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INFLUENCE OF SOIL-FOUNDATION-STRUCTURE INTERACTION ON SEISMIC RESPONSE OF BRIDGES

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ABSTRACT

In this paper we investigate the effects of soil-foundation-structure interaction (SFSI) on the dynamic response of typical highway bridge systems. Of particular interest are the effects of variable stiffness and strength of soils and structural components in the SFS system on the dynamic response. It will be shown that certain configurations of soil stiffness and strength (their distribution beneath bridge bents) together with certain configurations of stiffness and strength of bridge components (columns, joints...) may be detrimental to the dynamic response of the SFS system. This goes against common assumption that the SFSI is allways beneficial to seismic response. The detrimental effects of SFS interaction have not been investigated in depth in the past. One of the main reasons was the widespread belief that the SFSI is always beneficial to the behavior of the structural system under earthquake loading. The Applied Technology Council's development of seismic regulations (known as ATC-3) propose simple formulae for computing fundamental period (T) and the effective dumping ratio (Î²) of structures founded on mat foundations on a homogeneous half-space. All codes today use an idealized envelope response spectra which attain constant acceleration values up to certain period (of order of 0.4 second to 1.0 second at most) and then decrease monotonically with period. As a consequence, SFS interaction leads to smaller accelerations and stresses in the structure and thereby smaller forces onto the foundation. The beneficial role of SFS interaction has been essentially turned into dogma for many structural engineers. For example the NEHRP-94 seismic code states that: "These [seismic] forces therefore can be evaluated conservatively without the adjustments recommended in Sec. 2.5 [i.e. for SFS interaction effects]". Eventhough design spectra are derived on a conservative basis, and the above statement may hold for a (possibly large) class of structures, there are case histories that show that the perceived role of SFS interaction is an over-simplification and (may) lead to unsafe design. Several examples illustrating the main findings of the study will be presented. In particular, the effects of soil spatial variability on the response of bridges will be investigated. The SFSI hypothesis, balancing the input and dissipated seismic energy will be used to explain the role SFSI has in seismic response of bridge (and other structural) systems.

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INTRODUCTION

Current design practice for structures subject to earthquake loading regards dynamic Soil--Foundation--Structure (SFSI) Interaction (SFSI) to be mainly beneficial to the behavior of structures (jeremic and Preisig, 2005). Including the flexibility of the foundation reduces the overall stiffness of a system and therefore reduces peak loads caused by a given ground motion. Even if this is true in most cases there is the possibility of resonance occurring as a result of a shift of the natural frequencies of the SFS-system. This can lead to large inertial forces acting on a structure.

As a result of these large inertial forces caused by the structure oscillating in it's natural frequency the structure as well as the soil surrounding the foundation can undergo plastic deformations. This in turn further modifies the overall stiffness of the SFS-system and makes any prediction on the behavior very difficult.

Dynamic SFSI also becomes important in the design of large infrastructure projects. As authorities and insurance companies try to introduce the concept of performance based design to the engineering community more sophisticated models are needed in order to obtain the engineering demand parameters (EDP's). A good numerical model of a soil-foundation-structure system can therefore not only prevent the collapse or damage of a structure but also help to save money by optimizing the design to withstand an earthquake with a certain return period.

There is a a variety of methods of different levels of sophistication that are currently being used by engineers to analyze SFSI effects. For long time structures were (and some cases still are) analyzed without taking any SFSI into consideration. This approach is even sanctioned in the NEHRP-94 seismic code which states that: *"These [seismic] forces therefore can be evaluated conservatively without the adjustments recommended in Sec. 2.5 [i.e. for SFSI interaction effects]".*

The SFSI effects can in fact be beneficial but also detrimental to the behavior of structural system. The generic statement like the one mentioned above (from NEHRP-94 seismic code) have to be carefully used in the light of a great variety of structural, foundation and soil systems and a great variety of seismic motions that these systems can be exposed to.

A number of papers in recent years have investigated the influence of the SSI on behavior of bridges (Kappos et al., 2002; Makris et al., 1993; Makris et al., 1994; Sweet, 1993; McCallen and Romstadt, 1994; Chen and Penzien, 1977; Dendrou et al., 1985). In particular Sweet (1993) and McCallen (1994) performed a finite element analysis of bridge structures subjected to earthquake loads. The two studies by Chen and Penzien (1977) and by Dendrou et al. (1985) analyzed the bridge system including the soil but the developed models used a very coarse finite element meshes. More recently, excellent studies done by Gazetas and Mylonakis (1998) and Mylonakis et al. (2006) showed the very important influence of SFSI that benefits or detriments dynamic behavior of a complete bridge--foundation--soils system. It should be noted that previously mentioned studies by Gazetas and Mylonakis (1998) and

Mylonakis et al. (2006) were performed by using a viscous (dashpot, velocity proportional damping) approximation of nonlinear soil response.

In this paper we present an overview of simulation approach as well as an overview of SFSI behavior of simple and more complex structures. Both simple and more complicated SFS system are founded on a number of different soils and are exposed to a number of different earthquake motions. The soil, foundation and the structure are treated as a unique system, and this system approach was followed from the particular seismic motions input method (the Domain Reduction Method, DRM) to the analysis of natural periods of the complete system of components.

Both the soils, the foundations and the structure are treated as fully nonlinear, elastic--plastic system. Each components (soil as solid), foundations (shallow foundations or pile) as structural elements) and structure (piers and superstructure as structural elements) responds to seismic motions following it's own inelastic constitutive response.

As the paper represent an overview of methodology used in Soil--Foundation--Structure interaction modeling and simulations, only select results are shown. A more comprehensive paper, describing SFSI effects in detail is in preparation for publication.

METHODS FOR MODELING OF SFSI

Dynamic analysis of structures has been performed for the last few decades with varying success. One of the main reasons for the lack of much progress in modeling of SFSI is the problem associated with the consistent application of seismic motions (forces or displacement/accelerations) into SFS models. Several methods with different degrees of approximation exist. A more recent approach providing a number of attractive features is the so called Domain Reduction Method (DRM) originally proposed by Bielak et al. (2001) and Yoshimura et al. (2001).

The Domain Reduction Method is a modular, two-step dynamic procedure aimed at reducing the large computational domain to a more manageable size. The method has additional benefits in terms of the ability to control radiation damping, it is able to take into account very consistently the seismic wave propagation from the source all the way to the model of interest. In addition to those benefits, the consistent application of seismic loads (displacements, accelerations) on the finite size, finite element model, the main feature of the DRM method, is solved (analytically) by method design.

A large physical domain, including Soil--Foundation--Structure system is to be analyzed for seismic dynamic response. The source of disturbance, a known time history of a force field $P_e(t)$ at the hypocenter, is far away from a local feature (SFS system) (see Figure 1).

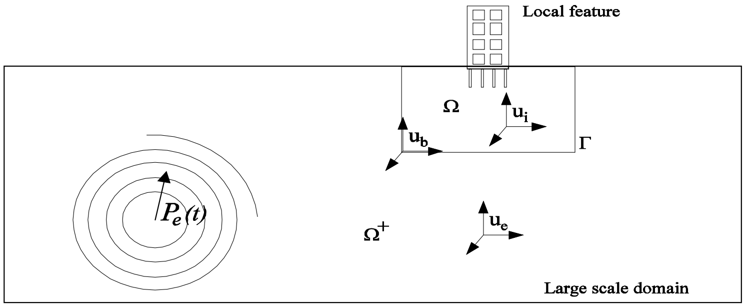

Figure 1: Large physical domain with the source of load Pe(t) and the local feature (in this case a soil–foundation–building system.

As in practice it is not feasible to model the entire domain between the source and the local feature of interest the domain is separated into two parts: The simplified large domain from which the local feature has been subtracted, and the local feature inside the boundary Γ (Figure 1). Through an appropriate method (analytical solution, Green's function, dynamic FE or FD on a coarse grid) the motion is propagated from the source to the boundary Γ where the free-field motion u_b^0 is recorded.

The Domain Reduction Method consists in finding the set of forces P^{eff} to be applied to the boundary Γ that produce exactly the same motions inside Γ as would be generated by applying the motions u_b^0 to the boundary. For an in-depth analysis of the procedure the interested reader is referred to Bielak et al. (2001).

SIMPLE STRUCTURES ON INELASTIC SOIL

In this section, DRM is used to analyze simple 2D and 3D SFS systems. The intent is to explore the behavior of the full SFS system and contrast that with usually performed dynamical analysis of structural system alone. Three different models are considered. The first two models are for a simple structure (elastic or inelastic) with shallow foundation. Model # 1 is in 2D while model # 2 is in full 3D. For this particular system, it will be shown that the addition of full 3D modeling capabilities brings little difference in response. The third model is for a single pile-column system. In this case 2D model is not deemed appropriate and the system is analyzed in full 3D.

Two Dimensional Model with Shallow Foundation

A 2d-model is proposed as a simplification of the full 3d-model. Representing a cross section of the full model it is expected to provide insight into its dynamic behavior while requiring considerably less computational resources. The 2d-model consists of one slice of eight-node brick elements as shown in Figure 2. The nodes of the two lateral faces are constrained to move together in x- and z-direction, the out-of-plane displacement in y-direction is fixed. The model approximates a plane strain situation.

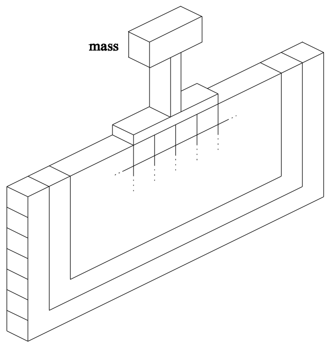

Figure 2: The 2D SFSI-model

The earthquake motions are applied to the model by the DRM method. As input for the 2d model the motion from the Northridge earthquake recorded at LA University Hotel (Figure 3) is used. The acceleration time history is scaled to a peak ground acceleration of 1 g. Motion is applied in x-direction only, that is, this is a 1--D wave propagation. This is consistent with a hypothesis of a deep earthquake source, in which case the seismic waves propagates in 1D vertically.

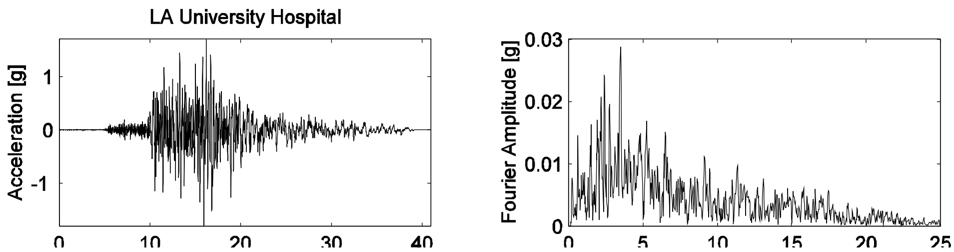

Figure 3: Acceleration time histories and Fourier amplitude spectra's of the selected ground motions

The material properties of the soil are obtained from simple in--situ and laboratory tests. The friction angle of soil was found to be $\phi' = 37^0$, while the undrained shear strength is c_u=101 kPa , mass density is ρ = 1800 kg/m^3 and finally the shear wave velocity is v_s = 200 m/s . The material model used is a simple frictional Drucker-Prager model. This is the only model available if data is given only in terms of friction angle and the undrained shear strength. The model is clearly simplistic in terms of simulating cyclic loading and properly modeling energy dissipation coming from elasto--plasticity of soils.

The boundary conditions applied to the model allow displacements in x-direction (horizontal). On the vertical boundaries at ±10.5m horizontal dashpots are placed. The in-situ earth pressure is applied on the same nodes in horizontal direction.

Acceleration time histories at all the nodes of the boundary layer are obtained by vertically propagating a plane wave using the program SHAKE91 (Idriss and Sun 1992).

Structure

Four very simple structures are chosen to illustrate the effects of dynamic SFSI. A beam-column element of length L and moment of inertia I_y is fixed to a footing. A lumped mass is added to the translational degrees of freedom of the top of the structure. The rigid footing is 0.5 m deep, spans over four soil elements and is rigidly connected to the adjacent soil nodes. The mass density of the footing is ρ = 2400 kg/m^3, the column is considered massless. The moment connection between the nodes of the footing, having 3 (translational) degrees of freedom, and the 6 degrees of freedom of the nodes of the column is assured by a very stiff beam element that is connected to a node at the bottom and a node at the top of the footing.

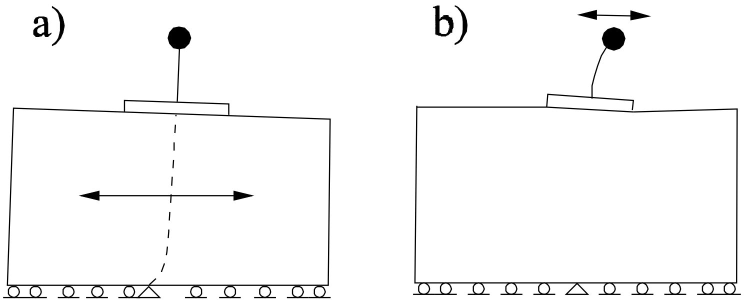

Figure 4: a) First eigenmode, b) second eigenmode of SFSI-system

The parameters of the four columns are chosen such that the second natural frequency, that is the natural frequency attributed to bending of the column (Figure 4 b)), is evenly distributed over the frequency range of the input motion. Structure 4 is designed such that it's second natural frequency matches the largest spike in the input motion. Table 1 lists the properties of the structures used in the analysis. The Young's modulus for all four structures is E = 210 GPa , the mass on top of the structures is M = 100, 000 GPa.

Table 1: Properties of the analyzed structures

Structure	Length [m]	Stiffness $E\,I_y$ $[MN\,m^2]$	1^{st} natural frequency of fixed-base system [Hz]	2^{nd} natural frequency of SFSI-system [Hz]
1	5.5	1680	2.71	2.07
2	3.5	5670	9.82	3.89
3	2.5	13440	25.1	5.53
4	5.0	5670	5.75	3.52

On the four structures mentioned above a series of fixed-base analysis is also performed. The first natural frequencies of the four structures with its base fixed, corresponding to the second mode of vibration of the SFSI-model, are given in Table 1. It can be seen that the influence of the soil on the natural frequency of the SFSI-system increases as the overall stiffness of the structure increases.

Results

The results of the SFSI- as well as the fixed-base analysis are presented in the following. In order to investigate the forces causing plastic deformations in the structures we look at the base moments between foundation and column. In Figure 5 the moments at the base of the linear structures are plotted.

For structures 1 and 4 the moments for the fixed-base model are higher than for the SFSI-model. This means that in this case neglecting the effects of SFSI leads to a conservative design. Structures 2 and 3 however have to resist higher moments when SFSI is taken into account. Because the SFSI-system is more flexible than the fixed-base structure its modes of vibration are excited by a different range of frequencies contained in the input motion. For a particular motion this can lead to resonance of the SFSI-system. This result is in contradiction with current engineering practice suggesting that neglecting SFSI in general leads to a more conservative design.

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REALISTIC 3D SOIL--FOUNDATION--STRUCTURE MODEL

Model Description

A 3D 4-span bridge finite element SFS model has also been developed to investigate dynamic response of the complete SFS system. Different soil profiles have been used underneath bridge bents in order to investigate effects of soil variability on SFS response. The model uses on DRM to its advantage, which helps reduce the overall finite element model size. The mesh is shown in Figure 6.

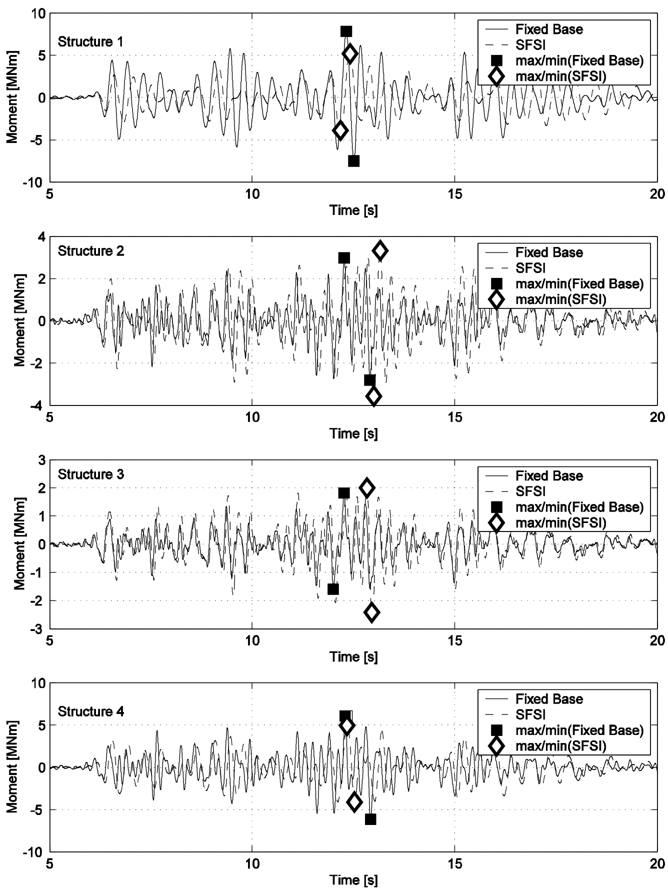

Figure 5: Moments at the base of the linear column

Concrete Structure

Structural components of the model have been developed by researchers from UC Berkeley (Professor Fenves and collaborators) and calibrated using experimental data from UNR shake table tests.

Beam--column element utilized for bent columns use nonlinear, force based element based with fiber section. The material properties of these fibers are defined in 1D for confined and unconfined concrete. The moment rotation characteristics of the concrete sections are (fibers) are modeled using Kent--Scott--Park concrete material model with degraded linear unloading/reloading stiffness. The steel rebars, on the other hand, are modeled by Giuffre--Menegotto--Pinto steel material model with isotropic strain hardening. Fibers form a circular section for which elastic axial, torsional and shear stiffness are assumed and aggregated to complete the whole section definition for the pile column. A simplified bar--slip hinge model is developed to model the reinforced concrete beam--column joint.

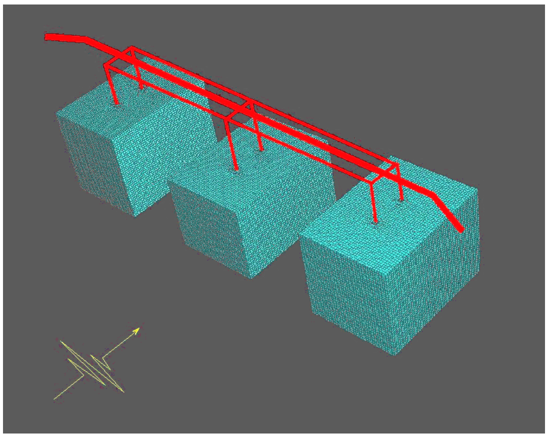

Figure 6: FEM model for seismic response of a three bend bridge.

Soil

In order to explore the effect of the underlying soil on SFS behavior, two types of prototype soil properties have been used.

The first soil model is for the dense send (as used in subsequent centrifuge experiments at UCD). This model is using Drucker--Prager cone with nonlinear Armstrong--Frederick kinematic hardening rule for yield and potential surfaces. The constitutive model is calibrated using in situ test data from UT Austin.

The second type of soil was assumed to be soft Bay mud, and is based on elastic--Perfectly--Plastic Von Mises model, thus modeling the total stress response of fully saturated soft soil with short period loading (seismic) without the possibility for pore fluid dissipation.

Seismic Response in Heterogeneous Soils

The finite element analysis on the full 3D prototype 4-span bridge SFS system has been performed using parallel computers and locally developed and implemented Plastic Domain Decomposition method.

Among many interesting results, due to space limits, we show only bending moment time histories at the top of all three bents (which are all of different height) in Figure 7. The moment diagram starts from the static values as there is a self weight loading phase before the seismic event. For particular foundation--bridge system, one can observe quite a bit of difference in response coming from the underlying soil. The SFS response with stiff sand beneath the structure is affecting the SFS system in such a way that the bridge structure reaches its failure moments in the first 8 or so seconds, while the system is then oscillating with reduced intensity for the remaining of the simulation (and duration of the earthquake). On the other hand, the SFS system founded on soft clay reaches failure bending moments much later, around 15 seconds into the simulations, and even then only for bent # 1 both sides do get damaged while for the bent # 2 and # 3, the damage is localized to one side only. This much stronger (and damaging) response in stiff soil might seem counter--intuitive, but it quite nicely explainable if one takes into account all the characteristics of the soil, structure and the seismic motions used (component of Northridge 1994 motion).

As the earthquake intensity increases, the SFS system period is elongated (as inelastic effects accumulate). At some point in time, depending on particulars of the seismic motions, and those of the SFS system, the periods of the earthquake and that of the SFS system might be very close to each other, or might coincide. At that point, the energy dissipation (plasticity and damage in the structure and in the soil) will have to be balanced against the seismic input energy. If that balance is such that more energy is dissipated, the SFS system might survive with limited damage. If, on the other hand, the energy dissipation is smaller than the energy input, and that balance is maintained long enough, the SFS system will experience catastrophic failure (as it will go through a nonlinear resonance).

In the case of our SFS system, the Northridge input motions have had a much closer period to the particular structural system founded on stiff sand, and the corresponding periods got to be very close, so that the plasticity of soil and the damage in the structure was used to the full extent to balance (positively) the energy input and dissipation. The similar energy balance was established much later for a soft soil site, but due to not much damage developing in the structure and not much dissipation in the soft soil the seismic shaking lasted much longer and with greater intensity. If the main part of the earthquake has lasted shorter period of time, this SFS system in soft soil would have not seen much damage all.

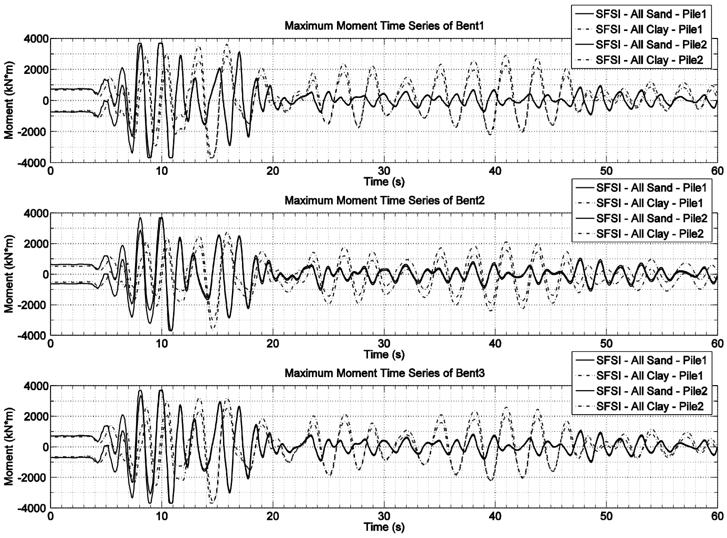

Figure 7: Dynamic Structure Response by FEM – Moment Time Series

SUMMARY

In this short paper we presented methodology for seismic SFS system interaction analysis. In addition to that we presented an overview of effects SFSI has on seismic response of soil--foundation--bridge systems. It was shown that each SFS system needs to be analyzed on its own as the characteristics of soils, foundations, structural system and the seismic motions do affect the response, which can be counter--intuitive to what is currently predominantly believed. In addition to that, a balance of input and dissipation energy hypothesis can be used to estimate if the particular seismic event will result in catastrophic failure of just limited damage to the particular SFS system.

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