Archaeoseismology - How quantitative does it have to be?

Klaus-G. Hinzen, Cologne University, Germany

Historical- Palaeo- and Archaeoseismology

By utilizing quantitative and qualitative methods to determine parameters for preinstrumental earthquakes, the nascent field of achaeoseismology fills in gaps between the well-established disciplines of historical seismology and palaeoseismology. Historical seismology and macroseismic methods were developed long before the first adequate seismological instruments were available. Recently developed advanced quantitative macroseismic methods provide tools for deriving earthquake parameters including location, strength and source dimensions (e.g. Bakun and Wendworth, 1997; Gasperini et al., 1999). Earthquake catalogs based on historic data and advanced macroseismic methods are the backbone of any seismic hazard analysis. Reaching back to pre-historic times, in some regions only a few centuries BP, the palaeoseismic discipline has evolved into a vital field only since the 1980s. However, due to the laborious field and lab work, only a few earthquake zones, like New Madrid, have been studied extensively enough to extend the earthquake catalog significantly. In other areas, including the intraplate earthquake zones in Europe, much work still needs to be done to reach comparable levels of completeness. Even though both historic and palaeoseismology can generate appropriate earthquake parameters for catalogs and hazard studies, historical catalogs generally contain only a few percent of the damaging earthquakes for any particular region (Ambraseys et al., 2002), and paleoseismology is limited to events producing visible effects in the surface geology.

The younger discipline of archaeoseismology has been traditionally more descriptive and frustratingly vague, especially concerning quantitative information about the damage-inducing seismic sources. Ever since man-made structures have been erected, earthquakes have left their marks on these constructions. But damages in archaeologically excavated buildings or continuously preserved monuments are often hard to unravel in terms of the causative effects. The use of archaeological data to investigate unknown or poorly known historical earthquakes and descriptions of earthquake effects recorded in the archaeological heritage started in the 19th and early 20th century. (e.g. De Rossi, 1874; Evans, 1928; Agamennone, 1935). It is only since the 1980s that increased interest in the subject led to the publication of special volumes and articles in seismological and geological journals (e.g. Guidoboni, 1989; Stiros and Jones, 1996; McGuire et al., 2000; Galadini et al., 2006; Reicherter et al., 2009). While earlier investigations were dominated by qualitative descriptions of damages and common sense arguments pro or contra a seismogenic cause, more recent studies follow a quantitative approach.

The main questions to be answered by archaeoseismic investigations are:

(1) how probable is seismically induced ground motion, or secondary earthquake effects, as a cause of damage observed in man-made structures from the past,
(2) when did the damaging ground motion occur, and
(3) what can be deduced about the nature of the causing earthquake?

When all three questions can be answered successfully, archaeoseismology helps to extend the earthquake records of a region and eventually improve the hazard estimate. A pro of achaeoseismology is that it directly deals with earthquake damages on buildings, usually what hazard studies try to minimize.

Historical data and archaeoseismic investigations must be carefully integrated. As outlined by Niemi (2008), circular referencing should be strenuously avoided. Correlating archaeological findings with a historically reported earthquake matching the often large time window for a proposed archaeo-earthquake may be manifest but not necessarily correct. Due to the ambiguity between site intensity, earthquake size and epicentral distance, ascription of archaeo-damages to a certain historic event can lead to a tremendous overestimation of the earthquake source size.

Archaeoseismic Observations

The marks in ancient structures relevant for archaeseismology fall into four main categories (Galadini et al., 2006):

(1) Displacements along shear planes directly linked to the earthquake fault plane or side branches of it. In particular, earthquakes with strike slip mechanisms can leave distinctive traces in buildings and lifelines like aqueducts, roads, and sewer systems (Figure 1). Case studies (e.g. Meghraoui, 2003, Ellenblum et al., 1998) show that under favorable conditions the amount of slip, and for repeated events the slip rate, of the faults can be revealed.

(2) Off fault shaking effects including fractured building elements, tilted walls, shift of building elements, lateral warping, breaking and overthrow of walls, rotations of vertically oriented objects (tomb stones, columns, monuments), spalling of block corners due to stress concentration (Figure 1). For most of these features a seismogenic origin is not the only possible interpretation. Therefore, alternative causes must be taken into account during the damage analysis (Nikonov, 1988).

(3) The secondary shaking affects lateral spreading and cyclic mobility as a consequence of subsurface liquefaction (e.g. Hinzen and Schütte, 2002). Liquefaction requires a certain level of dynamic excitation. So secondary damages in buildings and monuments due to liquefaction help exclude alternative causes from a damage scenario. Similar to palaeoseismology, these clear dynamic effects help to classify fault movements as coseismic.

(4) Archaeologically detected abandonment of a site and evidence of repair and rebuilding. These observations are mainly of interest in when observed with other indications of earthquake damage, because as isolated observations, they generally do not provide enough conclusive evidence for a seismogenic cause (Galadini et al., 2006). In addition, they are very hard to quantify.

While the first category is limited directly to the quasi-linear features of active faults, off fault shaking affects a much larger area. Damages due to shaking are therefore the main targets of archaeoseismic studies. Even though they are more common, they are harder to reveal. Ancient structures show deformations related to seismic shaking similar to those observed in recent earthquakes. Typical earthquake effects on masonry walls are (1) cross fissures nucleating at corners of doors and windows and driven by shear forces, (2) corner expulsion of walls caused by differential movements in orthogonal directions, (3) horizontal and independent lateral and rotational shift of wall blocks, best visible in uncemented walls of rectangular blocks, (5) spall of block corners due to stress concentrations during shaking, (6) height reduction by vertical crashing, (7) movement of keystones and rupture of arch piers, (8) rotation of vertically oriented objects, and (9) domino-like toppling of structured columns and walls (see Figure 1).

Most of these deformations may also originate without dynamic earthquake excitation. Therefore, a single piece of evidence, or evidence available only at a single edifice, cannot be considered a conclusive sign of an earthquake. Seilacher (1969) introduced the term ‘seismite’ for sedimentary layers showing the effects of earthquake shaking. Following this definition of a coseismic disturbance, I call the above-mentioned effects on archaeologically excavated structures in the following ‘archaeoseismites’. If sound arguments are found for one or several of these archaeoseismites (1-8) at an archaeological site, the challenge remains to translate these into meaningful quantitative measures of ground motion.

Quantitative Models in Archaeoseismology

Current earthquake engineering models are used to quantify the vulnerability of buildings. Connatural methods and models applied in archaeoseismology help to back- calculate the nature and strength of ground movements which may have caused the documented damages. For a systematic approach we suggest a scheme structured in four main parts (Figure 2): (1) precise documentation of the findings including a damage inventory and 3D laser scan models supplying the foundation for a virtual reconstruction, (2) determination of site specific strong ground motions as well as dynamic load functions for non-earthquake causes, (3) the evaluation of the dynamic behavior of damaged structures, and (4) deducing the damaging ground motion characteristics and the uncertainty ranges (Hinzen et al. 2009).

In contrast to current engineering problems, in archaeoseismology it cannot be distinguished a priori whether findings are truly archaeoseismites or whether other natural forces (flooding, storm, mass movement) or even human action were the real cause. Therefore, besides the modeling of earthquake ground motions, a common tool in engineering seismology, motions or forces of other nature might have to be tested. An example for alternative possible causes of deformation is a Lycien sarcophagus (Figure 3) located in the ancient city of Pınara, southwest Turkey. This structure shows a clockwise rotation of 5.37° with respect to its North-South oriented foundation (Figure 1(K)). Considering the seismotectonic potential of the area, this rotation had been attributed to earthquake ground motion. However, the sarcophagus contains a crater in the eastern side of the coffin most probably caused by the detonation of an explosive charge during looting. Dynamic tests with a rigid block model (Figure 3(C)) of the sarcophagus show only minimal rotations for even large earthquake ground motions. The back-calculated size of the blast, on the other hand is sufficient to explain the observed rotation.

A further difficulty arises when the reconstruction of a damaged archaeo-building is complicated. Uncertainties in knowledge of the original construction increase the uncertainties of the causative ground motions. Examples are the columns of a Byzantine church in Sussita, located above the Lake of Galilee. The nearly perfectly aligned toppled columns of the ‘Great Cathedral’ at Sussita (Figure 1(C)) suggest an earthquake as the causing event. The previously proposed correlation of the column orientation and the ground motion direction is a common sense interpretation, however has not been verified. A study of the dynamic behavior of three part columns exposed to measured 3-dimensional earthquake ground motions, show rather arbitrary downfall directions and a strong influence of the column’s top load, stronger than that of the ground motion polarization (Hinzen, 2010).

Summary

The use of quantitative methods in archaeoseismology, including calculation of synthetic site-specific strong motion seismograms, modeling of natural non-earthquake-related forces, anthropogenic forces, and finite or discrete element models of structures, supports conclusive discrimination between potential damage scenarios. However, if model parameters cannot be well constrained, modeling result uncertainties might still be too large to draw definite conclusions. Common sense interpretations of archaeoseismites as solitary evidence are generally too vague to complement earthquake catalogs for a seismic hazard analysis. Recent advances in ground motion simulation methods and computational possibilities promise to refine quantitative archaeoseismological methods and establish them at levels equal to historical and palaeoseismologial methods. Finally, even if an archaeoseismic study does not deliver the often-requested improvement of hazard determination, it can still advance our picture of the past by attempting to answer open archaeological, historical and geologic questions in a scientific manner.

References

Agamennone, G. (1935). Come e quando rovinò il tempio di Venere Genitrice. Boll. Soc. Sism. It., 33, 89-91.

Ambraseys, N.N., J.A. Jackson and C.P. Melville (2002). Historical Seismicity and Tectonics: The Case of the Eastern Mediterranean and the Middle East. In: International Handbook of Earthquake and Engineering Seismology (edited by Lee, W. H. K., Kanamori, H., Jennings, P. C. and Kisslinger, C.). International Geophysics Series 81A. Academic Press, Amsterdam, 747-763.

Bakun, W.H. and C.M. Wentworth (1997). Estimating earthquake location and magnitude from seismic intensity data. Bull. Seism. Soc. Am., 87, 1502-1521.

De Rossi, M.S. (1874). La basilica di Santa Petronilla presso Roma, testé discoperta, caduta per terremoto. Bull. Vulc. It., 1, 62-65.

Evans, A. (1928). The Palace of Minos, part II, London, 844 pp.

Ellenblum, R., S. Marco, A. Agnon, T. Rockwell, T., and A. Boas (1998). Crusader castle torn apart by earthquake at dawn, 20 May 1202. Geology, 26, 303-306.

Galadini, F., K.-G. Hinzen, and S. Stiros (2006). Archaeoseismology: methodological issues and procedure. Journal of Seismology, 10, 395-414.

Gasperini, P., F. Bernadini, G. Valensise and E. Boschi (1999). Defining seismogenic sources from historical earthquake felt reports. Bull. Seism. Soc. Am., 89, 94-110.

Hinzen, K.-G. and S. Schütte (2002). Evidence for earthquake damage on Roman buildings in Cologne, Germany. Seismological Research Letters,74, 121-137.

Hinzen, K.-G., C. Fleischer, S. K. Reamer, S. Schreiber, S. Schütte, and B. Yerli (2009). Quantitative methods in archaeosesimology, in: R. Pérez-López, C. Grützner, J. Lario, K. Reicherter, and P.G. Silva (eds.), Archaeoseismology and Palaeoseismology in the Alpine-Himalayan Collisional Zone, Baelo Claudia, Cadiz Spain, 50-51.

Hinzen, K.-G., 2010. Sensitivity of earthquake toppeled columns to small changes in grond motuin and geometry. Submitted: Israel Journal of Geosciences.

Meghraoui, M., F. Gomez, R. Sbeinati, J. Van der Woerd, , M. Mounty, A.N. Darkal, Y. Radwan, I. Layyous, , H. Al-Najjar, R. Darawcheh, F. Hijazi, R. Al-Ghazzi and M. Barazangi (2003). Evidence for 830 years of seismic quiescence from palaeoseismology, archaeoseismology, and historical seismicity along the Dead Sea Fault in Syria, Earth Planet. Sci. Lett., 210, 35-52.

McGuire, W.J., Griffith, D.R., Hancock, P.L. and Stewart I.S., (eds.) (2000). The archaeology of geological catastrophes, Geological Society Spec. Publ. no. 171, London, 417 pp.

Niemi, T. (2008). Historical earthquake catalogues and archaeological data: Avoiding circular reasoning. Seismological Research Letters, 79, 289.

Nikonov, A.A. (1988). On the methodology of archaeoseismic research into historical monuments. In: Engineering Geology of Ancient Works (edited by Marinos, P. G. and Koukis, G. C.). Balkema, Rotterdam, 1315-1320.

Reicherer, K., A.M. Michetti and P.G. Silva (eds.) (2009). Palaeoseismology: Historical and praehistorical records of earthquake ground effects for seismisc hazard assessment. Geological Society, London, Special Publications, 316, 324 pp.

Seilacher A. (1969) Fault-graded beds interpreted as seismites. Sedimentology, Elsevier, Amsterdam, 13, 155-159.

Stiros, S.C. and Jones, R.E., (eds.) (1996). Archaeoseismology, British School at Athens, Fitch Laboratory Occasional Paper 7, 268 pp.

Figure 1: (A) Horizontally deformed wall of a crusader fortress build on top of the Dead Sea Transform Fault in the Jordan Valley; (B) deformed vault of a Roman sewer in Cologne, Germany; (C) toppled columns of a Byzantine church in Sussita located above the Sea of Galilee; (D) toppled column of the great palace in Patra, Jordan; (E) moved block in an arch of the Nimrod fortress in the Golan Heights; (F) shifted blocks of an analemma of a Roman theatre in Pınara, SW Turkey; (G) moved blocks of a corner wall of a Roman monument in Patara, SW Turkey; (H) shifted blocks of a Roman grave house in Pınara, SW Turkey; (I) spall of block corners, same object as in (G); (J) broken and horizontally displaced fortification wall of the Roman Tolbiacum (Zülpich, Germany); (K) rotated Lycien sarcophagus in Pınara, SW Turkey.

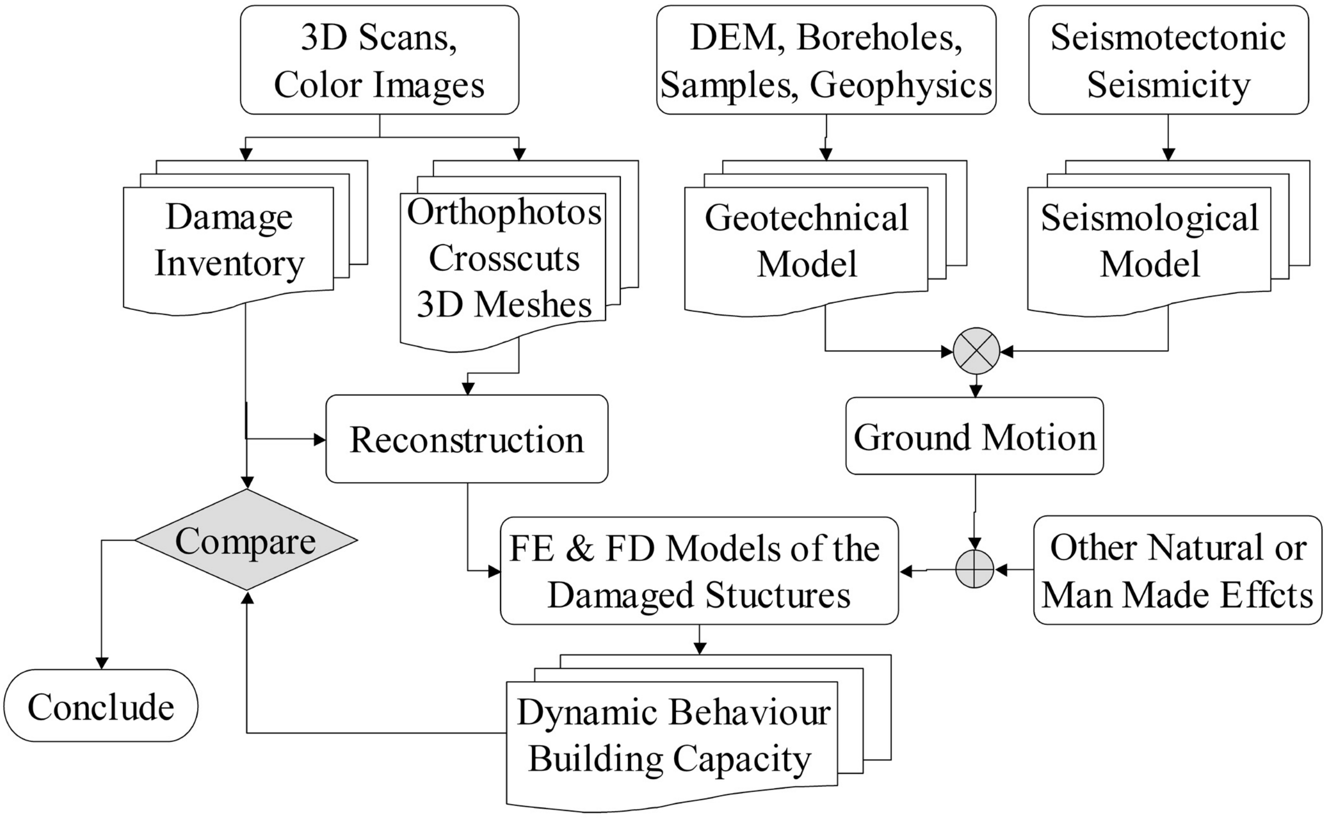

Figure 2: Schematic flow chart of quantitative archaeoseismic modeling.

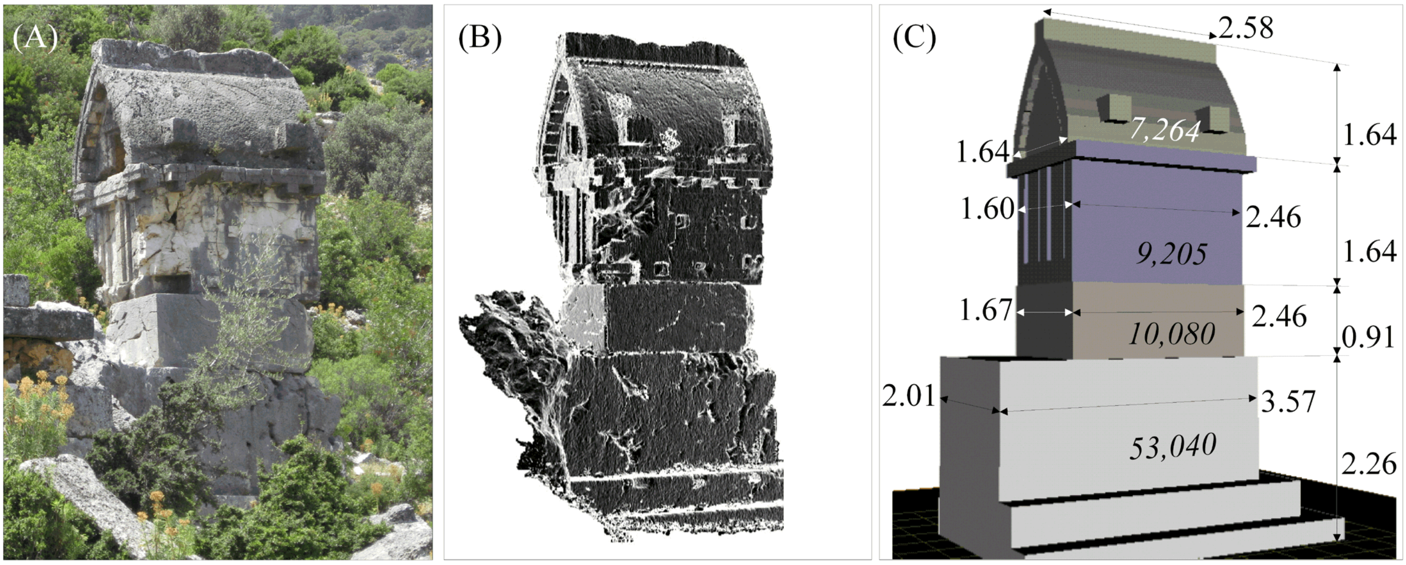

Figure 3: (A) Photo of a Lycien sarcophagus in Pınara, SW Turkey, with a blast crater on the eastern side of the coffin and which is rotated 5° out of its original position (s. Figure 1(K)). (B) Cloud of 11 Mio. 3D points measured with a phase-laserscanner, and (C) rigid block model with measures in m and kg, basis for dynamic stability studies.