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Seismic energy propagation and dissipation in earthquake soil structure interaction systems

Han Yang, Hexiang Wang, Boris Jeremić
Department of Civil and Environmental Engineering, University of California, Davis, CA, USA

Abstract

Seismic energy propagation and dissipation within a soil-structure interacting (SSI) system controls response of infrastructure objects (buildings, bridges, dams, tunnels, etc.) to seismic/earthquake response. Seismic energy is radiated from the earthquake hypocenter zone, passes through deep and shallow geology, and excites embedded and surface infrastructure objects (IOs). Energy of incoming earthquake waves, in the vicinity of IOs, is then dissipated through a number of physical and numerical mechanisms.

Key words: kjdkkvkxvklxvkxkvlbxlkbv

1 Introduction

Seismic energy propagation and dissipation within a soil-structure interacting (SSI) system controls response of infrastructure objects (buildings, bridges, dams, tunnels, etc.) to seismic/earthquake response. Seismic energy is radiated from the earthquake hypocenter zone, passes through deep and shallow geology, and excites embedded and surface infrastructure objects (IOs). Energy of incoming earthquake waves, in the vicinity of IOs, is then dissipated through a number of physical and numerical mechanisms [Yang et al., 2019c]:

- Seismic wave reflections, incoming waves reflect from the free surface and from structural foundations, back into the shallow and deep soil and rock domain,
- Structural oscillations, radiation damping, send waves from dynamically excited, oscillating structure, back into the shallow and deep soil and rock domain,
- Viscous coupling of porous material with internal pore fluids is particularly important for saturate soil,
- Viscous coupling of external fluids in reservoirs and pools,
- Inelastic behavior of rock, soil, concrete, steel, interfaces/joints and energy dissipator devices is the main source of energy dissipation for earthquakes of any significance, with occurrence of even small amount of damage in structures,
- Numerical, algorithmic energy dissipation and production, is usually neglected, although this, artificial, numerical damping mechanism can dissipate and/or produce energy in an SSI system [Argyris and Mlejnek, 1991, Krenk, 2014].

Of particular interest is accurate modeling and simulation of the most significant energy dissipation mechanisms for larger earthquakes, the plastic dissipation, within engineering solids and structures. Plastic dissipation is responsible for damage in solids and structures and, as such, it is important to be modeled properly inn order to improve safety and economy of infrastructure objects.

2 Seismic Energy Computation Framework

Significant amount of potential energy is released at the earthquake source, fault, when the earthquake initiates [Aki and Richards, 2002], and is radiated in all directions. Small amount of seismic energy from fault rupture that is radiated toward surface finds its way to the location of SSI system of interest. As noted above, of particular interest is modeling of the plastic dissipation within engineering solids and structures. Detailed discussion of energy propagation and dissipation for SSI system is presented in previous studies [Yang et al., 2018, 2019c,a,b]. It is important to note the difference between plastic work and plastic dissipation, that was experimentally discovered and then theoretically explained by Farren and Taylor [1925] and Taylor and Quinney [1934].

3 Numerical Example

Energy calculation methodology has been implemented in the Real-ESSI Simulator [Jeremić et al., 1988-2021], a software, hardware and documentation system for high fidelity, high performance, time domain, linear or nonlinear/inelastic, deterministic or probabilistic, FE modeling and simulation (http://real-essi.us). An SSI model, composed of a moment frame structure, foundation and the underlying soils, is used to illustrate energy calculation methodology. A variation in foundation design is used to illustrate how presented methodology can by used in design and retrofit assessment. An overview of the SSI model is shown in Figure 1.

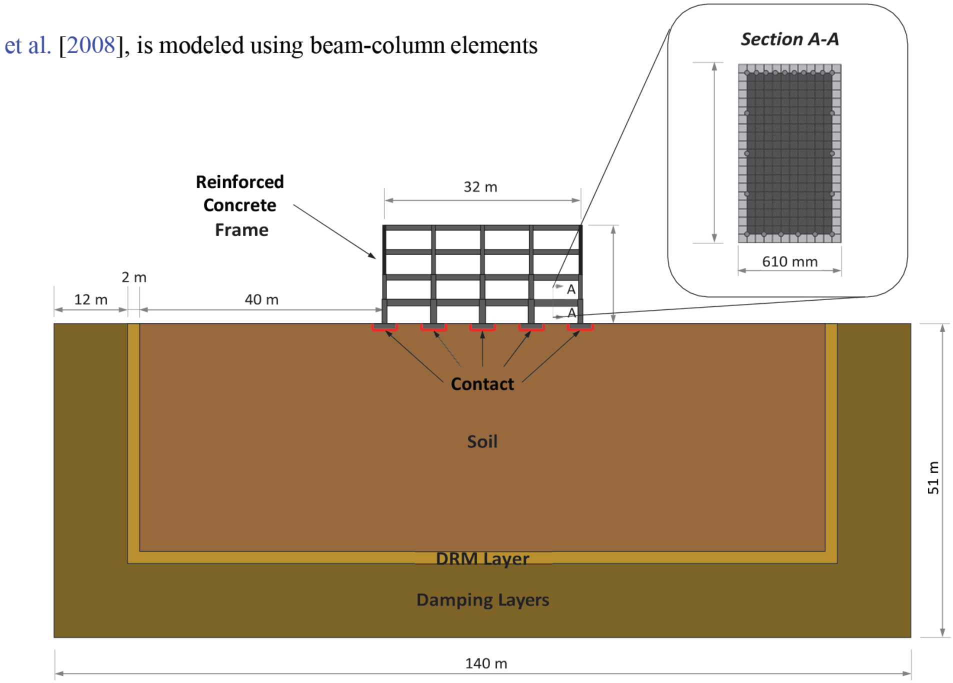


Figure 1. Numerical model of the reinforced concrete frame, inelastic soil, and foundation-soil interfaces

The main components of the model are:

1. A nonlinear/inelastic reinforced concrete frame, that is based on a code-conforming designs by Haselton et al. [2008], is modeled using beam-column elements
2. The underlying soil that is modeled using standard 27-node-brick elements and Drucker-Prager inelastic material model with Armstrong-Frederick kinematic hardening [Jeremić et al., 1989-2021],
3. The interfaces between soil and foundation is modeled using the nonlinear, stress-based, frictional, gap open-close interface elements.

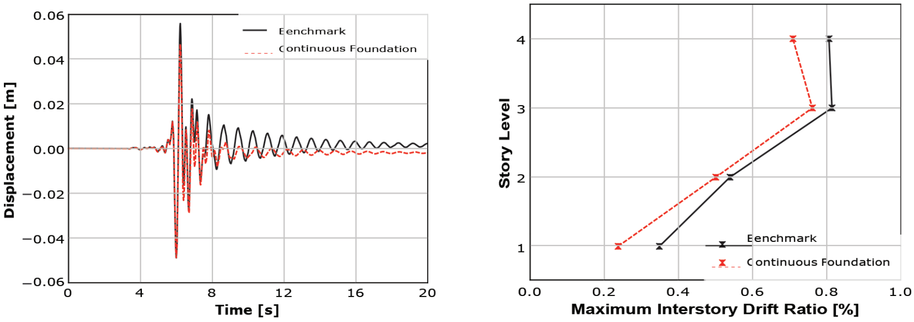
4. A layer of Domain Reduction Method (DRM) elements, for applying earthquake loading [Bielak et al., 2003], is modeled using 27-node-brick elements and linear elastic material.
5. A few damping layers outside of the DRM layer, to absorb the very small outgoing waves, representing radi- ation damping from oscillations of the structure, are used, with progressively increasing Rayleigh damping.

Details of the developed model and illustrative results are presented by Yang et al. [2020] and will not be repeated here. Select results will be used to illustrate design alternative.

3.1 Influence of Foundation Type

It is common to have multiple preliminary designs for an engineering project, and then choose the best one by comparing their performances. One possible design change for SSI system is the change in the type of foundation. In this section, the influence of foundation type on SSI performance is analyzed. As seen in Figure 1, the benchmark case has separate, spread foundation underneath each column. For comparison, a case with continuous, slab foundation is analyzed as well.

Figures 2 shows the displacement responses and maximum IDR results of the frame with different foundation designs. Figure 3 shows the distribution of plastic energy dissipation for the two cases with different foundation types. Visible differences in plastic dissipation density can be observed in the frame, soil, and interface elements. For continuous, slab foundation, more energy is dissipated in the soil and soil-foundation interface before reaching the structure. This means that less energy dissipation, or material damage, is accumulated within the frame elements. Please note that the same scale is used for energy dissipation density color in both figures, in order to visually compare dissipation. For example, for a spread foundation case, Figure 3a, more dissipation is observed in columns on third and fourth floor, in comparison with slab, continuous foundation case, as seen in Figure 3b.



a) Top Response **b)** Interstory Drift

Figure 2. Horizontal displacement and interstory drift responses for benchmark (spread) and continuous/ slab foundation

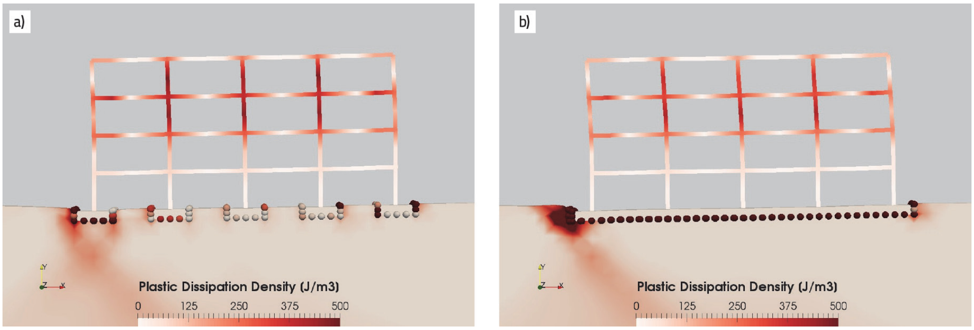


Figure 3. Distribution of plastic energy dissipation for different foundation types: a) Separate foundations (Benchmark), b) Continuous foundation

By comparing traditional design parameters, such as peak displacement or maximum IDR, with energy analysis results, it is clear that the former tends to underestimate the variation in system performance when evaluating design changes. This is especially true if seismic performance is the main concern. The source of such underestimation can be largely attributed to the fact that traditional, displacement-based design concepts focus on peak response, while EBD follows accumulated material damage and system performance as a time history throughout the entire loading event.

4 Conclusions

Modeling and simulation of a seismic energy propagation within earthquake-soil-structure interacting (ESSI) system is used as a method to improve safety and economy of infrastructure objects. Brief overview of methodology was presented, with a number of references for further investigation of the methods used. Simple frame ESSI example was used to illustrate seismic energy calculations. It was shown that energy dissipation calculations can be used to explore design alternatives. Presented design and assessment methodology is promoted over traditional analysis methods that cannot account for the continuous accumulation of material damage.

It is noted that full, detailed ESSI modeling and simulation that properly models all the components, including earthquake, soil, structure, and soil-foundation interface elements is available and can/should be used to improve safety and economy of infrastructure objects. The presented analysis approach is developed, implemented and available within the Real-ESSI Simulator [Jeremić et al., 1988-2021]. Moreover, examples used in this work are available at the Real-ESSI Simulator web site http://real-essi.us.

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