The ruin of the Roman Temple of Kedesh, Israel; example of a precariously balanced archaeological structure used as a seismoscope

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ABSTRACT
In certain regions and under favorable geologic conditions, precariously balanced rocks may form. These types of unusual formations have been used to estimate yield ground motions. Because such balanced rocks have not been “unbalanced”, they can be used as a rough estimate for ground motions which have not been reached or exceeded since the balanced formation achieved its contemporary state. We hypothesize that other ancient manmade structures, delicate in terms of stability and particularly those that have survived earthquake ground motions intact, can be used in the same manner. We therefore suggest that these structures act as local seismoscopes which might be capable of determining maximum upper ground motion bounds. We apply the concept of the study of precariously balanced rocks to the ruin of the Roman Temple of Kedesh, located in close proximity to a branch of the Dead Sea Transform Fault. The delicate-looking ruin was surveyed with a 3D laser scanner. Based on the point cloud from that survey, a discrete element model of the remaining temple wall was constructed. To test the stability of the model we used 54 analytical ground motion signals with frequencies ranging from 0.3 to 2 Hz and PGAs between 1 and 9 m/s². These calculations reveal two failure mechanisms. Additionally, ground motions of eight earthquakes, including two assumed local earthquake scenarios, five historical earthquakes of the region and one strong motion record of the 1999 Taiwan Chi Chi earthquake have been used to test the hypothesis. None of the simulated earthquakes (assumed or historically documented) toppled the ruin; only the strong motion record collapsed the structure. The simulations reveal a surprisingly high stability of the ruin of the Roman Temple of Kedesh mainly due to the small height to width ratio of the remaining walls. However, ground motion with large PGAs at a low frequency range in EW direction does collapse the remains of the temple.

1. Introduction
Following the definition by C.F. Richter [1958], a seismoscope is a device which indicates the occurrence of an earthquake but does not write a record. In the second half of the 19th and early 20th century a wide variety of such instruments were designed; some were even still in use in the middle of the 20th century [Hinzen and Kovalev 2010]. However, not only specifically designed instruments are capable of measuring the occurrence (or absence) of an earthquake; nature herself created numerous natural seismoscopes in the form of precariously balanced rocks (PBRs) [e.g. Brune 1996, Anooshehpoor 2004]. In certain geologically preferred conditions, e.g. in California and Utah, numerous such rocks have formed. The basic concept to use these PBRs as seismoscopes is (1) to measure their shape; (2) determine a yield force or acceleration which would be necessary to topple the PBR; (3) estimate the amount of time the formation exists in its present appearance; and (4) estimate the upper limit of ground motion level (often expressed as peak ground acceleration, PGA) which has not been exceeded in this time span.

Nature has formed such seismoscopes, but they are not unique. Many ancient manmade structures are so delicate that it seems unlikely, from appearance alone, that they can remain standing even under static conditions (Figure 1). As is customarily the case in archaeoseismology, hypothesized earthquake-ruined ancient constructions are the major focus of interest, and in quantitative studies [Galadini et al. 2006, Hinzen et
al. 2009a] ground motion parameters are estimated in order to determine how and under what circumstances the constructions were damaged [Hinzen 2005, Ambraseys 2006, Hinzen 2012, 2013]. Additionally, structures such as those shown in Figure 1 can also be used as seismoscopes. We address this hypothesis and refer

Figure 1. Examples of precariously balanced archaeological structures: (a) ruin of the Roman harbor bath in Ephesus, Turkey; (b) pre-Roman rock cistern at Patara, Turkey; (c) ruin of Montfort Crusader castle, Israel; (d) Lycien sarcophagus Xanthos, Turkey; (e+f) Mycenaean corbeled vault, Tiryns, Greece; (g) ruin of Cyclopean wall of Tiryns, Greece; (h) Roman mausoleum Pınara, Turkey; (i+k) ruins of Roman bath Pınara, Turkey; (l) delicate Roman arch, Patara, Turkey; (m) ruin of the Roman Temple, Kedesh, Israel.
to such formations in the following as precariously balanced archaeological structures (PBASs). In order to draw conclusions about the earthquake activity in a region, or more precisely, the vibration history of a certain site, the same four steps have to be followed for the PBASs as in case of the PBRs. One advantage of the PBASs is that often the archaeological context provides more precise estimates of the time span of their existence. On the other hand, the time spans of PBASs are in general much shorter than those of PBRs. And, as the PBASs tend to be more complex than single block PBRs, sophisticated measuring and modeling is necessary to evaluate the yield ground motions. An advantage of this approach in quantitative archaeoseismology as opposed to examining ancient structures that are not PBASs, is that the often difficult task of ascertaining the pristine form of a structure before the damaging earthquake occurred is not necessary. The PBASs have to be ‘merely’ analyzed in their current form.

In this study, we use the ruins of a Roman Temple in Kedesh (Figure 1m), Israel, located some 4 km west of a branch of the Dead Sea Transform Fault (DSTF), to perform the aforementioned four steps with an emphasis on step (2) the determination of the vulnerability of the ruin. We use a Discrete Element Model (DEM) based on a 3D laser scan in combination with analytic ground motions, synthetic site specific seismograms for seven earthquake scenarios, and one measured strong motion record.

2. Geology, Seismotectonic, Seismicity

The DSTF (Figure 2) is the dominating tectonic feature in Israel and neighboring countries Jordan, Lebanon and Syria. The DSTF separates the Arabian plate in the east and the Sinai subplate in the west. Formed in the early Miocene, the DSTF transitions into the opening of the Red Sea (RS) Rift in the south to the Bitlis-Zagros collision zone of Arabia and Eurasia in the north [Quennell 1956, Freund et al. 1968]. Early Miocene geologic features are offset 105 km [Quennell 1956, Freund 1965, Bartov et al. 1980], indicating that the long term sinistral slip rate of 4-6 mm/year is very similar to short term geodetic rate [Wdowinski et al. 2004, Gomez et al. 2007, Sadeh et al. 2012]. The DSTF in Israel and Jordan is divided into segments named according to the valleys, from south to north: the Araba Valley (AV), the Jordan Valley (JV), and the Hula Valley (HV). These valleys connect the Gulf of Aqaba, the Dead Sea (DS) and the Sea of Galilee (SG), all pull-apart basins along the DSTF (Figure 2).

North of the SG and in the HV, the faults branch into several non-parallel faults. SE-NW shortening characterizes the Lebanese Restraining Bend north of the HV. The DSTF has been seismically active since the Miocene. The instrumental record includes mainly weak to moderate-sized earthquakes [Hofstetter 2014]. In 1954, the first seismological station of Israel was installed at the Hebrew University of Jerusalem (JER). Earlier, stations in Athens, Istanbul and Cairo registered earthquakes in Israel. In the 1980s with the Israel Seismic Network (ISN) and the Jordan Seismological Observatory (JSO), two networks with short period stations were established. Over time, the networks have been upgraded with accelerometers and broadband stations. Occasionally, temporary networks were used to monitor the seismicity of the DSTF [Hofstetter 2014].

The catalogue of the Geophysical Institute of Israel (GII) lists 6821 earthquakes with magnitudes above 2.0 between 1900 to 2015 (http://www.gii.co.il last accessed 09.2015) (Figure 2). The recorded seismicity is concentrated in five spatial clusters. The first cluster, in the RS area in the south, exhibits widespread earthquake activity. Further north, the second cluster of epicenters in the AV aligns close to the DSTF. In the third cluster at the DS, the epicenters again show a wider distribution. The last two clusters are located at the JV and the HV section of the DSTF including the SG.

Recently, Wetzler and Kurzon [2016] relocated regional earthquakes of the last 30 years. The depth distribution of the relocated events shows a maximal depth of 35 km and a peak of the distribution at 15 km. The strongest instrumentally recorded earthquake in 1993 occurred near Nuweiba [Baer 1999, Klinger 1999, Shamir 2003] with an MW 7.2 (Figure 2). In 1927, a M5.6 earthquake occurred on the western coast of the DS [Shapira 1993, Zohar and Marco 2012] and in 1956 an M5.6 occurred at the SG, close to the Mediterranean coastline south of Beirut (http://www.gii.co.il last accessed 09.2015).

The pre-instrumental earthquake activity of the Levante has been intensively investigated based on the area around the DSTF which is rich in cultural tradition including an abundance of historical documents and old masonry structures. In numerous historic, palaeo- and archaeoseismological studies, evidence of past earthquakes have been researched and catalogs for the last 2000 years compiled [e.g. Garfunkel 1981, Ben-Menahman 1991, Ambroseys and Barazangi 1989, Klinger et al. 2000a, Migowski et al. 2004, Wdowin-
ski et al. 2004, Marco et al. 2005a, Marco and Klinger 2014, Ellenblum 2015. In total, 31 pre-instrumental earthquakes could be identified (Table 1).

3. Kedesh Temple, History and Structure

The Roman Temple of Kedesh was constructed as a long lasting project through the 2nd and 3rd century CE. It is located on a mound 25 km north of the SG and 4 km east of the HBF (Figure 2), a western branch of the DSTF. The original temple area included a cella, the inner chamber of the temple, of 20.66 m x 22.63 m and a portico and was encircled by a large temenos [Fischer et al.1984]. It has been aligned east-west with the entrance facing east just opposite the main entrance of the temenos. Its well-worked ashlars are made of limestone and dolomite [Fischer et al. 1984]. Mortar was not used to support the construction.

The only persisting standing walls are two sections of the temple front (Figure 1m, Figure 3a). The roof and the rest of the temple walls are missing though a rather large amount of tiles found in the excavation points to the roofing of the temple or at least part of it. Parts of the cella foundation are still visible. The two remaining sections of the front wall are separated by a 3.33 m gap of the former ceremonial gate. The northern and southern sections have a remaining height of 7.26 m and 3.59 m respectively. Each section includes a smaller entrance for worshippers. The southern door-jamb of the main gate is still in situ; however, the northern one and the lintel are missing. Both wall-sections are double shell ashlar masonry, and some ashlars are oriented orthogonal to the wall trend and connect the shells to increase stability. The wall is pseudoisodomic, i.e. within rows all ashlars are of equal height, but among rows the heights differ. The northern wall has a concave bend to the east. The blocks at the foundation of the structure are currently buried in the ground and the foundation line is not leveled over the length of the construction. Sediments from a slope dipping from north to south have buried some blocks of the northern wall (Figure 3a).

Fischer et al. [1984] suggest the temple was destroyed by an earthquake on May 19, 363 C.E. Unearthed ceramics and coins show that the temple was abandoned after the earthquake. An early photo of the ruin (Figure 3d) taken by Kitchener during his Survey
of Western Palestine (1871 - 1878), shows that most parts of the temple were already missing at that time. Comparing the photo, which was published in Conder and Kitchner [1882] (Figure 3d), with the current state (2013) of the structure (Figure 3c) reveals some alterations to the southern wall. The ashlars highlighted in Figure 3d have vanished over the past 14 decades. As none of the ashlars can be found next to the wall and they were likely easily accessible to looting, it can be assumed that they were taken from the site for secondary use. Some archaeologists assume that the whole temple was used as a quarry after it was abandoned as evidenced by large fragments of the temple found atop the Tel Kedesh, the ancient city, and in some of the set-

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Table 1. List of on-fault palaeoseismic investigations at the DSTF system arranged by year of publications [after Marco and Klinger 2014]. Bold letters indicate earthquakes used to simulate ground motions in this study.*unless indicated different all dates are Common Era (CE).
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lements of the surrounding. Fenner [1905] has documented that local inhabitants wanted to annoy scientists studying the temple by trying to overturn some blocks. With this background, it is not possible to differentiate with certainty which damage is of anthropogenic or of natural cause. However, the wall in Figure 3a shows horizontal shifts and gaps between the ashlars which indicate that, at least in part, dynamic shaking has ruined the Kedesh Temple. In particular, we interpret the gaps between the ashlars in the northern section and its bend as the consequence of earthquake ground motions.

4. Modeling

Laser scanning technology has become a common tool in archaeoseismology [Schreiber et al. 2012, Fleischer et al. 2010, Hinzen et al. 2012]. It combines the advantages of fast, non-invasive field application, high precision, and safe and easy measuring of distances, angles, surfaces and volumes. For the PBAS of the Roman Temple of Kedesh, we used a phase scanner set up at 24 locations (including the top of the temple) to capture the complete structure with only minor shadowing effects. Vegetation close to the walls was removed to create an undistorted view, particularly to the foundation line of the structure. Checkerboards and 0.25 m diameter spheres were used as markers for referencing the scans. The resulting 3D model of the temple has a mean target tension of 0.0026 m and contains more than 80 million points. Figure 4 shows a view from the West towards the point cloud of the virtual model of the ruin and the corresponding perspective view to the DEM. One challenge in designing and displaying the scans was the double wall nature of the temple front requiring painstaking attention to detail in order to gather sufficient data for reconstruction of the inner wall. A total of 141 ashlars were identified from the point cloud in combination with the digital photographs. The 3D coordinates of the vertices of these ashlars were determined. Individual blocks in the model have between 8 and 24 vertices. The size ranges from 0.06 to 2.62 m³, resulting in a mass of 151 to 6306 kg estimating a uniform density of 2400 kg/m³.

After the raw modeling of the ashlars, fine-tuning to precisely align corners of adjacent blocks was neces-

Figure 3. (a) View from west towards the remains of the Roman Temple of Kedesh. The northern and southern sections have heights of 7.26 m and 3.59 m, respectively. The door-jamb at the southern section is 4.4 m high. (b) View from the south to the northern section showing the gap between the two shells. (c) Photo showing the current state of the southern section of the ruin (Photos: Schweppe). (d) Photo by Kitchener from ‘The Survey of Western Palestine’ [Conder and Kitchener 1882]. The red highlighted ashlars are missing today.
sary to avoid any unrealistic penetration of one block into another which would lead to unrealistic stresses in the DEM and instability or even uncontrolled ‘explosion’ of the model. Ashlars with complex structure had to be combined from several simply structured shapes, so that all of these by themselves were of concave shape. This important precondition was necessary to ensure edge detection and provide collision control in some DEMing codes.

The first version of the model was created in 3DEC (see data and resources) a software initially written for rock-mechanical applications and based on the discrete element method by Cundall [1988], Hart and Cundall [1988], Cundall and Hart [1992]. 3DEC’s built-in scripting language is a powerful tool for model creation and simulations. Custom written routines facilitated importing the vertices, surveyed with the laser scan, and created the according blocks. In 3DEC, advanced rock mechanical properties can be applied to the discrete objects. To analyze the dynamic behavior of structures with models containing numerous objects, the damping parameters must be set to rather low values to achieve a reasonable runtime [Psycharis et al. 2003]. Otherwise, the time-steps for calculation cycles become impractically small. Due to the low damping parameters, the objects become bouncy and the options of monitoring internal movement and collapse mechanisms are therefore limited.

As shown by Hinzen and Montabert [this issue] the software development tool UNITY (see data and resources) is capable of modeling the dynamic behavior of wall-type structures including their internal deformation and collapse pattern. For verification, the authors compared the calculated movement of a rocking block with the equations presented by Housner [1963] and the average amplitude misfit for the first 25 extremal values of the displacement of the rocking block was 0.7 %. They found a time step of 0.001 s as suitable for such calculations. Compared with 3DEC, UNITY is lacking many of the rock mechanical features. However, UNITY, originally developed for game design, it is highly customizable. To detect collision between two objects, colliders are assigned to each object. If a collision is detected, contact points between the two shapes are generated. The energy dissipation during a collision

Figure 4. Top: Ortho-view of the laser scan point cloud of the ruin the Roman Temple of Kedesh from west towards east. Bottom: Same view to the discrete element model of the temple remains.

Figure 5. (a) Time-series of a cycloidal pulse with a frequency of 0.3 Hz @ PGA of 3 m/s², (b) Acceleration response spectra of 54 cycloidal impulses used to test the dynamic behavior of the model of the Roman Temple of Kedesh.
is defined by a coefficient of restitution, in our case 0.86; friction follows a coulomb friction model. With UNITY it is possible to observe the collapsing structure and internal deformation with a reasonable calculation time not least due to its GPU processing capabilities. The model, composed of 142 discrete objects, containing 141 ashlars and the baseplate, was exported from 3DEC and subsequently converted with Blender (see data and resources) into a UNITY-readable file-format. To represent the buried ashlars at the foundation of the ruin, the according objects in the model were fixed to the baseplate by setting the break force of the joints to infinity. The dynamic and static coefficient of friction for all other joints between the blocks was set to 0.6.

5. Calculations

Analytic ground motion signals in form of cycloidal pulses [Zhang and Makris 2001] were chosen for a first series of test calculations. These signals have previously been applied in archaeoseismology [Hinzen 2009b, Hinzen and Montabert this issue]; they fulfill the boundary condition of zero displacement, velocity and acceleration at the start of the calculations and zero velocity and acceleration at the end. The displacement history can be seen as a simple version of a horizontal ground motion close to a strike slip fault [Hinzen and Montabert this issue]. The response spectra of the 54 impulses which were applied only in the horizontal directions (parallel and orthogonal to the wall trend) are shown in Figure 5. Major frequencies of the signals were in the range from 0.3 to 5.0 Hz and PGA ranged from 1 to 9 m/s².

Further, eight earthquake scenarios were used, five of which resemble historical earthquakes along the DSTF, two are local speculative events in the HV in close proximity to the Kedesh site, and the last signal is a measured strong motion record of the M 7.7 Chi Chi earthquake in Taiwan. The 1999 Chi Chi earthquake was chosen (1) because it was recorded in close proximity to the epicentre; (2) earthquakes with M 7.7 are possible in the study region; and (3) the large PGA provided a chance to double-check if the model does simulate failure of the remains cor-

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Table 2. Parameters of two assumed earthquakes (†), five historic earthquakes along the DSTF and in addition a strong motion record (*) from the 1999 Taiwan earthquake.
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Table 2 summarizes the parameters of the earthquakes which were modeled with one to three fault segments. All segments were assumed to have left-lateral movement as the DSTF in total. The second segment of the 749 JVF earthquake has a dip of 70°; all other segments in the model dip with 90°. The largest of the historical earthquakes dated to 1202 had a $M_W$ of 7.6. The rupture is modeled along three fault segments following the Jordan Gorge Fault (JGF), the Hula Valley Central Fault (HCF) and the Yammouneh Fault (YF). The epicenters of the assumed and historical earthquakes are shown in Figure 2 (b,c).

Green’s functions were calculated on the basis of a crust model by the Geophysical Institute of Israel (GII) [2013] and the earthquake source is represented by an arbitrary number of rectangular dislocation planes [Wang 1999]. The geometry for each segment was simplified from the maps shown in Figure 2 and the seismic moment was estimated based on the surface rupture length following Wells and Coppersmith [1994]. Subsources are distributed on each segment following a Gutenberg Richter law. Figure 6 shows the synthetic displacement and acceleration seismograms of the seven scenarios as well as the corresponding response spectra.

Figure 6. Displacement and acceleration time series and acceleration response spectra of the earthquake ground motions used in the calculations. The earthquake source code given in the upper left of each figure corresponds to the list in Table 1. In addition magnitude and minimum distance to the surface trace of the faults ($D_{\text{min}}$) are: HBF $M_w$ 5.76, $D_{\text{min}}$ 4.2 km; HCF $M_w$ 5.85, $D_{\text{min}}$ 7.9 km; JVF $M_w$ 7.39, $D_{\text{min}}$ 32.5 km; YF $M_w$ 7.62, $D_{\text{min}}$ 6.4 km; JGF $M_w$ 6.14, $D_{\text{min}}$ 13.6 km; RaF $M_w$ 7.06, $D_{\text{min}}$ 21.7 km; RoF $M_w$ 6.8, $D_{\text{min}}$ 9.0 km; Tai, $M_w$ 7.7.
6. Results

Figure 7 shows snapshots of the simulation with a cycloidal pulse with a PGA of 3 m/s² and frequency 0.3 Hz applied as ground-motion orthogonal to the wall trend (the simulation is available as animation in the electronic supplements to this article). The movement of the pulse lasts 3.3 seconds. In this specific case two failure mechanisms affect the two wall sections. The southern (smaller) wall is falling in the direction of the ground-motion during its stopping phase (denoted as first failure mechanism in the following). The northern wall topples in the opposite direction, due to the inertial forces during the starting phase of the pulse (second failure mechanism).

In order to quantify the effect of the ground motions, we monitored the motion of the center of geometry of all ashlars during the time window of the modeling, which lasted 7 s for the analytic impulses and 10 s longer than the earthquake records in order to allow all moving ashlars to settle. The length of a vector connecting the original position of each ashlar with its final resting position, i.e. the modulus of displacement vector (MDV) [Hinzen 2009b, Hinzen and Montabert this issue] is used as a measure for the overall deformation. In Figure 8 the MDVs of all ashlars are shown together with a summary of their distribution in form of box plots of the MDVs separate for the northern and southern section of the wall.

As an example, the results using an impulse with 0.3 Hz frequency and 3 m/s² PGA are given in Figure 8 (a). Figures 8 b,c summarize the results of 54 tests in a matrix of six frequencies and nine PGAs. They show that higher ground motion amplitudes are necessary to topple the walls when the frequency of the impulses increases; a diagonal is separating the damaged from the surviving cases. It is also evident that the northern (taller) wall is more vulnerable at lower frequencies than the southern (smaller) wall. For a PGA of 1 m/s², no toppling occurs at frequencies between 0.3 and 2 Hz; at 2 m/s², the northern wall topples while the southern wall survives the test. The toppling occurs to the left which is the direction of the ground motion (directed from east to west), i.e. the first failure mechanism. The next row of plots in Figure 8 for a PGA of 3 m/s² shows a changeover of the toppling to the right, i.e. the second failure mechanism. However, as at frequencies above 0.3 Hz and PGA above 3 m/s², the shorter wall still undergoes first mechanism failure. At larger PGAs the frequency increases at which the change of the failure mechanism from the first to the second occurs in case of the smaller wall. The transition from the first to the second failure mechanism occurs at 0.4 Hz by 5 m/s². At 0.5 Hz, the ashlars of the smaller wall fall to both sides, indicating that this parameter combination falls just in-between the two failure modes at PGAs between 5 - 7 m/s². The experiments with a frequency of 1 Hz show that here the smaller wall starts toppling at 4 m/s² with the first failure mechanism, while the larger wall topples at 6 m/s² with the second mechanism. In some cases, close to the diagonal of the matrix in Figure 8 separating the collapse from non-collapse (e.g. 5 m/s² @ 1 Hz), a few
falling ashlars indicate the higher vulnerability of the edges of the walls. At the higher frequencies of 1.5 Hz and 2 Hz, a clear increase of the internal deformation with increasing PGAs is expressed by the increasing median values of the MDVs for both wall sections. However, only a few ashlars from the edges fall down at the largest PGAs tested.

As expected, the vulnerability of both walls is much smaller for ground motion in a north-south direction, parallel to the wall trend (Figure 8b). Here PGAs above 6 m/s² are necessary to initiate major collapsing of ashlars. While the downfall directions for the smaller wall are varied, the majority of toppling blocks from the higher wall fall in the direction of the ground motion, indicating the first failure mechanism. It is noticeable that at PGAs of 4 and 5 m/s², blocks start dropping out of the smaller wall, a result which is not observed in case of the taller wall.

None of the simulated earthquake ground motions initiates a collapse of the ruin; only internal deformation of the model is observed. As shown in Table 2 for the historical earthquakes JVF, JGF, RaF and RoF, the largest PGA occurs consistently in the north-south direction, the direction in which the walls are least vulnerable (Figure 8). Furthermore PGAs do not exceed 4 m/s². The only exception is the largest
historical earthquake (YF) where the largest PGA of 5 m/s² occurs in the east-west direction. The response spectra of the event YF (Figure 6) show that the acceleration response peaks between 3 and 6 Hz; at lower frequencies the acceleration response is below 1 m/s².

For comparison, the recorded strong motion of the 1999 Chi Chi earthquake, with PGAs exceeding 7.0 m/s² in both horizontal components (Table 2), collapses the remains of the Roman Temple (Figure 9). The response spectra of the Tai earthquake (Figure 6) show acceleration responses at 0.5 Hz above 5 m/s² in the horizontal directions and the peaks at a value above 10 m/s².

7. Discussion and Conclusions

The investigation of precariously balanced rocks is an established method to determine the vibration history of a site and to arrive at reasonable conclusions about the seismic activity of a region. In this study, we apply the same concept to a precariously balanced archaeological structure: the ruin of the Roman Temple of Kedesh. The temple was surveyed with a 3D laser-scanner. Based on this survey, a discrete element model was created to study the dynamic behavior of the ruin. In addition to 54 analytic ground motion signals (cycloidal pulse) with frequencies ranging from 0.3 Hz to 2 Hz and PGAs from 1 m/s² to 9 m/s², ground motions from eight earthquake scenarios were applied to the model. Two of these are assumed events in close proximity to the ruin; five of the scenarios resemble historical earthquakes of the region documented through archaeo- and palaeoseismological research; the eighth ground motion is a strong motion record from the 1999 Taiwan Chi Chi earthquake.

Simulations with analytical signals reveal two different failure mechanisms: (1) the wall collapses in the direction of horizontal ground motion during the stopping phase of the cycloidal pulse; (2) the wall is falling due to the high inertial forces in the opposite direction of the ground motion. The performance of a wall depends strongly on the ratio between its height and width (h/w-ratio). As expected, the northern wall with the larger h/w-ratio is more vulnerable to lower frequencies than the southern (smaller) wall.

It is important to emphasize the conclusion that none of the simulated historic earthquakes toppled the temple remains. The actual ground motion at the Kedesh site might have differed somewhat from our forward model, but if the ground motions would have been significantly stronger than in our model, the ruin would have suffered further damage.

At first sight it might be surprising how stable the remains of the Roman Temple of Kedesh are. However, the h/w-ratio of the two wall sections is small compared to most single shell walls. It is hard to give an exact measure due to the varying width at the base of the walls and the differing height; however, an h/w-ratio can be estimated to 6.5 and 3.2 for the larger and smaller wall sections, respectively. The larger wall reaches the maximum height of 7.26 m only at its center (Figures 2, 3, and 4) and with the last complete row of ashlars at a height of about 5 m, the effective h/w-ratio in the dynamic tests might be as small as 4.5. As pointed out by Hinzen and Montabert [same issue] the h/w-ratio of a simple free standing wall is at least as important for its dynamic stability as the geometry of the blocks by which it is formed. Some of the Inca walls described as earthquake resistant had h/w-ratios below 3
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res 2014). Therefore, we conclude that the remains of the Kedesh Temple achieve their relative low vulnerability from small h/w-ratios of both wall sections.

The dynamic response of the original temple building has to be assumed to be substantially different from that of its current remains, and therefore it cannot be postulated with certainty that the earthquake of May 19, 363 C.E. transformed the temple from an intact state directly to its current configuration. In addition to (relatively mild) weathering and erosion over the centuries, recent looting has altered the temple structure, and it can be hypothesized with some confidence that many more human alterations occurred in the preceding 1653 years. On the other hand, it is plausible that the front wall of the temple proved to be its most earthquake resistant part. The double shell nature of the wall, the h/w-ratio, and its north-south orientation contributed to the temple’s survival of the historic earthquakes of the region. Also, the two hypothetical earthquakes in the Hula Valley (HBF and HCF in Table 2) did not topple the temple remains. In conclusion, based on our model, we cannot exclude that such earthquakes have happened during the past one and a half millennia. The comparison with a measured strong ground motion from the 1999 Chi Chi earthquake in Taiwan on the other hand shows that such a strong load exceeds the strength of the temple remains. The probability of toppling of the Kedesh Temple ruin during earthquake ground motion depends on frequency prevailing direction and amplitude. In general, according to the simulations, low frequencies at 1 Hz with PGAs of 6 m/s² and above in EW direction would collapse both sections. So in conclusion, if the ruin came to its current appearance during the destruction of the temple in 363 C.E. a PGA of 6 m/s² has probably not been reached at the site during any earthquake in the past 1650 years.

Under the aspect of preservation of cultural heritage, the results from this study are reassuring. Even a reoccurrence of one of the strong historic earthquakes is not as threatening to the Kedesh Temple ruins as it might be to other important archaeological structures in the area.

In this study only one interesting structure from the vicinity of the DSTF was studied. An extension of the suggested approach to other (more or less) precariously balanced archaeological structures in the area can help to gain additional information about past seismicity and the nature of ground motions in this interesting region. One of the chief advantages of this approach is that no reconstruction of an archaeological structure is required. This type of process therefore reduces uncertainties in the archaeoseismological modeling process and, similar to the case of precariously balanced rocks, ground motion levels can be estimated which have not been exceeded during certain time periods.

8. Data and Resources

The initial DEM model was created in 3DEC 5.0, Itasca Consulting Group. 3DEC Universal Distinct Element Code. Minneapolis, USA, 1998. With Blender (v. 2.77a), a 3D modelling and rendering package, Blender Online Community, Blender Foundation Blender Institute, Amsterdam, the initial model was transformed in a format readable by UNITY (v. 5.3.5f1), Unity Technologies Ltd. Photo editing was done with Gimp 2.8 (http://www.gimp.org/, last accessed April 2015).

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