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# RICOCHET OF NON-SPINNING PROJECTILES, MAINLY FROM WATER*
# PART I: SOME HISTORICAL CONTRIBUTIONS

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**Summary**—After defining ricochet and associated terms, a survey is presented of several studies made of it throughout history—nearly all experimental—reported in *military* contexts. © 1997 Published by Elsevier Science Ltd.

## PROJECTILES À RICOCHET

"... at sea, as on land, cannon balls effect greatest damage not when striking directly the object aimed at but when rebounding in "playful" mood from land or water and "bowling along". This is called ricochet practice."

(From an early 18th centuary manual.)

The charming "in playful mood" quotation shows little understanding of what it must have been like to encounter an 80 lb wt. cannon ball, "bowling along" even at a speed as low as say, 400 ft/s! In fact, the quotation is erroneous because balls *do* effect their greatest damage when possessed of their greatest kinetic energy and striking directly; ricochet continuously diminishes the kinetic energy available for inflicting damage at the final point of destined impact. The damage in mind in the quotation is typically of the de-masting of ships and the clearing of decks (of sailors and gunners!)

## INTRODUCTION AND EARLY HISTORY

The phenomenon of ricochet is well known but not widely understood because it takes place in circumstances difficult to control and define—e.g. either at sea or "in the field"—and even in the artificial environment of the laboratory. It is a succession of oblique high speed impact events, mostly of a solid against a liquid surface (for our purposes), in which the geometry of each individual strike is different.

### *Definitions*

If a round hard projectile impinges on the flat surface of a target mass of liquid, solid or powder, and remains thereafter integral, it will enter and sink, or simply penetrate a significant amount, bounce, ricochet or broach. Which kind of behaviour is followed depends principally on the angle at impact and the velocity range within which the projectile impinges, the density of the projectile and that of the target, and the mechanical properties of both bodies. The kinds of path near a surface which are followed by a projectile have been identified by E. G. Richardson, see Fig. 1; the shapes followed by water as it splashes over a sphere have also been studied, Fig. 2. *Bouncing* describes rebound† due to elastic restitution in either or both of a projectile or target material. In *ricochet* the projectile usually undergoes little or no permanent deformation but the target is ploughed. Rebound or ricochet is essentially due to the dynamic pressure of the target material acting upwards

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*This two-part paper is based on one originally presented at the 3rd Hellenic Conf. on Applied Mechanics, at Athens, Greece (1992) but here with amendments and now including figures.

Fig. 1. Four types of trajectory identified by Richardson: (a) definite ricochet with the angle of exit somewhat less than the angle of entry, (b) break-surface often followed shortly by re-entry, (c) flattening-out and continuing on a straight path for a certain distance followed by diving, and (d) continuing straight ahead, then diving.

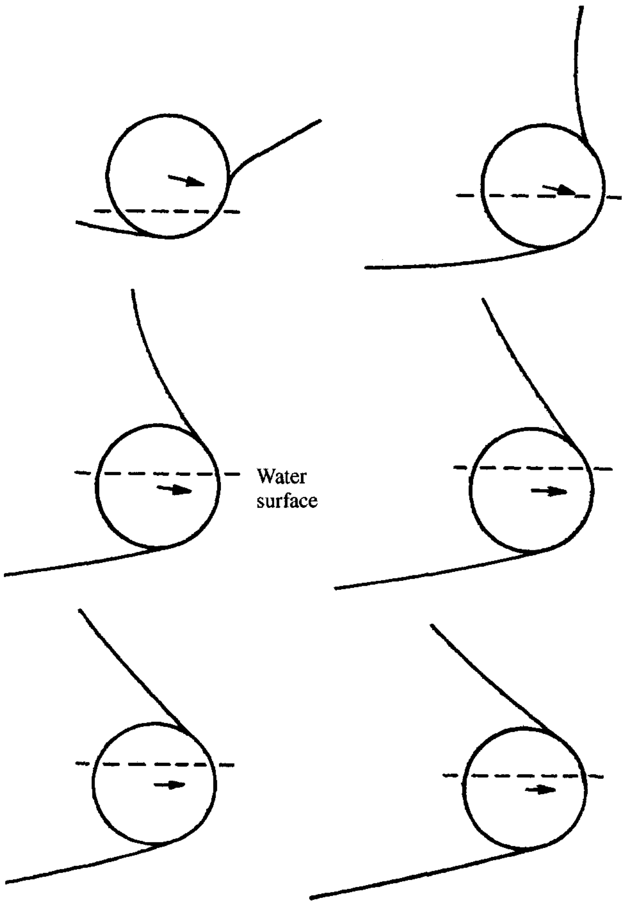


Fig. 2. Shapes of water surface in the vicinity of the sphere.

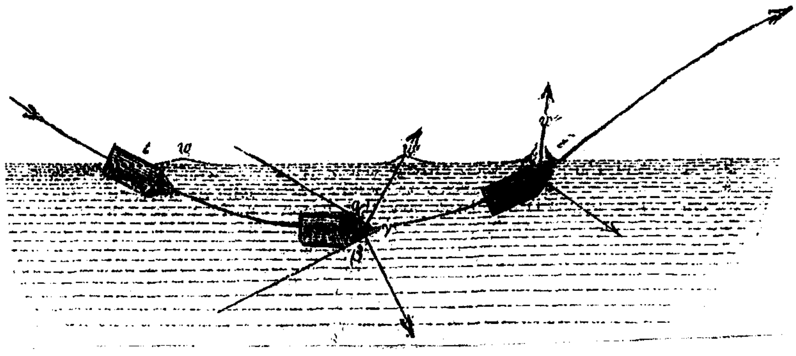


Fig. 3.

on the projectile to overcome its gravitational weight. The mechanisms of elastic restitution and dynamic pressure are of different kinds. *Ricochet* usually describes impact and rebound such that at no time has the projectile been wholly below the water surface. *Broaching* pertains to rebound which occurs even though the top surface or indeed whole body of an impinging sphere has penetrated below the surface of the target before emerging—in effect there has been complete immersion. Broaching may be accompanied by a surface "wave" or projection running above and ahead of a sufficiently deeply broaching body, Fig. 3,w,w′,w″.

Ricochet has long been known of empirically. Causing flat stones to skip over a water surface is a pleasure or pastime that one may assume has been enjoyed since time immemorial.

## RICOCHET: ORIGIN OF THE TERM AND EARLY NAVAL AND MILITARY USES

The Oxford English Dictionary defines ricochet as 'the skipping of a shot or a flat stone on water' and contains a reference to the Dictionary of Marine of 1780; it mentions ricochet-firing with gun-pieces elevated from 3° to 6°. As with many military terms, the word ricochet is of French origin and initially appertained to the endless repetition which accompanies some songs. The earliest use of the term known to the author in the English language is contained in Benjamin Robins' Preface to his book New Principles of Gunnery, published in London in 1742.

### *Ricochet not described in ancient writings*

Ricochet seems not to be described as a phenomenon in itself in ancient writings. It was never conspicuously achieved at sea or on land for battle purposes, which would have had to be achieved using catapults and ballistae. The speeds of projection that could have been achieved would have been much too small. Maximum range with these engines of war are always reported as around 400 m and to achieve this pre-supposes a speed of about 200 ft/s.

### *The first mention of the phenomenon of Ricochet*

The title of Ch. 23 of The Art of Shooting in Great Ordnaunce by William Bourne (died 1583) is, "How and by what order the shot (doth) graze or glance upon the land or water". It was probably first published in 1578. The chapter clearly shows diagrams of the ricochet or shot when, shooting at ships from a tower, see Fig. 4. Bourne was at one time master-gunner at Gravesend, Kent, near the mouth of the River Thames, during the reign of Elizabeth I of England (1533–1603).

The Art of Shooting

And furthermore, if you doe mount the piece at much advantage, then it will not graze at all; if it doe graze, then it will be made in this manner.

And furthermore, if you doe shoot at any ship upon the water, and you shoot in that pace that doe lye very high, and the ship very near, to that you must give your level downwards, then if you give your level shoot of the ship, the shot will fly over the ship, by the means of the direct hitting of the water, for that the shot glances from the water, by that proportion that it hit the water, as by this example.

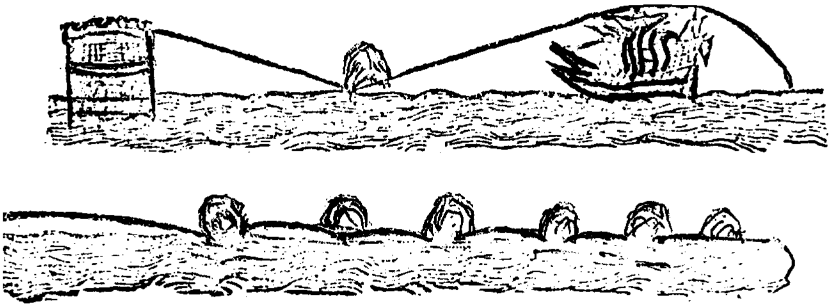


Fig. 4.

### *Sebastien le Prestre de Vauban (1633–1707) and the naming of the Phenomenon*

Born in Burgundy, France, at 17 Vauban joined the regiment of the renowned Maréschal Condé in the war of the Fronde—a popularist uprising against prime minister Mazarin and the aristocracy in the mid-17th century—was captured by royalist troops and converted to serving the king as engineer in 1751. From being born a man of the people he rose to become Maréschal de Camp when 33. He wrote treatises on the conducting of sieges, providing manuals such as The Directeur Génerale des Fortifications written 1683–1685, Traité des Mines, (Paris, 1740) and Traité de l 'attaque des places, 1669. The latter includes material about ricochet fire. It was at Aeth in 1697 that he first employed ricochet as a principal means of "reducing" forts. He besieged the renowned Dutch engineer, Coehorn, in Namur using ricochet fire in 1692, though the first time it was used at all was in 1688 at Phillipsburg. Ricochet fire on land took two forms, one was *direct* and the other *enfilade*. Bounding cannon balls shot head-on at rows of advancing infantry, passed through ranks scattering men but fired at a small angle to a line of defence or against a line of infantry probably caused greater damage. Firing á ricochet as opposed to ordinary gun or howitzer shooting ensured a long range for a cannon ball because of its many ricochets and was always directionally accurate; ordinary gun or howitzer shooting was only effective at its one point of impact.

Direct fire at the walls of forts aimed to shake and loosen masonry but oblique ricochet-like fire aimed to cut and dislodge pieces, which led to breaching. At this time a range of 700 m. was recognised as the maximum effective cannon range.

### *Benjamin Robins (1707–1751): New Principles of Gunnery (1742)*

Robins, commenting on Vauban's use of gun batteries à ricochet wrote,

"But the most important improvement in the practical Management of Artillery … is the Method of firing with small Quantities of Powder, and elevating the Piece so that the Bullet in its Descent may just go clear of the Parapet of the Enemy, and drop into their works (enceinte). By this Means the Bullet coming to the Ground in a small Angle, and with a small Velocity, it either bounds or rolls along in the Direction it was fired in: and therefore, if the Piece be placed in a Line with the battery it is intended to silence, or the Front it is to sweep, each Shot rakes* the whole Length of that Battery or Front, and has thereby more Chance of disabling the Defendents, and dismounting their Cannon, than it would have, if it was fired against the same Works in the common Manner. This Disposition of Artillery, ... a most useful one, is the Invention of the Maréchal de Vauban, and is by him stiled Batterie à ricochet and was first put in Practice at the Siege of Aeth, in the year 1692."

(* Raking: sweeping from end-to-end of a line or of a boat from stem to stern in naval action.)

### *T.S. Beauchant: The British Gunner (1829)*

This book has a section, pp. 355–361, on ricochet firing and refers to a French writer who advises that to secure ricochet inside a "fortification of any kind the elevation of the gun should seldom exceed 10°, aiming to throw shot over a parapet a little higher than the level of the battery". "In the field, the objects to be fired at, being principally infantry and cavalry, the guns should seldom be elevated above 3° ... ". Beauchant gives four pages of test results "compiled from ricochet firings at Woolwich in summer, 1821".

### *Howard Douglas (1776–1861): Naval Gunnery (4th ed.) 1855*

This book of 645 pages is one of the best works, in English, on the armament of warships as they were known during the first half of the 19th century and is a reference book for exterior ballisticians. This was the final period of the cast iron, smooth-bore gun when a new age was beginning which saw the emergence of rifled guns with ogival shells being substituted. It was the period when "wooden-sides" of 20 in thickness, wind-driven ships firing cannon balls were giving way to steam-propelled all-metal ships: recall the French warship La Gloire of 1859 and the first British "iron-side", 1860/1, H.M.S. Warspite. Great effort was put into the book by Douglas whose authority derived from a distinguished family, early training in the Royal Military Academy and service in action, first in Canada and then in the Peninsular War in Spain. He was Head of the senior department of the R.M.A., 1804–1809, and in the years 1823–1830.

Firing à ricochet at sea was limited because it could have to take account of the steep sides of waves which at sea could be a few feet high; velocity was very rapidly lost if a cannon ball had to penetrate water to some extent. Ricochet firing at sea was clearly only effective in circumstances where it was relatively calm and this was frequently only so close to a shore line.

Tables of ricochet practice as compiled from "experiments" made on board H.M.S. Excellent in 1838 show up to 80 lb cannon balls being fired to cause more than 20 grazes, see Fig. 5.

The results of Piobert who had written his Traité d' Artillerie (comprising tests at Gavre, France) in about 1843, were carefully examined at the time in England. The belief that shot fired over the sea differed from that over level land because the different phases, liquid and solid, reacted differently to close shot over them, was shown to be substantially untrue.

Thomas Hastings too, in 1838 studied the tracks revealed after the penetration of target ships such as the hulk Prince George after ricochet firing but found paths of penetration quite unpredictable.

The penetration of shot, in water, when the entry angle of impact was small, was studied in 1848 and it concluded that it would not penetrate more than 2 ft and remain effective. Screens were placed in water so that the path of broaching shot could be studied by penetrating them.

Table X. Ranges, by Ricochet, with Sea-service Iron Ordnance, Single-shotted, obtained on board H.M.S. "Excellent." Elevations by Spirit-level.

| Nature of Guns. | Weight. | Length. | | Diameter of Bore. | Charges | Height above the plane. | | Elevation | First Graze | Extreme Graze before Deflection. | Number of Grazes. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cwt. | Ft. | in. | Inches. | lbs. | Ft. | in. | 0 | Yards. | Yards. | | |
| 10 – inch ... | 84 | 9 | 4 | 10 | 12 | 12 | 6 | ¼ | 280 | 2850 | 16 | Hollow shot, 84 lbs. |
| | | | | | | | | 1 | 658 | 2700 | 14 | |
| | | | | | | | | 2 | 770 | 2680 | 18 | |
| 8-inch . . . | 65<br>&<br>60 | 9<br>8 | 0<br>6 | 8.05 | 10 | 12 | 6 | ¼ | 340 | 2900 | 32 | Hollow shot, 56 lbs. |
| | | | | | | | | 1 | 626 | 2766 | 23 | |
| | | | | | | | | 2 | 970 | 2576 | 14 | |
| 8-inch . . . | 50 | 6 | 8 | 8.05 | 7 | 5 | 4 | ¼ | 331 | 2150 | 14 | Hollow shot, 56 lbs. |
| | | | | | | | | 1 | 653 | 2017 | 14 | |
| | | | | | | | | 2 | 933 | 2333 | 9 | |
| 32-pounder . | 64<br>&<br>56 | 9<br>9 | 7<br>6 | 6.41 | 10 | 12 | 6 | ¼ | 350 | 2850 | 24 | |
| | | | | | | | | | 800 | 2900 | 15 | |
| | | | | | | | | 2 | 1220 | 2650 | 12 | |
| 32-pounder . | 50<br>&<br>48 | 8 | 0 | 6.41 | 8 | 5 | 4 | ¼ | 306 | 2613 | 12 | |
| | | | | | | | | 1 | 706 | 2593 | 14 | |
| | | | | | | | | 2 | 1117 | 1907 | 8 | |
| 32-pounder . | 50 | 9 | 0 | 6.3 | 8 | 5 | 6 | 0 | 346 | 3183 | 33 | |
| | | | | | | | | 1 | 747 | 3033 | 26 | |
| | | | | | | | | 2 | 1173 | 2490 | 13 | |
| 32-pounder . | 45 | 8 | 6 | 6.3 | 7 | 5 | 6 | 0 | 333 | 2450 | 15 | |
| | | | | | | | | 1 | 716 | 2150 | 8 | |
| | | | | | | | | 2 | 1040 | 2260 | 8 | |
| 32-pounder . | 40 | 8 | 0 | 6.3 | 6 | 5 | 6 | 0 | 326 | 2366 | 19 | |
| | | | | | | | | 1 | 700 | 2100 | 8 | |
| | | | | | | | | 2 | 1026 | 2480 | 16 | |
| 32-pounder . | 46 | 9 | 0 | 6.35 | 6 | 5 | 4 | 0 | 300 | 2800 | 32 | |
| | | | | | | | | 1 | 730 | 2510 | 14 | |
| | | | | | | | | 2 | 1026 | 2210 | 10 | |
| 32-pounder . | 42<br>40<br>39 | 8<br>7 | 0<br>6 | 6.35 | 6 | 12 | 6 | 0 | 333 | 2003 | 9 | |
| | | | | | | | | 1 | 637 | 1867 | 8 | |
| | | | | | | | | 2 | 857 | 2007 | 18 | |
| 32-pounder .. | 32 | 6 | 6 | 6.3 | 5 | 12 | 6 | 0 | 300 | 1980 | 15 | |
| | | | | | | | | 1 | 580 | 1800 | 10 | |
| | | | | | | | | 2 | 800 | 1950 | 15 | |
| 32-pounder . | 25 | 5 | 4 | 6.3 | 4 | 5 | 4 | 0 | 270 | 1980 | 21 | |
| | | | | | | | | 1 | 480 | 2027 | 16 | |
| | | | | | | | | 2 | 990 | 1670 | 6 | |
| 24-pounder .. | 50<br>&<br>48 | 9<br>9 | 6<br>0 | 5.823 | 8 | 12 | 6 | 0 | 406 | 2143 | 14 | |
| | | | | | | | | 1 | 880 | 2060 | 10 | |
| | | | | | | | | 2 | 1186 | 1637 | 5 | |
| 18-pounder .. | 42<br>&<br>38 | 9<br>8 | 0<br>0 | 5.292 | 6 | 12 | 6 | 0 | 410 | 2943 | 34 | |
| | | | | | | | | 1 | 680 | 2717 | 24 | |
| | | | | | | | | 2 | 1093 | 2233 | 9 | |
| 18-pounder . | 22 | 7 | 6 | 5.18 | 3 | 5 | 4 | 0 | 250 | 2660 | 29 | |
| | | | | | | | | 1 | 596 | 2500 | 20 | |
| | | | | | | | | 2 | 926 | 2293 | 9 | |

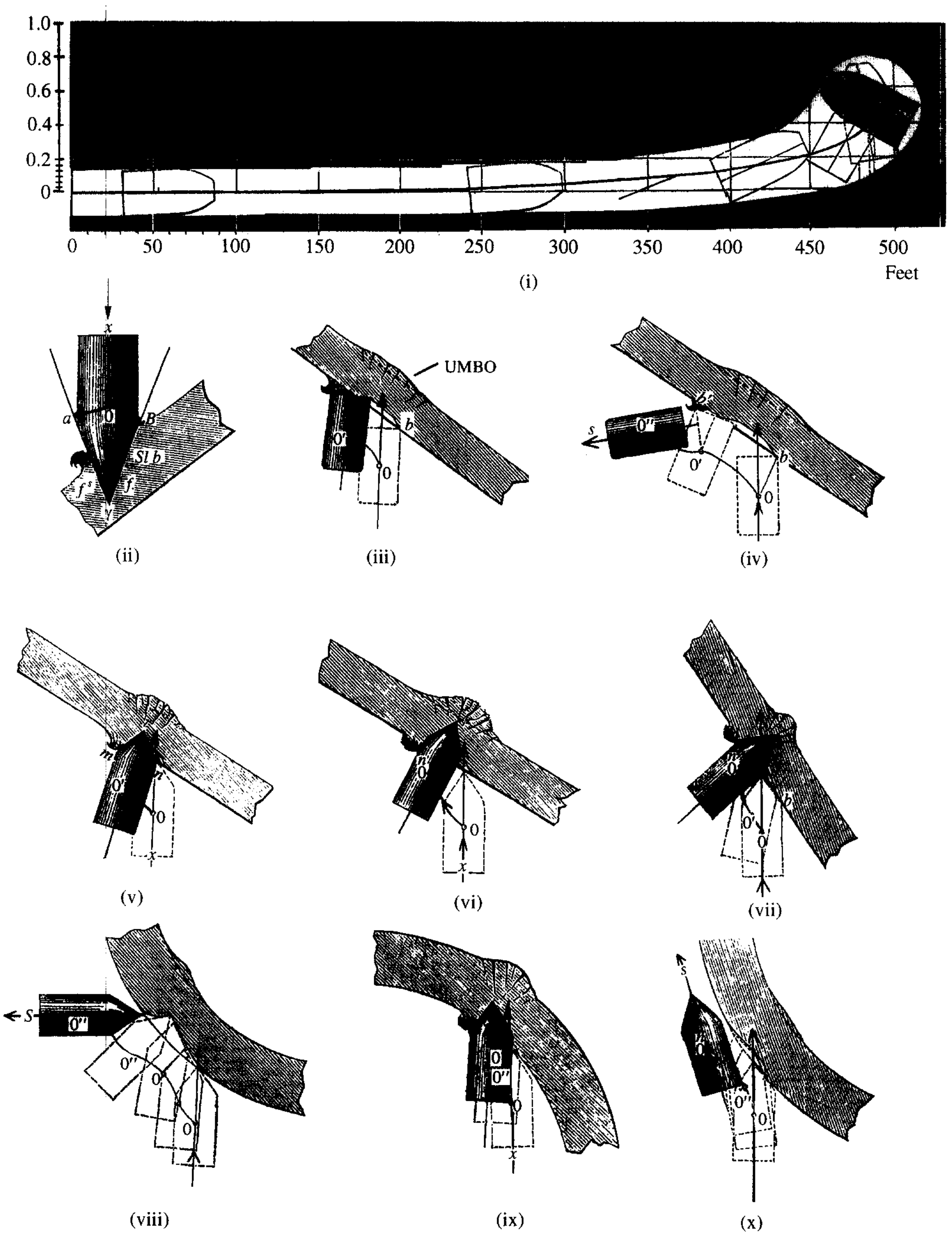
Fig. 5.

### *Robert Mallet (1810–1881)*

Robert Mallet was born in Dublin, Ireland, and did much of his work from that city in about the mid-19th century, though his parentage was English and he subsequently completed his life by returning to London where he set up as a consulting engineer.

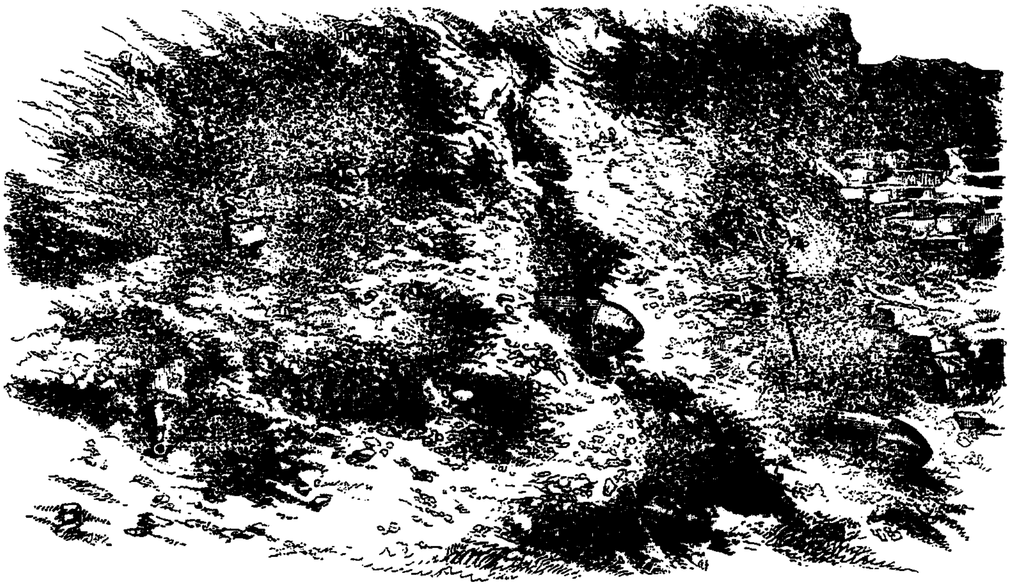
Robert Mallet published in 1867 in The Engineer (pp. 1, 39, 52 and 73), a long four-part article entitled "On the Trajectories of Elongated Rifled Projectiles on Striking and in Penetrating Solid Resisting Media" giving fascinating examples of the behaviour of artillery shells in war. His paper was a result of observations made on his visit to the Crimean warfields, 1853–1856.

One example shows a volumetric shape and the trajectory (a thick central line)—a kind of tunnel—made by a short truncated shell penetrating earth; it is "a sort of curved club-ended hollow path (which) is bored out". See Fig. 6(i). This is what we presently recognise as a



(i) (ii) (iii) (iv) (v) (vi) (vii) (viii) (ix) (x)

Fig. 6.



A HUNDRED-AND-TEN POUND SHELL FIRED INTO CONCRETE, AND DEFLECTED.
From a Photograph.

Fig. 7. Ogival shells, after passing through soil and concrete, pointing "backwards" in the direction from which they came. (From Mallet: *The Engineer*, 1867, pp. 1, 39, 52, 73.)

J-shaped trajectory. Yet other figures show projectiles impinging obliquely against thick metal (flat and curved) target plates being deflected or indeed reflected with the rear-end leading. (Close inspection of the figures reveals how this 180° rotation occurs.) See Fig. 6(ii)–(x).

An artillery officer was reported as showing photographs in which "a considerable number of cylindro-ogival Armstrong 110 pdr shells after plunging to earth and into masses of concrete, were found, when carefully dug down upon ... invariably (to have) turned through 180° so that the point of the shell presented itself towards the direction whence it had been fired by the gun"; see Fig. 7.

### *Cranz and Beckers' Exterior Ballistics, Vol. I, 1921.*

In Cranz and Beckers' well-known book it is quoted from von Chrismar, that,

(i) French shells of 10 cm diameter, shot at less that 10° against a sandy surface will ricochet and,
(ii) 32 cm shells at up to less than 28°. Also that,
(iii) on the Krupp firing range certain 26 cm shells were found first to graze from frozen ground at 1500 m and then to bound 8000 m more, whilst
(iv) from a smooth sea, shells are said to ricochet if their descent impact angle is less than 25°.

From the work of E. de Jonquieres (*C.R. Acad. Sci., Paris,* **97** (1883) 1278), it became widely recognised that the critical ricochet angle for solid steel spheres was 7°, off water.

Ramsauer had reported that brass balls of 11 mm diameter, and 5.85 gm wt, ricochet at speeds of about 620 m/s at up to 7° angle of impact. The measured angle of emergence $\theta_e$, or reflection from the water, he found always less than that at incidence, $\theta_0$. Experimentally he found that $\theta_e = 0.9\theta_0$.

Bircher and Ramsauer are described as using partially immersed vertical and parallel targets at specific distances apart to obtain information about the shape of ricochet trajectories below a water surface.

Cranz and Becker in Sections 74 & 75, pp. 442–454, include short discussions about the path usually taken by (non-spinning) projectiles through clay masses when the point of entry, though normal to a surface, is significantly more distant from one bounding surface than another.

The latter two authors (Cranz and Becker) brought together information not otherwise easily available. It is noteworthy that the book was translated into English and published by H.M.S.O. only in 1921.

Dr. Barnes Wallis (see Part II of this paper) when questioned about his early knowledge on the subject, told the writer that this book had been borrowed by him from the library of the I.C.E. in London in 1940. The sole piece of scientific information he possessed at the beginning of his work was that steel spheres would ricochet off water if the angle of impact was 7° or less.

Cranz and Becker comment that ricochet was known in the 16th century (see p. 2) and only systematically used by and after Vauban. They refer to an extensive work on "ricocheting and the rules by which the best results would be obtained", by Paul Jacobi, written in 1756 and of a mathematical theory developed by Bordoni, 1816 and Otto, 1841. Additional references are given to French and German literary sources on p. 459 and several early books on ballistics are listed on pp. 456–457. However, none of the latter are easily available in the U.K. for perusal.

## SOME POST W.W.II MISCELLANEOUS WORKS

1. *Structural Effects of Impact.* M. Kornhauser, 1965. See chapters 2 and 9 for force–penetration curves with water and soils made by projectiles of various head forms. Much Report literature is referenced.
2. *E. G. Richardson*, (*Proc. Phys. Soc.* **61** (1948) 352–367) is a paper dealing somewhat with ricochet and presenting experimental results concerning water entry by solid spheres at various angles of impact; interesting force–penetration curves and records of splash performance are given.
3. *Von Karman* presented theory for forces sustained by sea-plane floats (effectively ricochet), during landings on water.
4. *Hydro-Ballistic Modelling*, Waugh & Stubstad (published 1960s) was devoted to the penetration of water from air by torpedo-shaped bodies; it contains many illuminating high-speed photographs of under-water phenomena—e.g. cavity formation with surface or deep closure of entrained air bubbles—and the suggestion of *J*-curves formed by bombs moving through soils.
5. *Fundamentals of Protective Design* (*non-nuclear*) is a valuable G. E. C. handbook (Dept. of the U.S. Army Tech. Manual FM5-855-1, 1965) giving useful diagrams and nomograms concerning propensity to ricochet from thick concrete slabs. Results for plates of thicknesses 9 and 22 in with normal incidence down to 35° for reinforced concrete are given for projectile impact speeds of 1500 and 3000 ft/s. Canal creation between incident craters and scabs at the rear face are shown. The tendency to reversal of projectile direction with angle change is sketched for different parameters.
6. The trajectories of spherical and elongated projectiles when fired in the range 150–350 m/s initially parallel and near to the free surface of a layer of clay and leading to their emergence for small values of depth/projectile-diameter ratio have been discussed by Johnson and Daneshi (*Int. J. Mech. Sci.*, **20**, 255–264, 1978).
7. Dr S. Clyens in a Note (1981) to the author drew attention to the alternating long and short hops of flattish pebbles when ricocheting on wet sand, providing measurements and sketches of tracks ploughed in the sand. I have recently found this phenomenon to be described in The Scientific American Book of Projects for the Amateur Scientist by C. L. Strong (Simon & Schuster, 1960, pp. 561–563.)
8. *The Effect of Spherical Projectile Speed in Ricochet off Water & Sand* [A. S. Soliman, S.R. Reid and W. Johnson, *Int. J. Mech. Sci.*, **18** (1976) 279–284]. Experiments firing small diameter spheres of steel, lead and duralumin into water and sand showed that (i) the critical angle for ricochet off water *increases* with speed; for steel it is 3° at 50 ft/s, becoming a maximum of 7° at 240 ft/s; exit speed is 0.81 times entry speed.

(ii) The maximum angle for ricochet off sand decreases with speed. A cut-off angle of 29° is found for steel projectiles, and for aluminium and lead at 51° and 26°, respectively, all at about 400 ft/s; this phenomenon was unexpected at the time it was encountered. Typical plaster-casts of the furrows made in sand are given in this paper.

9. The booklet *Terminal Ballistics* (1976) of projectiles by M. Backman, has a useful section, *Deflection and Ricochet*, pp. 87–90. Results for steel spheres impinging obliquely on aluminium plate of modest thickness are given and analysed.