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TOWARDS A NONLINEAR DISCRETE MODEL FOR SITE-CITY INTERACTION THROUGH A SINO-EUROPEAN SYNERGY

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ABSTRACT

In this contribution, we present a review of the experimental evidences and the state-of-the-art of numerical methods for site-city interaction (SCI) simulations for seismic events. We summarize the main model parameters and discuss the current findings on SCI. Finally, we describe the project idea of a nonlinear discrete model for a large scale site-city interaction, which will be developed within the upcoming collaboration between the Chair of Structural Mechanics of the Technical University of Munich and the Institute of Disaster Prevention and Mitigation of the Tsinghua University Beijing.

Keywords: Soil-Structure Interaction (SSI); Soil-City Interaction (SCI); Structure-Soil-Structure Interaction (SSSI); Lumped Parameter Models (LPM), nonlinear, multi degrees of freedom (MDOF)

1. INTRODUCTION

According to the United Nations Report (Nations 2016), by 2030 sixty per cent of people will live in cities with at least half a million inhabitants. Consequently, most of the population, buildings, strategic public utilities and business activities will be centralized in densely urbanized areas, especially in megacities. These areas can be exposed to a high seismic hazard and the consequences of a strong earthquake may have an irremediable socio-economic impact. Thus, an accurate prediction of the potential seismic damage to urban areas is of huge importance.

Figure 1 shows a dense cluster of governmental and business buildings in the Beijing Central Business District, where the seismic risk is high (Liu, Wang et al. 2013).

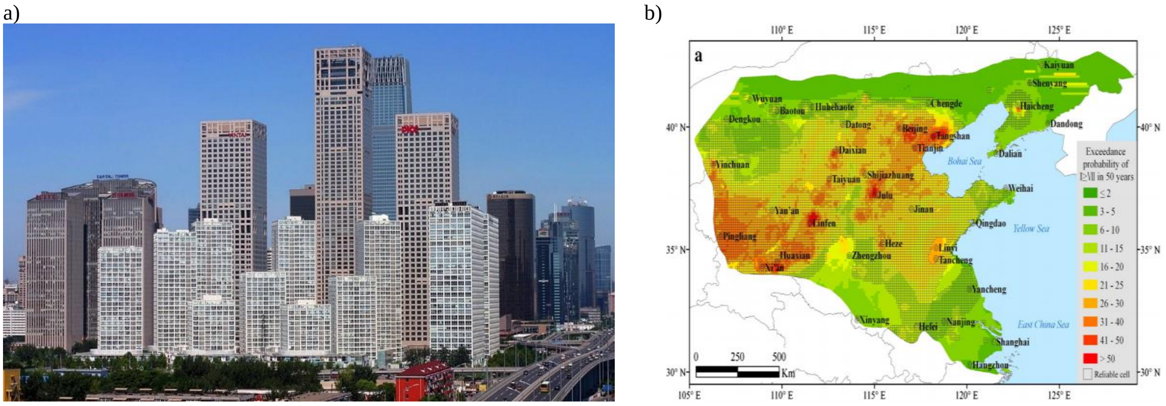

Figure 1. a) Cluster of high-rise buildings in the Beijing Central Business District (Wikipedia 2017). b) the Seismic Hazard Map shows the exceedance probability of more than 50 % for the seismic intensity I=VII in 50 years in Beijing (Liu, Wang et al. 2013).

Neighboring buildings can exchange a significant amount of vibrational energy with each other

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through the soil, forming a fully coupled system (Lou, Wang et al. 2011). This aspect is addressed as structure-soil-structure interaction (SSSI) and it is related to the research field of the structure-soil interaction (SSI) (Kausel 2010). It is also broadly accepted that the presence of a dense urbanization modifies substantially the seismic ground motions with respect to the free field. This aspect is referred to as “contamination of ground motion by buildings” (CGMB)(Castellaro and Mulargia 2010). The CGMB is even more accentuated in the case of an alluvial basin underneath the city: the seismic wavefield radiated by the city appears to be trapped within the alluvial basin and the seismic wave field exhibits specific directivity features (Kham, Semblat et al. 2006, Semblat, Kham et al. 2008).

The interaction of a large number of buildings with the underlying soil is called site-city interaction (SCI). Conventional seismic analyses of buildings do not account for the SCI effects, which, however, are relevant for seismic microzonation, pre-earthquake planning, post-earthquake emergency management and insurance policies. The system response can be either amplified or attenuated according to the distance between adjacent buildings, which is related to dynamic properties of the overall system.

During a seismic event, depending on the magnitude of the earthquake, the city system can be seriously damaged, exhibiting nonlinear material and structural properties.

In this case, a realistic representation of the seismic behavior of the conglomerate requires a massive computational workload, especially when computing the transient nonlinear city response.

The main questions of SCI investigations are:

1) How does the response of a cluster of buildings is influenced by the reciprocal interaction of the buildings through the flexible soil?
2) How does the city group-effect influence the seismic vibrations?

Given the large dimensions and the non-repeatability of the study subject (city-soil scenarios), in-situ or small-scale experiments face many challenges, especially huge costs. Therefore, computer-based simulations represent the preferred approach for damage estimation.

In the following paragraphs, we review the experimental evidences and the state-of-the-art of numerical methods for SCI seismic investigations. We summarize the main problem parameters and discuss the current findings on SCI. Finally, we describe the project idea of a nonlinear discrete model for a large-scale site-city interaction, which will be developed within the upcoming collaboration between the Chair of Structural Mechanics of the Technical University of Munich and the Institute of Disaster Prevention and Mitigation of the Tsinghua University Beijing.

2. STATE OF THE ART

2.1 Experimental studies

Due to the large number of variables at play, it is difficult to isolate and quantify the SCI effects during past seismic events from the available recorded data.

However, clear atypical phenomena were observed in cities grounded on a soft clay basin. During the Caracas earthquake in 1967, a significant damage occurred to groups of similar buildings, for which the natural period did match closely the period of the soil layer underneath (Seed, Whitman et al. 1973). Similarly, a “damage belt” was identified based on the collapse of several 2- to 3-storey wooden buildings with a heavy roof (and a natural frequency of 2-3 Hz) in a very densely occupied area of Kobe during the earthquake in 1995 (Kawase 1996).

For a single building or a few neighboring buildings, researchers have carried out several tests and an exhaustive literature review on experimental SSSI and FSFI can be found in (Lou, Wang et al. 2011) and (Bard, Chazelas et al. 2008). It is experimentally demonstrated that a vibrating building transfers seismic waves into the soil, superimposing the generated soil displacements to the existing seismic field generate by an earthquake (Jennings 1970, Kanamori, Mori et al. 1991, Wirgin and Bard 1996, Gueguen, Bard et al. 2000, Trifunac, Hao et al. 2001, Chávez-García and Cárdenas 2002, Gueguen and Bard 2005, Castellaro and Mulargia 2010). Physical shaking-table tests and centrifuge tests with few adjacent scaled buildings showed the adverse and beneficial effects of the SSSI, isolating inertial and kinematic interaction phenomena (Yano, Naito et al. 2003, Xu, Costantino et al. 2004, Li, Hou et al. 2012, Li, Hou et al. 2012, Mason, Trombetta et al. 2013, Aldaikh, Alexander et al. 2015, Ge, Xiong et al. 2017).

Concerning the SCI, only a few experimental studies dealt with a large number of buildings interacting with the underlying soil.

(Schwan, Boutin et al. 2015) presented an experimental specimen of an idealized site-city setup with up to 37 anisotropic resonant structures arranged at the top surface of an elastic layer. The structures were made up of vertical aluminum sheets welded at the base to a footing and periodically spaced (at distance *l*). The soil was made up of cellular polyurethane foam. The shear resonance of the soil layer is tuned to the city natural frequency of 8.45 Hz. The experimental set-up was excited with transient and harmonic vertically-polarized shear (SH) waves. The results showed that the city acts as a resonant surface, enforcing frequency-dependent free-like and rigid-like boundary conditions to the soil. This phenomenon drastically changes the surface-wavefield with respect to the free field and unconventional depolarization effects can be observed. Following up with this study, (Schwan, Boutin et al. 2016) presented additional periodic city scenarios, for periodic distances 2*l* (19 buildings), 4*l* (9 buildings), 8*l* (5 buildings). In frequency domain, the signatures of the site-city interactions can be identified as a split of the soil layer resonance peak into two soil-city resonance peaks, a reduction of the resonance peak and a strong modification of the phase. In the time domain, such a two-peak-spectrum is favorable to beatings, which is a resonating and prolonged vibrational behavior caused by distinctive close coupling modes. Unfortunately, there still is a lack of scale model experiments of SCI scenarios and recorded data during seismic events.

2.2 Numerical models

From a structural engineering point of view, the major task of computer-based simulation is to develop accurate and reliable mathematical models to mimic the actual behavior of real structures. The existing simulations tool are mainly based on the finite element method (FEM), which allows a very accurate 3D representation of each structural components and can account for the endless soil. However, their application for a large urban region can become costly or even impractical. Simpler models are imperative for SCI application. The biggest challenge is to be able to account for the most important city, soil and earthquake parameters, without running into unaffordable computational time.

2.2.1 Soil models and Earthquake models

The modelling of the seismic loading and the soil response are intrinsically related, because they are obtained from the same mathematical description: the Lamé equations. These give the ground motions according to prescribed loads and boundary conditions, such as a seismic wave travelling from one point in the soil (the earthquake source), through the soil, to the structure base.

For SCI scenarios, the spatial variability of the seismic free-field due to the actual path of the seismic waves play a major role for the response of a buildings cluster (Assimaki, Gazetas et al. 2005, Isbiliroglu, Taborda et al. 2015). However, analytical solutions for the Lamé equations only exist for very idealized soil profiles and, therefore, numerical approaches are preferred.

Currently, the most established method for computing large-scale three-dimensional 3D seismic fields is the FEM with several extensions such as high order (Semblat and Brioist 2009), spectral (Komatitsch and Vilotte 1998, Khan, van der Meijde et al. 2017) and discontinuous Galerkin method (Faccioli, Maggio et al. 1997, Park and Antin 2004, Mazzieri, Stupazzini et al. 2013).

The grid size of the computational domain is proportional to the lowest shear wave velocity in the model and inversely proportional to the highest frequency of interest.

When computing the soil motion field at large scale without the city, a low maximum considered frequency between 2 and 5 Hz is chosen to keep the element number affordable. This is acceptable to simulate the propagation of the seismic waves, travelling long distances and reaching the buildings. However, for studying the vibration of the excited buildings in a smaller scale, a higher maximum frequency is necessary and, therefore, a much finer mesh is required. Therefore, the SCI problem is a multiresolution problem. A way to deal with this two-scale problem is the Domain Reduction Method (DRM) (Bielak, Loukakis et al. 2003, Yoshimura, Bielak et al. 2003, Fernández-Ares and Bielak 2004, Kontoe, Zdravkovic et al. 2008, Jeremić, Jie et al. 2009). In the DRM, the problem is solved in two steps: in a first step, the displacement field of the soil due to a far field source is computed for a specific region at the boundary of the near field; in a second step, equivalent seismic loads are derived from this displacement and applied as input to a small-scale model, which includes the near field and the buildings.

In the following paragraphs, we will concentrate on the building cluster scale and we assume that the seismic field is known at a certain near field surface (either at the SSI interface or at the near field boundary). Once the excitation has been computed with large-scale models, the small-scale scenario requires a refined model for the near field soil, which couples the buildings with each other and, at the same time, satisfy the radiation conditions.

One common option for the modelling of the infinite soil is the FEM extended with transmitting boundaries (TB) (Kausel 1988). These are special elements at the boundaries of the FEM domain: paraxial boundaries, perfectly-matched layers (PML), infinite elements or scaled boundary finite elements (SBFEM). The FEM can account for nonlinearities in the structure as well as in the soil near field and can be solved using direct time integration methods such as central difference method or Newark method. The soil's far field is assumed to remain linear.

Even for the small-scale scenario, the number of degrees of freedom can become large and a simplification must occur either in the soil model or in the buildings models. Improvement for reducing of the FEM are the 2D coupling of the fourth-order staggered-grid finite difference method with the second-order FEM (Ma, Archuleta et al. 2004, Sahar, Narayan et al. 2015, Kumar and Narayan 2017).

An alternative to the transmitting boundaries, the boundary element method (Karabalis and Mohammadi 1991, Taborda 2010) and the discrete wavenumber method (Bouchon, Campillo et al. 1989, Restrepo, Gómez et al. 2014) have been popular for problems with relatively simple geometry and geological conditions. These are based on the fundamental solution of the Lamé equations and can be coupled to the FEM using the substructure approach, but their application is limited to linear cases and homogenous or horizontally layered soils.

Besides complex models, discrete mechanical models such as the lumped parameter models (LPM)(Mulliken and Karabalis 1970, Mulliken and Karabalis 1998) can be used. These are nested spring-dashpot discrete elements for the through-the-soil coupling. Their coefficients are calibrated in the frequency domain so that they simulate the impedance of the coupled foundation-soil-foundation system, but they do not depend on frequency. The LPM can be applied directly in time-domain, allowing non-linearities in the city model. However, for the application of the LPM for SSSI a modification of the time integration algorithm is necessary, to account for the time-lagging effects associated with the wave propagation between the foundations.

Another important aspect is the nonlinear behavior of the soil during strong earthquake events, which typically results in an increase in damping and reduction of shear modulus at high levels of strain (Todorovska and Trifunac 1992, Beresnev, Atkinson et al. 1998, Assimaki and Kausel 2002, Bonilla, Archuleta et al. 2005, Solberg, Hossain et al. 2013).

Beside deterministic methods, an interesting approach is the random theory applied to soil vibrations, where the soil parameters, such as the shear modulus, the density and the layers depth become random variables (Hryniewicz 1993).

2.2.2 Urban models

There is not a unique definition for urban conglomerates, neither in terms of buildings number, nor in terms of buildings density or building type. One may distinguish between cities and megacities, with more than 10 million of inhabitants. New megacities tend to exhibit separated socioeconomic blocks, several areas with several similar buildings, such as business areas with high-raise buildings or residential areas with townhouses. Moreover, buildings can be categorized according to their different structural types (FEMA, 2012a): steel and glass, reinforced concrete, masonry, timber, etc….

In the majority of the available SCI studies, the focus of the analysis is on the influence of the city system on the seismic free field and, therefore, the city model is highly simplified.

The simplest and most common representation of a city is a series of oscillators (single-degree-of-freedom systems, SDOF) made up of a spring, a dashpots and a mass, tuned to the first natural frequency of each building (Fernández-Ares and Bielak 2004, Boutin and Roussillon 2006, Ghergu and Ionescu 2009). The SDOF model does not allow a realistic modelling of the buildings, because it only considers the first natural mode of the city elements. It does not deliver details about the interstory drift, which represents an important quantity for detecting damages (Xu, Lu et al. 2014).

More complex approaches are the analytical approaches based on the Dyson equation (Lombaert and Clouteau 2009) and the coupling between the boundary elements and a modal representation for the buildings (Clouteau and Aubry 2001). However, these are computational demanding.

The urban conglomerates can be interpreted as a frequency-dependent boundary condition at the surface of the soil (Groby, Tsogka et al. 2005, Groby and Wirgin 2008). In the case where the frequency of the excitation (of the seismic field) get closer to the natural frequency of the building, the presence of the building turns into a rigid boundary conditions, an impedance. In the other cases, the building acts as a free boundary. This method is called city-impedance method and it is only applicable for linear cases. It is a very simplified representation of the city and requires: a) the possibility to identify a representative periodic city element; b) the condition that the size of the city element is much smaller than the seismic wavelength. The latter condition can be fulfilled only in very idealized cases.

Idealized cities with groups of identical buildings can be represented through block models, which need to be tuned in order to match the vibrational properties of shear and bending beams (Tsogka and Wirgin 2003, Taborda and Bielak 2011, Kumar and Narayan 2017).

Because of the building-diversity and the nonlinearity of the city scenarios, nonlinear multi-degrees-of-freedom systems (MDOF) with shear and bending properties seem to be the most suitable solution. (Xu, Lu et al. 2014, Tian 2017) developed practical computational models for urban areas with buildings in reinforced concrete masonry and steel, and for tall buildings, which exhibit a combined flexural-shear deformation mode. The parameter calibration of the nonlinear building models is automatic and only requires the widely accessible building attribute data from GIS (i.e., structural height, year of construction, site condition, and structural type). The MDOF urban models used in the time domain is considered the most accurate method for seismic damage prediction of regional buildings.

3. A NONLINEAR DISCRETE MODEL FOR SCI ANALYSES

Previous studies summarize the SCI problem into a series of key parameters (Table 1), such as the resonant frequency of the structure and soil, building material and typology, foundation type and the soil stratification.

Table 1. Governing parameters of the SCI models based on the currently available experimental and numerical investigations.

Buildings		**Soil**		**City**	
c_b	wave velocity	c_s	shear wave velocity	N	number of buildings
h_b	height	h_s	thickness	l	length in x of a building period
ξ_b	damping	ξ_s	damping	L	length in y of a building period
ρ_b	density	ρ_s	density	$\Sigma = \mathrm{l} \cdot \mathrm{L}$	periodic area of a building
σ_b	foundation area			$\mathrm{S} = \mathrm{N} \cdot \Sigma$	total city area
m_b	mass				
k_b	stiffness				
$f_b = \frac{c_b}{4h_b}$ or $f_b = \frac{1}{2\pi}\sqrt{\frac{k_b}{m_b}}$	resonant frequency	$f_s = \frac{c_s}{4h_s}$	resonant frequency		

Table 1 shows the governing parameters of the SCI problem according to most of the currently available investigations. The most important parameters are the resonant frequency of the building f_b (assumed to repeat itself with a period Σ) and the soil f_s . Table 2 shows the indices for estimating the importance of the SCI effects, with the ratios between the properties of the soil and the city.

Table 2. Relative indices for estimating the SCI effects: the most important ratios are the frequency ratio and the impedance ratio between site and city.

$\frac{f_s}{f_b}$	Frequency ratio: the closer this gets to 1, the higher is the interaction
$\frac{h_b}{h_s}$	Height ratio for isotropic cities
$\frac{\frac{1}{N}\sum_i^N h_{ib}}{h_s}$	Height ratio for anisotropic cities
$\frac{\sum_i^N \sigma_{bi}}{S}$	Urbanization ratio: sum of the area of the building footings divided by the city area. An index for the group effects.
$2\sum_i^N \frac{\sigma_{bi}}{S}\cdot\frac{h_{bi}}{h_s}\cdot\frac{f_s^2}{f_{bi}^2}$	Kinematic energy ratio: brings together the main parameters for SCI effects.
$\frac{m_b\omega_b}{\Sigma\,\rho_s c_s}$	Impedance ratio: the larger this contrast, the larger the energy ratio.

These indices (Table 2) have been demonstrated to give a general estimation of the SCI effects in past studies. However, the city model remains in the linear domain in most of these studies. To include the structural damages of the buildings in a SCI scenario, transient analyses are necessary, which require a high computational effort.

We believe that a way to deal with this problem is to couple the nonlinear MDOF models for urban areas (Xu, Chen et al. 2008) and the LPM models for the through-the-soil interaction(Mulliken and Karabalis 1970, Mulliken and Karabalis 1998). This allows simplified practical SCI analyses based on the few key variables, which serve properly the purpose of detecting optimal urban configurations for damage scenarios, without compromising the required accuracy.

The LPM are based on geological data, which are available for most cities worldwide. From geometry and material properties, considerations about wave propagation phenomena can be extracted. In particular, the frequency-domain impedance functions for adjacent foundation within the influence radius of a building, can be computed numerically with existing methods (Mykoniou, Taddei et al. 2012, Radisic, Mueller et al. 2014, Radišić, Petronijević et al. 2017). The impedance functions are then used for calibrating the mechanical models for the soil, also called lumped-parameter models (LPM)(Radišić, Petronijević et al. 2017, Taddei, Schauer et al. 2017).

The main assumptions are: 1) the coupling between structure is determined for each mode of vibration independently of the other degrees of freedom; 2) the static stiffness of each foundation-soil system is not affected by the presence of adjacent buildings; 3) the coupling forces at one foundation due to the displacement at an adjacent foundation occur after a certain time, which depends on the seismic wave speed. Figure 3 shows the resulting LPM-MDOF model of a typical cluster of buildings subjected to a seismic motion field. This model is able to deliver the main parameters listed Table 1 and Table 2.

The LPM-MDOF treats the soil as a special boundary which can reproduce the through-the-soil interaction of the buildings directly in time domain. His coefficients are calibrated upon physical impedance functions but have no physical meaning and cannot be used to reproduce the nonlinear behavior of the soil.

A possible improvement of the LPM-MDOF model for a nonlinear soil is the extension of the LPM through an additional one-dimensional nonlinear spring in each direction of motion. Typical approaches for the estimation of the nonlinear force-displacement law of these springs are the Masing's rule (Masing and Mauksch 1925, Iwan 1967), the Ramberg-Osgood models (Ramberg and Osgood 1943, Maotian 1992) or hyperbolic models (Seed, Wong et al. 1986).

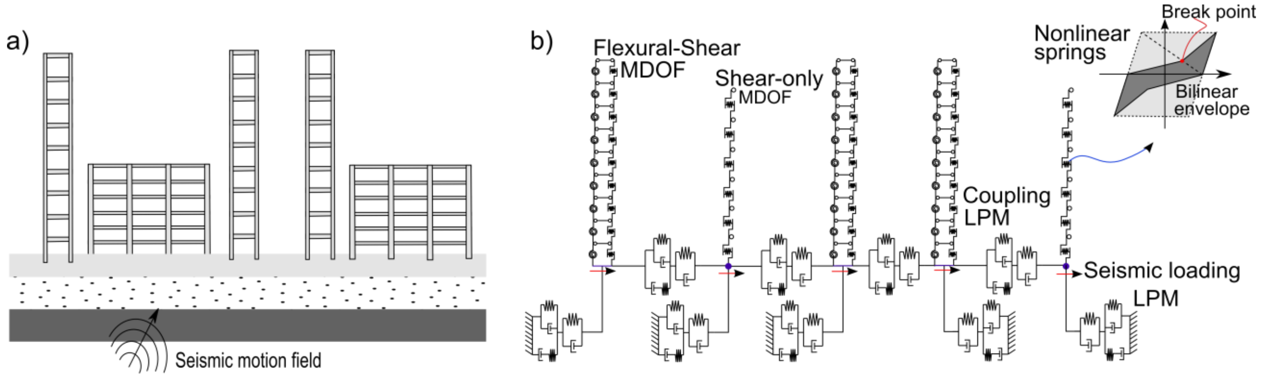

Figure 1. a) Urban scenario; b) Nonlinear discrete model for site-city interaction

4. SUITABILITY OF THE LPM/MDOF MODELS FOR SCI NONLINEAR ANALYSES

The SCI effects can be extrapolated from site-city simulations as the difference between the response of an isolated building (SSI) and a group of building (SCI) lying on the same soil and subjected to the same spatially variable (site effects) seismic ground motion.

To assess the suitability of the LPM-MDOF model for SCI analysis, we summarized the main effects due to the site-city interaction demonstrated in previous studies and experiments.

For idealized homogenous, linear and regular (or periodic) cities lying on a single layer fixed at its base, general conclusions can be drawn:

1) The ground motion and the building amplification spectra of the deformations are reduced. The denser the city, the stronger is this reduction, thanks to the group effects. The mean roof displacements, averaged over the response of all the city buildings, deviate from that of an isolated building at the center of the city by no more than 20%.
2) In frequency domain, the resonant peaks of the ground motion get split into two peaks due to the city resonance, when the frequency of the soil gets closer to the frequency of the buildings. These resonant peaks correspond neither to the building's resonant frequency nor to the soil resonant frequency.
3) Higher frequencies get desynchronized. The transfer function of the building and the variability of the motion increases linearly with frequency. At higher frequencies, the group effects of the SCI effects reduce while the SSI effects increase, due to the geometrical damping.
4) Also in time domain, lower accelerations are observed. Beating effects, constructive and destructive interferences of the waves travelling between the structures are also observed. These effects depend on the impedance contrast between buildings, foundations, soil layer and underlying half space or bedrock. Duration lengthening and reduced spatial coherency are observed.
5) A coherent wave propagates outwards from the city. At the city border area, the ground amplitudes increase significantly leading to "edge effects" even with values of 50% with respect to isolated building scenarios. This may be relevant for small buildings built right at the periphery of a dense city, which may be subjected to the edge large motions. The edge effects can explain unusual phenomena in seismological recordings nearby dense cities.
6) From the combination of SSI, SCI and site effects, the latter represent the most significant contribution and it depends on the variability of the seismic field. In other words, the difference between the maximum and the minimum relative response of the various buildings of the city can be mainly attributed to the spatial variability of the ground motion. This spread increases as the separation between buildings increases. This aspect does not depend on the SCI model, but it is the result of the large-scale wave propagation from the seismic source to the SCI domain. We assume, that the computation of the spatially variable free field is known and can be directly applied to the LPM-MDOF at the site-city interface.

Real city scenarios are in general irregular and exhibit different characteristics in different direction, leading to a three-dimensional problem.

The following conclusions can be drawn for irregular cities:

1) The top surface motion gets depolarized with respect to the input motion at the soil base or bedrock.
2) For a city with a strong geometrical asymmetry, the motion is mainly polarized in the direction of the main strength axes of the city. This property is called directivity and it is mainly related to surface waves.
3) Depolarization decreases or even disappear for out-of-resonance frequencies.
4) The beneficial effects of the SCI are reduced for irregular cities, being the group effect weaker.
5) Still, a general reduction of displacements and deformations can be observed, even if local maxima may exhibit increases with respect to the isolated building.

The more complex becomes the soil profile, the less applicable are the previous conclusion. For non-linear cities, no clear path can be identified, and further studies are necessary.

We believe that all the mentioned aspects can be represented with the discrete LPM-MDOF models. Moreover, the LPM-MDOF model allows the transient representation of nonlinear response of the site-city system models and can deal with spatially variable seismic loadings.

5. CONCLUSIONS AND OUTLOOK

In this contribution, we discussed the current state-of-the-art of experimental evidences and simulation method for site-city interaction analysis for seismic events.

For idealized linear site-city scenarios, several methods have been proposed in the past. However, for realistic complex and non-linear urban areas further studies are necessary.

We propose an idea for a practical nonlinear discrete model for site-city interaction through a Sino-European collaboration. The aim of the collaboration between the Institute of Disaster Prevention and Mitigation of the Tsinghua University Beijing (TUB) and the Chair of Structural Mechanics of the Technical University of Munich (TUM) is to join their complementary knowledge to implement a practical nonlinear simulation method for soil-city scenarios during earthquakes.

We focus on practical lumped parameter models (LPM) for the through-the-soil coupling, which will be coupled to the available urban models. Their coefficients are calibrated so that they simulate the coupled foundation-soil-foundation system, but they do not depend on frequency. Therefore, the LPM can be directly used in time domain for nonlinear analysis. The calibration uses impedance functions computed with semi-analytical methods.

The proposed discrete model, the LPM-MDOF model, is suitable for SCI analysis, because it can trace the main interaction processes between the site and the city during a seismic event. It could be used for preliminary design and for the selection of the most appropriate city structural scheme. The models can provide indicators for improving urban planning and increasing community resilience in case of strong seismic events.

9. REFERENCES

Aldaikh, H., et al. (2015). "Two dimensional numerical and experimental models for the study of structure–soil–structure interaction involving three buildings." Computers & Structures **150**: 79-91.

Assimaki, D., et al. (2005). "Effects of local soil conditions on the topographic aggravation of seismic motion: parametric investigation and recorded field evidence from the 1999 Athens earthquake." Bulletin of the Seismological Society of America **95**(3): 1059-1089.

Assimaki, D. and E. Kausel (2002). "An equivalent linear algorithm with frequency-and pressure-dependent moduli and damping for the seismic analysis of deep sites." Soil Dynamics and Earthquake Engineering **22**(9): 959-965.

Bard, P.-Y., et al. (2008). Site-city interaction. Assessing and Managing Earthquake Risk, Springer**:** 91-114.

Beresnev, I. A., et al. (1998). "Stochastic finite-fault modeling of ground motions from the 1994 Northridge, California, earthquake. II. Widespread nonlinear response at soil sites." Bulletin of the Seismological Society of America **88**(6): 1402-1410.

Bielak, J., et al. (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.

Bonilla, L. F., et al. (2005). "Hysteretic and dilatant behavior of cohesionless soils and their effects on nonlinear site response: Field data observations and modeling." Bulletin of the Seismological Society of America **95**(6): 2373-2395.

Bouchon, M., et al. (1989). "A boundary integral equation-discrete wavenumber representation method to study wave propagation in multilayered media having irregular interfaces." Geophysics **54**(9): 1134-1140.

Boutin, C. and P. Roussillon (2006). "Wave propagation in presence of oscillators on the free surface." International journal of engineering science **44**(3): 180-204.

Castellaro, S. and F. Mulargia (2010). "How far from a building does the ground-motion free-field start? The cases of three famous towers and a modern building." Bulletin of the Seismological Society of America **100**(5A): 2080-2094.

Chávez-García, F. J. and M. n. Cárdenas (2002). "The contribution of the built environment to the 'free-field'ground motion in Mexico City." Soil Dynamics and Earthquake Engineering **22**(9): 773-780.

Clouteau, D. and D. Aubry (2001). "Modifications of the ground motion in dense urban areas." Journal of Computational Acoustics **9**(04): 1659-1675.

Faccioli, E., et al. (1997). "2D and 3D elastic wave propagation by a pseudo-spectral domain decomposition method." Journal of seismology **1**(3): 237-251.

Fernández-Ares, A. and J. Bielak (2004). Interaction between earthquake ground motion and multiple buildings in urban regions. Proceedings of the Third UJNR Workshop on Soil-Structure Interaction, edited by M. Celebi, M. Todorovska, I. Okawa, and M. Iiba.

Ge, Q., et al. (2017). "Shaking table test of dynamic interaction of soil–high-rise buildings." European Journal of Environmental and Civil Engineering **21**(3): 249-271.

Ghergu, M. and I. R. Ionescu (2009). "Structure–soil–structure coupling in seismic excitation and "city effect"." International journal of engineering science **47**(3): 342-354.

Groby, J.-P., et al. (2005). "Simulation of seismic response in a city-like environment." Soil Dynamics and Earthquake Engineering **25**(7): 487-504.

Groby, J.-P. and A. Wirgin (2008). "Seismic motion in urban sites consisting of blocks in welded contact with a soft layer overlying a hard half space: II. large and infinite number of identical equispaced blocks." arXiv preprint physics/0610277.

Gueguen, P. and P.-Y. Bard (2005). "Soil-structure and soil-structure-soil interaction: experimental evidence at the Volvi test site." Journal of Earthquake Engineering **9**(05): 657-693.

Gueguen, P., et al. (2000). "Experimental and numerical analysis of soil motions caused by free vibrations of a building model." Bulletin of the Seismological Society of America **90**(6): 1464-1479.

Hryniewicz, Z. (1993). "Dynamic response of coupled foundations on layered random medium for out-of-plane motion." International journal of engineering science **31**(2): 221-228.

Isbiliroglu, Y., et al. (2015). "Coupled soil-structure interaction effects of building clusters during earthquakes." Earthquake Spectra **31**(1): 463-500.

Iwan, W. D. (1967). "On a class of models for the yielding behavior of continuous and composite systems." Journal of Applied Mechanics **34**(3): 612-617.

Jennings, P. C. (1970). "Distant motions from a building vibration test." Bulletin of the Seismological Society of America **60**(6): 2037-2043.

Jeremić, B., et al. (2009). "Time domain simulation of soil–foundation–structure interaction in non‐uniform soils." Earthquake Engineering & Structural Dynamics **38**(5): 699-718.

Kanamori, H., et al. (1991). "Seismic excitation by the space shuttle Columbia." Nature **349**(6312): 781-782.

Karabalis, D. and M. Mohammadi (1991). "Foundation-soil-foundation dynamics using a 3-D frequency domain BEM." Boundary Elements XIII **13**: 447.

Kausel, E. (1988). "Local transmitting boundaries." Journal of engineering mechanics **114**(6): 1011-1027.

Kausel, E. (2010). "Early history of soil–structure interaction." Soil Dynamics and Earthquake Engineering **30**(9): 822-832.

Kawase, H. (1996). "The cause of the damage belt in Kobe:"The basin-edge effect," constructive interference of the direct S-wave with the basin-induced diffracted/Rayleigh waves." Seismological Research Letters **67**(5): 25-34.

Kham, M., et al. (2006). "Seismic site–city interaction: main governing phenomena through simplified numerical models." Bulletin of the Seismological Society of America **96**(5): 1934-1951.

Khan, S., et al. (2017). "Impact of mesh and DEM resolutions in SEM simulation of 3D seismic response." Bulletin of the Seismological Society of America **107**(5): 2151-2159.

Komatitsch, D. and J.-P. Vilotte (1998). "The spectral element method: An efficient tool to simulate the seismic response of 2D and 3D geological structures." Bulletin of the Seismological Society of America **88**(2): 368-392.

Kontoe, S., et al. (2008). "The domain reduction method for dynamic coupled consolidation problems in geotechnical engineering." International journal for numerical and analytical methods in geomechanics **32**(6): 659-680.

Kumar, N. and J. P. Narayan (2017). "Quantification of site–city interaction effects on the response of structure under double resonance condition." Geophysical Journal International **212**(1): 422-441.

Li, P., et al. (2012). Shaking table model tests on dynamic structure-soil-structure interaction during various excitations. 15th world conference on earthquake engineering, Lisbon, Portugal.

Li, P., et al. (2012). Shaking table model tests on dynamic structure-soil-structure interaction during various excitations.

Liu, J., et al. (2013). "Seismic hazard assessment for greater North China from historical intensity observations." Engineering Geology **164**: 117-130.

Lombaert, G. and D. Clouteau (2009). "Elastodynamic wave scattering by finite-sized resonant scatterers at the surface of a horizontally layered halfspace." The Journal of the Acoustical Society of America **125**(4): 2041-2052.

Lou, M., et al. (2011). "Structure–soil–structure interaction: literature review." Soil Dynamics and Earthquake Engineering **31**(12): 1724-1731.

Ma, S., et al. (2004). "Hybrid modeling of elastic P-SV wave motion: A combined finite-element and staggered-grid finite-difference approach." Bulletin of the Seismological Society of America **94**(4): 1557-1563.

Maotian, L. (1992). "Ramberg-Osgood constitutive model with variable parameters for dynamic nonlinear analysis of soils." Earthquake Engineering and Engineering Vibration **2**: 007.

Masing, G. and W. Mauksch (1925). Eigenspannungen und Verfestigung des plastisch gedehnten und gestauchten Messings. Wissenschaftliche Veröffentlichungen aus dem Siemens-Konzern, Springer**:** 244-256.

Mason, H., et al. (2013). "Seismic soil–foundation–structure interaction observed in geotechnical centrifuge experiments." Soil Dynamics and Earthquake Engineering **48**: 162-174.

Mazzieri, I., et al. (2013). "SPEED: SPectral Elements in Elastodynamics with Discontinuous Galerkin: a non‐conforming approach for 3D multi‐scale problems." International Journal for Numerical Methods in Engineering **95**(12): 991-1010.

Mulliken, J. and D. Karabalis (1970). "Discrete model for foundation-soil-foundation interaction." WIT Transactions on The Built Environment **15**.

Mulliken, J. S. and D. L. Karabalis (1998). "Discrete model for dynamic through‐the‐soil coupling of 3‐D foundations and structures." Earthquake Engineering & Structural Dynamics **27**(7): 687-710.

Mykoniou, K., et al. (2012). "Dynamic foundation-soil interaction: A comparative study." Bauingenieur DACH Bullettin **87**: 9-13.

Nations, U. (2016). The World's Cities in 2016, UN.

Park, S. H. and N. Antin (2004). "A discontinuous Galerkin method for seismic soil–structure interaction analysis in the time domain." Earthquake Engineering & Structural Dynamics **33**(2): 285-293.

Radisic, M., et al. (2014). "Impedance Matrix for Four Adjacent Rigid Surface Foundations." Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014.

Radišić, M., et al. (2017). "Vibrations of Flexible Strip on Viscoelastic Halfspace." Procedia Engineering **199**: 2420-2425.

Ramberg, W. and W. R. Osgood (1943). "Description of stress-strain curves by three parameters."

Restrepo, D., et al. (2014). "SH wave number Green’s function for a layered, elastic half-space. Part I: Theory and dynamic canyon response by the discrete wave number boundary element method." Pure and Applied Geophysics **171**(9): 2185-2198.

Sahar, D., et al. (2015). "Study of role of basin shape in the site–city interaction effects on the ground motion characteristics." Natural Hazards **75**(2): 1167-1186.

Schwan, L., et al. (2015). Multi-building interactions and site-city effect: an idealized experimental model. Experimental Research in Earthquake Engineering, Springer**:** 459-476.

Schwan, L., et al. (2016). "Site-city interaction: theoretical, numerical and experimental crossed-analysis." Geophysical Journal International **205**(2): 1006-1031.

Seed, H. B., et al. (1973). "Soil conditions and building damage in 1967 Caracas earthquake." Journal of Geotechnical and Geoenvironmental Engineering **99**(sm7).

Seed, H. B., et al. (1986). "Moduli and damping factors for dynamic analyses of cohesionless soils." Journal of Geotechnical Engineering **112**(11): 1016-1032.

Semblat, J.-F. and J. Brioist (2009). "Efficiency of higher order finite elements for the analysis of seismic wave propagation." arXiv preprint arXiv:0901.3715.

Semblat, J.-F., et al. (2008). "Seismic-wave propagation in alluvial basins and influence of site-city interaction." Bulletin of the Seismological Society of America **98**(6): 2665-2678.

Solberg, J. M., et al. (2013). Development of a Generalized Methodology for Soil-Structure Interaction Analysis Using Nonlinear Time-Domain TechniquesNEAMS Program, DOE Office of Nuclear Energy (NE-41), Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States).

Taborda, R. (2010). Three dimensional nonlinear soil and site-city effects in urban regions, Carnegie Mellon University.

Taborda, R. and J. Bielak (2011). "Large-scale earthquake simulation: computational seismology and complex engineering systems." Computing in Science & Engineering **13**(4): 14-27.

Taddei, F., et al. (2017). "A practical soil-structure interaction model for a wind turbine subjected to seismic loads and emergency shutdown." Procedia Engineering **199**: 2433-2438.

Tian, Y., et al. (2017). "Regional seismic damage simulation and case study considering site-city interaction." Proceedings of the 26th National Conference on Structural Engineering, Oct.,2017, Changsha, China. .

Todorovska, M. and M. Trifunac (1992). "The system damping, the system frequency and the system response peak amplitudes during in‐plane building‐soil interaction." Earthquake Engineering & Structural Dynamics **21**(2): 127-144.

Trifunac, M. D., et al. (2001). Response of a 14-story reinforced concrete structure to nine earthquakes: 61 years of observation in the Hollywood storage building, University of Southern California, Department of Civil Engineering.

Tsogka, C. and A. Wirgin (2003). "Simulation of seismic response in an idealized city." Soil Dynamics and Earthquake Engineering **23**(5): 391-402.

Wikipedia (2017). "Beijing central business district." Retrieved 12.2017, 2017, from https://en.wikipedia.org/wiki/Beijing_central_business_district.

Wirgin, A. and P.-Y. Bard (1996). "Effects of buildings on the duration and amplitude of ground motion in Mexico City." Bulletin of the Seismological Society of America **86**(3): 914-920.

Xu, F., et al. (2008). "Earthquake disaster simulation for an urban area, with GIS, CAD, FEA, and VR integration." Tsinghua Science & Technology **13**: 311-316.

Xu, J., et al. (2004). Seismic response prediction of NUPEC's field model tests of NPP structures with adjacent building effect. ASME/JSME 2004 Pressure Vessels and Piping Conference, American Society of Mechanical Engineers.

Xu, Z., et al. (2014). "Seismic damage simulation in urban areas based on a high-fidelity structural model and a physics engine." Natural Hazards **71**(3): 1679-1693.

Yano, T., et al. (2003). Model test on dynamic cross interaction of adjacent building in nuclear power plants overall evaluation on field test. Proceedings of the 17th International Conference on Structural Mechanics in Reactor Technology.

Yoshimura, C., et al. (2003). "Domain reduction method for three-dimensional earthquake modeling in localized regions, part II: Verification and applications." Bulletin of the Seismological Society of America **93**(2): 825-841.