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ON TECHNICAL ANALYSIS OF CANNON SHOT CRATER ON DELHI IRON PILLAR

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A cannon ball that struck the Delhi Iron Pillar surprisingly did not break the Pillar. The history of the ball strike and the probable reason why a second shot was not attempted have been explained. The trajectory of the cannon ball and the surface features of cannon ball indentation area are critically examined. Plaster of Paris depression of cast obtained from the subjected cannon ball crater has been put under digital simulation technique to estimate the diameter of the cannon ball that struck the Pillar. Surprising ability of the Pillar to have withstood the cannon shot and the possible type of cannon used to fire the shot have also been briefly analysed.

Key words: Cannon ball, Cannon ball diameter, Delhi Iron Pillar, Digital image simulation, Impact, Plaster of Paris cast, Trajectory.

Introduction

The Delhi Iron Pillar[1-3] located in the courtyard of the Quwwat-ul-Islam mosque near the Qutub Minar in New Delhi is a marvelous engineering construction [see Fig. 1(a)], considering that it was forged out of individual iron lumps, almost 1600 years ago during the reign of Chandragupta II Vikramaditya (375-413 AD). Its exceptional atmospheric corrosion resistance (due to the presence of significant amount of phosphorus in solid solution[4]) has further attracted the notice of corrosion technologists and scientists, eager to unravel its mysteries. New insights have been obtained on several aspects of the Pillar, including its history[5], manufacturing methodology[6], corrosion resistance[7] and astronomical significance[8].

One of the significant marks on the Iron Pillar is the indentation of a cannon ball that struck the Pillar for a brief moment ($<10^{-6}$ s) in its history (see

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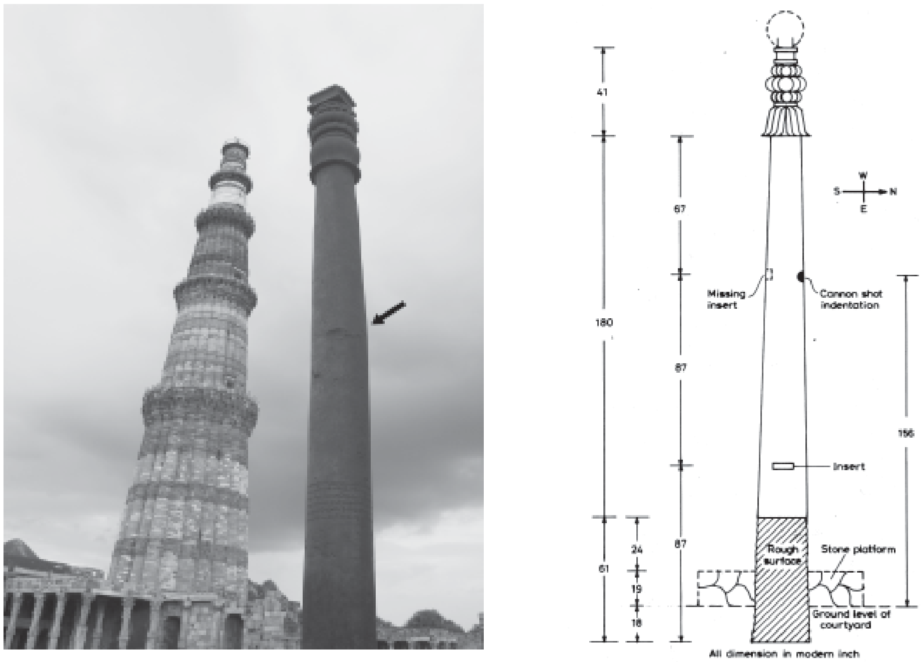


(a) (b)

Fig. 1. Delhi Iron Pillar located at the Quwwat-ul-Islam mosque in the Qutub Complex at New Delhi showing (a) the cannon ball strike location on the Iron Pillar (arrowed) and (b) the salient dimensions of the Pillar showing the relative position of the cannon ball indentation and the inserts. The overall symmetric design of the Delhi Iron Pillar is a matter of great appreciation

middle location of the Pillar shown in Fig. 1(a). The indentation is located at a level of about 156 inches from the current courtyard ground level. The salient dimensions of the Pillar are shown in Fig. 1(b), from which the overall symmetric design must be appreciated.

The impact of the cannon ball strike on the stability has been analyzed and it has been shown that the surprising resistance of the Pillar to fracture was due to the deflection of the propagating horizontal crack from the radial direction to the axial direction by the presence of lump-lump interfaces in the main body of the Pillar. Special attention was paid to understand the origin of different kinds of cracks observed around the cannon ball impact location [see Figs. 2(a) and 2(b)] and this has been correlated with the Pillar's stability[9]. The history of the damage caused to the Quwwat-ul-Islam mosque structure due to wayward cannon fire

(a)

(b)

Fig. 2. Close up views (a) crater and (b) cracks in the location diametrically opposite to the cannon ball indentation area

has also been examined[10]. Interestingly, this appears to have prevented further shots being fired at the Pillar from the well positioned cannon.

The aim of the present paper is to technically analyze the cannon shot crater to obtain insights on the type cannon ball used and the trajectory of the cannon ball. This will help us to understand the cannon location when it fired on the Pillar. The paper will conclude with a brief discussion on the type of cannon that was used to fire at the Pillar.

Let us first consider the origin of the cannon ball indentation briefly.

Historical Background

Practically speaking there is no record, in the form of inscriptions or documents when the cannon ball had struck the surface, or who fired the cannon ball. We may guess the cannon ball strike must have occurred after the arrival of cannon technology in India, which has been analyzed in great detail elsewhere[11]. There are literary evidences to prove that cannons were used in the subcontinent in the fifteenth century AD, the first large scale use was by Babur in the First Battle of Panipat in 1526. Therefore, the incident of cannon ball strike cannot be more than 500 years old, a period after early sixteenth century AD.

It is fact taht Nadir Shah[12,13] among others used the cannon balls, is likely to have fired the shot, his attack and loot of Delhi in 1739 AD is legendary which undoubtly hastened the decay of Mughal Empire[14]. After liberating his home country Persia (i.e. modern Iran), he first mounted an attack on his Afgan enemies following them up to India by the end of 1738. He captured Khyber Pass on 26 November 1738, took Peshawar on 29 November, Lahore on 23 January 1739, defeated the Mughal imperial army at Karnal on 13 February 1739, promptly looted the Mughal treasury on 20 March, 1739. When he went to the Golden Mosque in Chandni Chowk in the morning on 21 March 1739, he was attacked which angered Nadir Shah so much that he ordered a general massacre of the population of Delhi. While there are no particular records of the massacre, reports in Marathi letters[15] mention three to four lakhs of the population being killed. Nadir Shah did not stay long and he left Delhi on 16 May 1739 leaving Delhi with the wealth (amounting to nearly 100 crore rupees in coins and jewels) accumulated over two centuries of Mughal rule, carted away in less than a month's time[15]. It was during this time that Nadir Shah moved away some of the important objects from Delhi, which included the celebrated Peacock Throne. It is against this background there is enough reason to suggest that Nadir Shah might have fired the cannon ball on the Iron Pillar.

Other powers like the Marathas and British have ruled Delhi (apart from the Mughals) since the arrival of gunpowder technology in India. The cannon shot fir cannot be linked with their reigns. The history, however, does not record these powers as destroyers of monuments but rather as preservers of objects and buildings of historical significance.

Detailed analysis of the cracks resulting from a cannon shot reveals a single shot would have been sufficient to have broken the Pillar into two, had it been a solid homogeneous structure[9]. The cannon ball was possibly aimed above the central portion of the Pillar (see Fig. 1(b). The intention being remove the top portion of the Iron Pillar, which contains the artistically meritorious decorative bell capital[16]. Nadir Shah was keen to cart away Delhi's historic and famous possessions to Persia. It is reasonable to conclude that the cannon shot was fired by him during the period 21 March 1739 to 16 May 1739, the time he was in total control of Delhi. Other efficient methods by using gunpowder was well known in India as early as fifteenth century[17] but not used so the intention to dislodge the top portion of the Pillar from the main body is considerably clear.

Another possible reason for dislodging the top portion of the Pillar could be that he was eager to look for hidden "treasures" inside the Pillar, as it was well known that ceremonial religious temple objects were associated with precious metal and stones. Major interest might be to break the Pillar into two and carry the top portion away.

It still remains a mystery who ordered cannon shot to be fired on the Pillar and the exact time period of the cannon ball strike. The final judgment must wait till further corroboratory evidences surface, especially the complete details of activities of Nadir Shah during his stay in Delhi.

Absence of Second Cannon Strike

Prominent indentation due to one cannon shot on the surface of the Pillar and no further, earlier addressed by Prasad and Ray[13], also point out that the cannon strike was intentional, handled by an expert and attributed the shot to Nadir Shah (without any supporting evidence) and stated that his motive for destruction of the Pillar was to remove this Hindu temple monument from the mosque premises.

They also proposed that a second shot was not attempted, because the deflected cannon ball damaged something else in the mosque. This is an original and interesting proposal that has been elaborated in great detail elsewhere[10]. Wayward shooting caused damage to part of the significant Muslim monument, the Quwwat-ul-Islam mosque. Incidentally, it is the first mosque in India proper and the first Indo-Islamic building in India[18]. Technical analysis of the cannon ball indentation crater also revealed that the cannon ball which struck the Pillar shattered into smaller pieces after its impact on the surface[9]. It is important to reconstruct the direction of cannon fire and correlate this with the existing structures of Quwwat-ul-Islam mosque. Based on a detailed analysis of the existing structures of the Quwwat-ul-Islam mosque[18] and the position of the cannon shot indentation area on the northern side of the Pillar (see Fig. 1(b), it can be reasonably concluded that the cannon that fired the shot was moved into the courtyard through the gap (which can be still prominently noticed) in the north western portion of the wall of the mosque and positioned on the northern side relative to the Pillar when it was fired. Based on careful analysis of the existing structures in the mosque, it is clear that wayward shot(s) from the cannon fire has resulted in destruction of the structures on the southwestern portion of the mosque. The schematic of Fig. 3 summarizes the scenario, showing the gap in the wall through which the cannon was most likely dragged in, the probable location of the cannon when it was fired and the non-existent structures on the south western portion of the mosque. The existing structures are present only in the shaded hatched area in Fig. 3.

The location of the cannon indicted in Fig. 3 has been determined from the estimated trajectory of the cannon ball. The trajectory has been determined to be 15 degrees based on two approaches, namely analysis of the cannon shot crater and the direction of propagation of the shock wave generated on impact[9]. Utilizing the height of the strike (156 inches) and that the cannon must have positioned at a height of 5 feet (or 60 inches) from the mosque courtyard level (i.e. resting on carriage), it is estimated that the cannon was located at a distance of approximately 30 feet (namely, 358 inches = (156-60) / tan 15°) from the Pillar when it was fired. This is the basis on which the cannon location has been marked in the schematic of Fig. 3.

The possible damage caused to the structures of the mosque can be appreciated based on the trajectory of the cannon ball and analysis of existing structures in the Quwwat-ul-Islam mosque. Since the cannon ball was fired from the northern direction, the missing structures in the south western part of the mosque must have probably been destroyed due to wayward cannon shot. It must be appreciated that even one cannon shot landing in the cloistered hall on the southwestern portion would have caused considerable damage, considering the close range of the cannon fire. Therefore, it is reasonable to conclude that the damage caused by wayward cannon shot must have resulted in further shots not being attempted on the Pillar, even with the cannon well positioned to take a second shot.

It could also be speculated that the cannon ball strike may have been unintentional, assuming that the cannon ball could have reached the Pillar's surface after having been lobbed over the mosque boundary. The estimated trajectory of

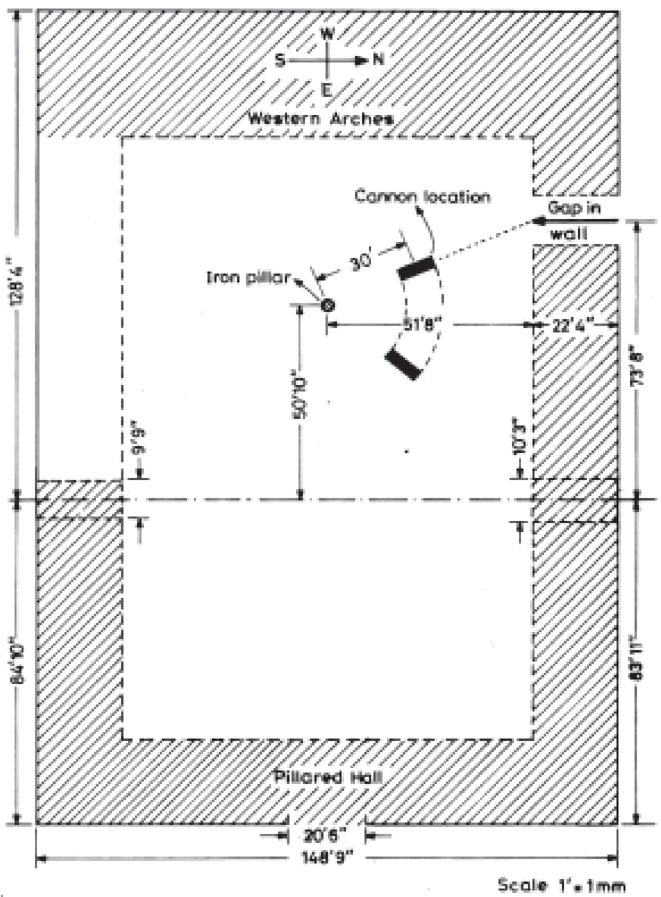


Fig. 3. Schematic of the Quwwat-ul-Islam mosque showing the salient dimensions of the mosque premises and the possible location of the cannon that fired the shot

the cannon ball (to be discussed later) discounts this possibility. The ball appears to have traveled straight to the Pillar and hit the surface on its upward motion, thereby indicating that the hit of the cannon ball on the Pillar was intentional, with the explicit purpose of breaking the Pillar into two.

The good stability of the Pillar, in spite of the severe hit by the cannon ball, has been addressed in detail elsewhere[9] wherein the entire sequence of events that took place from the beginning of the impact of the shot on the surface has been discussed. This will be briefly reviewed in the section below before analyzing the crater using Plaster of Paris impression.

Stability of the Pillar

It has been shown by scientific analysis elsewhere[9] that the single shot that struck the Pillar would have been sufficient to topple the Pillar had the Pillar been a solid body. Therefore, the stability and ability of the Iron Pillar to withstand the cannon shot will be finally addressed as it is an important issue, due to which the Pillar is still standing at its current location. This will be based on recreation of the events that took place after the cannon ball struck the Pillar. It may be very interesting for the readers to note that all the events to described below took place in a time period of less than a microsecond (10^{-6} seconds).

The sequence of events after the cannon ball strike can be recreated as follows[9]. The cannon ball was directed from the north direction, based on the position of the cannon shot indentation on the northern side of the Pillar. The cannon was positioned quite close to the Pillar when it fired the shot on the Pillar. The cannon ball impacted the surface on its upward trajectory. The cannon ball first grazed the surface before coming to rest [see Fig. 2(a)]. The cannon ball shattered on impact. The impact did not lead to fracture at the impact location but resulted in the creation of an intense compressive plastic shock wave. The intensity of the shock wave increased with distance of propagation, due to the unique mechanical property of yield point phenomenon, exhibited by the material of construction of the Pillar, namely iron. The result was a highly concentrated stress wave. This compressive stress wave was reflected by the free surface at the end diametrically opposite to the cannon impact area. The reflected wave was tensile in nature and resulted in generation of a tensile stress in the rear. This led to horizontal cracking of the main body of the Pillar [see Fig. 2(b)]. A triangular shaped patchwork material and rectangular shaped insert on the surface were removed due to the fast propagating horizontal crack. This horizontally traveling crack did not lead to fracture of the Pillar into two because it was deflected in the axial direction of the Pillar due to the presence of lump-lump interfaces aligned along the axial direction of the Pillar. In this manner, the horizontal crack did not traverse the cross section of the Pillar and break it into two.

The processes, by which the impact energy of the cannon ball was dissipated, were heat and sound generation, creation of the crater (i.e. plastic deformation) at the point of impact, cracking on the side and the rear, horizontal cracking and spallation of lumps from the rear and deflection of fast propagating horizontal crack by separation of lump-lump interfaces. It is very important to note that the ductility and strength of the Iron Pillar (or toughness, which considers both strength and ductility) was not important because the critical fact that determined the Pillar's stability was the presence of lump-lump interfaces.

Estimation of Trajectory

Attention will now be focused on the cannon shot indentation area as this holds valuable material evidences for understanding the impact of the cannon ball on the Pillar. In one preliminary analysis of the details of the cannon shot location, Prasad and Ray[13] observed that the metal flow from the indentation indicated that the recoil of the cannon ball was somewhere to the right of the direction of the aim. It is unlikely, as we shall discuss shortly, that the impacted cannon ball was deflected. Evidences point to shattering of the cannon ball after impact. Prasad and Ray incorrectly observed that cracks emanate from the side of the cannon shot indentation and go round halfway to the back. This is not completely correct because there are different kinds of cracks at the indentation location and each type of crack has to be individually analyzed. For example, the cracking adjacent to the cannon shot indentation crater [see Fig. 2(a)] is very different from the cracking noticed on the back side of the Pillar [see Fig. 2(b)], almost diametrically opposite to the indentation area. In fact, the nature of cracks provided valuable clues to reconstruct the sequence of material events, immediately following the impact of the cannon ball[9].

Evidences, as available from the cannon shot indentation on the surface on the Pillar, need to be first recorded and highlighted. A close-up view of this area is shown in Fig. 4a. The following observations can be readily made. First, the complete impression of the cannon shot is not perfectly circular and the depression is skewed. Prasad and Ray[13] have earlier also pointed out that cannon ball indentation mark is not symmetrical. The depth at the right side [see Fig 4(a)] of the indentation is more than the left side. The left side of the indentation, due to its lower depth, indicates grazing of the ball on its way to the impact. The exact location of the final impact is on the right side of the indentation.

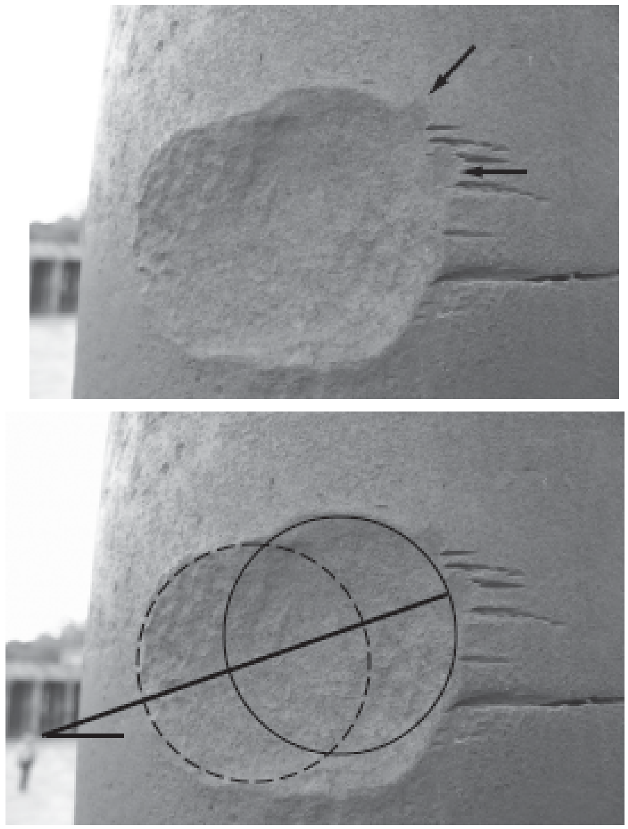
The direction of cannon shot was from the northern direction, as discussed earlier. Based on the observed surface features, it is possible to further conclude that the cannon ball first made contact on the left side of the indentation area and then came to rest on the right side [shown by full circle in Fig. 4(b)]. The trajectory of the canon ball can also be understood by noting the relative position of the centers of these two circles [see slanting line in Fig. 4(b)]. The important fact is that the trajectory points from the bottom to the top thereby confirming that the cannon shot landed on the Pillar on its upward motion from cannon. Another important conclusion is that the angle of the trajectory is 15 degree, as determined using the slanting and the horizontal lines in Fig. 4(b). This angle has been utilized earlier in this communication to estimate the location of cannon which fired the shot on the Pillar (see Fig. 3).

Estimation of Cannon Ball Diameter

The depression of the crater proves that plastic strains were generated due to the impact and that there was no cracking at the impact location. This had an important bearing on the consequences of cannon ball impact and this has been explained in great detail elsewhere[9]. The plastic strains generated due to the initial grazing motion of the ball and the final impact can be clearly distinguished on the indentation area [see Fig. 4(a)]. The surface features on the left of the cannon ball indentation area reveal material removal due to the grazing motion of the high velocity projectile. The features on the right reveal higher degree of deformation, caused by the final impact. That the final impact was on the right site of the indentation is further corroborated by a important material evidence, namely the creation of shear lips just at the right of the cannon ball strike location. This is indicated in Fig. 4(a), where two shear lips have been arrowed.

The origin of the shear lip is due to material erosion effects at high velocity projectile impact. When a dense material (like lead cannon ball) impacts the surface with force, it is shattered due to the impact force and the shattered small pieces cause further deformation at the edges of the main impact location[19]. The appearance of these shear lips confirms the fracture of the cannon ball into smaller fragments after striking the surface. It is indeed surprising to still notice such a visible evidence even after a long period of the event (2007-1739) = 268 years of the event.

The cannon ball indentation area was carefully photographed to obtain information on minute details of the structure and the relative features. In order to obtain accurate dimensions and also aid analysis in the laboratory, plasticine clay was placed over the cannon ball strike area such that the clay contained an impression of the cannon ball strike indentation. This was taken out carefully from the surface and Plaster of Paris was poured immediately on the clay thereby transferring the impression of the crater. Once the cast was set, it was used for further analysis in the laboratory.



(a)

(b)

Fig. 4. Close-up view of the cannon ball indentation location: (a) Two shear lips around the cannon ball crater have been arrowed, and (b) analysis of the indentation area showing the location where the cannon ball first made impact (dotted circle) and the location where the cannon ball came to a halt (full circle). The trajectory of the ball is indicated by the slanted line

In order to digitally analyze the dimensions of the cast, the cast was first digitized using the Moire fringe imaging method[16]. The digitized image of the cast is shown in Fig. 5. The dimensions at different sections could now be obtained from the digitized image. The aim of the study was to obtain the radius of the cannon ball and the procedure for this was as follows. The trajectory of the ball was first marked out from the known trajectory analysis that was performed earlier (see Fig. 5). This was marked on the cross section and it was ensured that the line passed through the mid-points of the two depressions (see Fig. 5). At the slanted line in Fig. 5, the image was cut digitally to obtain the cross section. When this is viewed in two dimensions, the image appeared as shown in Fig. 6. The relation between pixels and real length was first established from the known dimensions of the Plaster of Paris cast and the image. The aim was to determine the radius and for this purpose, the end flat portion of the cross section that was

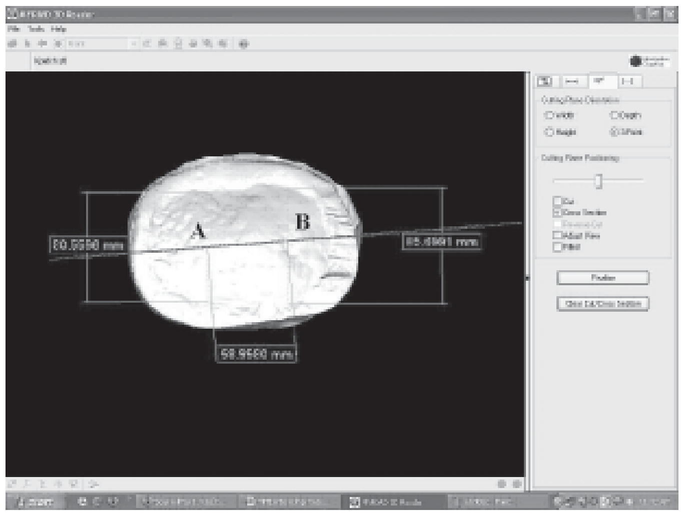


Fig. 5. Three dimensional digitized image of the Plaster of Paris cast after point-mapping of the surface. The trajectory of the cannon ball is given by the slanted line joining A and B

Fig. 6. Cross sectional view of the Plaster of Paris digital image along the slanted line shown in Fig. 5

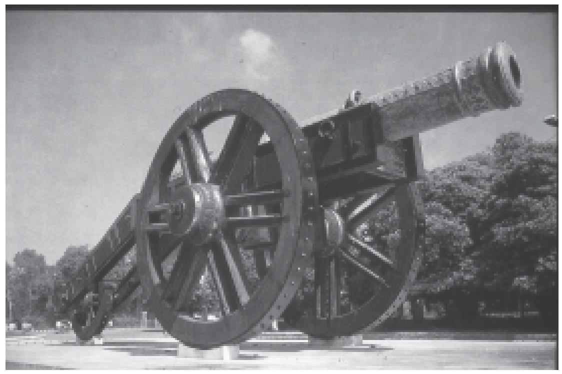
from the outside the cannon ball mark was not desired and therefore was cut out. The remainder of the arc was also removed and we kept only the region within the arrows, shown in Fig. 6. This image was converted to a binary image for use in MATLAB. The binary image was utilized in MATLAB to approximate fit the best circle for the arc.

The radius of the circle therefore provided the radius of the cannon ball that struck the Pillar. The radius was obtained in pixel units, which was later converted to units of mm. The entire procedure was as follows. The coordinates of the two points A and B on the line (see Fig. 6) were A (x=832, y=207) and B (x=568, y=258), which corresponded to length of 268.88 pixels. This corresponded to the real length of 45.12 mm. The correspondence between pixels and real lengths were thus established.

Now, the estimated radius of the circle was 358.54 (717.08/2) pixels, which when converted using the established relationship between pixels and millimeters, provides result that the cannon ball that struck the Pillar had a diameter of 120.33 mm. This translates to units of inches as 9.48 inches. This must be considered as an upper bound value because the estimated diameter value includes additional plastic deformation due to cannon impact. Additionally, given the extent of error inherent in this estimation using a plaster of Paris cast, it is reasonable to propose that the diameter of the cannon ball that was fired was approximately nine inches.

Utilizing this value of cannon ball, it can be further proposed that the bore of the cannon that fired the shot must have been about 9 inches. Therefore if one has to analyze the types of cannon that was used to fire on the Iron Pillar, one has to look at the pieces from the early 18th century that are still present in India and the critical factor to look out for will be that the diameter of the inside of the cannon barrel must be about 9 inches. In this regard, the *Zamzamāh* cannon [see Fig. 7(a)], now at Lahore, and the Sind cannons now located inside Fort William in Kolkatta [see Fig. 7(b)] and outside the Archaeological Survey of India Museum at Fort St. George in Chennai [see Fig. 7(c)] can be considered similar to the cannon that fired the shot on the Iron Pillar due to their time period of construction and also their bore diameter is about nine inches.

The shear lips [marked in Fig. 4(a)] indicate that the material of the cannon ball splintered after its impact and possibly became molten on hitting the Pillar. The ball may not have been of stone because the impact would not have



(a)

(b)

(c)

Fig. 7. Example of type of cannon that fire the shot on the Pillar (a) the *Zamzamāh* cannon now at Lahore, (b) Sind cannon located inside Fort William in Kolkatta and (c) Sind cannon located outside the Archaeological Survey of India Museum at Fort St. George in Chennai.

been great. The impact would have been the greatest if the density of the material of the cannon ball was very high. The best option would have been to use lead ball because then the damage that it can create for the same distance traveled and for the same velocity would have been far greater than using iron or copper based cannon balls. Plus, historically it is known that lead cannon balls were very popular in India in Mughal India[21].

With the known diameter of the cannon ball, different kinds of materials can be assumed for the cannon ball material and it should be possible to estimate the weight of the cannon ball that was fired on the Pillar. The weight of the cannon ball has been deduced in Table 1 assuming it to be made of iron, lead or copper, using the known material properties[22]. In the calculations, the cannon ball diameter has been taken as 120.33 mm and therefore, the estimated weights of cannon shot are upper bound values. The cannon type as per the British system has been provided in the last column of Table 1 to provide the readers with an idea of the size of the cannon, compared to British vintage guns.

Table 1. Estimated weight of cannon ball assuming the material of construction to be iron, copper and lead, and diameter of ball as 120.33 mm

Material	Density (g/cc) [22]	Weight (kg)	Weight (lb)	Cannon type (British pounder)
Fe	7.87	7.18	15.83	14-16
Cu	8.94	8.16	17.99	16-18
Pb	11.35	10.36	22.84	20-22

A more detailed analysis of weight of gun powder used and the weight of the shot used that is mentioned on several Mughal cannons needs to be carefully analyzed in order to gain insights on the kind of ball used. The problem is complicated by the fact that different weight systems are mentioned in the Mughal cannons, for example even cannons belonging to Aurangzeb's period, the weights of the shot and gunpowder to be used are mentioned in units of *maunds* and *seers* as per Ākbarī system in Tope *Fath Guṣā* ("Victory Opener Gun", 1667-68 AD) now at Pune[23], Jahāngirī system in Tope *Qila Kuṣā* ("Fort Breaking Gun") (1666-67 AD) now at Golconda[24] and Shāhjahānī system in Tope *Azdāha Paikār* ("Dragon Body Gun", 1674-75 AD)[25] and Tope *Fath Raihbār* ("Guide to Victory Gun", 1672 AD)[26], both these now at Golconda. The lack of standardization of engineering measures played an important role in the decline of Indian science and technology during the 18th century and this needs to be analyzed in great detail. The weight and size information on available Aurganzeb's cannons (distributed all over India now) could provide valuable insights on this problem.

Conclusions

The history of a cannon ball that struck the Delhi Iron Pillar has been traced. The probable reason why a second shot was not attempted has been explained. The trajectory of the cannon ball has been established from the surface features of cannon ball indentation area. Plaster of Paris cast obtained from the cannon ball crater has been utilized to digitally simulate the crater and based on the digital simulation, the diameter of the cannon ball that struck the Pillar has been estimated to be about nine inches. Aspects related to the kind of cannon used to fire the shot have been discussed.

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