TITLE: THE TREBUCHET THROWING TRIAL OF THE THIRTEEN CENTURY

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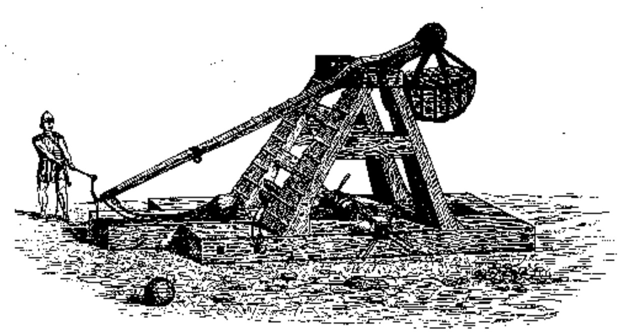
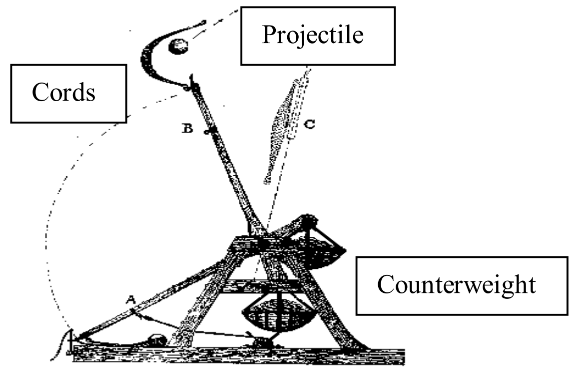
I. BACKGROUND

The outstanding medieval innovation to siege warfare was the trebuchet, a stone-throwing catapult powered by a counterweight.





II. PURPOSE

Studying different sources of information, several alternate solutions were developed to build this device.

The purpose of this study was to determine which combination of solutions would provide the best results in terms of MAXIMUM THROWING DISTANCE.

Throwing distance was the straight line measured from the trebuchet to the initial point of impact on the ground.

III. PROCEDURE

Variables used

- **The counter weight**
- **The presence or absence of wheels**.
- **The length of the cords**
- **The size of the shot**.

I **hypothesised** that longer sling cords would yield a flatter trajectory for the projectile due to the slow sling rotation and later release time.

The second **hypothesis** was that due to increased friction in the release mechanism a heavy projectile would release early with the result of a higher and longer trajectory.

TABLE 1

#	VARIABLES	SYMBOL	CONSTRUCTIVE SOLUTION	
1	Structure	S	NO wheels	WITH wheels
2	Counterweight	C	On the beam	In weight box
3	Length of sling cords	L	Short	Long
4	Projectile	P	Lighter	Heavier
			(-) SIGN	(+) SIGN

Materials

- A 1:40 scale model of a trebuchet was built
- Steel washers were used as the counterweight
- The cloth pouch was affixed to the arm with string
- Wire was used for the release mechanism (attached with tape)
- Different size marbles served as projectiles
- A measuring tape

Method: The Design of the Experiment

While the approach of manipulating one variable at a time can analyse how each variable individually affects the results of the experiment, it unfortunately cannot capture the interaction between different factors, and determine which combination of two or more variables will yield the best result.

For this experiment I used the factorial approach in which several variables (factors) are studied SIMULTANEOUSLY IN A BALANCED MANNER.

The experiment is based on a **CONTRAST MATRIX**, which provides the most efficient combination of variables with the minimum number of throws.

To study 4 variables I needed to test 16 different setups for the trebuchet's throws with the constructive solutions combined as follows. (Table 2)

THROW	PROJECTILE	LENGTH OF SLING CORDS	STRUCTURE	COUNTERWEIGHT
1	LIGHT	SHORT	NO WHEELS	ON THE BEAM
2	HEAVIER	SHORT	NO WHEELS	ON THE BEAM
3	LIGHT	LONG	NO WHEELS	ON THE BEAM
4	HEAVIER	LONG	NO WHEELS	ON THE BEAM
5	LIGHT	SHORT	WITH WHEELS	ON THE BEAM
6	HEAVIER	SHORT	WITH WHEELS	ON THE BEAM
7	LIGHT	LONG	WITH WHEELS	ON THE BEAM
8	HEAVIER	LONG	WITH WHEELS	ON THE BEAM
9	LIGHT	SHORT	NO WHEELS	IN WEIGHT BOX
10	HEAVIER	SHORT	NO WHEELS	IN WEIGHT BOX
11	LIGHT	LONG	NO WHEELS	IN WEIGHT BOX
12	HEAVIER	LONG	NO WHEELS	IN WEIGHT BOX
13	LIGHT	SHORT	WITH WHEELS	IN WEIGHT BOX
14	HEAVIER	SHORT	WITH WHEELS	IN WEIGHT BOX
15	LIGHT	LONG	WITH WHEELS	IN WEIGHT BOX
16	HEAVIER	LONG	WITH WHEELS	IN WEIGHT BOX

The construction of the trebuchet was changed after each throw to allow the 16 combinations as per Table 2.

To verify the results of the experiment each throw combination was repeated twice in random order (**REPLICATION**). If the difference between the 3 throws with the same constructive solution was bigger than 15%, the cause would be investigated.

The average of the 3 throws for each combination was then recorded.

The Contrast Matrix for this experiment was configured as follows:

CONTRAST MATRIX

Throw No.	P	L	PL	S	PS	LS	PLS	C	PC	LC	PLC	SC	PSC	LSC	PLS C	Distance (Avg. cm)
1	-	-	+	-	+	+	-	-	+	+	-	+	-	-	+	462
2	+	-	-	-	-	+	+	-	-	+	+	+	+	-	-	270
3	-	+	-	-	+	-	+	-	+	-	+	+	-	+	-	330
4	+	+	+	-	-	-	-	-	-	-	-	+	+	+	+	290
5	-	-	+	+	-	-	+	-	+	+	-	-	+	+	-	498
6	+	-	-	+	+	-	-	-	-	+	+	-	-	+	+	265
7	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	338
8	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	285
9	-	-	+	-	+	+	-	+	-	-	+	-	+	+	-	563
10	+	-	-	-	-	+	+	+	+	-	-	-	-	+	+	488
11	-	+	-	-	+	-	+	+	-	+	-	-	+	-	+	307
12	+	+	+	-	-	-	-	+	+	+	+	-	-	-	-	452
13	-	-	+	+	-	-	+	+	-	-	+	+	-	-	+	494
14	+	-	-	+	-	-	-	+	+	-	-	+	+	-	-	486
15	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	478
16	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	447

Contrast Total	-487	-599	529	129	-163	209	-215	977	549	-95	-135	61	-55	265	-271
Effect	-61	-75	66.1	16.1	-20	26.1	-27	122	68.6	-12	-17	7.63	-6.9	33.1	-34

For Throwing Distance:

- A CONTRAST TOTAL is the sum of the 8 results of the 8 throws with "+"signs minus the corresponding sum of the 8 throws with "-" signs. (Previous table)
- An EFFECT is the CONTRAST TOTAL divided by 8 (or in general the number of runs for each constructive solution).

In statistical terms, it is the average result of the "+" option of the variable minus the average of the "-" option. The column corresponding to an interaction measures how the result of one variable depends of the solution of the second.

IV.RESULTS

The maximum difference between the 3 throws performed for each constructive solution was 8%.

Method #1:Main effect analysis (see the " Effect " row on the Contrast Matrix)

- The most significant factor was the counterweight, the box solution producing the maximum distance (largest main effect, the positive sign indicating that the average distance for the box was bigger than the average distance for the beam solution).

- The second largest factor was the length of the rope: the shorter rope yielded longer distance (second largest main effect, the negative sign indicating that the average distance for the short rope was bigger than the average distance for the long rope).
- The third significant factor was the interaction between the size of the projectile and the counterweight solution (PC was the third largest main effect).
- The fourth significant factor was the interaction between the size of the projectile and the length of the rope (PL was the forth largest main effect).
- The last significant factor was the size of the projectile: lighter shot yielded longer distance (fifth largest main effect, the negative sign indicating average distance for the light projectile was bigger than the average distance for the heavy projectile).
- The presence or absence of wheels had no effect on the throwing distance (minor effect compared to previous ones)

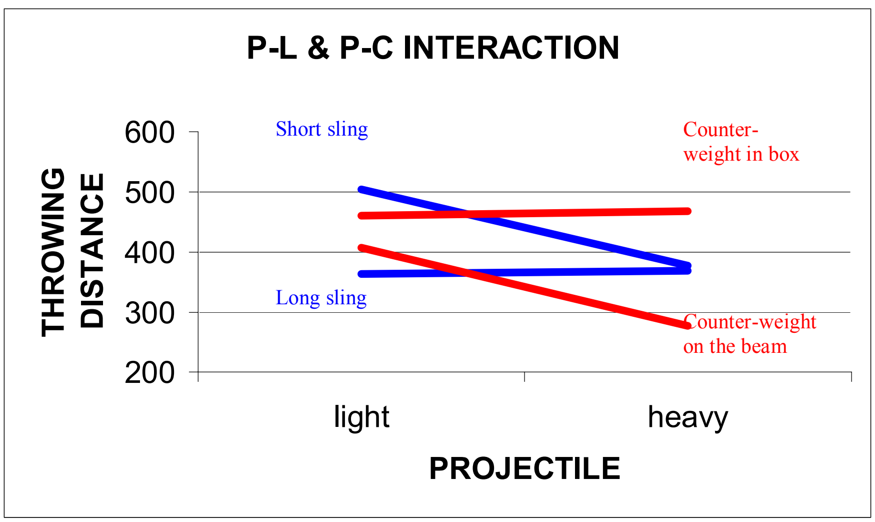
This can be analyzed using a two-way table and an interaction diagram. The next tables show the 16 responses with respect to upper and lower levels of L,P and C.

The P-L Interaction

Projectile "P"	"L" Length of Rope	
	Short (-)	Long (+)
Light (-)	462,498,563,494 average=504.25	330, 338, 307, 478 average=363.25
Heavy (+)	270,265,488,486 average=377.25	290,285,452,447 average=368.5

The P-C Interaction

Projectile "P"	"C" Counter-Weight	
	On the beam (-)	In Weight Box (+)
Light (-)	462,330,498,338 average=407	563, 307, 494, 478 average=460.5
Heavy (+)	270,290,265,285 average=277.5	488,452,486,447 average=468.25



- The graph shows that the projectile weight had a significant effect only when the sling was short or the counterweight was attached to the beam (the throwing distance changes significantly based on the use of a light or heavy projectile).

Method #2:Percent Variation

$$\frac{(\text{Contrast Total})^2}{\text{Number of trials in the experiment}}$$

Throwing Distance

Contrast	Contrast Total	Sum of Squares	% Variation
P	-487	14823.062	**9.7**
L	-599	22425.062	**14.7**
PL	529	17490.062	**11.5**
S	129	1040.0625	0.7
PS	-163	1660.5625	1.1
LS	209	2730.0625	1.8
PLS	-215	2889.0625	1.9
C	977	59658.062	**39.1**
PC	549	18837.562	**12.3**
LC	-95	564.0625	0.4
PLC	-135	1139.0625	0.74
SC	61	232.5625	0.2
PSC	-55	189.0625	0.1
LSC	265	4389.0625	2.9
PLSC	-271	4590.0625	3
Total		152657.435	100

Percent Variation Analysis

The C, P and L considered together explained more than 87% of the variation in distance. The presence or absence of wheels had no significant effect. This may explain why the vast majority of medieval sources do not show wheels attached to the trebuchet.

V. CONCLUSIONS

- This study provides an answer to one of the big debates among historians in recent years. The results support the theory that most trebuchets were build on-site, without wheels, with counterweights hanging from the end of the arm contrary to the theory that wheels were used to increase efficiency and make them more portable.
- This is also consistent with the sources consulted during my research, which did not show the presence of wheels.
- My study also supports the idea that the length of the rope was used to fine-tune the throwing distance to be able to hit the desired area of the city or castle wall.
- The accuracy of this medieval siege device allowed the user to target with remarkable precision the most vulnerable areas of the fortifications.

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