QUANTITATIVE METHODS IN ARCHAEOSEISMOLOGY

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Abstract: *Within the multidisciplinary field of archaeoseismology, quantitative methods have begun to be utilized more prevalently. We propose a scheme of applying quantitative models to test the seismogenic hypothesis of observed damages. The combination of 3D structural models of buildings or their remains based on phase shift laser scanner measurements with high resolution digital images allow the construction of damage and/or deformation inventory and assists the archaeological work during an excavation. 3D surface meshes derived from the same scan data are the basis for Finite or Discrete Element models of the structures. The effect of site-specific earthquake-related ground motions, other natural causes, and anthropogenic influences, are simulated and compared with the damage inventory. However, due to the high level of complexity of the problems no definite answers should be expected from quantitative models in all cases.*

Key words: *Quantitative Methods, archaeoseismology.*

INTRODUCTION

The early approaches in the relatively young field of archaeoseismology were qualitative, consisting mainly of descriptions of observed damages in archaeological excavations and were often highly speculative with regards to the damage processes. Increasingly, quantitative models have recently begun to be employed. Galladini et al. (2006) summarized complete archaeoseismic studies in a flow chart, emphasizing quantitative models as crucial tools to validate or eliminate a seismogenic hypothesis, which usually forms the basis for an archaeoseismic investigation. In Fig. 1, we propose a scheme that concentrates on archaeoseismic problems in which off-fault ground motions are the suspected cause of damages to manmade structures. We apply this scheme in two projects: the Archaeological Zone Cologne, Germany and the ancient Lycian City of Pinara, SW Turkey.

LASER SCANNING

Advanced 3D laser scans combined with high-resolution digital photographs allow detailed damage analysis even for cases where the stability of the excavated objects, safety or the lack of time prevents a thorough classical archaeological documentation. (An example will be given in the accompanying paper of Schreiber et al., 2009). Using the phase shift instead of travel time of the laser beam allows very rapid data acquisition with several million points per minute and results in a resolution of 1-2 mm in the 0.5 to 75 m distance range.

While we combine individual scans, perform signal-enhancing filtering and combination with color photos with the Reconstructor software tool, standard CAD and GIS tools are used to set up the damage inventory. Parallel to this inventory and based on the same raw data, orthophotos, crosscuts and 3D mesh surfaces are constructed. In excavation-parallel studies, as in the above-mentioned Cologne field case, the scanned images

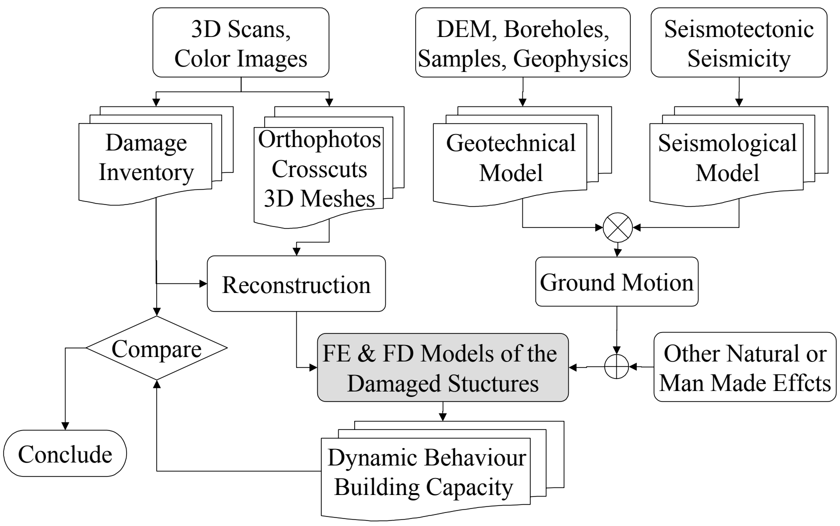

Fig. 1: Schematic flow chart of quantitative archaeoseismic modelling.

are a valuable addition to the routine archaeological work and essential for the reconstruction of heavily damaged structures. The 3D mesh surfaces are processed and transformed into Finite Element or Discrete Element models of the structures under consideration.

GEOTECHNICAL MODEL

Subsoil behaviour during earthquake-like ground motion loading can have a profound influence on damages. Even buildings with a high structural resistance to vibration loading can be heavily damaged if ground failure occurs, as is suspected for the Cologne field case. Based on contemporary DEM reconstructed from 370 boreholes, explorations, penetration tests, and geotechnical in situ and laboratory measurements 2D models are evaluated with the GeoSlope program in terms of static and dynamic slope stability and liquefaction potential. The detailed geotechnical models of the Tertiary and Quaternary *softrock* layers also help to determine site-specific seismic ground motions.

GROUND MOTION MODEL

The seismotectonic regime of the region under consideration and active fault maps provide the framework to deduce potential seismic sources. Standard seismological procedures such as the calculation of Greens functions and subsource models can be used to calculate synthetic seismograms for extended earthquake sources including appropriate rupture simulation (Fig. 1). In regions where strong motion records of recent earthquakes are available, these can be used to calibrate the models.

In addition to the computation of synthetic earthquake-related ground motions, the realization of input time functions for testing non-seismogenic causes is necessary. In the accompanying paper by Yerli et al. (2009), the possible effects of looters using explosive charges and levers is discussed. The effects of these possible causes should be compared to earthquake loading for the case of Arttumpara's sarcophagus in the ancient Lycien city of Pinara, SW Turkey.

STRUCTURE MODEL

In the central part of the flowchart in Fig. 1 is the model of the damaged structure. Classical Finite and Discrete Element models (FE and DE models) provide insight into the static and dynamic behaviour of buildings in whole or in part. FE models allow the formulation of elastic and non-elastic deformations of dynamically loaded structures and the determination of building capacities. DE models are based on the assumption of rigid bodies, coupled by visco-elastic forces, and allow calculation of block trajectories even if the structure disintegrates due to the strength of the loading. The third accompanying paper by Hinzen (2009) shows possibilities and limits in the application of DE models applied to columns and a simple block wall.

CONCLUSION

The nature of the damage-causing effects as a result of numerical test series is compared with the damage inventory. Under favourable conditions, the damage pattern of archaeologically-excavated structures can reveal enough information to conclusively test a seismogenic hypothesis or narrow down the parameter range of the ground motions. However, a detailed damage inventory and precise measurements of the structure(s) are necessary. Often the site conditions are crucial and have to be included in the determination of site-specific strong motion seismograms. Due to the high level of complexity of the problems, no unambiguous results can be expected from all quantitative models. Large efforts are necessary to narrow down the manifold model parameters enough that clear conclusions can be postulated. In some cases, changes and alterations during the period since the damage occurred might even make this impossible.

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