The Lycian sarcophagus of Arttumpara, Pınara, SW Turkey: Testing seismogenic and anthropogenic damage scenarios

Abstract
A Lycian sarcophagus located in the ancient city of Pınara, southwest Turkey, shows a clock-wise rotation of 6.37° with respect to its north-south oriented foundation. Considering the seismotectonic potential of the area, this rotation has been attributed to ground motions caused by earthquakes. A 3D model of the sarcophagus is presented here, based on 11.5 million points from a 3D laser scan. The sarcophagus shows a crater in the eastern side of the coffin, which was most probably caused by the detonation of an explosive charge during looting. As the direction of the rotation agrees with the sense of motion expected from a blast, it is attempted to quantify whether the rotation has a natural, seismogenic origin or an anthropogenic cause. With a rigid block model the feasibility of an explosion or earthquake ground motion was studied as the reason for the rotation of the coffin. Scaled recorded ground motions from local earthquakes and a strong-motion record from the recent L’Aquila, Italy, earthquake (Mw 6.3) were used to study the dynamic reactions of the sarcophagus. The calculations show that the geometry of the structure requires large peak ground acceleration amplitudes to initiate rocking (above 4 m/s²); this rocking in turn is necessary to produce rotation around the vertical axis by translational movements. The size of the explosion is back-calculated from the crater size and compared with duration and amplitude of an impulse necessary to rotate the coffin. The small rotations resulting from all earthquake simulations and the plausible explosion size necessary to rotate the coffin by the observed amount make an explosion a much more probable cause for the rotation of the sarcophagus than an earthquake.

6.1 Introduction
The cause of damages observed on archaeological sites and preserved monuments is often hard to determine unequivocally. Various types of natural causes may result in very similar damage patterns (Galadini et al. 2006), while actions carried out by man can also produce similar looking damages or deformations (Nikonov 1988). If objects of archaeoseismological studies are being excavated in context in an ongoing project, it can be excluded that major anthropogenic actions of damaging have not occurred since the burial of the objects. With regard to the natural causes, it can be said that, unless located directly on a fault zone, earthquake ground motions that affected the location after the burial of the objects in general are not responsible for significantly altering such buried objects. However monuments and sites, which have been visible and accessible at the surface since their construction, could have suffered subsequent damage or deformation. In addition, anthropogenic alterations also could have occurred throughout the history of these monuments and sites including restorations, superposition of more recent buildings, and architectural modifications to permit a different use (Galadini et al. 2006).

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1 This Chapter has been adapted with minor textural alterations from Hinzen K-G, S Schreiber & B Yerli 2010b. The Lycian Sarcophagus of Arttumpara, Pınara, Turkey: Testing Seismogenic and Anthropogenic Damage Scenarios, Bulletin of the Seismological Society of America 100 (6), 3148-64. The paper was added to this thesis, because the archaeological, geological, and historical background information of the Pınara site, which forms an essential and substantial (~ 60%) part of this study, was performed by the author of this thesis.
Prominent examples of such monuments are the Parthenon in Athens and the Colosseum in Rome. Compared with such large architectonical structures for practical use, grave houses, large sarcophagus, and other structures of necropolises are less likely to be rebuilt or used for other purposes. However, numerous examples show that such structures were often the target of looters, sometimes just subsequent to the construction, sometimes late in the history of the object.

In cases where natural and man-made causes of damage or deformation have to be taken into account (Guidoboni 2002, Ambraseys 2005, Galadini et al. 2006), both kinds of disturbances should be modelled and parameterized. This also entails constructing the appropriate parameter space to test the plausibility of the competing hypotheses.

An interesting and promising site to test competing hypotheses is the ancient city of Pinara in southwestern Turkey, which has an occupational history extending back at least to Lycian times (5th century BC). Up to now, the Pinara site has not been systematically excavated. In the 1970s Wurster and Wörrle (1978) documented the current condition of the site in detail. Yerli et al. (2011) have addressed the potential of Pinara for archaeoseismic studies. The site of Pinara is located along the fault-controlled western border of the Eşen Basin, near the modern village of Minare (Fig. 41). The archaeological site is spread over a 3 - 4 km² area (Fig. 42), that includes a variety of exposed geological units (Fig. 43). Different kinds of damage exist in Pinara: (1) vertical cracks and joints of numerous beams, doors, and window frames; (2) undulated walls; (3) a reconstructed temple wall that has been destroyed and rebuilt at least two times; (4) slid blocks of masonry arch; (5) slid blocks of a Roman grave house; (6) collapsed edge of a Roman theatre; (7) rotated blocks of its analemma, the retaining wall of the auditorium; and (8) toppled and rotated sarcophagus.

Figure 41 Seismicity of south-western Turkey. Epicentres of historical earthquakes from 2100 BC to 1959 AD from Tan et al. (2008) are indicated by light colour circles; for those with $M \geq 6$, the year is also given ($M_w$ was used if available, otherwise $M_s$ and $m_b$ are given). Seismicity (1960 - 2008) indicated by dark circles is from the International Seismological Center online bulletin. Instrumental earthquakes with $M \geq 6$ are indicated by filled circles. Triangles and diamonds indicate broadband and short-period seismic stations, respectively. A circle shows the location of Pinara and other places mentioned in the text. The white rectangle in the insert in the lower right corner indicates the location of the main map within the Eastern Mediterranean.
Many of these deformations and damages indicate possible seismogenic causes (Stiros & Jones 1996, Galadini et al. 2006, Marco 2008, Sintubin & Stewart 2008). Yerli et al. (2011) found an inclination of the Roman theatre of 0.81°, which was interpreted as a result of a movement of a local fault. Among the rotated features in Pınara a large well preserved Lycian sarcophagus is built at a pronounced topographic location at the northern slope below the city wall (Fig. 43). This sarcophagus exhibits possible earthquake related deformations as well as signs of an explosion.

The ca. 4 m high sarcophagus construction is deformed, and the upper two massive limestone blocks have been rotated ca. 6° clockwise with respect to the base block. On the rotated coffin, a cone-shaped structure is visible that we interpret as the result of an explosion. The possibility of an explosion was first mentioned in a footnote in the paper by Wurster and Wörle (1978).

Rotations of ancient objects have been described for major columns and colonnades in Greece and Rome; examples are the Theseion Temple in Athens and Colona Antonina in Rome (e.g. Stiros 1996). In these cases, earthquakes were identified as the cause for the alterations of the monuments. In this study a laser scanning technique is used to set up a precise 3D model and quantify the deformations of the sarcophagus of Arttumpara. This model is transformed into a numeric rigid block model, which is then in turn used to test two damage scenarios including the application of explosives for looting purposes and earthquake ground motions.

6.2 The Pınara site

6.2.1 Topographic, geological and tectonic setting

The ancient city of Pınara (36.508° N, 29.258° E) is located at the western flank of the Eşen Basin on the eastern Kargos (Babadağ) mountain range near the modern village of Minare in south-western Turkey. The strong changes in topography gave (and still give) the city a unique character. Elevation changes are from 300 to 765 m. Figure 42 shows a digital elevation model of the terrain at Pınara and its surroundings. Most striking is a steep cliff covered with hundreds of pigeonhole type graves directly carved into the northeast-southwest trending ~ 80 m high fault surface in the limestone basement rock. A deep creek cuts through the basement from west-southwest to east-northeast and separates the southern necropolis from the city (Fig. 42).
The largest part of the city was built on a down-faulted limestone basement block, except for the Roman theatre, which was built on a Pleistocene terrace that rests on top of the flysch (Fig. 43). The basement flysch was most likely used for agricultural purpose. These geographic conditions provided fertile soil, water, and also a protected location against enemy attacks. The strong changes in topography are due to different geological units and faults, which are exposed at the Pınara site (Fig. 43). The city is situated on Lycian Nappe basement rocks and Pleistocene terraces in the Eşen Basin, which is part of the Fethiye-Burdur Fault Zone (BFMZ; Barka & Relinger 1997). The basement along the western margin consists of Cretaceous limestone nappes and early Miocene flysch with exotic components. These Lycian Nappe units with pre-late Miocene thrust-contact were down-faulted along the subparallel basin margin normal faults. Tilted Miocene-Pliocene alluvial and fluvial deposits with an erosional unconformity overlie the basement rocks. The slightly tilted Pleistocene terrace deposits are overlying the basement and Miocene-Pliocene basin fill with an angular unconformity (ten Veen 2004, Alçıçek 2007).

The tectonic structure of south-western Turkey is characterized by many different faults that attach southward to major fault zones related to the Hellenic and Cyprus subduction zones (Eyidoğan & Barka 1996, ten Veen & Kleinspehn 2002, 2003, ten Veen 2004). The FBFZ covers many subparallel fault segments roughly in the area between Fethiye and Burdur. The variation of deformation and their orientations indicate that basically three different tectonic regimes took place in the FBFZ from late Miocene till Holocene (ten Veen 2004, Alçıçek 2007, ten Veen et al. 2009). The recent seismic activity (Fig. 41) in the FBFZ includes large earthquakes ($M \geq 6$), particularly in north-eastern and south-western extremities (Rhodes 1957; offshore Turkey 1926, 1969, 1975, 1980, and 2001; Burdur 1914; Afyon-Dinar 1925; Dinar 1995), but the central part of the FBFZ shows no significant events (Fig. 41). The strongest earthquake among these was the 26 June 1926 earthquake offshore east of the Island of Rhodes with $MS 7.4 \pm 0.3$ (Ambraseys & Adams 1998). Due to the intermediate depth of this earthquake (115 km), it did not produce excessively large intensities (Ambraseys & Adams 1998) with maximum of intensity 8 (MSK) at the coastline and 7 further inland (e.g. Fethiye). The tectonic activity east of Rhodes was studied by Kontogianni et al. (2002) based on coastal uplift observations. They see evidence for a magnitude 7.8 earthquake that occurred after 227 BC and five smaller ($M \approx 7.4$) earthquakes associated with a major reverse fault running offshore along the coast of Rhodes. However, archaeoseismological studies in the central segment of the FBFZ, for example, Sagalassos (Sintubin et al. 2003, Similox-Tohon et al. 2006), Hierapolis (Hancock & Altunel 1997), and Cibyra (Akyüz & Altunel 2001), indicate that destructive earthquakes have occurred in that area in historic times.

Yerli et al. (2011) have shown that Pınara, an ancient city on the tectonically complex FBFZ, is a suitable target for archaeoseismological studies. The western margin of the Eşen Basin is characterized by north-northeast - south-southwest trending normal faults. Within the western basin margin faults, the Pınara segment of Kabaağaç fault is passing through the ancient city and separating the necropolis (pigeon tombs) from the rest of the city.

6.2.2 History and archaeological setting
According to the ancient records, colonists from Xanthos founded the city of Pınara between the fifth and fourth century BC. It was one of the largest cities in the influential Lycian league and was located on the main Lycian road (Akurgal 1978). In the course of time, the city was under Roman and Byzantine control. The city has been struck by three major earthquakes in 141 AD (Guidoboni 1994, Lang 2003, Akşit 2006), in ~240 AD (Lang 2003, Akşit 2006), and in 1851 (Soysal et al. 1981). Pınara received financial aid for the reconstruction of the city after the first two earthquakes during the Lycian occupational period (Wurster & Wörrle 1978, Guidoboni 1994, Lang 2003, Akşit 2006). In the 9th century AD the ancient city of Pınara lost its strong influence and importance in the Lycian league; by the end of the ninth century the city was abandoned. Nowadays, a modern village called Minare replaced Pınara just two km away from its remains.
The sarcophagus of Arttumpara (Fig. 44), who probably was a Lycian king (Wurster & Wörrle 1978), shows several traces of damage and deformation. On the southern front of the lid an original rectangular opening of 0.3 x 0.4 m was widened to 0.7 m to ease access to the coffin chamber.
Weathering of the broken front indicates that this damage is significantly older than the traces of an explosion, which was detonated at the upper left corner of the eastern side of the coffin (Fig. 45a). The use of explosives was first mentioned by Wurster and Wörrle in a footnote of their 1978 paper. For a clear terminology, we call the whole structure in the following Attumpara’s sarcophagus and the individual parts base block, coffin, and lid as indicated in Figure 44.

The coffin is rotated clockwise around the vertical axis by an angle of 6.37° and measured at its north-eastern corner shifted by 0.025 m to the south (Fig. 44). While the location of the explosion (Figs. 44 and 45) in general agrees with the rotational movement, it was not a priori clear whether a blast was sufficient to rotate the coffin to its present position or earthquake ground motions caused the movements. Kozák (2009) reviewed historical examples of earthquake rotational effects. He found that the majority of rotational effects in the epicentral zone were mainly induced by shallow earthquakes. If reactivation of the FBFZ (Fig. 43) is assumed as the earthquake’s source, the Pinara site is centred in the mesoseismal zone at a Joyner-Boore distance of 0 km.

Figure 44  a: Photo of the current (May 2009) situation of the site of Attumpara’s sarcophagus. The view is toward the northeast; b: Detail of the rotated coffin in a northerly view; the explosion crater is labelled; c: Close-up view of the explosion crater on the eastern side of the coffin; d: 3D perspective from the southeast to the laser-scan model of the explosion crater with a vertically oriented surrounding box measuring 1.5 x 0.95 x 0.5 m. A hole in the coffin wall, produced by the explosion, is visible (Photos K-G Hinzen).
A second general observation by Kozák (2009) is that mostly vertically oriented objects, such as chimneys, obelisks, and tombstones, are affected by rotations. Translational ground motions easily cause rocking of such slender structures; during rocking, rotation can be induced around the vertical axis (Hinzen, unpublished manuscript 2010). While the sarcophagus of Arttumpara initially gives the impression of a vertically oriented object, the foundation is not part of the movable structure. Additionally, the centre of gravity of the movable parts is below the geometric centre of the structure because of the hollow coffin and lid (Fig. 46).

6.3.1 3D laser-scan model
The sarcophagus was scanned from 10 different positions with a phase-shift laser scanner from distances of 3 to 10 m with a distance resolution of 0.6 mm. The horizontal and the vertical resolution of the laser-scan model (LSM) were 0.5 mm and 6 mm, respectively, at a distance of 10 m. The 10 individual point clouds were combined to a composite model of the sarcophagus and its surroundings of 100 million 3D-points and to a submodel of Arttumpara’s sarcophagus with 11.5 million points (Fig. 45).

From this model the geometry was measured, and where necessary, missing parts were virtually restored. Damages were analyzed in detail. The rotation of the coffin versus the base block was measured as the angle between two virtual planes fitted to the eastern walls of the coffin and the base block to +6.37° (Figs. 45 and 46). The volume between the base of the current crater in the upper left of the eastern side of the coffin and the restored original surface is 0.0821 m³, representing 236 kg of missing material. North of the crater the coffin shows a 1 to 5 cm wide vertical crack, which might also be an effect of the blast. The edge of the lid and other decoration elements show smaller cracks and break offs of unknown origin.

Weathering effects of the limestone are found on all sides of the structure, with increased intensity on the southern side of the coffin and the northern side of the foundation. The well-matching weathered cleavage structures with a 45° dip suggest that the coffin was possibly crafted at the spot from the same material as the foundation.

Figure 45  A: Photo of Arttumpara’s sarcophagus from the southeast; B: Cloud of 11.5 million points of the 3D laser scan-model. The gray tones indicate reflectance, the normalized amplitude of the reflected beam; C: Measures of the discrete element model of the sarcophagus in m. The numbers in italics give the weights of the foundation, base block, coffin, and lid (from bottom to top) in kg.

6.3.2 Rigid block model
The 3D LSM was used to set up a rigid block model (RBM) of the sarcophagus of Arttumpara. This RBM consists of three parts: base block, coffin, and lid, which are stacked on top of each other on top of a foundation that was chiselled out of in situ rock. While the base block could be transformed straightforwardly into a cuboid, the coffin and lid and their connection are more complex.
Cross-sections from the 3D LSM were transferred to a computer-aided design program. Here, the general outline of the lid was drawn following the measured points. The top of the coffin has a tongue at the inner side corresponding to a groove in the lid. The side and top of the tongue are not in contact with the lid when both are resting; however, this 4 cm high tongue influences the dynamic interaction of the coffin and the lid. To a certain degree of motion amplitude, which is in the centimetre range, the tongue prevents a sliding of the lid off the sarcophagus during shaking. The real tongue shows rounded edges; however, in the model we used rectangular shaped tongue and grooves. All dimensions are given in Figure 45. The density of the local conglomerate from which the sarcophagus is made was determined from a specimen to be 2.87 Mg/m³, and the resulting mass of the model parts is also shown in Figure 45.

6.3.3 Friction

The dynamic behaviour of the structure depends on the frictional forces between the stacked blocks that are held in place by gravity. Ramana and Gogte (1989) experimentally determined the dynamic coefficient of friction for a large variety of rock types with different mineral content. They found coefficients between 0.53 and 0.89, with the lower values for metamorphic rocks and the largest for limestone. They also found systematically smaller friction coefficients, on average 76% for saw-cut contact surfaces versus fractured surface contacts. We assume a dynamic coefficient of 0.7 for the fractured surface of the Pinara conglomerate. As the contact surfaces were very well worked by the Lycian craftsmen, we use 76% of this value (0.53) for the dynamic friction coefficient, \( f_d \), with a ratio of 0.72 between the dynamic and static coefficient (Langer et al. 2009), the static friction coefficient, \( f_s \), can be estimated at 0.74.

![Direction of the coordinate system and sense of rotational motions of the model of the sarcophagus of Arttumpara.](image)

Figure 46 Direction of the coordinate system and sense of rotational motions of the model of the sarcophagus of Arttumpara. The crossed circles indicate from bottom to top the location of the centre of gravity of the 2 m thick ground block, the foundation, fixed to the ground, the base block, the coffin, and the lid.

6.3.4 Model tests

In order to rotate a block around the Z axis (Fig. 46) by lateral ground motions (rotational components are not considered in this study), the block must either have an asymmetric distribution of its mass or friction, or an initial rocking of the structure in X- and/or Y-direction must occur.
The LSM indicates that the sarcophagus is almost perfectly symmetric with respect to the vertical planes in X- and Y-directions; there is no evidence for a significant variable density of the material used for the construction. Therefore, a Z-rotation during a rocking around the X- and/or Y-direction seems plausible. A block resting on only one of its baselines (or even a corner) during a rocking motion is susceptible to lateral movements of the ground in a direction perpendicular to the baseline trend, and the combination of both rocking and translational movements can result in significant rotations (Koh & Hsiung 1991a,b, Konstantinidis & Makris 2007, Hinzen, unpublished manuscript 2010).

The rocking motion of freestanding blocks has been extensively studied and described in the literature (i.e. Kirkpatrick 1927, Housner 1963, Yim et al. 1980, Ishiyama 1982, Sinopoli 1995, Anooshehpoor & Brune 1999, Zhang & Makris 2000). In a preliminary series of calculations, the free motion of a solid cuboid was compared with the same mass as the complete sarcophagus (base block, coffin, and lid) to the analytic solution.

By keeping the dimensions of the base area, a block with a height of 2.3 m was assumed, making it a rather blockish structure with h/b ratios of 1.34 and 0.93 for the X- and Y-directions, respectively (Fig. 47). When such a block is given an initial inclination \( \theta_0 \) and the friction is high enough, it will oscillate about the edges A and A’ (Fig. 47). The equation of motion has been given by Housner (1963) and others as

\[
I_0 \ddot{\theta} = -WR \sin(\alpha - \theta), \quad (1)
\]

in which \( I_0 \) is the mass moment of inertia about the edge A, R is the diagonal from the centre of mass to the edge of the block, and \( \alpha \) is the angle between this diagonal and the direction of gravity. Introducing the frequency parameter

\[
p = \sqrt{\frac{3g}{4R}}, \quad (2)
\]

and assuming a slender block (\( \sin \alpha \approx \alpha \)) equation (2) can be written as

\[
\ddot{\theta} - p^2 \theta = -p^2 \alpha, \quad (3)
\]

This equation is independent of the block’s density. For an initial rotation \( \theta_0 \) and the boundary condition \( \dot{\theta} = 0 \), the solution for equation (3) is

\[
\theta = \alpha - (\alpha - \theta_0) \cosh(pt), \quad (4)
\]

and the natural period \( T \) of the vibration can be approximated by

\[
T = \frac{4}{p} \cosh^{-1}\left(\frac{1}{1 - \frac{\theta_0}{\alpha}}\right), \quad (5)
\]

which is strongly dependent on the ratio \( \theta_0/\alpha \), a sign for the highly nonlinear nature of the rocking problem (Housner 1963).

In Figure 6.7 a comparison is given of the angle of rotation during the first quarter rocking cycle for different values of \( \theta_0 \) in the X-direction from equation (5) and numerical modelling. Also shown is the relative deviation between the period \( T \), as predicted by equation (5) and the outcome of the numerical experiment. This deviation increases with decreasing \( \theta_0 \) and reaches a value of 2.93% in case of \( \theta_0 = 0.05 \) rad. This appears to be a large deviation between the analytical and numerical test; however, the block representing the sarcophagus is not a completely vertically oriented structure. Figure 47b shows the relative deviation in rocking period for 10 tests, all with \( \theta_0 = 0.05 \) rad, but with varying h/b ratios of the blocks.
The absolute relative deviation decreases with increasing $h/b$ ratio. Within the time resolution used in the test ($1 \times 10^{-4}$ s), the deviation is zero for $h/b > 10$. The ratio $\sin \alpha / \alpha$, also shown in Figure 47b, approximates clearly the trend of the absolute relative deviations of the rocking period. The deviations shown in Figure 47a are due to the violation of the slenderness criterion in the assumption of equation (3).

The coffin and its lid are hollow and held in place only by gravitational forces; there are no clamping devices, etc. Therefore, differential movements between the three parts are possible; the dynamic rocking behaviour of the sarcophagus is more complex than that of the solid cuboid used in the previous calculations. A translational ground motion signal with the form of a Morlet-wavelet (Goupillaud et al. 1984) was used to analyze the rocking of the sarcophagus. The wavelet has the form

$$g(t) = \frac{1}{\sqrt{2\pi}} e^{\frac{t^2}{2}} \cos(2\pi v_0 t),$$

where $v_0$ is a constant determining the frequency.

Wavelets of 10 s length and frequencies between 1 and 10 Hz (Fig. 48) and maximum acceleration up to ca. 10 m/s$^2$ were applied in the $X$-direction (corresponding to east-west) to cause rocking around the $Y$ axis (Fig. 46). Figure 48 shows the ratio of the maximum peak-to-peak displacement of the coffin from the sarcophagus model to the displacement of a model in which the base block, the coffin, and the lid are fixed to each other. Above 4 m/s$^2$ maximum acceleration, small rocking motions are initiated. Above a level of 5.5 m/s$^2$ maximum acceleration, the displacements in the $X$-direction reach the centimetre range (Fig. 48). Between 4 and 6 m/s$^2$ acceleration, the ratio of the displacements between the loose and fixed components of the sarcophagus fluctuates. However, at maximum accelerations above 6.0 m/s$^2$, the ratio is systematically smaller than unity.

Figure 47 A: The black lines show the angle of rotation of a solid block with the same weight and size of the base as Arttumpara’s sarcophagus with a height of 2.3 m from 7 numerical free motion tests. Initial inclinations in the tests are between 0.05 and 0.6 in rad units (2.9° to 34.4°). The dashed gray lines give the values from the analytical solutions after equation (6) for comparison. Crosses, which correspond to the axis on the right, show the relative deviation in percent of the rocking period between the numeric tests and the analytical solution. The two insets indicate the initial inclination of the block for the smallest and largest value. B: Dots show the relative deviation in percent between the period of the rocking motion from numeric tests and the analytic solution for 10 blocks with different slenderness ($h/b$). Initial inclination was 0.05 rad (2.9°) in all cases. The dashed line is the ratio between the sine of angle $\alpha$ and $\alpha$ with respect to the $h/b$ ratio. Three inserts illustrate the varying slenderness and the drawing in the centre shows the nomenclature of a rocking block used in the text.
The average value of all ratios between 6 and 10 m/s² maximum acceleration is 0.49 ± 0.08. The motion of the sarcophagus is on average 49% smaller than that of the model with the fixed components. An explanation for this observation is given in Figure 49, which shows the rotation angle in the Y-direction of the coffin versus the rotation of the base block for the Morlet-wavelet excitation with 5 Hz frequency and 7.9 m/s² maximum acceleration.

The result is a hysteretic curve. The rocking cycle starts with a positive inclination of the whole sarcophagus. In this phase the equal rotation angles for the base block and the coffin result in a straight line of 45° in the first quadrant of the plot in Figure 49. At the turning point of the rocking motion, the base block starts to fall back to its equilibrium position; however, the coffin (including the lid) does not follow immediately and partially detaches from the coffin. While the base block reaches the equilibrium position and stays there, the rotation angle of the coffin also decreases. This corresponds to the path downward along the vertical axis of the plot and to the short time windows where the Y-rotation of the base block is zero in the upper panel of Figure 49. This motion is then followed by a similar cycle in the opposite direction with negative angles of Y-rotation and so forth.

Figure 48  Ratio of the maximum displacement in the X-direction of the sarcophagus model and a model in which the base block, coffin, and lid are fixed to each other, versus the maximum ground acceleration. Ground motion examples for three frequencies are shown as an insert in the lower left. Frequency of the ground motion is indicated by different symbols as given in the legend. The average of the maximum displacements is indicated by the gray filled circles; the corresponding scale is on the right side. Above maximum accelerations of 6 m/s², the average ratio between the sarcophagus and the single block model is 0.49 ± 0.08 as indicated by the heavy black line.
Rocking angles above 1° are only reached for maximum accelerations above 5 m/s\(^2\). This rattling effect is also obvious in the displacement of the coffin, which is shown for the same ground motion in Figure 50.

For comparison, the calculation was also made with the model in which the base block, coffin, and lid are fixed to each other. In this case the maximum displacement of the coffin is much more harmonic with significantly larger maximum amplitude as shown in Figure 48. The onset of the movements is shortly after 4 s into the time series, when 4 m/s\(^2\) acceleration are reached and the rocking around the \(y\) axis starts (Fig. 49).

Rocking around the \(y\) axis driven by \(x\)-lateral harmonic motion starts around 4 m/s\(^2\); however, the rocking amplitudes are limited due the rattling effect of the sarcophagus components. Applying ground motions with the same amplitude and frequency range as shown in Figure 48 in the \(Y\)-direction did not initiate any rocking around the \(X\) axis, which is due to the small \(h/b\) ratio of 0.93.

![Figure 49](image)

Figure 49. Angle of rotation around the \(Y\) axis of the coffin versus the \(Y\)-rotation of the base block during the excitation of the sarcophagus in the \(X\) direction with a translational ground motion in the form of a Morlet-wavelet of 5 Hz frequency and 7.9 m/s\(^2\) amplitude. Arrows indicate the time flow along the graph and the insets show the corresponding type of motion of the sarcophagus. The upper and right panel gives the time series of the angles of rotation in the time window from 4 to 7 s.
6.4 Modelling anthropogenic action

6.4.1 Back calculation of charge weight

The proposed explosion was detonated at the upper left corner of the eastern side of the coffin (Fig. 45). Most probably the looters used one of the openings in the coffin material that was formed by the natural weathering process. Several of such openings still exist and would make a good blast hole without the necessity of laborious drilling. The advanced weathering status of the lid indicates that the southern face of the coffin’s lid was already broken and opened at the time of the recent explosion. Therefore, the probable purpose of the detonation was to move the coffin off the base block. Several sarcophagus at the site, including the one neighbouring Arttumpara’s sarcophagus in the south (Fig. 44), have cavities underneath the coffin, which are most attractive for looters.

The detonation created a typical blast crater (Fig. 45). The size of the crater was determined from the 3D scan model to a volume of 0.0821 m$^3$ and a diameter of 0.4 m corresponding to 236 kg of missing material. The crater size correlates with the size of the explosives charge, and these measures can be used to estimate the amount of explosives and the force applied to the coffin. Dick et al. (1990) presented an empirical relation between the characteristic length $R'$ of the crater and the explosive charge. The parameter $R'$ is often estimated from the depth of burial $d_{bur}$ and the apparent crater radius $r_{app}$ with the simple relation:

$$R' = \sqrt{d_{bur}^2 + r_{app}^2}.$$  (7)

![Figure 50](image.png)

Figure 50 The black line in the bottom graph shows the horizontal displacement of the coffin in the X-direction during an excitation with the time series shown in the top graph. Here the zoomed time window between 4 and 8 s of the bottom graph is indicated by the gray rectangle. The gray line shows the displacement of the coffin when base block, coffin and lid are fixed to each other as indicated by the inserts.
The characteristic length for the blast crater of the coffin was estimated from the scan model to 0.39 ± 0.01 m. Dick et al. (1990) could show that the empirical relation

$$\log R' = 1.846 + 0.312 \log Y,$$  \hspace{1cm} (8)

with $Y$ being the charge weight in kilotons of TNT equivalent, is valid over ten orders of magnitude. This range of charge sizes spans from model explosions in Plexiglas to underground nuclear explosions. With equation (8) the charge weight comes to $6.22 \times 10^{-8}$ kT, corresponding to some 60 g of explosives, equivalent to $2.60 \times 10^5$ J of explosive energy, $E_{\text{exp}}$.

A Heaviside step function with an exponential decay (e.g. MacPherson et al. 2000) was chosen as a time function for the force generated by the explosion (Fig. 51). A time window with zero force amplitude prior to the step was set to a constant value of $2 \times 10^{-5}$ s. Within this time all residual static settling in the model occurs. The time function is parameterized by two values, maximum force amplitude $F_{\text{emax}}$ and the decay constant $t_{d10}$. Because the duration of an impulse with exponential decay is theoretically infinite, we characterize the time duration of the blast impulse by $t_{d10}$, the time between the peak force and the time when the force decayed to 10% of the peak value, in the following.

### 6.4.2 Reaction of the sarcophagus

In a set of model calculations, the parameter space of $F_{\text{emax}}$ and $t_{d10}$ was increased from 4.5 to 285 meganewton and from 0.00123 to 0.2308 s, respectively. This range represents minimal movement of the coffin to pushing it off its base. With a total mass of the coffin and lid, $m_{\text{CL}}$, of 16,469 kg, the energy from the impulse can be estimated through

$$E_{\text{imp}} = \frac{P^2}{2m_{\text{CL}}} \text{ with } P = \int F \, dt,$$  \hspace{1cm} (9)

and compared with the explosive energy estimated from the crater size. Figure 51 shows the ratio $E_{\text{exp}}/E_{\text{imp}}$ in the parameter space of $F_{\text{emax}}$ and $t_{d10}$.

During the blasting test calculations, the angular rotations of the base block, the coffin, and the lid around the $Z$ and $Y$ axis were recorded. Figure 51 summarizes the final rotation angle of the coffin for the $Z$ axis, $\phi_{ZC}$ (Fig. 46) following the notation suggested by Evans et al. (2009). For the set of test calculations three finishing conditions were defined: (1) a time of two s is reached; (2) the displacement of the coffin exceeds 1.11 m in the $X$-direction, meaning it will topple off the base block; and (3) rotation angle $\phi_{ZC}$ exceeds 90°. The dots in Figure 51 indicate a final rotation $\phi_{ZC}$ of 6.37° ± 1.5°, which is a 1.5° window around the measured rotation of the coffin. These rotations occur in the parameter space of $F_{\text{emax}}$ and $t_{d10}$ along a trace roughly parallel to the $E_{\text{exp}}/E_{\text{imp}} = 1.0$ line, where the blast efficiency increases from 17% to 44% between impulse durations of 0.0014 s and 0.0216 s.

These efficiencies are feasible considering the imperfect stemming of the blast. The range of combinations of $F_{\text{emax}}$ and $t_{d10}$ values for which the window of ± 1.5° around the observed angle of rotation is achieved is rather narrow. Deviations toward larger or smaller energies of the impulse result in a large deviation of the rotation angle indicated by the ± 4° window in Figure 51. If we assume that the duration of the rotation, which lasts longer than the blast impulse, was on the order of 0.1 s, a rough calculation of the rotational energy

$$E_{\text{rot}} = \frac{1}{2} I \omega^2,$$ \hspace{1cm} (10)

where $I = 1/3 m_{\text{CL}} (w^2 + l^2)$ is the moment of inertia for a rotation around an vertical axis through the northwestern corner of the coffin of the width $w$ and length $l$, and $\omega$ is the angular velocity, comes to 32 kJ. This value corresponds to 12% of the back-calculated $E_{\text{exp}}$ and shows the plausibility of the result of the numerical test.
Figure 51  Results of model calculations to test the possibility of an explosion as the cause of the observed rotation of the sarcophagus of Arttumpara. Isolines indicate the ratio of explosives energy back calculated from the size of the blasting crater and the energy of the impulse used in the numerical model in the parameter space of the duration of the assumed blast impulse, $T_{10\%}$, and the maximum force, $F_{\text{max}}$ (see text for details). Symbols explained in the legend indicate the difference of the angle of rotation of the sarcophagus at the end of the calculation to the observed value of 6.37°. The small graphs in the top of the figure give the shape of the impulse within a time window of 0.02 s.

The seven parameter combinations of $F_{\text{max}}$ and $T_{10\%}$ that resulted in a rotation of ±1.5° around the observed value (circle symbols in Fig. 51) were recalculated with changed friction parameters. For 10% higher values of the friction parameters, the angle of rotation is on average 7.3% smaller. In case of a 10% decrease in the friction parameters, the rotation angle is on average 4.7% larger. In both cases, the difference in rotation angles is smaller than 0.5°.

6.5  Modelling earthquake ground motion effects

6.5.1  Scaled ground motions

The base block of the sarcophagus rests directly on the levelled top of the in situ rock forming the foundation (Figs. 44 and 45). Therefore, soft sediment site effects can be neglected. We used measured ground motions of the nearby seismic broadband station FETY close to the city of Fethiye, 22 km northwest of Pinara. The three-component seismograms from two earthquakes were restituted to the ground displacement time history. The earthquakes of $M_w$ 5.4 and 4.0 occurred on 20th December 2004 and 8th September 2006, respectively, at epicentral distances of 90 and 38 km to the FETY station. In the following, the ground motions are called FETY01 and FETY02, respectively.

The record FETY01 of a total length of 30 s (Fig. 52) shows a small P-wave onset and a sharply impulsive S/LR-phase. The 60 s long time window from FETY02 (Fig. 53) is more harmonic in character with a mean period of 0.75 s Hz. The ground displacements of these two records (FETY01 and FETY02) were scaled to amplitudes given in Table 15, and Figure 51 equally spaced steps were used to sample the parameter space.
6.5.2 Dynamic reaction of the sarcophagus

Figures 52 and 53 summarize results from scanning the ground motion parameter space. Shown are the absolute values of maximum displacements and rotations as well as the final displacement and rotation measures at the end of the numerical experiments, which lasted 30 s and 60 s for the ground motions FETY01 and FETY02, respectively.

Figure 52. Displacements and rotations of the base block, coffin, and lid from 51 numeric experiments using the scaled ground motion FETY01. A: The seismograms show the displacement time history in the three components normalized to the absolute maximum. The three graphs on the left give the final displacements of the sarcophagus elements in the X-direction (B), Y direction (C), and the maximum displacement in the vertical Z-direction (D). The maximum rotations around the X- and Y-axes are shown in graphs (E) and (F) respectively, and the final Z rotation is shown in graph (G). The abscissa for all graphs is the maximum acceleration of the corresponding component; this way results from the same numeric experiment are vertically aligned.
For the horizontal components of translational movements, the final displacements at the end of the experiments are shown. For the vertical component, the absolute maximal values of displacement are shown, because the final displacements are always zero (the block is at rest at the end of the test). For the rotations it is reversed; the rotations at the end of the experiments are always zero for the $X$ and $Y$ axis, so that the absolute maximum values are used and the final $Z$ rotation is given.

Mean periods (Rathje et al. 1998) of the three acceleration components are between 0.233 and 0.260 s for ground motion FETY01. Movements of the base block, coffin, and lid start at maximum acceleration amplitudes between 4 and 5 m/s$^2$ in the horizontal directions. This is in agreement with the results of the basic tests with the Morlet-wavelet. Between this threshold and the maximum tested ground motions, the maximum and the final displacements increase steadily and the base block, coffin, and lid show minor relative displacements to each other (Fig. 52).

Figure 53 Displacements and rotations of the base block, coffin, and lid from 51 numeric experiments using the scaled ground motion FETY02. For details see caption of Figure 52.
Table 15 Minimum and maximum displacement, velocity, and acceleration amplitudes to which the ground motion FETY01 and FETY02 were scaled*.

<table>
<thead>
<tr>
<th>Component</th>
<th>PGD (m)</th>
<th>PGV (m/s)</th>
<th>PGA (m/s^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
</tr>
<tr>
<td>FETY01</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Z</td>
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<td>4.07E–02</td>
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</tr>
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<td>2.74E–02</td>
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</tr>
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<td>FETY02</td>
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<td>4.00E–01</td>
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<tr>
<td>EW</td>
<td>8.02E–05</td>
<td>3.28E–01</td>
<td>2.35E–04</td>
</tr>
</tbody>
</table>

*Amplitudes were increased in 51 steps from the minimum to maximum in the calculations.

At peak accelerations above 1 g in the horizontal direction, small differential movements between the coffin and the base block occur; however, the maximum total displacements do not exceed 7 cm in the X- and 3 cm in the Y-direction. Differential movements are smaller than 1 cm.

Due to the geometry of the sarcophagus, the translational ground motions do not induce a rocking motion around the X axis as clearly shown in Figure 52c. Significant rocking with rotations around the Y axis starts only around 8 m/s^2 maximum acceleration in the X-direction (Fig. 52c, f). This rocking correlates with the onset of the Z-rotations. However, even with extreme ground motions above 10 m/s^2 in the horizontal and more than 5 m/s^2 in the vertical direction, the final Z-rotation does not exceed 0.2°.

The second ground motion example based on a local earthquake, FETY02, contains lower frequencies than FETY01 with mean periods between 0.501 and 0.595 s, but the reaction of the sarcophagus is similar to the first example. Horizontal sliding starts again around 5 m/s^2 maximum acceleration. The final movements nearly reach 0.4 m in the Y-direction, when the maximum acceleration reaches 10 m/s^2.

As shown in Figure 53a and b, only small differential movements occur between base block and coffin and between coffin and lid. Rocking around the Y axis starts around 6 m/s^2; maximum acceleration in the X-direction and the maximum final Z-rotation slightly exceed 0.5°.

In addition to the two available scaled ground motions from smaller size earthquakes recorded in the vicinity of Pinara, a measured strong motion from the 6th April 2009 L’Aquila, Italy earthquake was used to test the sarcophagus motions. The L’Aquila event is one of the rare cases with records from Joyner-Boore distance zero for a normal faulting mechanism (Ameri et al. 2009).

Figure 54 shows the three acceleration components recorded at station AQV. The raw data were band-pass-filtered from 0.01 to 50 Hz and a linear baseline correction applied. The time history of the Z-rotation over 15 s in Figure 54 shows only small values reaching 0.001°. The phase during which the main rotation occurs correlates well with the strongest ground motion peaks of 5.1, 5.4, and 6.5 m/s^2 in the Z, north–south, and east–west components, respectively. Shaded areas in Figure 54 show that the differential movements between base block and coffin are also insignificant for the recorded earthquake example. This contrasts with the blast excitations, for which an example of the Z-rotation time history is shown as an inset in Figure 54. The base block rotates 0.5° around the Z axis, but the coffin reaches a rotation of 6°.

### 6.6 Discussion and conclusions

Pinara, an archaeological site in south-western Turkey, was occupied during Lycian, Greek, Roman, and Byzantine times. Many remains of buildings show damages most probably of seismogenic origin. The impressive sarcophagus of the Lycian king Arttumpara consists of a base block, the coffin, and its lid (Figs. 44 and 45). These structural elements rest on a foundation carved out of the in situ rock, a conglomerate. The coffin is rotated with respect to the base block by an angle of 6.37° (Fig. 44) as determined from a 3D laser-scan model. This rotation was previously interpreted as the result of seismic ground motions (Yerli et al. 2011).
The three accelerograms in the upper part are records of the 6th April 2009 l’Aquilia (Italy) earthquake at station AQV. The main plot shows the angle of rotation $\theta_z$ of the base block and coffin and the shaded area highlights the differences between the two. The dashed line links the onset of the rotations to the ground motion. The inserted plot (centre right) shows the rotation time history for an explosion detonated at the upper left corner of the eastern side of the sarcophagus with 2.1 ms impulse duration and a maximum force of $3.57 \times 10^7$ N (see Fig. 51).

The cloud of 11.5 million points from 10 combined laser scans was used to create a discrete element model of the sarcophagus. The general dynamic behaviour of Arttumpara’s sarcophagus was tested with harmonic ground motions in the form of Morlet-wavelets. Above a maximum acceleration of 4 m/s$^2$, the base block and coffin begin rocking motions with small amplitudes around the $Y$ axis, parallel to the long side of the sarcophagus. During the rocking, the coffin repeatedly detaches from the base block causing a strong rattling effect (Fig. 49). Horizontal displacements during the rocking phase are significantly larger if rattling is suppressed by fixing the three components of the sarcophagus to each other compared to the actual situation where these parts are loosely stacked (Fig. 50). This rattling effect consumes kinetic energy and can thus be regarded as an antiseismic design feature, as previously described for multidrum columns (Konstantinidis & Makris 2005, Hinzen 2009).

Traces of an explosion, which was likely detonated in the 1970s, confirmed by vague reports from local residents, suggest an anthropogenic cause for the misalignment of the sarcophagus and its base. Back calculation of the explosives charge weight based on the size of the blast crater result in ca. 60 g of TNT equivalent. This yield is a plausible amount of explosives for the proposed looting act during which the charge was probably pushed into one of the weathering holes of the coffin. Testing a wide range of durations and maximum amplitudes of an impulsive force shows that the previously stated estimated amount of explosives is capable of rotating the sarcophagus by the observed 6.37°. From comparing the back-calculated explosive energy with the kinetic energy, that rotated the coffin, an efficiency of the blast of 10% to 50% results. For the proposed looting situation with no optimized stemming of the blast hole, the lower efficiency of 10% combined with an impulse duration in the range of 1 ms is plausible.
Alternatively, a seismogenic cause for the rotation was considered. Two smaller, locally recorded
earthquakes were scaled to amplitudes capable of moving the sarcophagus. In addition, a strong-
motion record from the 2009 L’Aquila earthquake with normal faulting mechanism was used. The
shape of the sarcophagus requires strong accelerations (above 4 m/s²) to initiate a rocking motion
around its longer horizontal Y axis. A rocking around the shorter X axis does not occur for accele-
ration below 10 m/s². However, rocking is a precondition to achieve vertical rotation by pure trans-
lational ground motions if the masses and frictional conditions are evenly distributed. Even with hori-
zontal maximum accelerations of up to 10 m/s², only insignificant rotations smaller than 1° with
respect to the vertical axis occur. The maximum sliding of the sarcophagus is in the range of 0.4 m
and 0.1 m along the Y axis and X axis, respectively. This is more than the 0.02 m of observed sliding
of the northeast corner of the coffin with respect to the base block. But the sliding observed in the
numerical experiments occurs between the foundation and the base block; differential sliding between
the base block and coffin is insignificant.

In all earthquake simulations very little differential sliding and Z-rotation between the base block and
the coffin was observed. While the blast clearly rotates the coffin without significantly affecting
the base block due to its inertial mass, the earthquake ground motions, if at all, rotate the whole sarco-
phagus including the base block. This argument against a seismogenic cause of the vertical rotation is
backed by the results from excitations with harmonic signals.

The numerical tests favour a small blast in the upper left corner of the eastern side of the sarcophagus
of Arttumpara as the cause of the vertical rotation of the coffin and its lid. However, numerous other
structures at the Pinara archaeological site show damages and deformations that may have been
cased by one or several earthquakes. Their quantitative analysis is the subject of ongoing studies.

6.7 Data resources and acknowledgments

Seismograms from the Fethiye station were provided by the Kandilli Observatory and Earthquake
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accessed December 2009. The strong-motion data of the L’Aquila earthquake were accessed through
Recent and historic earthquake catalogue data were obtained from the International Seismological
Center, Thatcham, United Kingdom (2001) online bulletin through http://www.isc.ac.uk, last accessed
October 2009, and from the electronic supplement to The Historical Earthquake Catalogue of Turkey

Digital elevation data of Figures 51 and 52 are from the SRTM mission obtained through the U.S.
and the Geologic Map of Turkey (Şenel 1997a).

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