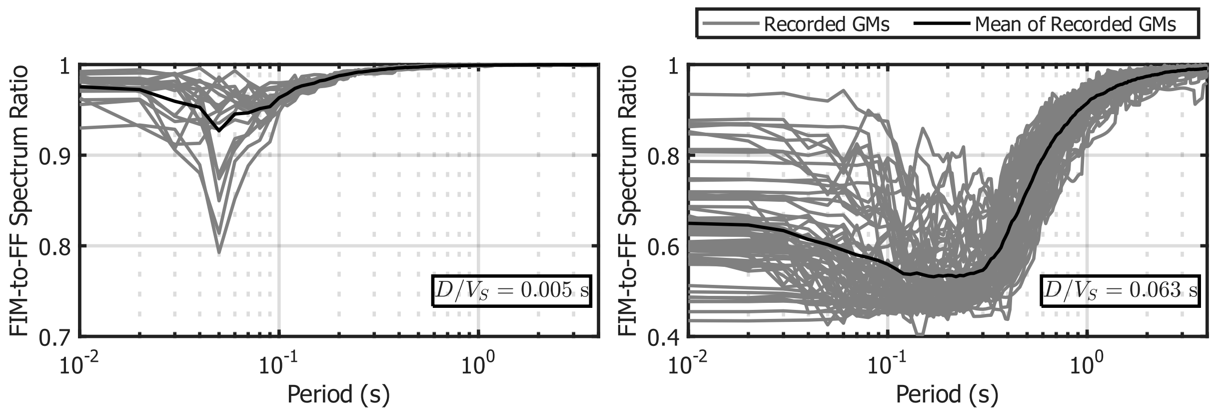

Fig. 3. Sample spectral ratios for the extreme cases.

Similar mean spectral ratios are also derived for the remaining shear wave velocity bins and embedment depths of 2.5 m, 5 m, 7.5 m, and 10 m. In total, 16 cases are evaluated, representing various combinations of embedment depth and shear wave velocity. For all of these cases, the spectral ratios recommended by FEMA-440 (2005) and the KI factors proposed by Elsabee and Morray (1977) are determined using the average shear wave velocity within each corresponding bin. The mean spectral ratios obtained from the recorded motions are then compared with the spectral ratios predicted by FEMA-440 (2005) and the KI factors of Elsabee and Morray (1977), as illustrated in Fig. 4. Each panel in the figure corresponds to a different value of D/V_S, which is also indicated on the plots.

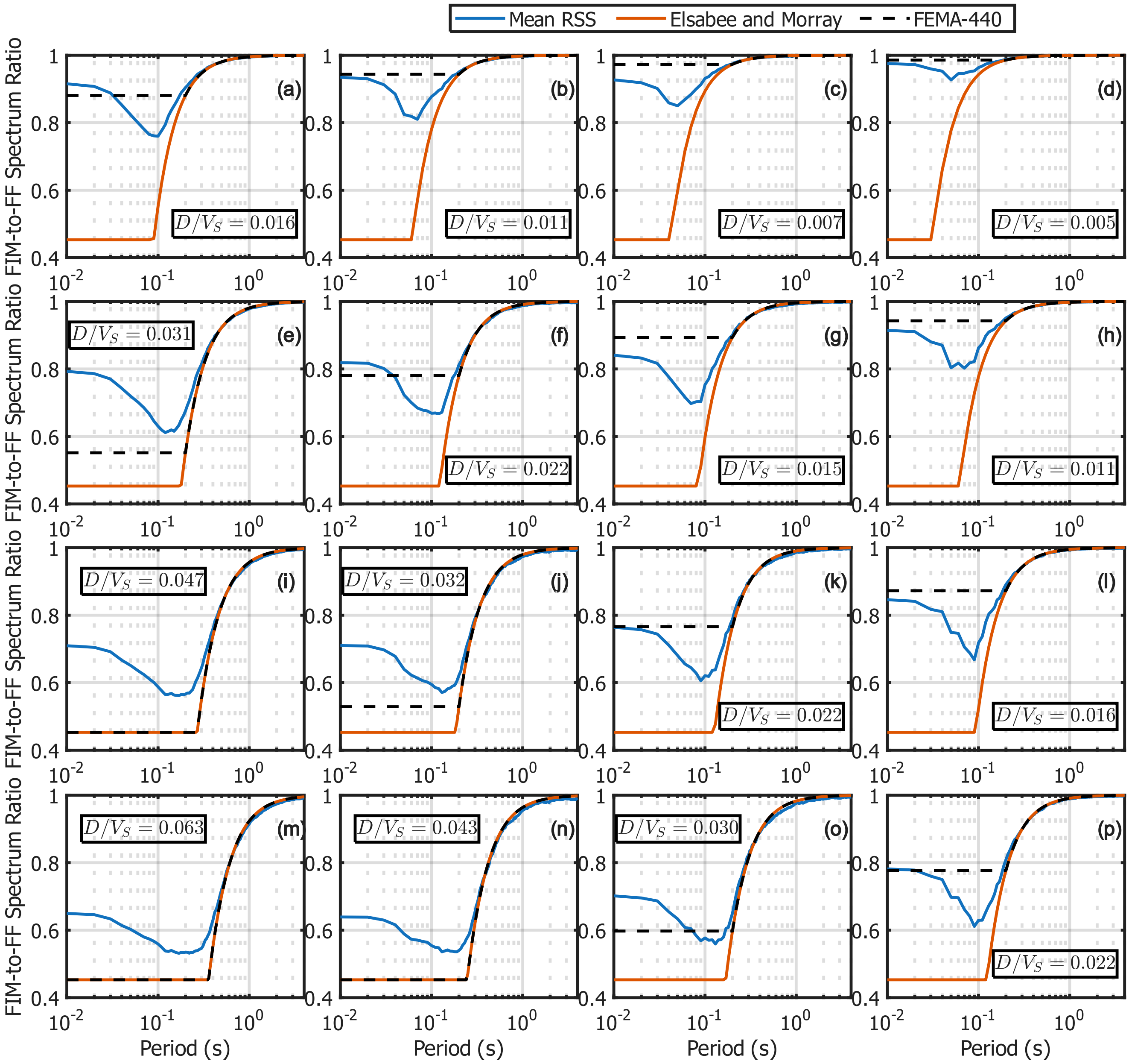

Fig. 4. Spectral ratios derived by using real recordings and obtained by using expressions used in current practice.

As seen in the figure, for larger values of D/V_s, i.e., above approximately 0.043 s, the spectral ratios recommended by FEMA-440 (2005) become identical to the KI factors proposed by Elsabee and Morray (1977). As stated earlier, the principal difference between these two formulations lies in the threshold period assigned to the constant spectral ratio region. For large D/V_s values, the threshold period exceeds 0.2 s, which is the fixed threshold used in FEMA-440 (2005). Consequently, both approaches yield the same spectral ratios in this range.

In fact, the threshold period in the FEMA-440 (2005) expression is not strictly constant but varies in an indirect manner. In the recommended formulation, if the computed spectral ratio is smaller than the spectral ratio obtained using a 0.2 s period, then the larger value must be adopted. This conditional adjustment is the reason why, for sufficiently large D/V_s, the effective threshold period in FEMA-440 (2005) coincides with that of Elsabee and Morray (1977).

One important characteristic of the computed spectral ratios is the consistent presence of a dip at short periods. The computed ratios generally align with those estimated by FEMA-440 (2005) and Elsabee and Morray (1977) at longer periods. However, at short periods, the frequency content of the recorded motions causes a noticeable dip. If the energy distribution across the harmonics of the ground motions were uniform, no such dip would occur; instead, the spectral ratios would converge toward the constant KI factor of Elsabee and Morray (1977), i.e., 0.453. The value approached by the computed ratios as the period tends toward zero is governed by both the response transfer function and the KI factors.

As shown in the figure, at shorter periods, the KI factors proposed by Elsabee and Morray (1977) consistently underestimate the computed spectral ratios, regardless of the D/V_s value. In contrast, the spectral ratios recommended in FEMA-440 (2005) appear to be reasonably suitable for practical engineering use across a wide range of periods and D/V_s levels. Nonetheless, for larger D/V_s values, even the FEMA-440 estimates fall below the actual spectral ratios. This suggests that when D/V_s exceeds approximately 0.03 s, more advanced SSI modelling is required to properly account for the kinematic interaction effects associated with foundation embedment.

Although this study focuses on spectral ratios rather than absolute demands, it is useful to illustrate how underestimating KI effects may influence engineering decisions. Consider a mid-rise building with a fixed-base fundamental period of 0.15 s, supported on a foundation embedded 7.5 m into soft soil with an effective shear wave velocity of 150 m/s, giving $D/V_s \approx 0.05$ s. At this embedment level, the classical KI factors of Elsabee and Morray (1977) predict a short-period spectral ratio of approximately 0.453, whereas the computed ratios derived in this study are closer to 0.55. Consequently, using the analytical KI factors would underestimate foundation-level spectral acceleration by roughly 20% at this period. While simplified KI procedures remain useful for shallow foundations or stiffer soils, this example highlights the potential for significant bias when relying solely on classical KI factors, emphasizing the importance of more refined SSI modelling in such cases.

4. Conclusions

This study evaluates widely used procedures for incorporating embedment-related kinematic interaction (KI) effects into design and response spectra and compares them against computed spectral ratios derived from 133 recorded ground motions. The main findings are:

- Analytical KI factors (Elsabee and Morray 1977) consistently underestimate short-period spectral ordinates, regardless of soil stiffness or embedment depth, because frequency-domain KI factors do not directly translate into response-spectral reductions for realistic damping levels.
- FEMA-440 (2005) provides reasonably accurate estimates across a broad range of periods and soil conditions, particularly for small to moderate values of D/V_s. However, it tends to underpredict spectral ratios for large embedment depths or very soft soils, where KI effects are more pronounced.
- Computed spectral ratios consistently show a distinct dip at short periods, driven by the nonuniform frequency content of actual ground motions. This behavior is not captured by simplified analytical KI expressions.
- For $D/V_s \gtrsim$ 0.03–0.04s, both analytical KI factors and FEMA-440 spectral modifications become increasingly unreliable, indicating that simplified spectral modification approaches may lead to unconservative estimates of foundation-level demands.

Based on these observations, simplified KI procedures can be used for practical design when embedment is shallow, and soil stiffness is moderate to high. For deeper foundations, soft soils, or cases requiring accurate short period demands, more detailed SSI modeling is recommended. Future studies should extend the evaluation to include rotational components, base-slab averaging, and layered soils to improve the reliability of KI predictions.

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Conflict of Interest

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

During the preparation of this manuscript, the author used Google Gemini to generate the conceptual schematic presented in Fig. 1.

Author Contributions

The author declares sole responsibility for all aspects of the study, including conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing of the original draft, and writing, review, and editing of the manuscript.

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