

TREBUCHET – A GRAVITY-OPERATED SIEGE ENGINE

A Study in Experimental Archaeology

Tanel Saimre

The most powerful weapons in the Middle Ages were catapults, the latest and technically most advanced type of which were counterweight-operated trebuchets. This article deals with their mechanics and describes some experimental reconstructions of such siege engines. In Estonia the interest in trebuchets is augmented by the fact that such engines were used here repeatedly in the beginning of the 13th century, during the German-Danish conquest, and thereafter. The author built an experimental reconstruction of a trebuchet and carried out experiments on the Otepää hillfort, which resulted in some new knowledge about this type of siege engines enabling us to better interpret the information available in historical sources.

Keskajal olid võimsaimateks relvadeks heitemasinad, mille hiliseimaks ja tehniliselt täiuslikumaks tüübiks olid vastukaalu jõul töötavad heitemasinad ehk blided. Käesolevas artiklis käsitletakse selliste masinate mehhaanikat ning esitletakse olulisemaid ajalooliste heitemasinate rekonstruktsioone ja katseid nendega. Eestis on huvi heitemasinate vastu põhjustanud eelkõige asjaolu, et neid kasutati siin alates 13. sajandi alguses asetleidnud saksa-taani vallutusest peale. Artikli autor ehitas blide rekonstruktsiooni, millega Otepää linnamäel tehtud katsed andsid uusi teadmisi keskaegsete heitemasinate kohta ning võimaldavad tõlgendada kirjalikes allikates nende kohta esitatud andmeid.

Tanel Saimre, University of Tartu (Tartu Ülikool), Lossi 3, 51004 Tartu, Eesti (Estonia); tank@ut.ee

Introduction

The purpose of trebuchet reconstructions

Experimenting with trebuchet reconstructions, just as other aspects of experimental archaeology, is essential to better understanding our past. The trebuchet is a rather complicated machine and thus its behaviour can be fully understood only through practical experience. On the one hand, this experience helps replenish the information presented in historical sources, and on the other hand complements the knowledge attainable from the modern science of mechanics. Simple high-school level of mechanical analysis can be of much assistance to the historian in developing a sense of criticism towards historical sources.

The goal of this paper is to analyse the trebuchet as a mechanical system, and to find the optimal parameters for trebuchet construction and its operation. The

reconstructions built by the author and other researchers are then examined from this point of view.

The trebuchet and the progress of technology

The trebuchet consists of a long beam which is attached to a rotating axle. The axle divides the beam into two arms of uneven length. A counterweight is attached to the shorter arm and a sling containing the ammunition is attached to the longer arm. When the trebuchet is cocked, the tip of the long arm touches the ground and the short arm with the counterweight is lifted up. When the trigger is released, the counterweight drops down and the long arm with the sling is pulled up with great acceleration. The sling releases the ammunition at the right moment and it is hurled away towards the enemy (Fig. 1).

The knowledge of mechanics had to be developed to a high enough level for such a concept to emerge. Furthermore – once these machines were being constructed and used in sieges, the crews and commanders of these machines were constantly exposed to the workings of mechanics and previously unsolved issues therein, forcing the brightest minds to contemplate these questions and issues. Thus it is fair to say that the trebuchet has contributed to the progress of science in its own way. One of the most outstanding scholars in the field of theoretical mechanics during the 12th-13th centuries was Jordan Nemorarius (died approx. 1237), who worked on the theory of the lever, based on the principle of the equality of work done and work gained (Piir 1996, 10). Jordan also claimed that a mass falling along a vertical trajectory is capable of doing more work than the same mass falling along a diagonal one. The connection to counterweight operated trebuchets is obvious here. The trebuchet constructors were aware that a hinged counterweight has a trajectory more vertical than that of a fixed counterweight and thus can fire stones to a longer distance (Chevedden *et al.* 1995, 63).

Terminology and historiography

The word *trebuchet*, which is used in English to denote a counterweight operated siege machine, originally meant only the largest and most powerful of these machines. *Trabucium*, *trabuchus*, *tripantium*, *trebusket*, etc. all are different forms of the same word. It probably meant ‘three legs’, referring to the appearance of the machine: bigger machines were supported by two diagonal struts – two legs, while the beam itself depicted the third leg (Chevedden 2000: 100).

The historical aspect of the topic is covered by a 1903 monograph *The Crossbow* by sir Ralph Payne-Gallwey, which has a richly illustrated and commented appendix on catapults. Although the book can be considered obsolete in some senses, it still is of great value. Another important source of information was the manuscript of Ain Mäesalu’s yet to be published monograph *Ammud, laske- ja heitemasinad muistses vabadusvõitluses ja keskaegses Eestis*.

In the study of the mechanical aspect of the trebuchet not many papers have been published. In the current paper two articles were used, both very thorough but unpublished and available only on the Internet: *Trebuchet Mechanics* by Donald Siano and *The Counterweighted Trebuchet – an Excellent Example of Applied Retromechanics* by W. E. Jahsman. Siano has also written trebuchet simulator software – WinTrebStar

4.0, which was used to conduct a number of simulations, the results of which were important for reaching some conclusions.

Interest in medieval arms and military technology has seen a significant increase over the last few decades. There are a number of ‘backyard hobbyists’ and more professional researchers occupying themselves with everything connected to medieval warfare, including reconstruction of trebuchets. This popularity has resulted in a lot of material available on the Internet and in popular magazines, but scientific study is still sparse.

Further complicating the research of this topic is the lack of archaeological finds. Contrary to hand weapons and armour, siege engines were too large to stay intact up to our day. German author Bernhard Rathgen reports that one such machine was found in 1890 in Liebenmühl, East Prussia during the knocking down of an old church. Unfortunately the value of that find was not recognised and the machine was used up for firewood (Hansen 1992, 193). Therefore we have to rely on indirect evidence – like the embankment erected for a trebuchet found in Viljandi castle excavations in 2000 (Valk 2001). Also we have written sources and the information obtained from experiments. In this paper I shall investigate the experiments conducted by Emperor Napoleon III (the first known experiment of its kind), Danish historian Peter Vemming Hansen (which yielded in the biggest amount of scientific information), and Estonian reconstructions in Varbola and Lihula. In addition, the author’s own reconstruction on Otepää hillfort is described.

The history of the use of the trebuchet

The working principle of the trebuchet is similar to that of the pole-sling, where the human muscle has been replaced by the heft of a counterweight or (in case of older machines) a rope-pulling crew. The pole-sling was in use already during the Stone Age. The history of the trebuchet however, begins in 5th–6th-century China, where the human-operated trebuchets were first invented. This type of machine had a set of ropes instead of a counterweight, which were pulled by a crew. The first image of such a machine originates from a wall painting in the Pendzhikent palace in Central Asia near Samarkand and dates back to the end of the 7th or the beginning of the 8th century. It depicts a human-operated machine employing a sling (Nickel 2002, 124).

However, human muscle strength is limited and only a certain amount of men can arrange themselves around the machine to pull the ropes. In addition, the rope-pullers were in danger themselves; in case the stone was not released by the sling for some reason, they were likely to be hit by it. For these reasons the counterweight was employed. The earliest accounts of counterweight-operated trebuchets are from the middle of the 12th century Islamic countries, Byzantium and Mediterranean area of Europe. The first such image originates from the end of the 12th century in Egypt (Nickel 2002, 124). Whether the counterweight was an oriental import or it was invented independently in Europe is unclear. According to Payne-Gallwey, the French were the first in Europe to employ the counterweight in the 12th century (Payne-Gallwey 1903, 309).

From the 13th century onward the trebuchet gained much popularity in Europe and we find many such accounts in both textual and image form. An example of the trebuchets’ is provided by Henry of Livonia in his *Chronicle of Livonia* as he describes in

detail the destruction brought about by such a machine during the siege of Mesoten by the Teutonic crusaders in December 1219:

At last the larger machine was put up and great rocks were cast at the fort. The men in the fort, seeing the size of the rocks, conceived a great terror. The duke took charge of the machine, shot the first stone, and crushed the enemy's balcony and the men in it. He shot a second one and dislodged the planks and the logs of the rampart. He discharged a third one and pierced and shattered three large logs in the rampart and struck some men. After seeing this, the people in the fort fled from the ramparts and sought safer places. But since they had no refuge, they asked for quarter so that they could come down and make their plea to the bishop.

(CHL, XXIII, 8)

The trebuchet described here was one of the biggest in Europe at the time. This excerpt vividly illustrates the power of a large trebuchet. The fact that Duke Albert himself took command of the machine demonstrates that the art of calling the fire of a trebuchet was of great prestige.

The trebuchet was gradually upgraded and improved, with the historical sources reporting heavier and heavier ammunition being used. Although the first firearms (gunpowder-powered cannons) were invented already in the 1320s, the trebuchet was able to compete with them for nearly two centuries.

The advantage of the trebuchet was the simplicity of its construction and use. It used robust stones as ammunition. Cannons, on the other hand, needed a constant source of fire and a supply of gunpowder, which could not stand humidity. The trebuchet could be used in any weather – be it rain, snow, scorching sun or freezing cold. It was constructed from timber and stone – materials easily available almost anywhere. Only the more advanced cannons of the 15th century could finally surpass the trebuchet.

One of the last accounts of the use of the trebuchet comes from the New World, where Hernan Cortés besieged Tenochtitlan (present day Mexico City) in 1521. Ammunition for cannons had run out and he accepted a proposal to build a trebuchet. Its first shot was an unfortunate failure – the stone went straight up and on its way down ruined the machine (Chevedden *et al.* 1995, 63). The last known case of trebuchet use for military purposes was in 1779, when the British used it to bomb Spaniards who were on a position in the bottom of a gorge inaccessible to cannons (Hansen 1992, 191).

TREBUCHET MECHANICS

The working principle of the trebuchet

In this chapter I deal with the trebuchet as a mechanical system, to better evaluate its capabilities and limitations and to learn to critically assess historical sources and the opinions of many historians.

Scientifically speaking, when the machine is cocked (the counterweight is raised) then potential energy is accumulated into it. When the trigger is released, the counterweight drops down and pulls the other end of the beam upward. The sling

containing the missile is pulled with it. The missile moves along an arc and is released above the machine. Thus the potential energy of the counterweight is converted into kinetic energy of the missile.

The sling is fixed to the beam at one end. The other end has a loop which slides on a hook attached to the beam. At precisely the right moment the loop slides off the hook and the sling opens, releasing the missile. The length and curvature of the hook must be exactly correct for the sling to open at the right moment – when the counterweight has reached the bottom of its trajectory and the tangent of the missile's trajectory is at the desired angle.

Power of the trebuchet

The main characteristic of a trebuchet is its power – which translates into ability to hurl heavy stones to a big distance. Power defines the destructive capability and military potential of a trebuchet.

The power of medieval trebuchets has been evaluated by different authors. Payne-Gallwey, after experimenting with models, believed the largest trebuchets had a 15 m beam, a 9 ton counterweight and could hurl a 140 kg stone to a range of almost 300 m (Payne-Gallwey 1903, 309). Some authors have mentioned a much higher power, for example the German author Bernhard Rathgen wrote of a missile weighing 1400 kg, unfortunately without referring to a source (Mäesalu 2005, 30). A missile of such mass is hard to conceive, for the counterweight for hurling it effectively would have to weigh around 100 tons.

The power of the trebuchet is defined by the amount of potential energy it is capable of accumulating. The formula for calculating the amount of potential energy is as follows:

$$E_p = m \cdot g \cdot h$$

This formula shows that the amount of potential energy depends on two variables – the mass of the counterweight (m) and the height of its drop (h). g denotes the acceleration due to gravity (9.8 m/s^2). By knowing these two variables we can calculate the theoretical maximum range of the throw (in case the missile leaves the machine at an angle of 45° to the horizon and the machine and the end point of its trajectory are at the same level):

$$R_T = 2 \cdot \frac{m_1}{m_2} H_{CW} \quad (\text{Siano 2001, 4}).$$

R_T – theoretical maximum range of the throw;

m_1 – mass of the counterweight;

m_2 – mass of the missile;

H_{CW} – height of the counterweight's drop.

Simply put – a trebuchet cannot hurl stones further than is allowed by the amount of potential energy accumulated into it. Hence we have a reference point for assessing the maximum capability of a machine.

There are always factors which decrease the actual range of the stone, like friction between machine parts, air resistance and imperfect tuning of the machine. A badly tuned machine may achieve only 10% of its theoretical maximum, best modern machines

(designed and built using computer simulations, modern engineering and materials) can throw to up to 70% of their theoretical maximum (Jahsman 2000, 28–30).

How can we employ this formula in historical research? All three parameters (mass of the counterweight, mass of the missile and counterweight drop height) are easily measurable. However, historical sources seldom mention exact values. Thus, we must appraise them using the information we do know. Figure 2 shows the relations between different angles and dimensions of the trebuchet. For example, if we know the length of the shorter arm (l_1), we can calculate the counterweight drop height using the following formula:

$$H_{cw} = l_1 \cdot (1 + \sin \psi) \text{ where}$$

ψ is the angle of the beam relative to the horizon before the shot (this is usually around 45°), (Jahsman 2000, 30)

Efficiency of the trebuchet

The ratio of the theoretical maximum range and actual range is called efficiency. This shows how much of the potential energy accumulated into the machine before the shot is converted into kinetic energy of the missile, in other words – how well the machine is tuned. Like any real world machine, it cannot achieve an efficiency of 100% or above – some energy is always lost. Air resistance of the missile further shortens the flight distance. As mentioned earlier, efficiency is between 0.1 and 0.7 for most machines.

Efficiency depends on a lot of factors; it illustrates the complexity of the trebuchet and the beauty of a well-tuned machine. Timing is of paramount importance here. To achieve the highest efficiency the machine must be tuned so that the missile is released at exactly the moment when two conditions are met (that is, three events must occur simultaneously).

First, the stone must be released when the counterweight has reached the lowest point of its trajectory (as we shall see later, hanging counterweight travels along an L-shaped trajectory). That way the highest possible amount of potential energy is delivered to the missile. If the missile is released earlier than this, some of the energy is left in the machine and hence lost. This causes a decrease in the range of the stone, and also causes the machine to swing for some time after the throw. Swinging is harmful to the machine due to fatigue and hinders the crew from preparing the next shot. The behaviour of the beam after the shot is a good indicator for evaluating how well the machine is tuned and medieval trebuchet operators probably knew that. On the other hand, if the missile is released too late, it loses some of its energy by dragging the sling uselessly through the air.

The second condition is that the missile be released when the tangent of its trajectory is at the correct angle. For the biggest range under normal circumstances, this angle is approximately 45° to the horizon. In a siege situation, however, the machine and the end point of the missiles trajectory are at different heights; so the angle must also be different. Furthermore, the goal was not to hurl the stone to the greatest possible distance, but to hit a target – enemy trebuchet or castle rampart. To achieve this, the trebuchet operators had quite a difficult problem to solve.

Parameters of trebuchet construction

Here I shall deal with the parameters to be observed while constructing, operating and tuning a trebuchet. I have divided these parameters into two categories: parameters to be observed while constructing the machine (that are difficult or impossible to change afterwards) and parameters to be observed while operating and tuning the machine.

The first section contains most of the machine part lengths, excluding length of the sling, which has an important role in the aiming of the trebuchet.

Lengths of the shorter and longer arms

The beam with the axle, sling and counterweight is the most important part of the whole machine. All the rest is just a supporting structure keeping the axle at the correct height from the ground. The beam must be strong and rigid, any flexibility causes it to vibrate after the release of the trigger and this has a negative effect on the precision of the shots.

The ratio of long arm and short arm lengths is considered to be one of the most important parameters of trebuchet design. This ratio defines the velocity of the tip of the beam compared to the drop of the counterweight. Different opinions have been expressed about the best ratio. P. V. Hansen describes a medieval author Marinus Sanutus who believed the best ratio to be 1:5.5 or 1:6 (Hansen 1992, 200). Also we know of captain Favé, who on the order of Emperor Napoleon III built a machine with a ratio of 1:33 (Hansen 1992, 193 f). This machine had a remarkably low power and the reason was this very ratio, which was poorly chosen.

Mechanically speaking, the shorter arm should simply be as long as possible. We can conclude this from the formulas above – the longer it is, the bigger is the counterweight drop height, thus the higher the amount of potential energy. The length of the shorter arm is limited by ground – in case of a too long arm, the counterweight hits the ground on its way down. If we have a fixed counterweight, we must simply leave some spare between the counterweight and the ground. But in case of a hinged counterweight, the distance between the axle and the ground must accommodate both the short arm and the counterweight hanger. Hence we must know the priorities of both the short arm and counterweight hanger. See more on that below.

Axle height

Axle height together with the length of the long arm defines the beam's initial angle before the shot. Simulations show that this angle should be around 45° to the horizon. If the angle is too small, the counterweight drop height remains small – hence the machine is incapable of accumulating much potential energy. If it is too big, the counterweight does not fall vertically, but diagonally. Hence the machine loses some energy to overcome its inertia to accelerate it in a horizontal direction. Optimal axle height causes the counterweight to fall almost vertically, transferring most energy to the missile (Fig. 3).

Counterweight hanger length

What happens if there is no hanger at all – i.e. the counterweight is fixed to the beam? The trajectory of a fixed counterweight is circular (Fig. 4). As shown above, this causes the trebuchet to lose energy to accelerate the counterweight in a horizontal

direction. The hanging counterweight drops more or less vertically and transfers the most energy to the missile.

In addition to that, the hanging counterweight has a lower centre of gravity and the forces on the whole structure of the machine are weaker. This allows a lighter and easier to build machine. Also, it is much handier to load stones into a hanging counterweight basket than to strap them to the beam.

We must find the optimal hanger length. Computer simulations show, that the longer the hanger, the more vertical the trajectory of the counterweight. So the hanger should be as long as possible without the counterweight hitting the ground. But the short arm should also be as long as possible – and we have only a limited distance between the axle and the ground.

I could find no undubious answer to this problem. Computer simulations show, that the length of the counterweight hanger should be at least half the length of the short arm, for the benefits of the hanging counterweight to appear at all.

Parameters of trebuchet operation

Missile mass

The goal of building a trebuchet is to hurl missiles of as big a mass as possible, to targets as distant as possible. The desire to hurl big stones is understandable, however, we must keep in mind that the kinetic energy of the stone, rather than its mass, determines the amount of destruction it is capable of inflicting on its target. Kinetic energy is defined by the following formula:

$$E_k = \frac{mv^2}{2} \text{ where}$$

E_k – kinetic energy of the missile at end of trajectory;

m – missile mass;

v – missile velocity at end of trajectory.

Since velocity is squared (v^2), kinetic energy depends on the missile's velocity more than on its mass. Therefore a smaller missile hurled from a greater distance (and thus with a greater velocity at end of trajectory) can inflict more damage than a bigger missile hurled from a closer range. Good distance between the siege machine and the enemy also offers better protection from enemy's crossbow fire.

This formula also reflects one advantage that the defenders had over the attackers – since their machines were positioned on higher ground and were shooting downwards towards the besiegers, their missiles had a higher velocity (in addition to the bigger range) than those of the besieging machines, which had to shoot upwards into the hillfort. Therefore their missiles also could do more damage.

Counterweight mass

Counterweight mass is the essential factor that characterises the power of the trebuchet. The principle is very simple here – the bigger the counterweight mass, the more powerful the machine. Mechanical analysis shows that the counterweight mass

should be approximately 100 times the mass of the intended missile for the machine to operate efficiently (Siano 2001, 40).

Sling length

The working principle of the sling is that it increases the length of the trajectory that the missile travels while under the influence of the machine, thus enabling it to achieve a greater velocity. The sling should be approximately as long as the long arm of the beam.

Sling of a correct length increases a trebuchet's power by several times. Adjusting the length of the sling is also the primary method of aiming the trebuchet to shoot to the correct distance. Bigger stone demands a shorter sling, smaller stone a longer sling. Unfortunately most medieval images omit the sling or depict it such a general detail that any mechanism for adjusting length cannot be seen. However, length can be easily adjusted by tying knots into it, for example. It is important that both ends of the sling are of equal length; otherwise the stone will fall out during the shot.

Length and curvature of the sling hook

Sling hook is the critical factor that makes the sling open at precisely the right moment. If the sling opens too early, the missile is hurled backwards or straight up. If it is released too late, the missile will crash down in front of the machine. Henry of Livonia describes such a mishap in his *Chronicle of Livonia*. In 1206 the Polozk Russians were besieging the fort of Holm on the lower course of the river Dvina, described by Henry:

The Russians also made a little machine like that of the Germans, but not knowing the art of throwing rocks, they hurled them backwards and wounded many of their own men.
(CHL, X, 12)

This failure must have been the result of an incorrect hook length or curvature.

The hook may also have zero curvature and be at a certain angle to the beam. Then it is the length of the hook that defines the moment of release – the longer the hook, the later the sling is released. P. V. Hansen (1992, 202) describes a clever way of adjusting the length of the hook – by putting wooden rings on it, so the effective length of the hook is decreased. Hansen notes that each such ring decreased the range by five meters (probably by causing the sling to open sooner, thus making the flight trajectory higher). This is quite a precise method of controlling range.

Rate of fire, precision and reliability

Rate of fire depends on the time it takes to prepare the machine for a shot. This includes cocking, tuning (if necessary) and loading the ammunition into the sling. Generally – the bigger the machine, the slower its rate of fire. Historical sources do not provide much detail here. Only prolonged and uninterrupted bombardments are mentioned very often. In 1147 during the siege of Lisbon the amount of missiles hurled at the city in one hour was said to reach 500 (Phillips 2002, 86), however we do not know how many machines were operating.

The lengthiest operation is cocking the machine. This includes pulling down the long arm of the beam or raising the counterweight, and securing the machine in a cocked position with a trigger. Smaller machines can be cocked by simply pulling the longer arm

down with a rope, with many men, if necessary. Larger machines need a winch, a treadmill or a similar device. These devices take much longer to operate, thus bigger machines have a lower rate of fire. Smaller machines can be cocked in a few minutes; larger ones need ten minutes or more.

Precision is affected by many factors, primarily the overall rigidity and sturdiness of the construction. Flabbiness causes instability. If the beam flexes under the gravity of the counterweight, it will vibrate after the trigger is released and shots will be less accurate. The rope of the sling must not stretch for this would cause chaotic movement of the missile when the trigger is released. The axle and the counterweight hanger must be sturdy and allow seamless movement. During the reign of Edward I (1273–1307) the English soldiers have been known to grease the axle with lard (Hansen 1992, 200).

Reliability generally depends on the same factors as precision. An inaccurate and flabby machine will not last long. Also, the machine must be well tuned, so that potential energy of the raised counterweight is transferred to the missile. If too much energy stays in the machine, it causes the beam to swing heavily after the shot. This causes wear and tear of the machine and lowers the rate of fire as the crew must wait for the beam to stop swinging before they can start preparing another shot.

Ammunition

Stones were the main ammunition used with trebuchets. For the purposes of aiming, the stones must be as spherical as possible and it is useful to have many stones of similar weight. The result of a shot can then be used to aim the next one. If a suitable configuration is found, the bombardment can be continued until a sufficient amount of destruction has been achieved on the target. Spherical stones also have the smallest air resistance for their mass, so they have the greatest range. The spinning of a flat stone has significant effect on its trajectory, so they are inherently inaccurate. There are notes of shaping stones for use as ammunition (Schmidchen 1983, 126).

Second most important type of ammunition was incendiary bombs. Sources tell of 'fire' being thrown at the enemy (for example CHL, X, 9), but usually do not specify in what form. 'Glowing irons or pots of fire' are mentioned (for example CHL, XXVIII, 5). Pot of fire probably means a clay vessel filled with some incendiary liquid with a wick that is lit before shooting. This sort of a vessel would shatter upon impact and splash its burning contents all over the target. Glowing iron may be a very effective weapon if it falls on wooden parts of a rampart, parapet or enemy machine. The sling does not withstand this kind of ammunition. Therefore the glowing iron may have been placed inside a clay wrapping, which also helps reduce the cooling effect of air during flight. Such pre-prepared ammunition could be standardized and thus have known shape and mass, therefore making the aiming task easier.

There are also notes of animal carcasses being hurled into enemy castles. In addition to the psychological effect the aim could have been to spread diseases and create unsanitary conditions among the enemy. The best-known example of such warfare is the siege of port town of Kaffa by the Mongols in 1345–1346. The Mongol army was devastated by 'black death'. They used trebuchets to hurl dead bodies of soldiers who died of the plague into the enemy castle. Later the disease spread all over the Mediterranean on Genoan merchant ships (Chevedden *et al.* 1995, 60).

Captured spies or their heads have been thrown at the enemy for psychological impact. Clay balls filled with little pebbles have also been used, to achieve a shrapnel-like effect. Barrels full of urine and faeces were similar to animal carcasses in their effect. Beehives and baskets filled with scorpions and snakes have also been described (Hansen 1992, 203). These would, however, present a significant problem of aiming, since any ammunition significantly lighter than stone would behave very differently both in the machine and during flight and thus such shots had a high risk of failure or even friendly fire.

EXPERIMENTAL RESEARCH

This chapter summarises the knowledge obtained from several authors' experimental research, including my own. It is evident, that trebuchets constructed using computer modelling and present-day materials have a much higher efficiency than their medieval counterparts, so we cannot take every result at face value. However, these machines show us the upper limit of the capabilities of the trebuchet. In addition, there are a number of experiments, where historical accuracy has been aimed for; the results of these are certainly of high value to us.

Emperor Napoleon III

One of the first experiments with trebuchets was the reconstruction built by order of Emperor Napoleon III by his adjutant captain Ildenfonse Favé (1812–1894). The machine had a beam of 10.3 m, with the short arm of only 30 cm. Such a ratio between the short and the long arm was a big mistake, as the trial shots demonstrated. The counterweight had a mass of 4500 kg, 1500 kg of which was fixed to the beam and 3000 kg hung freely. The supporting structure of the machine failed after only four shots and the experiment had to be stopped. Here are the results of these four shots (Hansen 1992, 194):

1. cannon ball, 24 lbs: 175 m;
2. shell, diameter: 22 cm, filled with sand: 145 m;
3. shell, diameter: 27 cm, filled with sand: 120 m;
4. shell, diameter: 32 cm., filled with sand: 120 m.

Because of such a small length of the short arm, the machine was incapable of accumulating much energy – the drop height of the counterweight was just around half a metre. Hence the ranges are very small considering the adequate mass of the counterweight.

Peter Vemming Hansen

During the second half of the 20th century such a vast amount of reconstructions have been built that it is impossible to describe all of them here. Of great importance to my own work was the experimental reconstruction of Danish scholar Peter Vemming Hansen in Nykøbing Falster Medieval Centre.

In his article of 1992 Hansen describes the thorough preparations that preceded the construction of the machine. Among the team there were a smith, millwright and a

rigger, and Hansen emphasises the importance of the practical knowledge provided by these team-members. Before the construction of the actual machine, two replicas were made, in scales of 1:10 and 1:5. The base of the machine was built according to a ground-plan of Villard de Honnecourt dating to the middle of the 13th century. The rest of the machine was constructed according to 1854 drawings of Viollet-le-Duc. At this phase Hansen stresses the importance of the base of the machine being completely flat and horizontal.

The machine was designed for easy assembly and unassembled. Operations require 10–12 people, of whom all but two were required for cocking the machine. Cocking is done without a winch, simply by pulling on a rope with a block and tackle mechanism. The machine can fire a shot approximately every ten minutes.

Hansen had performed 120 shots by the time of writing his article and almost all were successful. The machine needs little care besides checking the ropes and greasing the axle. Counterweight was originally planned at 4000 kg, but only 2000 kg had been tested so far. A range of 168 m was achieved with 15 kg cast cement ammunition. I know that by now three more machines have been built at Nykøbing Falster, but I have obtained no further publications on them.

Hansen has supplied the blueprint of the machine along with the article. From there I measured the long arm of the beam to be 5.85 m and the short arm to be 1.2 m. This means a ratio of 1:4.875, which fits nicely into the usual interval of 1:4 to 1:5. Counterweight hanger is 1.35 m, axle height only 3.15 m. This means the initial angle of the beam to the horizon is only 32° instead of the desired 45°. Therefore the counterweight drop height is 1.84 meters instead of 2.

Theoretical maximum range of a 15 kg missile and 2000 kg counterweight with this machine is 490 m. Hurl range of 168 m means an efficiency of 0.34, which is average. Raising the axle by 1 m would result in an increase of the theoretical maximum range by 17% all other factors remaining the same.

Earlier reconstructions in Estonia

The first attempt at trebuchet reconstruction was during the 1997 archaeological expedition to Lihula by archaeologist Mati Mandel and historian Jaak Mäll. Two trial shot results have been published: the first shot employed a counterweight of 300 kg and hurled a 5 kg stone to a distance of approximately 40 m. The second shot used a 600 kg counterweight and hurled an 8 kg stone to a distance of 100 m (Mäesalu 2005). Spruce and pine logs, forged nails, a hook and hemp rope were used in the construction for authenticity.

In the summer of 1999 enthusiasts lead by Priidu Pärna constructed a trebuchet at Varbola hillfort. This was significantly larger than the machine at Lihula. Unfortunately the results are not published. According to the enthusiasts themselves the counterweight was 1400 kg, beam length 7.5 m and the machine was capable of hurling a 10 kg missile to a range of 120 m. Judging on site by visual survey, the ratio of the short and long arms is approximately 1:5.5, hence the short arm is 1.15 m long. Counterweight drop height is thus 1.96 m and a 10 kg missile flight distance of 120 m gives us an efficiency of 0.22, which is mediocre. Probably it could be improved by lengthening the sling, which was much shorter than the long arm of the beam during my visual inspection of the machine.

Experiment carried out by the author on Otepää hillfort

In August 2002 a trebuchet reconstruction was erected on Otepää hillfort for experiments organized by the author (Fig. 5). The trebuchet was built on top of the hillfort to represent a defenders' machine – accounts of trebuchets being used for defensive purposes can be found in historical records. For example, the defence of Viljandi by Estonians during a siege by the Teutonic knights in 1223:

They were very much hindered by the ballistarii of the men in the fort; for the latter had a great many of the ballistas of the Brothers of the Militia which they used against the ballistas of the Christians and they had built paterells and machines against the Christians' machines. They fought against one another for many days.

(CHL, XXVII, 2)

During the planning phase a counterweight of 500 kg, ratio of the long and short arm (1.4:5) and axle height of 3.1 m were decided upon. Rest of the parameters were settled during construction.

Due to shortage of time and budget, no scale models were built. Construction work took six days, only up to three or four hours of work was done on each day. Historical look was less of a concern for us; most attention was given to the mechanical aspect of the task at hand. The trebuchet was constructed of spruce logs using present-day tools. The beam has a length of 5.5 m and the initial angle to horizon is 44 degrees.

The first trial shot used a counterweight of 300 kg. The machine turned out to be more efficient than expected, so the counterweight was never increased and the mass stayed in the interval of 200 – 300 kg. Stones of 2–11.5 kg were used as ammunition. Shots were fired from the top of the hillfort, which is approximately 35 m above the surrounding terrain. The best shot employed a counterweight of 250 kg and fired a 5 kg stone to a distance of 120 m. Before calculating the efficiency we must account for the effect of the machine being 35 m above the end point of the trajectory. By extracting the height of the hillfort from the flight distance, we shall get a distance equal to or less than the distance the machine would reach on level ground (because in the final part of its trajectory the missile must have fell at an angle greater than 45 degrees to the horizon); $120\text{ m} - 35\text{ m} = 85\text{ m}$. Such a range gives us an efficiency of 0.5, which is rather good.

The fact that a trebuchet is rather stabile in terms of trajectory found proof in our experiments. Three trial shots with the same missile landed in points no further than 2 m from each other. Also we gained an insight of the force of even a small (3–7 kg) missile. These stones penetrated so deep into the ground that it was impossible to retrieve them without a crowbar or a spade (although a part of it can be attributed to the rather soft ground and the 35 m height of the hillfort).

The reconstruction in general was a success, experience given by it was extensive and the author has acquired some degree of proficiency of operating such a complex mechanism.

CONCLUSION

Trebuchets were the historically latest and technologically most advanced siege engine type. In addition to the role on the field of war, these machines have also played an important part in the scientific thinking of mankind. The use of counterweight trebuchets has affected the views of many historically important thinkers, from Jordanus of Nemore to Leonardo da Vinci.

Most important conclusions of the theoretical analysis of and practical experiments with the trebuchet are the following.

The most important characteristic of a trebuchet is its **power**, which defines how big missiles and to what distance it is capable of hurling. A formula was given for calculating a trebuchet's maximum theoretical range from counterweight drop height, counterweight mass and missile mass.

Efficiency was defined, which characterizes the ratio of a machine's theoretical maximum range and actual range. Efficiency is between 0.1–0.7 for most machines. A machine may be deliberately tuned not to throw to its maximum range for the purposes of hitting a particular target.

The **extent of swinging of the beam** is a good indicator of how well a machine is tuned – a well-tuned trebuchet's beam all but stops right after the missile has been released. A badly tuned machine's beam swings heavily, because a large portion of the counterweight's potential energy has stayed in the machine.

A missile's **destructive capability** is defined by its kinetic energy at the end of trajectory. Since the kinetic energy is defined by missile mass in first power and missile velocity in second power, the destructive power is more dependent on missile's speed than on its mass. Missiles flying a greater distance also have a greater speed at arrival, thus it is more advantageous to hurl smaller stones from a greater distance than vice versa. Greater distance from the enemy also provides better protection. Since the machines of the defenders were situated on higher ground than those of the besiegers, the former had a significant advantage, not only of greater range but also of greater destructive power of their missiles, since the stones hurled from higher ground had a greater velocity at impact than at leaving the machine.

In spite of the amount of research done on the subject of trebuchet mechanics, there are still many questions that need further study. The most immediate need is for research of events at the end point of the trajectory. Experiments need to be performed with various missiles arriving at various velocities at various targets (logs, planks, soil, stone walls with lime mortar and without, etc.) and the amount of inflicted damage must be observed. By employing a combination of practical research and technical knowledge the forgotten 'art of the machine' can hopefully be restored to the benefit of the disciplines of military history and history of technology.

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Resümee: Vastukaalu jõul töötav heitemasin

Käesolevas artiklis võetakse vaatluse alla keskaegse Euroopa võimsaim relvaliik – vastukaalu jõul töötav heitemasin. See koosneb heitekangist, mis on ristuva pöörlemistelje abil jagatud kaheks ebavõrdse pikkusega õlaks. Pikema õla otsas on ling, millesse asetatakse heidetav kivi. Lühema õla otsas on vastukaal, mis masina vinnastamisel tõuseb üles ja salvestab seeläbi endasse potentsiaalset energiat. Kui masin valla päästa, vajub vastukaal alla, tõmmates heitekangi teise otsa suure kiirendusega üles. Selle otsas olev ling teeb kaare läbi õhu ja päästab parajal hetkel lahti heidetava kivi.

Oma arengu algaasides töötas nimetatud heitemasin inimjõul – vastukaalu asemel olid köied, millest tõmbas sõdurite meeskond. Selline masin võeti esmakordselt kasutusele 5.-6. sajandil Hiinas, esimesed teated vastukaaluga heitemasinastest on pärit 12. sajandi islamimaadest, Bütsantsist ja Euroopa Vahemerealadelt.

Heitemasina võimsust on erinevad autorid hinnanud erinevalt. Mehaanika seisukohast määrab heitemasina võimsuse potentsiaalse energia hulk, mille masin on võimeline vinnastamise käigus endasse salvestama. See sõltub vastukaalu massist ja kukkumisteede jooksul läbitavast kõrguste vahest. Järgnev valem määrab heitemasina teoreetiliselt maksimaalse heitekauguse:

$$R_T = 2 \cdot \frac{m_1}{m_2} H_{CW}$$

R_T – teoreetiliselt maksimaalne heitekaugus

m_1 – vastukaalu mass

m_2 – heidetava kivi mass

H_{CW} – vastukaalu poolt kukkumisteede jooksul läbitav kõrguste vahe

Reaalne heitekaugus sõltub sellest, kui hästi masin on häälestatud, teisisõnu sellest, kui hästi on reguleeritud heitekangi õlgade pikkused, lingu pikkus ja kinnituskonksu kõverus ning vastukaalu mass ja heidetava kivi mass. Seda iseloomustavat tegurit nimetatakse kasuteguriks. Autori enda rekonstruktsiooni ja teiste uurijate poolt ehitatud masinaid analüüsides näeme, et kasutegur jääb enamasti vahemikku 0,1-0,7. Kasutegurit vähendavad ka hõõrdumine, õhutakistus jmt.

Kriitilise tähtsusega on ling, mis peab vabastama kivi täpselt õigel hetkel. Kui kivi vabaneb lingust liiga vara, lendab see liiga kõrge kaarega, otse üles, või lausa selja taha. Sellisel juhul jääb ka osa vastukaalu salvestatud potentsiaalset energiat masinasse, mis põhjustab heitekangi pendeldamist. Liiga hilja vabanev kivi aga saab liiga madala trajektoori ja tungib maasse masina lähedal.

Reaalses sõjategevuses ei ole tähtis saavutada mitte maksimaalset heitekaugust, vaid tabada sihtmärki ja põhjustada võimalikult suuri purustusi. Kivi purustusjõu ei määra mitte selle mass, vaid kineetiline energia, mis sõltub kivi massist ja kiirusest tabamise hetkel:

$$E_K = \frac{mv^2}{2}$$

E_K – kivi kineetiline energia

m – kivi mass

v – kivi kiirus tabamuse hetkel

Näeme, et kiirusest sõltub kineetiline energia isegi suuremal määral kui massist, sest kiirus on antud valemis ruudus. Kaugemalt heidetud ja seega suurema kiirusega kergem kivi võib tekitada isegi rohkem kahju kui lähemalt heidetud massiivsem kivi.

Vastukaalu jõul töötavate heitemasinate rekonstruktsioone on ehitatud palju, esimene neist juba 1850. aasta paiku keiser Napoleon III käsul. Autori töö seisukohast oli oluliseimaks Taani eksperimentaatori Peter Vemming Hanseni poolt ehitatud ja 1992. aasta artiklis kirjeldatud rekonstruktsioon, mille paljud lähtekohad said aluseks ka autorile oma rekonstruktsiooni ehitamisel. Eestis on ehitatud veel kaks taolist heitemasinat – üks Lihulas arheoloog Mati Mandeli juhatusel ja teine Varbola linnuses ajalooühilise Priidu Pärna eestvedamisel.

Otepäälle 2002. aasta augustis ehitatud rekonstruktsiooni puhul kasutati 200-300 kg vastukaalu ning saavutati parimaks tulemuseks 250 kg vastukaalu ja 5 kg kivi puhul umbes 120 m; siin tuleb siiski arvestada, et masin asus 35 m kõrguse linnamäe otsas. Tasasel maal oleks masin heitnud arvestuslikult umbes 85 m kaugusele, mis annab kasuteguriks 0,5.

Edaspidi uurimist vajavatest küsimustest on kõige pakilisem erinevate masside ja kiirustega kivide purustusjõu väljaselgitamine kivist, puust ja pinnasest märklaudade puhul.

ILLUSTRATIONS

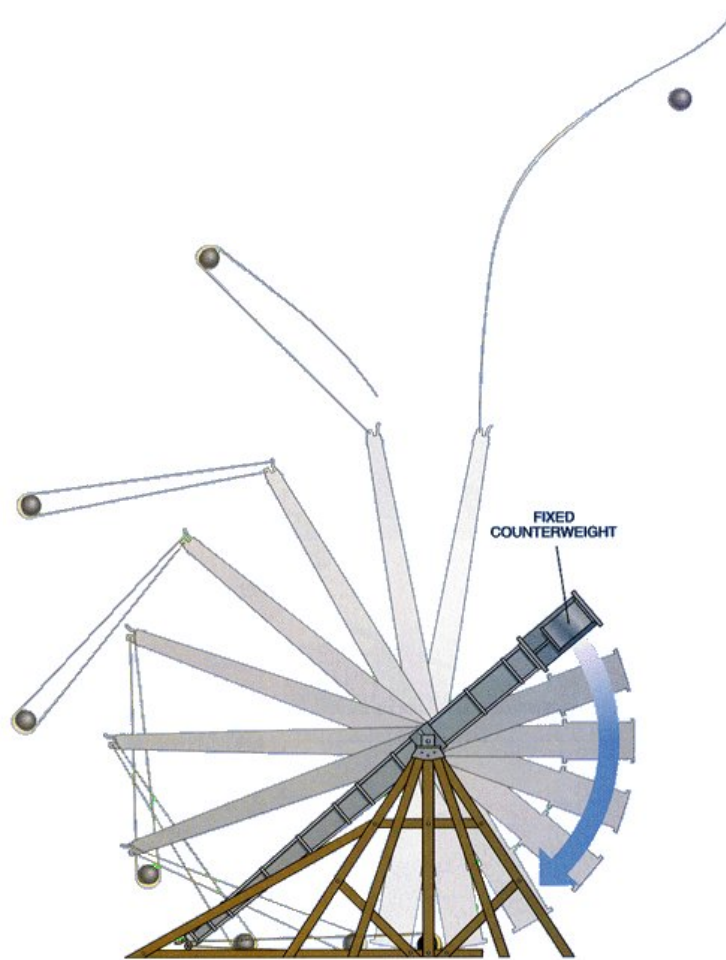


Fig. 1 – The working principle of the trebuchet (Chevedden et al. 1995: 60).

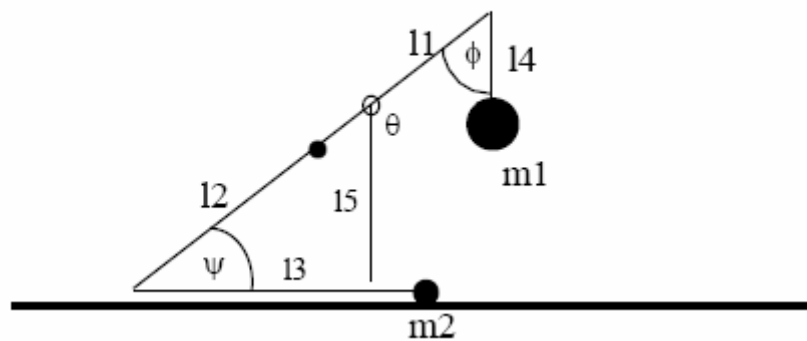


Fig. 2 – Mechanics of a trebuchet (Siano 2001, fig. 1). The machine is cocked and ready to fire.

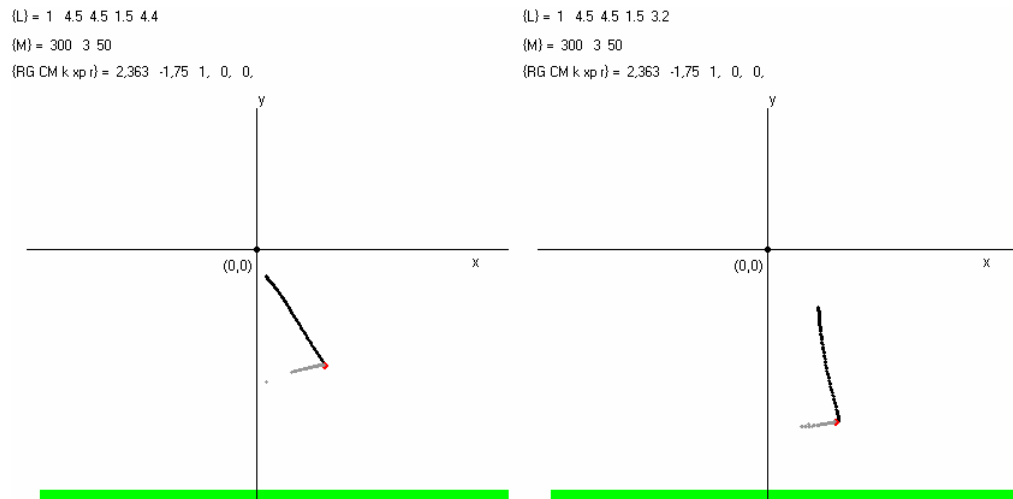


Fig. 3 – Counterweight trajectory: on the left the axle height is too big, on the right the axle height is optimal. Graph generated by WinTrebStar 4.0.

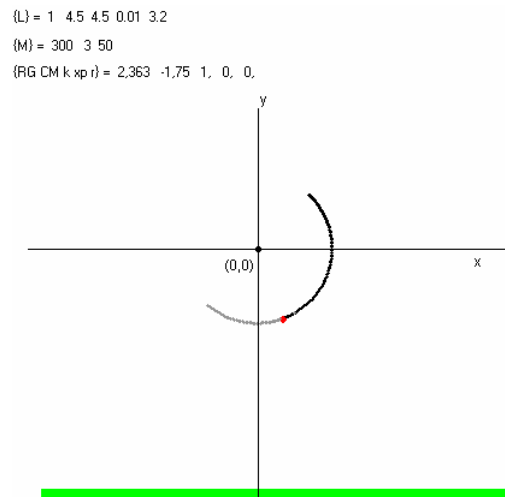


Fig. 4 – Trajectory of a fixed counterweight. Graph generated by WinTrebStar 4.0.



Fig. 5 – The trebuchet at Otepää hillfort, autumn 2004. The machine is cocked and ready to fire. Photo by author.