High fidelity modeling and simulation of SFS interaction: energy dissipation by design

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It is hypothesized that interplay of earthquake, soil, foundation and structure (SFS) dynamic characteristic, and their interaction in time domain, control the behavior of SFS system during earthquakes. Moreover, (passive and active) control of spatial and temporal location of seismic energy dissipation (preferably in soil) can improve safety and economy of SFS systems. Such energy dissipation by design requires high fidelity modeling and simulations. This paper briefly describes modeling and simulation aspects of energy flow in SFS system. In addition to that, examples of directed energy dissipation are presented that show how soil can be used for the benefit of overall SFS system response to seismic excitation.

1 INTRODUCTION

Seismic behavior of soil-foundation-structure (SFS) systems has recently gained increased attentions. Improvements in modeling and simulation technology currently allow modeling and simulations of a complete SFS interaction with high fidelity. These models and simulations allow us, in turn, to gain better understanding of seismic response of the SFS system. Moreover, such high fidelity models and simulations allow us to design the SFS system(s). Of particular interest is the notion that a designer can/should be able to direct/design the location, in time and space, where dissipation of seismic energy takes place. This notion is based on understanding that incoming seismic energy affects both soils and structures. While focus is usually on structural performance, interaction of soil with foundation/structure plays a very important (crucial) role in seismic response. The idea is that while energy dissipation in structure (and its components) leads to damage, and potentially failure, soil medium offers significant energy dissipation capacity and benefits.

In this paper we briefly discuss seismic energy dissipation mechanisms in soils and their potential use in improving seismic soil-foundation-structure system performance.

While SFS interaction has been modeled and simulated for a number of years. We mention a number of references related to SFS interaction importance and modeling, starting with the very first mention of SFS interaction beneficial and detrimental effects by Late Prof. Suyehiro (Suyehiro 1932). A number of researchers have developed and analyzed SFS systems in last 3 decades, and we mention some of them: (Chi Chen and Penzien 1977), (Makris et al. 1994), (McCallen and Romstadt 1994), (Gazetas and Mylonakis 1998), (Mylonakis and Nikolaou 1997), (Fenves and Ellery 1998), (Elgamal et al. 2008), (Jeremić et al. 2004), (Jeremić and Jie 2007), (Jeremić and Jie 2008),

In this paper we briefly describe energy dissipation mechanisms for SFS system. In addition to that, it is claimed that only high fidelity models can be used for such model based simulation (design) of energy dissipation.

Our main hypothesis is that the interplay of earthquake (nonlinear seismic wave propagating from source to the structure of interest) with soil and the structure plays major role in potentially catastrophic failures, but also in success. Timing and spatial location of energy dissipation within the SFS system, determines amount of damages and in general controls survivability of structure during earthquake. If timing and spatial location of energy dissipation can be controlled, one could optimize the SFS system for safety and economy. This is particularly true if energy dissipation can be directed to soil instead of foundation and structure.

Directing (by design) energy dissipation for SFS systems requires development and simulations on high fidelity numerical models. There are a number of cases where interaction of SFS and dissipation of seismic energy in soil can be deduced by observing structural damage. The very notion that soil SFS has significant role in dynamic response of structures comes from Professor Kyoji Suyehiro, (a Naval Engineer turned Earthquake Engineer, following his personal experience of Great Kantō earthquake (11:58am(7.5), 12:01pm(7.3), 12.03pm(7.2) (shaking until 12:08pm), 1st. Sept. 1923, in Tokyo) who reported $4\times$ (four) more damage to soft wooden buildings on soft ground than same building on stiff ground (Suyehiro 1932). This was probably due to the close to resonance of building (soft) with foundation soil (soft) with a long lasting (soft, long period) earthquake. Many years later, (Trifunac and Todorovska 1998), show how during Northridge earthquake, areas with damage to buildings (signifying structural damage) was quite nicely separated from areas of water pipe breaks (signifying much plasticity and energy dissipation in soil). In this case, much energy is dissipated in the (soft) soil, never making it to the building, while for stiff soil do not have such energy dissipation capacity, transmitting such energy to the building for dissipation (damage).

There are many other cases where such phenomena is observed. Our primary goal here is to emphasize how high fidelity modeling and simulations of SFS systems can help understand mechanics of such interactions. In addition to that, we use high fidelity models to present examples of interplay of earthquake, soil and structure dynamic characteristics, together with the location and timing of energy dissipation.

2 SEISMIC ENERGY INPUT AND DISSIPATION

2.1 *Seismic energy input into SFS system*

Earthquakes release large amounts energy at the source[1] Part of released energy is radiated as mechanical waves ($\approx 1.6\times 10^{-5}$) and part of that energy makes it to the surface where SFS system is located.

Mechanical seismic wave energy enters the SFS system through a closed surface Γ that encompasses (significant) soil volume as well as foundation system and the structure (Fig. 1). Kinetic energy flux through

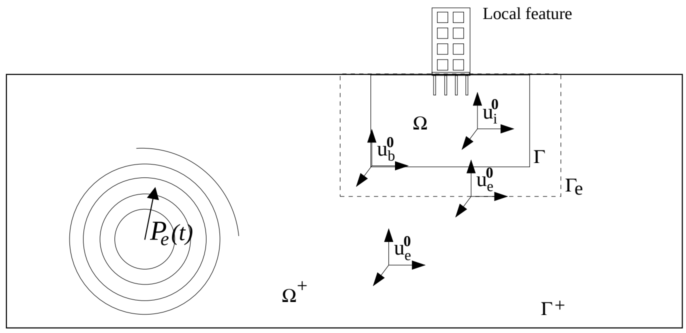

Figure 1: Geometry of the SFS system.

closed surface Γ includes both incoming and outgoing waves and can be calculated using Domain Reduction Method (Bielak et al. 2003) as:

$$E_{flux} =$$

$$\left[0; -M_{be}^{\Omega+}\ddot{u}_e^0 - K_{be}^{\Omega+}u_e^0; M_{eb}^{\Omega+}\ddot{u}_b^0 + K_{eb}^{\Omega+}u_b^0\right]_i \times u_i$$

where $M_{be}^{\Omega+}$, $M_{eb}^{\Omega+}$, $K_{be}^{\Omega+}$, $K_{eb}^{\Omega+}$ are mass and stiffness matrices, respectively for a single layer of elements just outside of the boundary Γ, while $\ddot{u}_e^0$ and u_e^0 are accelerations and displacements from a free field model for nodes belonging to that layer of elements. Alternatively, energy flux can be calculated using (Aki and Richards 2002):

$$E_{flux} = \rho A c \int_0^t \dot{u}_i^2 dt$$

[1] for example, some of the recent large earthquake energy releases are listed: Northridge, 1994, $M_{Richter} = 6.7$, $E_r = 6.8\times 10^{16} J$; Loma Prieta, 1989, $M_{Richter} = 6.9$, $E_r = 1.1\times 10^{17} J$; Sumatra-Andaman, 2004, $M_{Richter} = 9.3$, $E_r = 4.8\times 10^{20} J$; Valdivia, Chile, 1960, $M_{Richter} = 9.5$, $E_r = 7.5\times 10^{20} J$;

Outgoing kinetic energy can be obtained from outgoing wave field w_i, (from DRM, (Bielak et al. 2003)), while the difference then represents the incoming kinetic energy that needs to be dissipated with SFS region.

2.2 *Seismic energy dissipation in SFS system*

Seismic energy that enters the SFS system will be dissipated in a number of ways. part of the energy that enters SFS system can be reflected back into domain outside Γ by

- wave reflection from impedance boundaries (free surface, soil/rock layers...).
- SFS system oscillation radiation.

While the rest of seismic energy is dissipated through one of the following mechanisms within SFS domain:

- Elasto-plasticity of soil
- Viscous coupling of porous solid with pore fluid (air, water)
- Elasto-plasticity/damage of the foundation system
- Elasto-plasticity/damage of the structure
- viscous coupling of structure with surrounding fluids (air, water)

It is also important to note that in numerical simulations (advocated and used in this work), part of the energy can be dissipated or produced by purely numerical means. That is, numerical energy dissipation (damping) or production (negative damping) has to be carefully controlled (Argyris and Mlejnek 1991), (Hughes 1987).

Energy Dissipation by Plasticity. Elastic-plastic deformation of soil, foundation and structure is probably responsible for major part of the energy dissipation for large earthquakes. This, displacement proportional dissipation is a result of dissipation of plastic work ($W = \int \sigma_{ij} d\epsilon_{ij}^{pl}$) and is present in all three components of the system (soil, foundation and the structure). Ideally, majority of the incoming energy would be dissipated in soil, before reaching foundation and structures. The possibility to direct energy dissipation to soil can be used in design by recognizing energy dissipation capacity for different soils. For example, simple elastic-plastic models of stiff and soft clay as well as dense and loose send predict different energy dissipation capacities, as shown in Figure 2, for single loading-unloading-reloading cycle. While Figure 2 shows that stiff clay and dense sand

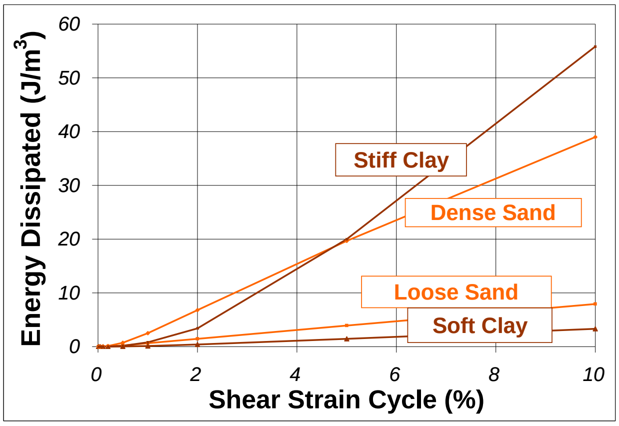

Figure 2: Energy dissipation capacity for one cycle at various strains for four generic soils.

have much higher dissipation capacity, it is important to note that soft/loose soils can undergo much larger deformation/strain, thus offering increased energy dissipation capacity through flexibility.

Energy Dissipation by Viscous Coupling. Viscous coupling of pore fluid (air, water...) and soil particles and/or foundation or structural components is responsible for velocity proportional energy dissipation. In particular, viscous coupling of porous solid and fluid results in $E_{vc} = n^2 k^{-1} (\dot{U}_i - \dot{u}_i)^2$ energy loss per unit volume. It is noted that this type of dissipation is realistically modeled using $u - p - U$ formulation (Jeremić et al. 2008).

Numerical Energy Dissipation and Production. As noted above, numerical integration of nonlinear equations of motions affects calculated energy in various ways. Most common effect for nonlinear (elastic-plastic) systems is the positive (energy dissipation) and negative (energy production) damping. For example Newmark (N) (Newmark 1959) and Hilber–Hughes–Taylor (HHT) (Hilber et al. 1977) are energy preserving for linear elastic system with proper choice of constants ($\alpha = 0.0; \beta = 0.25, \gamma = 0.5$). Both methods can also be used to dissipate higher frequency modes for linear elastic models by changing constants so that for N: $\gamma \geq 0.5, \quad \beta = 0.25(\gamma + 0.5)^2$, while for HHT: $-0.3\dot{3} \leq \alpha \leq 0, \quad \gamma = 0.5(1 - 2\alpha), \quad \beta = 0.25(1 - \alpha)^2$. However, for nonlinear problems it is impossible to maintain energy of the system throughout computations (Argyris and Mlejnek 1991).

2.3 UNCERTAINTY ASPECTS

Uncertainty of soil material parameters and forcing represents a significant source of uncertainty of a final computed (simulated) response of SFS system. Recent development of Probabilistic Elasto-Plasticity (PEP) and Spectral Stochastic Elastic-Plastic Finite Element Method (SSEPFEM) ((Jeremić et al. 2007), (Sett et al. 2007a), (Sett et al. 2007b), (Jeremić and Sett 2009), (Sett and Jeremić 2009b), (Sett and Jeremić 2009a)) allows accurate analysis of influence of uncertain soil properties and forcing on seismic response. Calculation of seismic energy (propagation and dissipation) is affected by such, ever present uncertainties and such uncertainties should be taken into account as best as possible, Above cite (already) published papers and a number of near future papers (under review) present development of methodology for forward and backward propagation of uncertainties in dynamic (and static) simulation of elastic-plastic solids made of (geo-)materials. Such newly developed, highly accurate, numerical methdology for treatment of material (left hand side) and forcing (right hand side) uncertainty allows for full quantification of stochastic (probabilistic) aspects of SFS interaction.

3 SELECT EXAMPLES OF ENERGY DISSIPATION

This section briefly describes two examples of SFS system modeling, simulation and energy dissipation.

Use of Soft Soil. Simulations on high fidelity model for bridge SFS system (Jeremić et al. 2009) were used to investigate energy flow and dissipation. Proper modeling of nonlinear wave propagation required large number of elements and DOFs (1.6×10^6 for largest model). Such large models required development of efficient parallel finite element methodology (Plastic Domain Decomposition, PDD) that could handle elastic-plastic computations on multiple generation distributed memory parallel computers including DataStar at SDSC, Longhorn at TACC and our own GeoWulf at UCD (Jeremić and Jie 2007), (Jeremić and Jie 2008). Great care was taken to develop high fidelity model for both soil, foundation and the structure. Seismic waves were input into the model using DRM (Bielak et al. 2003), and no numerical damping was used, leaving energy dissipation to elasto-plasticity and radiation damping. Figure 3 shows a detailed FEM model.

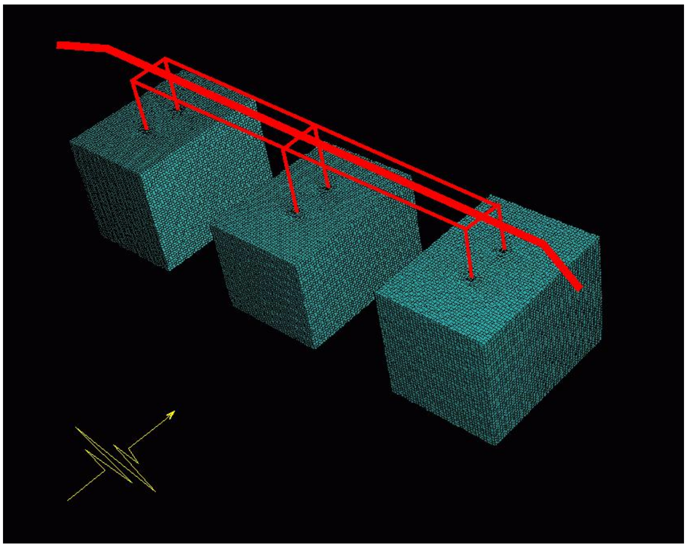

Figure 3: Detailed finite element model of a SFS system.

It is important to note that a full (numerical) construction process was performed, with soil self weight applied first, followed by excavation and pile installation, pile self weight application, with structure construction (self wight) application preceding application of seismic input via DRM.

Figure 4 shows moment response (upper) of the top of bent # 1, contrasted with relative velocity energy (lower) for the same bent. Two cases are analyzed, CCC is a case with all foundations (piles) in a soft clay (Bay mud) while SSS is for all foundations (piles) resting in dense send soil. Input motion is from Northridge earthquake, characterized with fairly high energy input in higher frequencies (stiff earthquake). It is obvious that soft soil dissipates seismic energy by plasticity and that SFS system in soft clay does not sustain much damage (possibly one case of plastic yielding on top of bent, at t between 14 and 15 seconds. On the other hand, in stiff sand, soil does not dissipate much seismic energy, hence bent # 1 suffers much plastic yielding (plastic hinge development be-

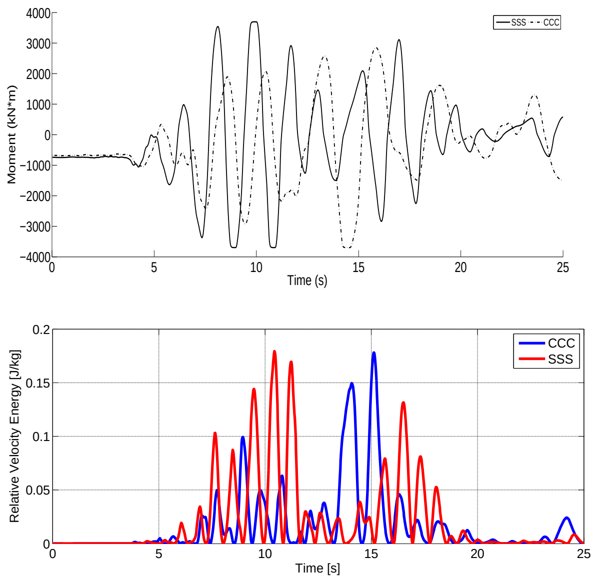

Figure 4: Bending moment response for bent # 1 (left column) (top) and relative velocity energy (lower).

tween t 8 until 12 seconds. It is noted also that the dynamic characteristics of stiff earthquake, with stiff soil and stiff structure contribute to early close to resonance response and increase damage. Relative velocity energy plot (Fig. 4, lower) presents similar information, this time in terms of kinetic energy, that is dissipated through plastic work. Note early peaks for SSS SFS system, that get dissipated by plastic hinging, while sole peak for CCC SFS system contributes to one sided plastic hinge development at $t \approx 14s$.

Use of Liquefaction. Liquefaction has been consistently put in negative connotation in geotechnical earthquake engineering. There are many cases where liquefaction is to be blamed for unacceptable SFS system performance ((Youd and Bartlett 1989), (Yokoyama et al. 1997), (Berril et al. 1997), (Kawakami and Asada 1966), (Hamada 1992a), (Hamada 1992b), (Japanese Society of Civil Engineers 1966)), However, there is not much evidence (it was not searched for) that liquefaction actually provided benefit by decreasing (damping out) ground motions. A simple example is used to illustrate this idea (Taiebat et al. 2009). Figure 5 presents two models for 1D seismic wave propagation, namely one (left) with all dense sand, while the other one (right) is dense sand on top of loose sand layers.

Seismic wave is propagated through the soil (input is also shown in Fig. 5) with resulting acceleration records at different soil depths shown in Figure 6. Since bottom loose soil layers do liquefy (from effec-

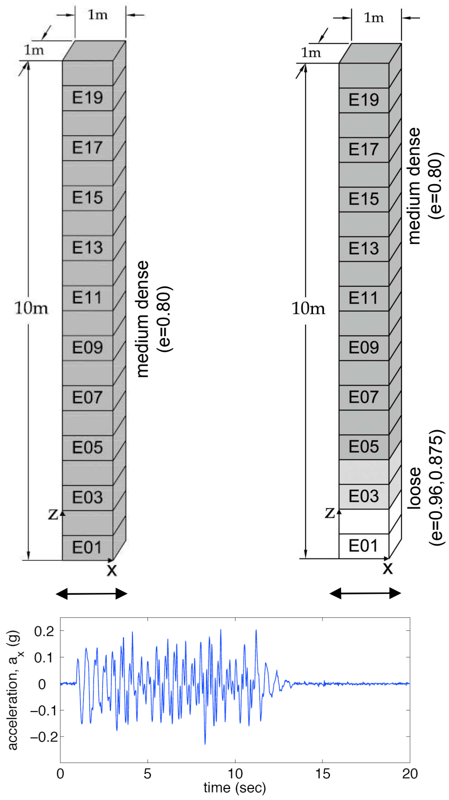

Figure 5: Two soil column models, left is all dense sand, right is dense sand on top of loose sand layers. Seismic motions applied to the bottom are also shown.

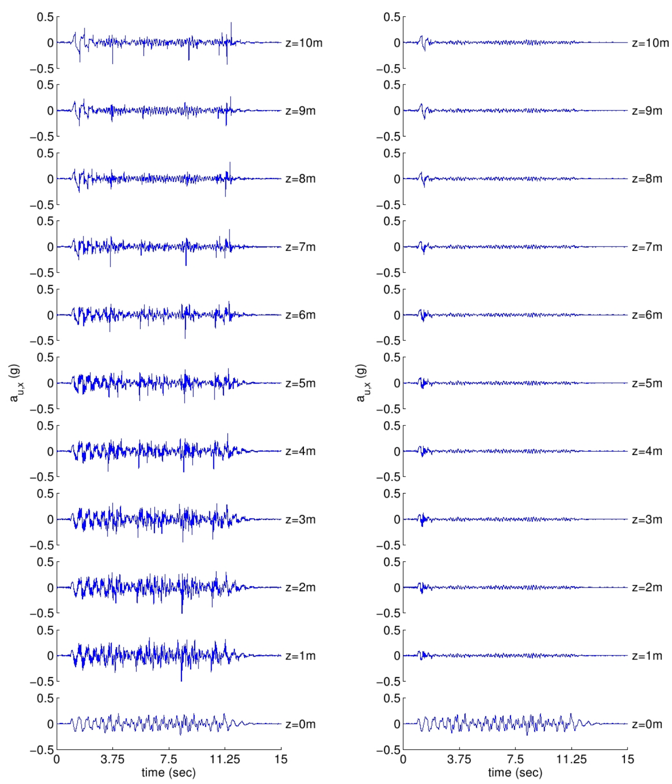

Figure 6: Acceleration time history, at different soil levels. Left is all dense sand model, right is dense with loose bottom sand layer.

tive stress results), seismic energy does not propagate much above bottom layers. Main dissipation mechanisms are related to soil plasticity and coupling of solid skeleton with pore fluid.

Figure 7 shows measured (simulated) kinetic energy at the top of both soil models. Layered model (with loose, liquefiable layer at the bottom) has reduction of top of model kinetic energy of at least three times, which might significantly contribute to damage reduction of any foundation and structure placed on top of such soil system.

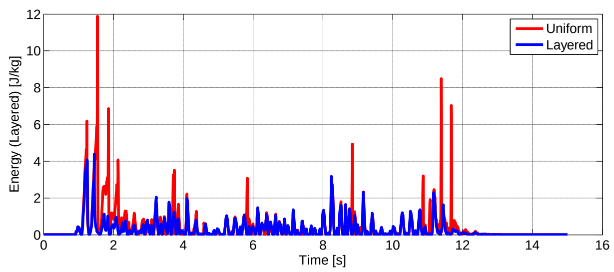

Figure 7: Kinetic energy at the top of soil layers.

4 SIMULATION PLATFORM

Numerical simulations described in this paper were done using sequential and parallel application programs developed at UCD, with use of a number of publicly available numerical libraries. Parallel simulation were based on recently developed Plastic Domain Decomposition (PDD) method (Jeremić and Jie 2007; Jeremić and Jie 2008). Graph partitioning used in PDD is based on ParMETIS libraries (Karypis et al. 1998)). Small part of OpenSees framework (McKenna 1997) was used to connect the finite element domain. In particular, Finite Element Model Classes from OpenSees (namely, class abstractions Node, Element, Constraint, Load, Domain and set of Analysis classes) where used to describe finite element model and to store results of analysis performed on a model. The domain and analysis classes were significantly modified to improve parallel performance and were organized as Modified OpenSees Services (MOSS) library. In addition to that, build process and organization of libraries was completely redone in order to remove known limitations of OpenSees program. On a lower level, a set of Template3Dep numerical libraries (Jeremić and Yang 2002) were used for constitutive level integrations, nDarray numerical libraries (Jeremić and Sture 1998) were used to handle vector, matrix and tensor manipulations, while FEMtools element libraries from UCD CompGeoMech toolset (Jeremić 2009) were used to supply other necessary libraries and components. Parallel solution of system of equations has been provided by PETSc set of numerical libraries (Balay et al. 2001; Balay et al. 2004; Balay et al. 1997)).

Application programs used for simulation were created by linking above mentioned libraries in the Finite Element Interpreter (FEI). Large part of simulation was carried out on our local sequential computers and and our parallel computer GeoWulf. Only the largest models (too big to fit on GeoWulf system) were simulated on TeraGrid machine at SDSC and TACC.

5 CONCLUSIONS

Interplay of Earthquake, Soil, Foundation and Structure dynamics in time domain plays a major role in catastrophic failures and great successes. High fidelity modeling and simulation offers an unprecedented opportunity to improve design. The ability to model and simulate flow of seismic energy in the SFS system with high fidelity, makes it possible to design energy dissipation in most economical way, in soil, Directing, in space and time, seismic energy flow in the SFS system will lead to increase in safety and economy. The main purpose of this brief paper was to overview modeling and simulations issues and show illustrative examples of directing energy flow for SFS systems.

It is hoped that public domain modeling and simulations tools, such as FEI and recently developed `www.OpenHazards.com` will be used more in future to increase safety and reduce cost of infrastructure objects in earthquake prone areas.

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REFERENCES

Aki, K. and P. G. Richards (2002). *Quantitative Seismology* (2^{nd} ed.). University Science Books.

Argyris, J. and H.-P. Mlejnek (1991). *Dynamics of Structures*. North Holland in USA Elsevier.

Balay, S., K. Buschelman, V. Eijkhout, W. D. Gropp,

D. Kaushik, M. G. Knepley, L. C. McInnes, B. F. Smith, and H. Zhang (2004). PETSc users manual. Technical Report ANL-95/11 - Revision 2.1.5, Argonne National Laboratory.

Balay, S., K. Buschelman, W. D. Gropp, D. Kaushik, M. G. Knepley, L. C. McInnes, B. F. Smith, and H. Zhang (2001). PETSc Web page. `http://www.mcs.anl.gov/petsc`.

Balay, S., W. D. Gropp, L. C. McInnes, and B. F. Smith (1997). Efficient management of parallelism in object oriented numerical software libraries. In E. Arge, A. M. Bruaset, and H. P. Langtangen (Eds.), *Modern Software Tools in Scientific Computing*, pp. 163–202. Birkhäuser Press.

Berril, J. B., S. A. Christensen, R. J. Keenan, W. Okada, and J. K. Pettinga (1997). Lateral–spreading loads on a piled bridge foundations. In S. E. Pinto (Ed.), *Seismic Behavior of Ground and Geotechnical Structures*, pp. 173–183.

Bielak, J., K. Loukakis, Y. Hisada, and C. Yoshimura (2003). Domain reduction method for three–dimensional earthquake modeling in localized regions. part I: Theory. *Bulletin of the Seismological Society of America 93*(2), 817–824.

Chi Chen, M. and J. Penzien (1977, August). Nonlinear soil–structure interaction of skew highway bridges. Technical Report UCB/EERC-77/24, Earthquake Engineering Research Center, University of California, Berkeley.

Elgamal, A., L. Yan, Z. Yang, and J. P. Conte (2008, July). Three-dimensional seismic response of humboldt bay bridge-foundation-ground system. *ASCE Journal of Structural Engineering 134*(7), 1165–1176.

Fenves, G. and M. Ellery (1998, December). Behavior and failure analysis of a multiple-frame highway bridge in the 1994 northridge earthquake. Technical Report 98/08, PEER Center.

Gazetas, G. and G. Mylonakis (1998, August 1998.). Seismic soil–structure interaction: New evidence and emerging issues. In P. Dakoulas, M. Yegian, and R. D. Holtz (Eds.), *Proceedings of a Specialty Conference: Geotechnical Earthwuake Engineering and Soil Dynamics III*, Geotechnical Special Publication No. 75, pp. 1119–1174. ASCE.

Hamada, M. (1992a). Large ground deformations and their effects on lifelines: 1964 niigata earthquake. In *Case studies of liquefaction and lifeline performance during past earthquakes*, Volume 1, Japanese case studies, pp. 3.13.123. State Univ. of New York, Buffalo, N.Y.: Natl. Center for Earthquake Engineering Research.

Hamada, M. (1992b). Large ground deformations and their effects on lifelines: 1983 nihonkaichubu earthquake. In *Case studies of liquefaction and lifeline performance during past earthquakes*, Volume 1, Japanese case studies, pp. 4.14.85. State Univ. of New York, Buffalo, N.Y.: Natl. Center for Earthquake Engineering Research.

Hilber, H. M., T. J. R. Hughes, and R. L. Taylor (1977). Improved numerical dissipation for time integration algorithms in structural dynamics. *Earthquake Engineering and Structure Dynamics 5*(3), 283–292.

Hughes, T. (1987). *The Finite Element Method ; Linear Static and Dynamic Finite Element Analysis*. Prentice Hall Inc.

Japanese Society of Civil Engineers (1966). *The report of damage investigation in the 1964 Niigata Earthquake*. Tokyo: Japanese Soc. of Civil Engineers. in Japanese.

Jeremić, B. (2004–2009). Lecture notes on computational geomechanics: Inelastic finite elements for pressure sensitive materials. Technical Report UCD-CompGeoMech–01–2004, University of California, Davis. available online: `http://sokocalo.engr.ucdavis.edu/~jeremic/CG/LN.pdf`.

Jeremić, B., Z. Cheng, M. Taiebat, and Y. F. Dafalias (2008). Numerical simulation of fully saturated porous materials. *International Journal for Numerical and Analytical Methods in Geomechanics 32*(13), 1635–1660.

Jeremić, B. and G. Jie (2007). Plastic domain decomposition method for parallel elastic–plastic finite element computations in gomechanics. Technical Report UCD–CompGeoMech–03–07, University of California, Davis. available online: `http://sokocalo.engr.ucdavis.edu/~jeremic/wwwpublications/CV-R24.pdf`.

Jeremić, B. and G. Jie (2008). Parallel soil–foundation–structure computations. In N. L. M. Papadrakakis, D.C. Charmpis and Y. Tsompanakis (Eds.), *Progress in Computational Dynamics and Earthquake Engineering*. Taylor and Francis Publishers.

Jeremić, B., G. Jie, M. Preisig, and N. Tafazzoli (2009). Time domain simulation of soil–foundation–structure interaction in non–uniform soils. *Earthquake Engineering and Structural Dynamics 38*(5), 699–718.

Jeremić, B., S. Kunnath, and F. Xiong (2004, February). Influence of soil–structure interaction on seismic response of bridges. International Journal for Engineering Structures *26*(3), 391–402.

Jeremić, B. and K. Sett (2009). On probabilistic yielding of materials. *Communications in Numerical Methods in Engineering 25*(3), 291–300.

Jeremić, B., K. Sett, and M. L. Kavvas (2007, October). Probabilistic elasto-plasticity: formulation in 1D. *Acta Geotechnica 2*(3), 197–210.

Jeremić, B. and S. Sture (1998). Tensor data objects in finite element programming. *International Journal for Numerical Methods in Engineering 41*, 113–126.

Jeremić, B. and Z. Yang (2002). Template elastic–plastic computations in geomechanics. *International Journal for Numerical and Analytical Methods in Geomechanics 26*(14), 1407–1427.

Karypis, G., K. Schloegel, and V. Kumar (1998). *ParMETIS: Parallel Graph Partitioning and Sparse Matrix Ordering Library*. University of Minnesota.

Kawakami, F. and A. Asada (1966). Damage to the ground and earth structures by the niigata earthquake of june 16, 1964. *Soils and Foundations 6*(1), 14–30.

Makris, N., D. Badoni, E. Delis, and G. Gazetas (1994, October). Prediction of observed bridge response with soil–pile–structure interaction. *ASCE Journal of Structural Engineering 120*(10), 2992–3011.

McCallen, D. B. and K. M. Romstadt (1994). Analysis of a skewed short span, box girder overpass. *Earthquake Spectra 10*(4), 729–755.

McKenna, F. T. (1997). *Object Oriented Finite Element Programming: Framework for Analysis, Algorithms and Parallel Computing*. Ph. D. thesis, University of California, Berkeley.

Mylonakis, G. and A. Nikolaou (1997). Soil-plie-bridge seismic interaction: Kinematic and inertial effects. part i: Soft soil. *Earthquake Engineering & Structural Dynamics 26*, 337–359.

Newmark, N. M. (1959, July). A method of computation for structural dynamics. *ASCE Journal of the Engineering Mechanics Division 85*, 67–94.

Sett, K. and B. Jeremić (2009a). Forward and backward probabilistic simulations in geotechnical engineering. In M. Iskander, D. F. Laefer, and M. H. Hussein (Eds.), *Contemporary Topics in Insitu Testing, Analysis, and Reliability of Foundations (Selected Papers from the 2009 International Foundation Congress and Equipment Expo, held in Orlando, FL, from March 15-19, 2009)*, Volume 186 of *Geotechnical Special Publications No. 186*, pp. 1–11. American Society for Civil Engineers.

Sett, K. and B. Jeremić (2009b). Probabilistic yielding and cyclic behavior of geomaterials. *International Journal for Numerical and Analytical Methods in Geomechanics*. in Print.

Sett, K., B. Jeremić, and M. L. Kavvas (2007a, October). Probabilistic elasto-plasticity: Solution and verification in 1D. *Acta Geotechnica 2*(3), 211–220.

Sett, K., B. Jeremić, and M. L. Kavvas (2007b, June). The role of nonlinear hardening in probabilistic elasto-plasticity. *International Journal for Numerical and Analytical Methods in Geomechanics 31*(7), 953–975. In Print (published online in the Early View section).

Suyehiro, K. (1932, May). Engineering seismology notes on American lectures. In *Proceedings of the American Society of Civil Engineers*, Volume 58, 4, pp. 2–110. American Society of Civil Engineers.

Taiebat, M., B. Jeremić, and A. M. Kaynia (2009, March). Propagation of seismic waves through liquefied soils. In *In proceedings of the GeoOrlando, Geo Institute Annual Conference*, Orlando, Florida.

Trifunac, M. and M. Todorovska (1998, January). Nonlinear soil response as a natural passive isolation mechanism - the 1994 Northridge, California, earthquake. *Soil Dynamics and Earthquake Engineering 17*(1), 41–51.

Yokoyama, K., K. Tamura, and O. Matsuo (1997, 27-28 Feb.). Design methods of bridge foundations against soil liquefaction and liquefaction induced ground flow. In *2nd Italy–Japan Workshop on Seismic Design and Retrofit of Bridges*, Rome, Italy, pp. 23 pages.

Youd, T. L. and S. F. Bartlett (1989, Feb 1.). Case histories of lateral spreads from the 1964 Alaskan earthquake. In *Proceedings of the Third Japan–U.S. Workshop on Earth Resistant Design of Lifeline Facilities and Countermeasures for Soils Liquefaction*, Number 91-0001 in NCEER.