# The Design and Construction of a Late Period Basket Weighted Trebuchet

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## PROJECT INTENTIONS AND SCOPE

This project was conceived and developed to demonstrate both to SCA members and the general public the skills and knowledge of medieval siege engineers by the construction of a large scale late period trebuchet. In order to achieve this we faced several constraints. The main constraints are listed below in no special order.

1 The engine needs to be as large as is feasible to make a good first impression.

2 The engine must be structurally safe to operate and demonstrate in a variety of field areas. We must be able to reliably dial in a desired range so that the fall of shot occurs within the safe area.

3 The engine must be constructed so as to represent medieval construction technology.

4 The engine must be portable and be able to be assembled using a small crew of people under the direction of one or two leads.

5 We wish that the engine be useable with a minimum of maintance for a number of years.



## THE TREBUCHET IN HISTORY

The origins of the Trebuchet may go back to the stone age when the even more ancient sling shot was modified for greater range by attaching it to a long pole. The earliest true trebuchet is the traction trebuchet where the throwing arm is balanced on a frame and the short end of the are is pulled down with a number of ropes. Such machines date to 5th to 6th century China (1). These machines would be rather inaccurate as it would be very difficult to control how hard each member of the "pull" crew was pulling to launch the projectile. Machines of this type would be limited in use to anti-personel weapons or perhaps throwing flaming projectiles into encampments or fortifactions, it would be difficult to see how enough energy could be generated to defeat even a thin stone wall.

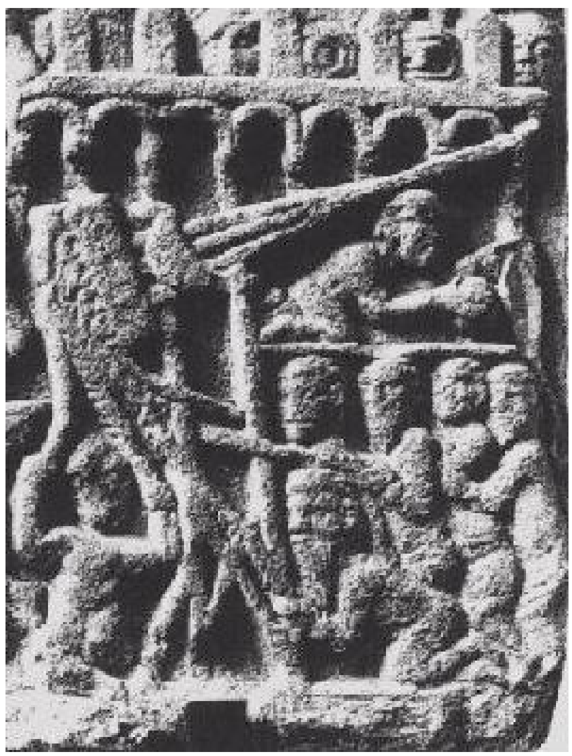

Figure 1. Detail from Carcassonne Cathedral dating to the 13th Century showing the operation of a Traction Trebuchet thought to depict the Siege of Carcassonne in 1209.

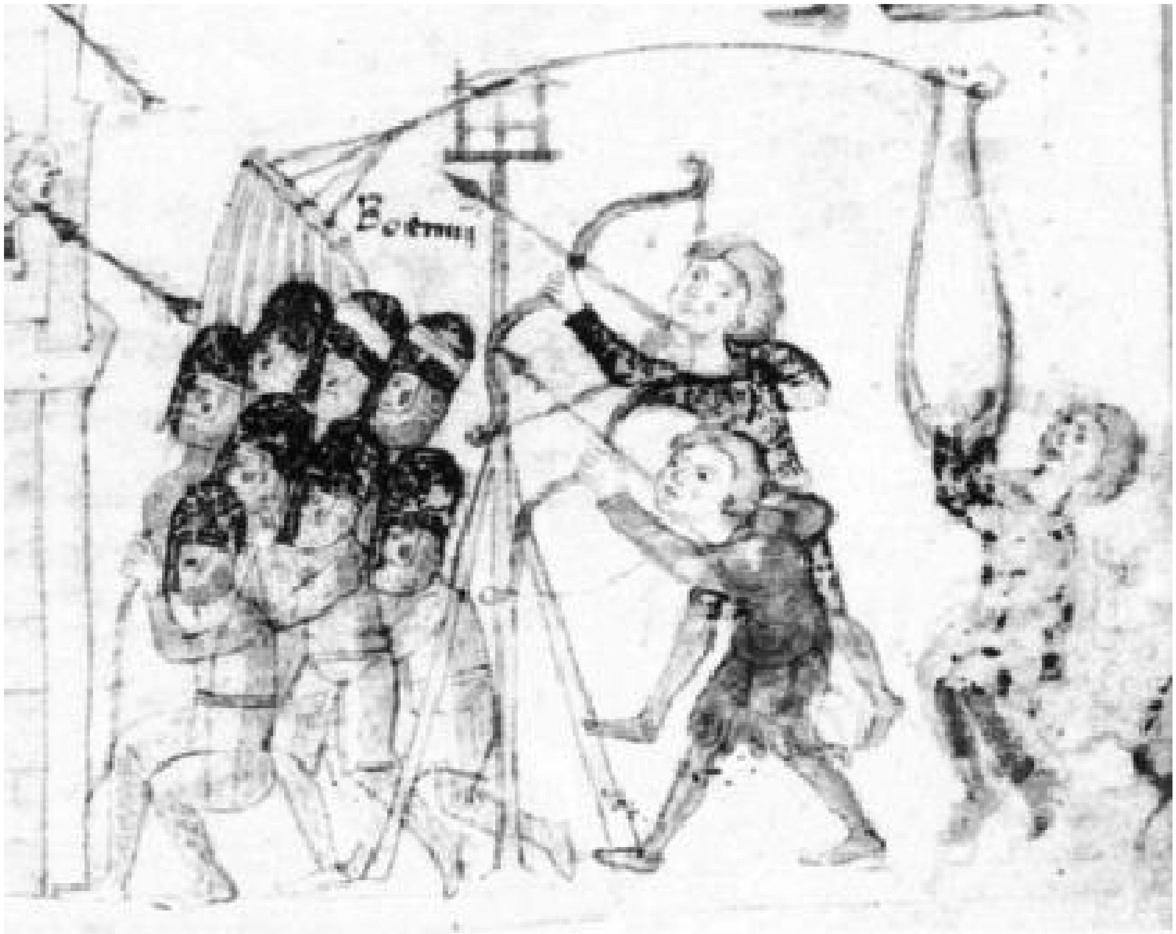

Figure 2 Detail from Chronicle of Petrus de Eboli c.1180

Shows a castle siege with a traction trebuchet. The stand is clearly separated from the mounting of the throwing arm, implying that the arm might be free to pivot on two axis to aid in aiming.

Figure 3 Byzantine manuscript depicting a traction trebuchet in siege of a fortification. Note the similarity to the design to the engine in figure 2. It is possible that the Byzantines were using these weapons by the late 500's.

In doing the research for this paper, I have run across many references to fixed counterweight trebuchet including a large number of modern reconstructions, however while I have found manuscript and stone carvings of traction and basket counterweight trebuchets, I have not found any in period pictorial evidence of the fixed weight counterweight trebuchets. While negative evidence is not conclusive I would point out that several of the early basket counterweight trebuchets depicted in manuscripts have the counterweight apparently suspended by ropes from the short end of the throwing arm, which would seem to be an easy transition from a traction trebuchet that would already be equipped with the ropes. I am not concluding that fixed counterweight trebuchets were not built, and I am aware that the physics of this type are proven, but they may not have been signifgent in numbers.

Figure 4 From a manuscript in the Bibliotheque Nationale de France.

Likely from the late 1100's or early1200's due to the prevalence of chain armour, note that the barrel containing the counterweight is suspended from the short end of the throwing arm by ropes, an easy transition from earlier traction trebuchets.

The addition of the counterweight to the trebuchet was revolutionary. The size of the machines could be vastly increased adding to the range, power and accuracy over traction types. The machines could now be set up outside of the range of crossbows and still have the power to destroy fortified walls. The down side of this increase is size was that the machine grew ever more complex to build and operate. Pulley systems with large



"hamster cage" winches were used to re-cock the arm, triggers were required to hold back the arm until all was ready.

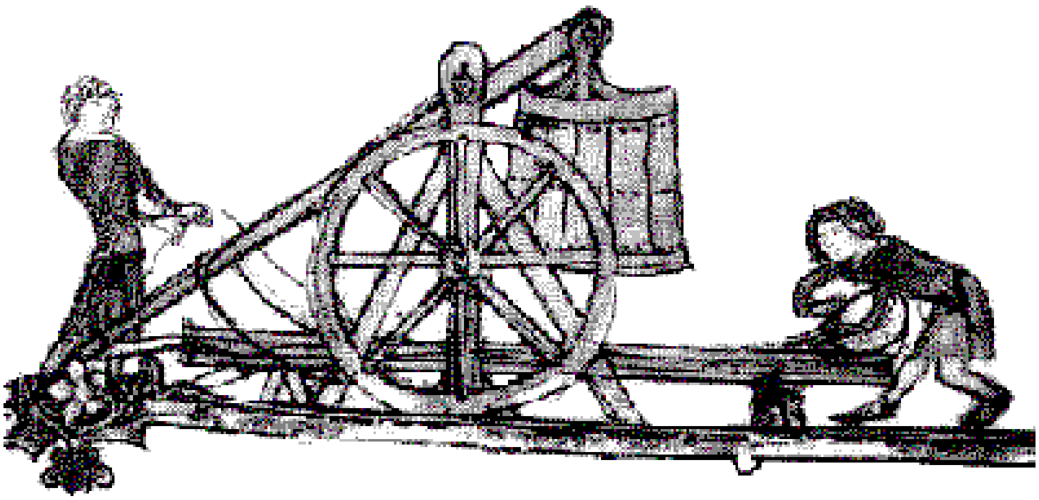

Figure 5 Winched Trebuchet, showing a winch that would presumably be used to re-cock the trebuchet for the next shot.

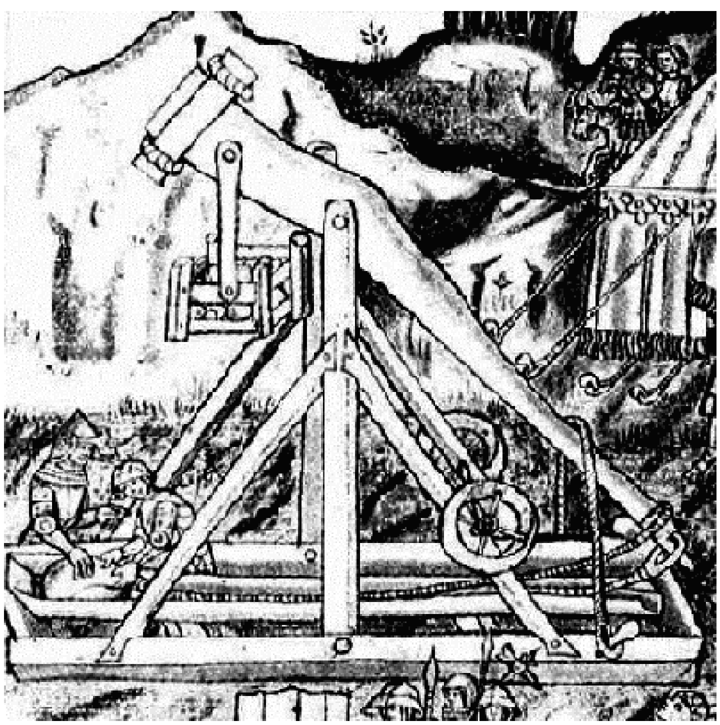

Figure 6 Later Period Winched Trebuchet. There is no source given



for this illustration, but it dose show a number of important design and fabrication details. The style of the armour implies a date of the late 1300's to early 1400's. Unusually, this shows an added weight to the short end of the throwing arm. The counterweight is clearly suspended in a hanging basket . The lower joinery of the fore and aft stays is remarkably similar to what we built for our machine. The drawing implies that the main uprights are held onto the main horizontal beams with a pinned mortise and tenon joint. The winch is attached to the aft stays, high enough that it will not interfere with the projectile sliding underneath it in the trough, but not so far to the rear (or high) that it would be hit by the swinging counterweight after release. Also shown is a rope overhanging the long end of the throwing arm ending with a pin. It is not clear if this is a safety or is the actual trigger to release the arm. The sling and release is shown well, with one end of the sling rope looped over the end of the arm and the other attached to a ring that is hooked onto a pin or extension of the arm. In both Figures 5 & 6, the usual out rigger braces are missing, these keep the main uprights vertical and parallel.

With the widespread use of large counterweights and winch systems to recock after a shot the trebuchet had reached the pinnacle of it's development during the middle ages. Trebuchets remained in use with little fundamental changes until the 1500's and served as artillery along side the early cannons until the development of the cannons resulted in their increased safety and rate of fire superseded the trebuchet in warfare.



## PHYSICS AND DESIGN

The definition of the Trebuchet is a catapult that uses the energy of a pulled rope or falling weight to throw a projectile.

How the trebuchet works can be describe by a complex set of equations that quite frankly, boggle my mind. However, the principals of how the proportions of the trebuchet affect its performance are more easily described.

The throwing arm is the principal leaver that takes the kinetic energy of the falling weight to throw the projectile. The counterweight end of the arm supports the counterweight. The sling end of the arm supports the sling that throws the projectile. Because the counterweight wants to accelerate towards the ground at 9.9 meters per second per second (the force of gravity on Earth) as the counterweight goes down, it lifts the other end up. Common proportions between the short and long ends is1/4 to1/5. The shorter the counterweight end of the arm is in proportion to the total length of the arm forces the sling end of the faster, but with less force, so it would be throw a lighter projectile faster, but a heavier projectile might receive insufficient energy to travel far. The longer the counterweight end of the arm is, the slower the sling end of the arm will move.

The arm itself must be able to support the counterweight in the cocked position, but this is not were the arm is under the greatest stress. The peak stress on the arm is when the arm and counterweight form a straight line after the release. This can be seen if watching video of a trebuchet launch when the counterweight falls almost vertically but then in the space of an inch or two it comes to a near complete stop. All the energy accumulated in the “drop” is transferred to the arm at that time. This is when the primary and secondary axles will pull through the rest of the structure or bend.



The counterweight must be constructed strong enough to withstand the forces developed from falling some distance. What is not obvious is that the dimensions, not just the weight have an influence on the efficiency of the trebuchet. While the weight is an obvious factor, the distance between the pivot point and the centre of gravity of the counterweight is important. When the arm is released by the trigger, the rear pivot on the arm transcribes an arc centered on the main pivot point. While the mass of the counterweight will by nature fall straight down, it will be pulled from falling straight down by the counterweight axle as it swings around the primary axle transcribing an arc. The greater the length of the counterweight allows it to fall closer to a straight line minimizing the forward and backwards inertia being transferred to the frame.

Please note however that the total height of the counterweight and the distance between the primary pivot of the throwing arm and counterweight pivot must be less than the height of primary pivot from any obstruction in the base of trebuchet frame or the counterweight will crash into that obstruction.

An overlooked part of the Trebuchet is the release pin. When re-loading a trebuchet the sling has one end fixed near to the end of the throwing arm and the other end with a small loop. This loop is hooked over the release pin that is fixed in the end of the arm. The pin is often bent upwards (in relation to the axis of the throwing arm) to modify the release point of sling and thus the trajectory of the projectile. A straighter pin permits an early release and a higher trajectory. A medium angle (perhaps 30˚) will result in a trajectory starting at an angle of 45˚, allowing the best for longest range. A sharper angle, (45˚ approximately) allows for a later release, a lower trajectory but a greater horizontal velocity. The surface of the pin can also affect the release moment. A smooth pin offers less friction and a more predictable release than a rougher or rusty pin. A metal ring in the end of the sling can also reduce the variability of the release moment over a simple loop in the rope.



The length of the sling affects the efficiency of the trebuchet as well. A short sling will release the shot early, in a high arc, but before it has received all the energy available to it from the machine, so it will fall very short of achievable range. If the sling is too long, the release is delayed and the trajectory of the shot is below the optimal 45˚. If the sling is well beyond its optimal length, it may fail to clear the machine at all and the lines tangle with the arm. The optimal length of the sling varies with other design parameters, but is frequently about 90% of the long end of the throwing arm, or the distance between the primary pivot and the end of the arm.

Other details that will affect the efficiency of the trebuchet are more workmanship than design. Pivots should be tight to constrain the motion to the desired direction, but free to move in that rotation. The major sub-assemblies must move in relationship to one and other without collision, therefore during fabrication great care must be taken to keep the primary and the counterweight pivots parallel to each other and aligned properly on the support structure.

## TRIGGER DESIGN

The trigger, that is the final release mechanism for the releasing the shot is a difficult issue in that I have found very little useful information as to what was used in period. One of the very few clues is shown in Figures 5 & 6 (on page 6) that shows the arm being held down by a rope going from one rail on the base frame to the other and terminating with what I assume to be a wooden pin. (Seen in Figure 6)

This would make for a difficult trigger as the arm would be restrained basically by the friction of the pin in the hole and to loose the trebuchet, one would have to pull the pin and then let go of it as it was pulled overtop of the arm.

I have also see (and used) a mangonel and trebuchet where the trigger was a pull pin that passed through two eye bolts that were attached to the frame and a third ring that was attached to a rope on the throwing arm. The problem with this design is that there are 3 points of contact between the pin and the rings and the pin must be pulled clear of all to cleanly release the arm. You also have at this point a steel pin flying towards your ankles at high speed. Any surface roughness on the pin would cause it to stick, a situation that gets progressively worse with the greater load on the pin making it very difficult to loose the trebuchet on cue.

We chose to use the levered hook trigger favoured by Danish Medieval Center. Shown in Figure 7 (below) the throwing arm is restrained by a hook that pivots around a bolt or anchor in the “X” frame on the trebuchet and is pulled out of engagement with a ring on the underside of the throwing arm by a rope tied to the long end of the trigger, thus a simple strong yank on the rope pulls the hook from the ring on the arm and the shot is released. The trigger remains attached to the “X” frame so the operator of the trigger dose not have to be concerned with metal pins flying towards him or her.



The trigger made by the DMC was forged for them by one of their own blacksmiths, but we were unable to obtain the services of a blacksmith to make this part for us so we modified the design and the part was made using a modern water cutting technology.

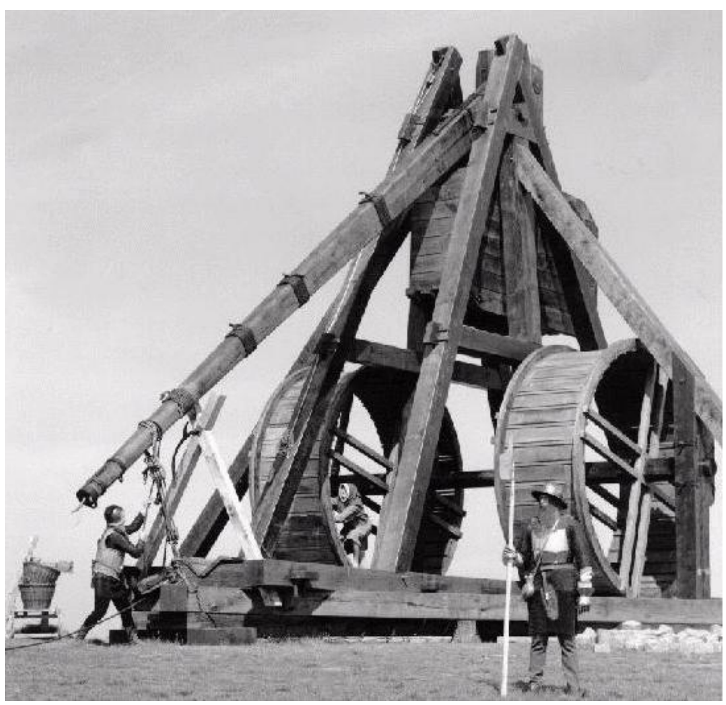

Figure 7 Modern Large Trebuchet Reconstruction showing trigger in uncocked position.

Figure 8 Trigger fabricated for our Trebuchet (5mm squares)

The trigger we designed for our trebuchet has the anchor ring shown on the left with the hook left of center and the ring for attaching the trigger rope on the right. The material is modern mild steel, ¼ of an inch thick.

This design maintains the function of the DMC design and when a blacksmith is available to fabricate a more medieval trigger we will be happy to replace the part.

The trigger is fastened to the frame by way of a quick link, this is a safety measure enabling us to remove the trigger entirely when the trebuchet is not in use to ensure that people not authorized to use the machine cannot use it.



HAUL DOWN DESIGN

With the counterweight fully loaded the up force at the end of the throwing arm is calculated to be close to 400 lbs. To run the trebuchet with a minimum sized crew and to best simulate those engines that might have a counterweight of 5 tons or more we decided to use a block and tackle that would reduce the forces involved to between 80 and 90 lbs.

The haul down system consists of three bocks, two lower blocks having two shives and the upper having three shives which will effectively divide the haul down force by 6. The bottom blocks are to be mounted on the rear supports. The upper block is hanging from a rope that is anchored to the underside of the throwing arm. This block has a second rope attached to it that allows the operators to pull in this line and pull the second block towards the primary pivot on the throwing arm. If this were not done then each time the trebuchet threw a stone, power would be lost from pulling the rope back through the upper block, by pulling it away to the fulcrum the arm will be free to move. When pulling the arm down, the block is free to move between the pivot point and the end of the arm. This seems to fit the bill for what is shown on some manuscript illustrations of trebuchets.



## TIMBER FRAME CONSTRUCTION

Although this is not a building, the construction technique for building the trebuchet is known as timber frame construction. In modern day construction with wood, pieces of wood are nailed together. So you would have a board joined to another with nails or screws with no joinery, no socket in the wood to transfer forces from wood to wood without going through a nail.

With timer frame construction, the pieces of wood are usually much bigger, squared logs are common and where the timbers meet, there is almost always a socket in one timber and a “tab” on the other so that forces transfer through the joinery to be carried to the ground. Joints are held together traditionally with “tree nails” but these are to keep the joint together when under construction or unusual stresses, under the design loading the joints are designed to be forced together.

When we were building our trebuchet, we had a requirement that the unit be assembled and disassembled multiple times and as a result, tree nails were ruled out as wear and tear on the holes through the joints would require us to make new tree nails on a continuous basis and the enlarging holes would weaken the joints so we opted for lengths of threaded rod, washers and nuts. These have been painted to conceal them from casual observation.

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## Initial Testing

Initial testing was started on the 14 October just at dusk when we conducted a “swing test” where we raised the arm to the shooting position but with no sling or projectile loaded and minimum weight in the counterweight and let the arm swing free to confirm free swing through the main structure. While the arm and counterweight swung wildly, no problems were observed.

The following day we fitted the sling and still with minimum weight in the counterweight (580 lbs) we loaded a 10 lb stone and pulled the arm down to just over 60 in from the rear tie on the base frame with a 40 degree release pin.

| SHOT | PIN ANGLE | COUNTER WEIGHT | STONE | PREDICTED RAGE | ACTUAL RANGE | PERCENT | ARM POSTION |
|---|---|---|---|---|---|---|---|
| 1 | 40 | 580 | 10 | 356 | 220 | 61.8 | 60 IN |
| 2 | 40 | 580 | 10 | 356 | 219 | 61.5 | 60 IN |
| 3 | 40 | 580 | 10 | 356 | 217 | 61.0 | 60 IN |
| 4 | 40 | 580 | 10 | 356 | 217 | 61.0 | 60 IN |
| 5 | 40 | 580 | 10 | 356 | 221 | 62.1 | 60 IN |
| 6 | 40 | 580 | 10 | 356 | 220 | 61.8 | 60 IN |
| 7 | 40 | 580 | 10 | 356 | 100 | 28.1 | 60 IN |
| 8 | 40 | 580 | 10 | 356 | 200 | 56.2 | 60 IN |
| 9 | 40 | 580 | 10 | 356 | 229 | 64.3 | 60 IN |
| 10 | 40 | 580 | 10 | 356 | 159 | 44.7 | 60 IN |
| 11 | 40 | 580 | 10 | 356 | 248.5 | 69.8 | 37 IN |
| 12 | 40 | 580 | 10 | 356 | 216 | 60.7 | 37 IN |
| 13 | 40 | 580 | 10 | 356 | 178 | 50.0 | 37 IN |
| 14 | 40 | 580 | 10 | 356 | 247 | 69.4 | 37 IN |
| 15 | 40 | 580 | 8 pumkin | 408 | 271 | 66.4 | 37 IN |
| 16 | 40 | 580 | 8 pumkin | 408 | 242 | 59.3 | 37 IN |
| 17 | 40 | 760 | 10 | 529 | 319 | 60.3 | 37 IN |
| 18 | 40 | 760 | 10 | 529 | 342 | 64.7 | 37 IN |
| 19 | 40 | 1015 | 10 | 746 | 431 | 57.8 | 37 IN |
| 20 | 40 | 1015 | 10 | 746 | 451 | 60.5 | 37 IN |
| 21 | 40 | 1250 | 10 | 925 | 483 | 52.2 | 37 IN |
| 22 | 40 | 1250 | 10 | 925 | 410 | 44.3 | 37 IN |



After our initial testing and comparing the results with predicted results from WintrebstarX, (a share ware program that models trebuchet performance) we have noted that one vital parameter is missing from Wintrebstar , that is release pin angle. This pin governs when the sling releases the projectile and is critical in adjusting the ranges.

What complicates the pin angle release calculation is the interaction between the launch forces and friction on the pin and ring. A pin angle of 40 degrees works well with 580 lbs for the counterweight but when we increased the counterweight to 1250 lbs we noted that the sling was releasing late, resulting in a flat trajectory and a lower range achieved. We switched to a 20 degree release pin and the release angle was improved but we failed to record the result because the pizza had arrived!

We achieved good launches with pumpkins weighing an estimated 8 lbs and approximately the size of a basketball after wrapping the sling with electrical tape to prevent the pumpkin from falling out of the sling until the sling had released from the release pin.

As time is available, we will continue with experiments adjusting weights of projectile and counterweight as well as release pin angles. Thus far we are very pleased with the repeatability of the trebuchet. We are by choice using natural stones that are irregular in shape and therefore the aerodynamics of the wildly spinning rocks are extremely complex.

By comparing the estimates from WintrebstarX and our best achieved shots we now feel that the best rang we could expect to achieve with a 10 lb stone will be approximately 650 ft but we will be able to “dial in” ranges from 200 ft and greater by adjusting the release pin and counterweight



## Conclusions

In comparing our trebuchet with those viewed on the internet we are extremely proud of the look and function of our machine. We feel that is a good representation of a medieval trebuchet in form and function and it is big enough to impress.

We learned much in the building of the trebuchet, first and foremost of these lessons is that building a large trebuchet is no trivial project. This took us far longer than we anticipated or planned for.

The total physics of a trebuchet would involve inputs of weights, dimensions and even surface types and friction. The math gets so complex that the simpler solution is to build the trebuchet and test it.

The best source of information I was able to find on the Internet is the website from the Grey Company, a group that goes into good detail on how to build an authentic trebuchet including details on triggers.