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Experimental Investigation of Geometric Effects on Ballistic Clay Backing Material

by Mary Jane Graham and Timothy G Zhang

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14. ABSTRACT The US Army Research Laboratory performed a series of impact tests on rectangular and cylindrical targets of Roma Plastilina #1 (RP#1) at various velocities to study the geometric effects of the target on behind-armor blunt trauma and to investigate rebound of the backing material. Time history of penetration was obtained by Phantom high-speed cameras, and depth of penetration was obtained by caliper. Column drop tests were performed to study rebound of the RP#1. Comparisons were made between both geometries in each test series.					
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1. Introduction

Roma Plastilina #1 (RP#1) has historically been used as a surrogate material for human tissue response when testing the performance of personal protective equipment (Prather et al. 1977). Other materials such as ballistic gelatin have been used in the past, but an advantage of RP#1 is its lack of full recovery after impact. After an event, RP#1 retains a permanent crater, which has been assessed as an imprint of the armor back-face deformation (BFD). From measurements of the diameter of the crater, the depth of penetration (DOP), and overall shape of the crater, correlations have been made of the probability of lethality (Clare et al. 1975; Prather et al. 1977). Behind-armor blunt trauma (BABT) experiments performed by Prather and, separately, by Clare, emphasized that the results were provisional, being limited by the paucity of data needed to adequately validate models. Other investigations reported that there was a measureable amount of elastic recovery in the clay that should not be overlooked (Lehowicz 2012).

Advances in X-ray imagery have provided a method to more fully investigate the mechanisms involved in the formation of indentation into surrogate backing material imposed by BFD and to capture physical features of the interaction of the target armor packet and the backing material. However, limits on the power of X-ray flashers common today do not allow viewing through the rectangular clay blocks that have been traditionally used (Prather et al. 1977; Ivancik et al. 2017). Hence, some body armor testing is now performed on a modified target consisting of cylindrical confining material, usually polyvinyl chloride (PVC), doped with clay backing material with various shoot packs (body armor configurations) affixed to the PVC. To obtain clear, useful, and nearly continuous images, the maximum allowable diameter of the PVC is limited.

This report presents the details and analysis of a new series of side-impact tests performed at the US Army Research Laboratory (ARL), modeled on Ivancik's work at various impact velocities for rectangular blocks of clay, and for the modernized target of confined clay cylinders at high velocity. Column drop testing was also performed on both geometric configurations to provide validation points for current clay modeling (Zhang et al. 2017). Comparisons are made between the rectangular and cylindrical targets for impact and drop testing.

2. Column Drop Tests

2.1 Initial Configuration

Twenty column drop tests were performed to address a previously observed (Lehowicz 2012) rebound of RP#1 after impact. Twelve of the targets were rectangular chunks of RP#1 contained by half an inch of aluminum with top and bottom unconfined; eight of the clay targets were confined by a PVC pipe of inner diameter 3 inches, with one end covered by plywood and the top exposed. See Fig. 1 for a schematic of drop test configurations for rectangular and cylindrical geometries.

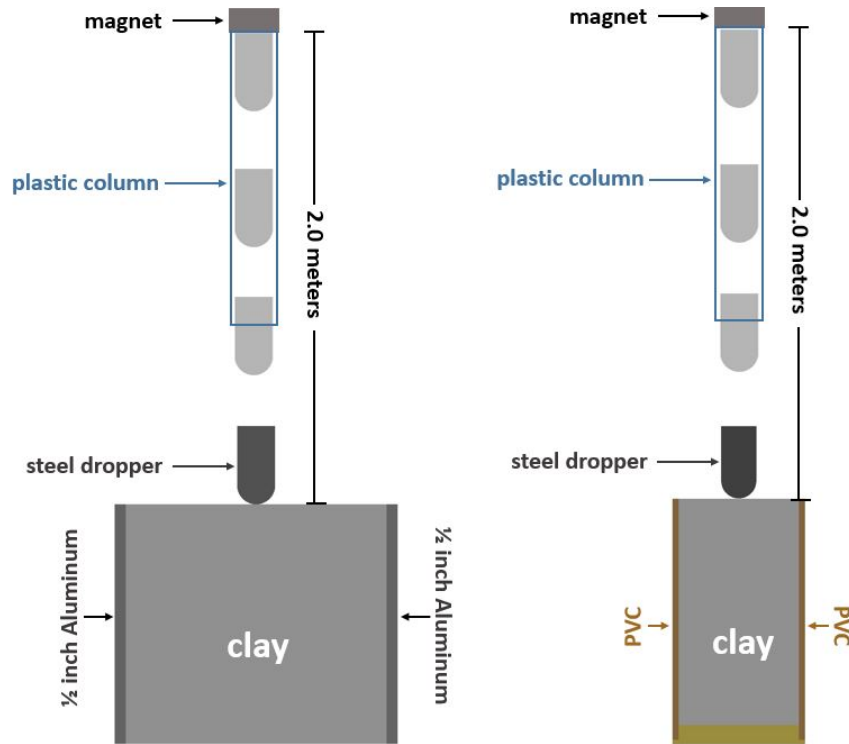


Fig. 1 Column drop test schematic of rectangular and cylindrical targets

The drop tests were designed following ARL test operating procedures (TOPs). The rectangular box has a 12- × 12-inch strike face and is 11 inches deep. The cylindrical target has a 6-inch-diameter strike face and is 11 inches deep. The diameter of the cylindrical strike face was chosen to match armor testing performed at ARL by Schuster et al. (2018) and the Netherlands Organisation for Applied Scientific Research TNO (van der Jagt-Deutekom et al. 2012), where the maximum diameter is dictated by the limits of the X-ray capabilities.

Prior to testing, two temperature gauges were placed in the clay rectangular configuration, and one gauge was used in the cylindrical clay setup. See Fig. 2 showing the strike face of clay targets and temperature gauges, and a picture of the dropper used for the experiments at the same scale of the targets.

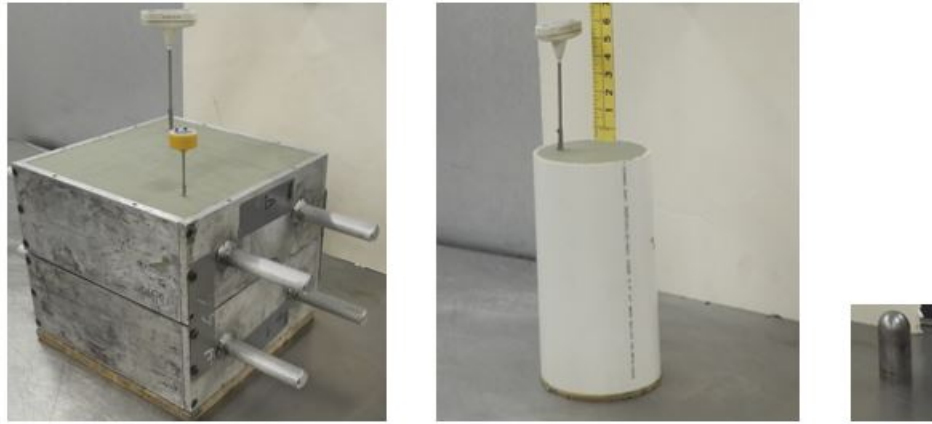


Fig. 2 Column drop test targets and steel dropper

According to TOP 110-2-210 (TOP 2008), the consistency of RP#1 must be in a state such that the indentation created by the dropper after impact is 25 ± 3 mm deep. The dropper mass is required to be $1 \text{ kg} \pm 10 \text{ g}$, the geometry of which is a cylinder with hemispherical striking end, where the cylinder diameter is 44.5 ± 0.5 mm; and the dropper must be released from a height of $2 \text{ m} \pm 2 \text{ cm}$. The full setup is shown in Fig. 3. The velocity for each drop test ranged from 5.8 to 6.26 m/s, measured from the high-speed cameras.

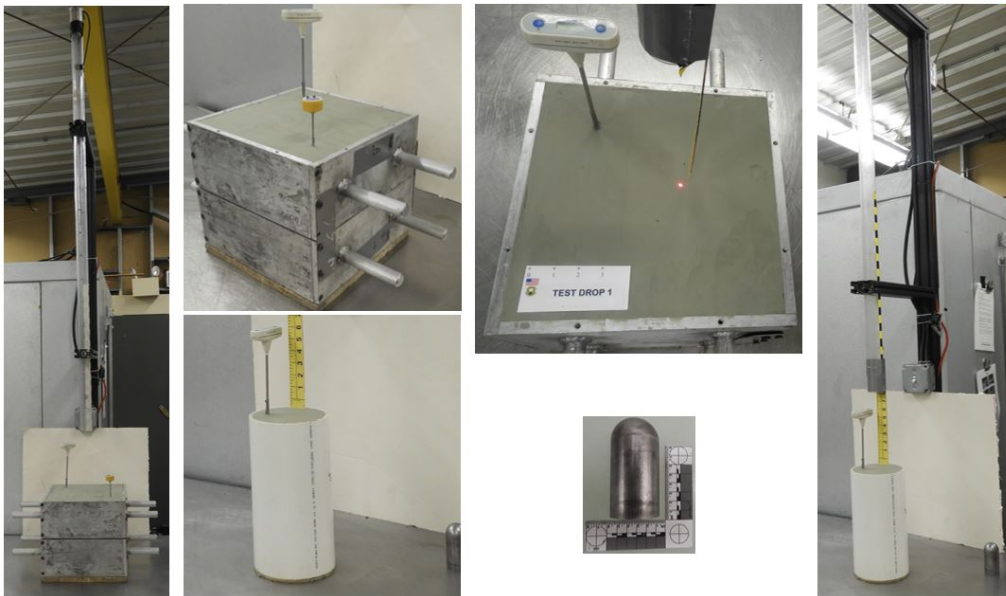


Fig. 3 Column drop test configurations

All of the indentations were measured for DOP with a caliper, and the evolution of the penetration and rebound was captured with a Phantom high-speed camera at 20,000 frames per second (fps). Figure 4 shows the first frame from each configuration before releasing the dropper.



Fig. 4 Initial frames from high-speed cameras

In the figure, the rectangular drop test on the left-hand side (LHS) has one temperature gauge, which remained during the test; and for the cylindrical drop test on the right-hand side (RHS), the temperature gauge was removed. However, a small chunk of clay is visible, formed upon the removal of the same prior to testing.

2.2 Rectangular Geometry

Prior to the experiment, the RP#1 in the rectangular box, including the aluminum frame, and the PVC were conditioned in a temperature-controlled environment to ensure that they passed the indentation depth requirement described in the previous section. The clay was packed and conditioned by a pneumatic to remove voids. When the target was removed from the temperature-controlled environment and placed in the testing area, gauges were placed in the clay. Based on the experience of the technicians, the experiment was either performed immediately or when the temperature reached a range of degrees to avoid, as much as possible, the influence that excessive heating may have on the indentation depth and time history. The table in Appendix A contains all of the data collected from the rectangular drop tests, Numbers 1–12, and cylindrical drop tests, Numbers 13–20, including the following:

- Rectangular box number (two different aluminum-encased RP#1 blocks were used)
- PVC cylinder number (two different RP#1-doped cylindrical setups were used)
- Rectangular box face number for the drop (top and bottom)
- Cylindrical face number (only one because the back end of the cylinder is confined by plywood glued to the PVC)
- Timing of removal from temperature-controlled environment to execution of test

- Temperature in the sample
- DOP and location of dropper on the target face

The evolution of a rectangular drop test is shown in Fig. 5. From left to right, the images show an experiment prior to striking the clay, at initial penetration, at maximum DOP, and after rebounding stops. The time from the initial contact of the dropper with RP#1 to the maximum DOP is 8.0 ms, and the rebound time is 7.0 ms; the penetration/rebound totals are 29.63 and 4.23 mm, respectively. The representative test of Fig. 5 is Drop 8. Drop 8 has a nearly vertical/on-axis drop from 2.0 m—that is, it was nearly yaw free.



Fig. 5 Evolution of DOP rectangular drop test

Appendix B contains images from all rectangular drop tests before contact (Fig. B-1), at maximum DOP (Fig. B-2), and after rebound ends (Fig. B-3), where Drops 1–12 are in order left to right, top to bottom. Many of the droppers in this test series experienced yaw—that is, at impact the dropper and surface of the clay were not at 90°. Thus, the rebound is also off axis, which is substantial at Drops 1, 4, 5, 6, 9, and 12. The precise reason for the yaw in some tests is unknown; however, it is believed that the long tubular guiding chamber, seen in Fig. 3 LHS and RHS, may not have been free of debris or other particles along its inner radius (Snyder 2018). The droppers were cleaned after each test.

The time histories of the DOP from the drop tests were extracted every half a millisecond from the individual frames gathered by the high-speed camera (at 20,000 fps) using Phantom Camera Control (PCC) 2.5 software. Time zero is set before penetration; images were advanced every 10 frames, and distances were measured from the back end of the dropper. Figure 6 demonstrates data extraction for Drop 1, which experienced larger yaw.

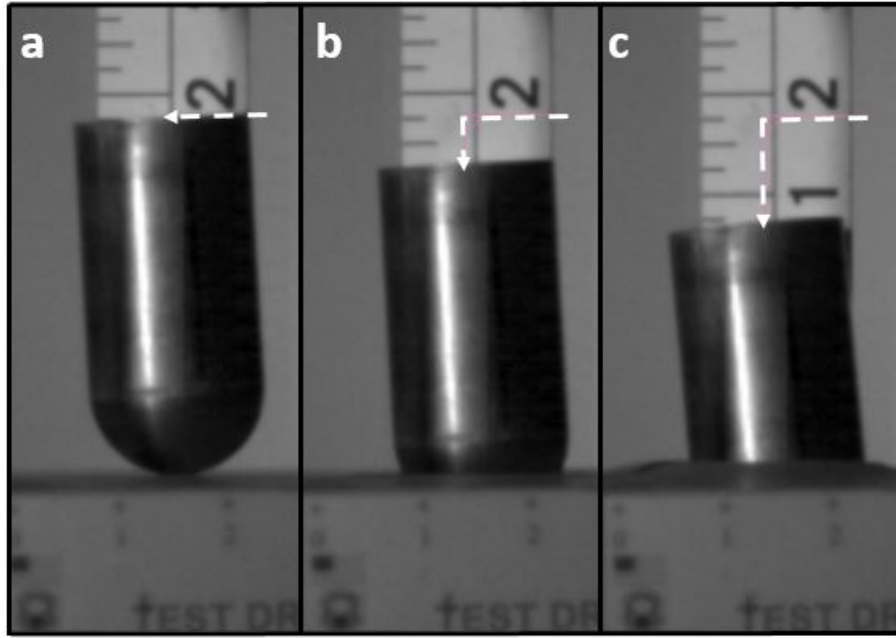


Fig. 6 Data extraction for time history of DOP rectangular drop test

Data are measured from the middle of the back end of the dropper at time zero (Fig. 6a at arrow head), advanced and a perpendicular line is dropped from the initial marker location to the middle of the back end of the dropper a little lower due to tilting of the dropper, and the distance is obtained (Figs. 6b and 6c at arrowhead). Figures 6b and 6c are measurements at different times, shown to emphasize processing of data with substantial yaw.

Time history data were extracted by hand using the PCC 2.5 software. Each test was measured twice, and some tests were measured three times for consistency. The error in an individual penetration depth measurement is ± 4 pixels. A schematic of the measurement error approximation is shown in Fig. 7, where the scale on the LHS is used to find the dimensions of the camera field of view (FOV), 11.39×5.08 inches. The number of pixels in the x-, y-direction are 896×400 , respectively, giving 0.32-mm square pixels. Since each depth measurement involves clicking two locations, the estimate of error is 1.29 mm.

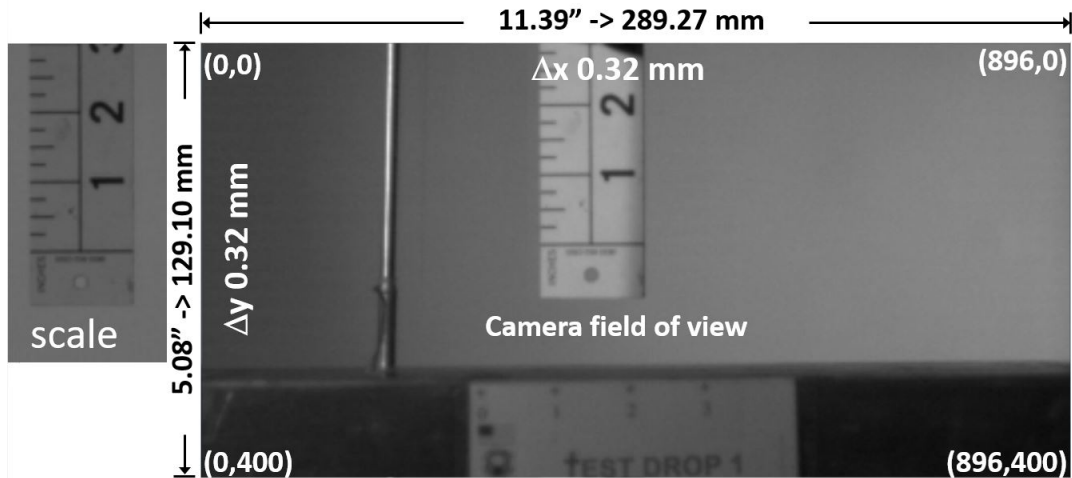


Fig. 7 Drop test DOP box and cylinder

Graphs of the extracted time histories of the DOP for Drops 1–12 are shown in Fig. 8. All graphs are qualitatively the same—that is, DOP increases rapidly to maximum DOP, rebounds, and stabilizes. The rate of increase from 0 to 3.0 ms is 5.26 mm/ms. The maximum DOP value ranges from 25.40 to 32.43 mm for times between 7.0 and 10.0 ms, respectively. Rebounding takes place for approximately 9 ms until leveling/stabilizing.

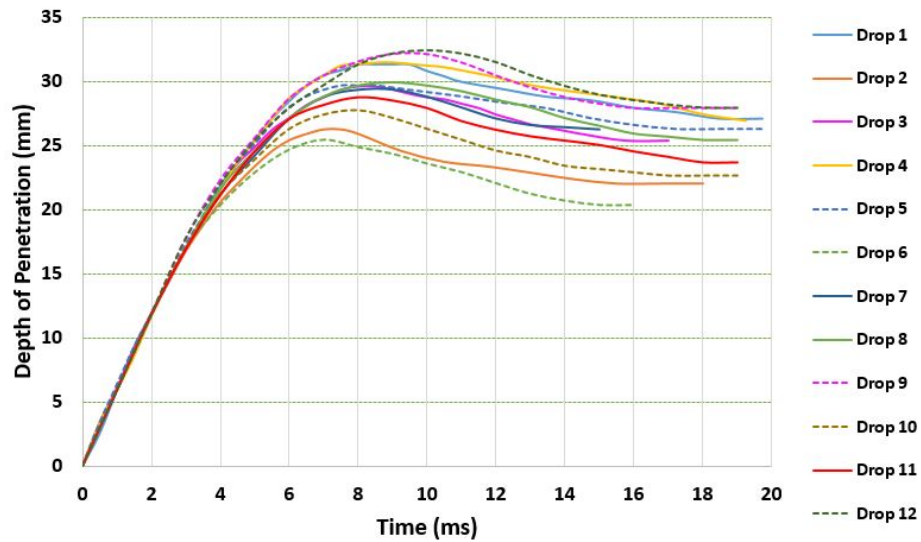


Fig. 8 Time history DOP rectangular drop tests

Graphs of the percentage of rebound and rate of rebound versus drop number are shown in Fig. 9. The average percentage of rebound and mean value is 14.87% and 14.38%, respectively (LHS Fig. 9). Removing Drop 6, whose maximum DOP is below the minimum allowed per the TOP (2008), gives average and mean values at 14.38.

The rate of rebound was calculated by finding the slope of the secant line at the time of maximum DOP and at the next time of data collection (where the change in time is 100 μ s. Rate of rebound is between 0.34 and 0.69 mm/ms, including the outlier Drops 2, 5, and 7 seen on the RHS of Fig. 9. The average rate of rebound is 0.53 mm/ms, and the mean is 0.54. The maximum DOP for Drops 2 and 7 are less than the minimum allowed per the TOP (2008), and the penetrator of Drop 5 had a larger yaw.

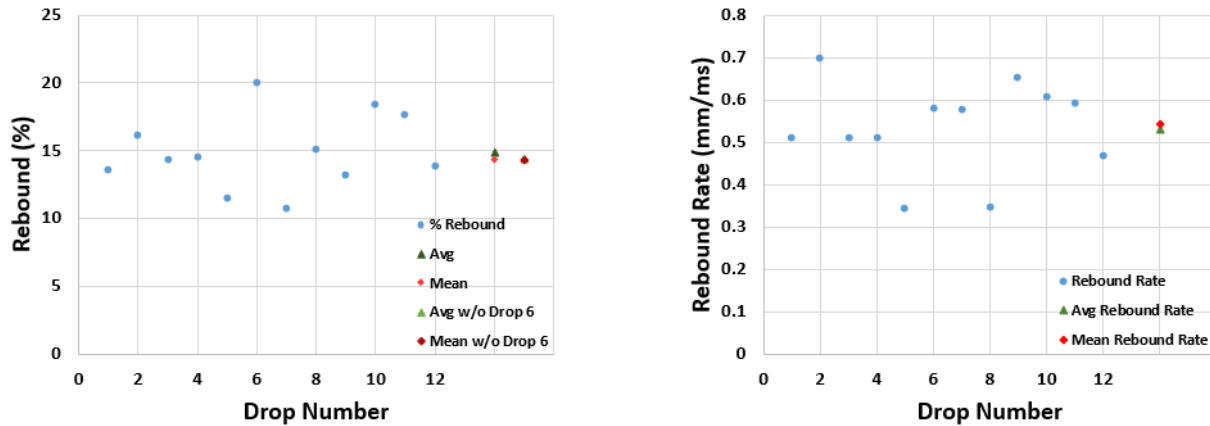


Fig. 9 Percentage and rate of rebound rectangular drop tests

Excluding the outlying Drops 2, 5, and 7 for the reason stated, the data from the remaining rectangular drop tests could be used as partial validation for future modeling efforts and as data in modifying the current model used for this study, as finite-element analysis does not capture the rebound or very slight and slight/slow recovery seen in the drop tests (Graham and Zhang 2019).

2.3 Cylindrical Geometry

The cylindrical samples are pretreated in a controlled, heated environment prior to testing. The experimental setup is the same as the rectangular configuration. The only difference is a change of target to 3-inch-diameter clay-doped PVC, and the location of the dropper with respect to the impact test varied. That is, four of the tests focused the dropper at the center of the clay in Drops 13, 14, 19, and 20; two of the tests are aimed off center by 1 inch for Drops 15 and 16, and two of the tests are focused off center by 2 inches in Drops 17 and 18.

The evolution of the cylindrical drop test is demonstrated in Fig. 10 from Drop 13, where, from left to right, the dropper is shown before initial contact with RP#1, at the beginning of the penetration process, at maximum DOP, and when the dropper completes the rebound process. For Drop 13, the time from initial contact of the dropper with RP#1 to maximum DOP is 8.5 ms, and the rebound time is 5.0 ms; the penetration/rebound totals are 35.22 and 3.28 mm, respectively.

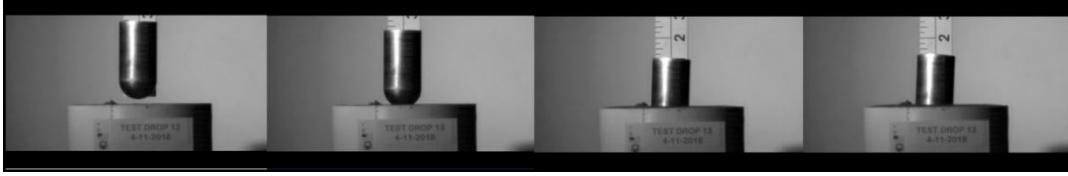


Fig. 10 Evolution of DOP cylindrical drop test

The rebound times for the cylindrical drop tests are shorter than the rectangular geometry due to the global motion of the PVC configuration from the examination table, which is not a level surface. The surface of the examination table had been previously struck over time (Crocket 2018), and the diameter of the PVC was not large enough to cover the irregularities in the surface like the rectangular configuration was for global motion (Fig. 11). The white dashed curve encapsulates the total global motion, which for Drop 13 is 3.28 mm.

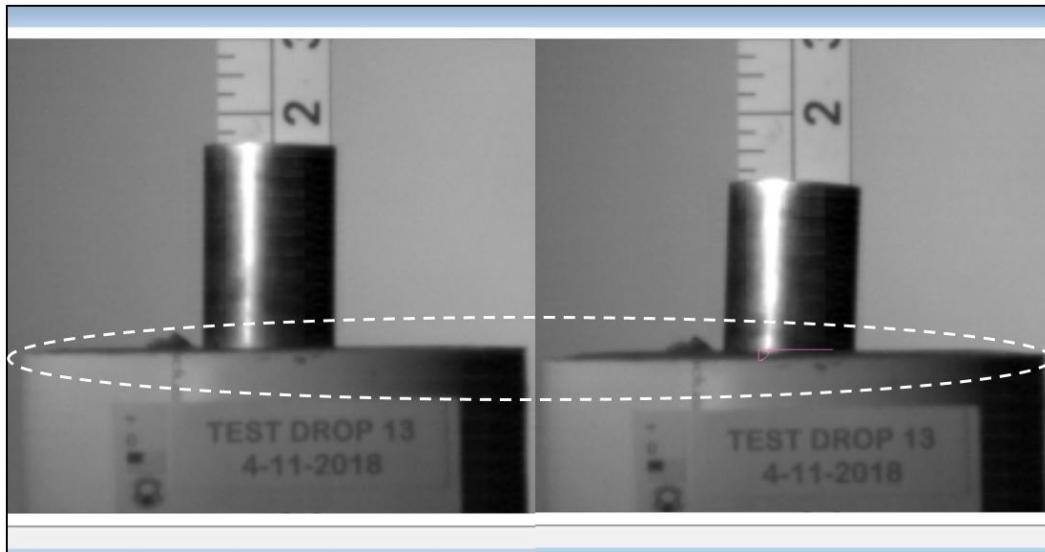


Fig. 11 Global motion of cylindrical setup drop testing

Appendix C contains images from all rectangular drop tests before contact (Fig. C-1), at maximum DOP (Fig. C-2), and after rebound ends (Fig. C-3), where Drops 13–20 are in order left to right, top to bottom. Some of the droppers experienced yaw, and therefore, the rebound is also off axis, as in Drops 14, 16, and 18. The high-speed camera FOV for Drops 19 and 20 was changed to determine the source of previously observed global motion.

To remove global motion, measurements for the time history of the DOP were performed in a different manner from the rectangular setup. The timing of data collection is described in Section 2.2; the same high-speed camera was used with 20,000 fps. The data were extracted using the back of the dropper as Point 1 and the top of the PVC as Point 2. That distance was then subtracted from the total length of the dropper. Figure 12 demonstrates the data extraction process. Figure

12a shows the total measurement of the dropper prior to penetration; Figs. 12b and 12c are two data collections. The total distance obtained in Fig. 12b was subtracted from the total length in Fig. 12a. Two separate data collections are shown to demonstrate how yaw is handled.

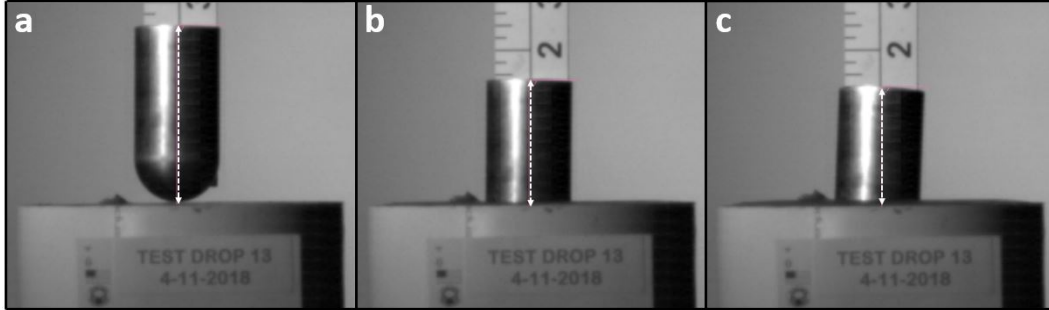


Fig. 12 Data extraction for time history of DOP cylindrical drop test

Graphs of the extracted time history of the DOP for Drops 13–20 are shown in Fig. 13. Drops 19 and 20, marked by black solid and dashed thin curves, respectively, are not included in the analysis because the high-speed camera FOV was too large to perform accurate data extraction within the estimated error demonstrated in Fig. 7.

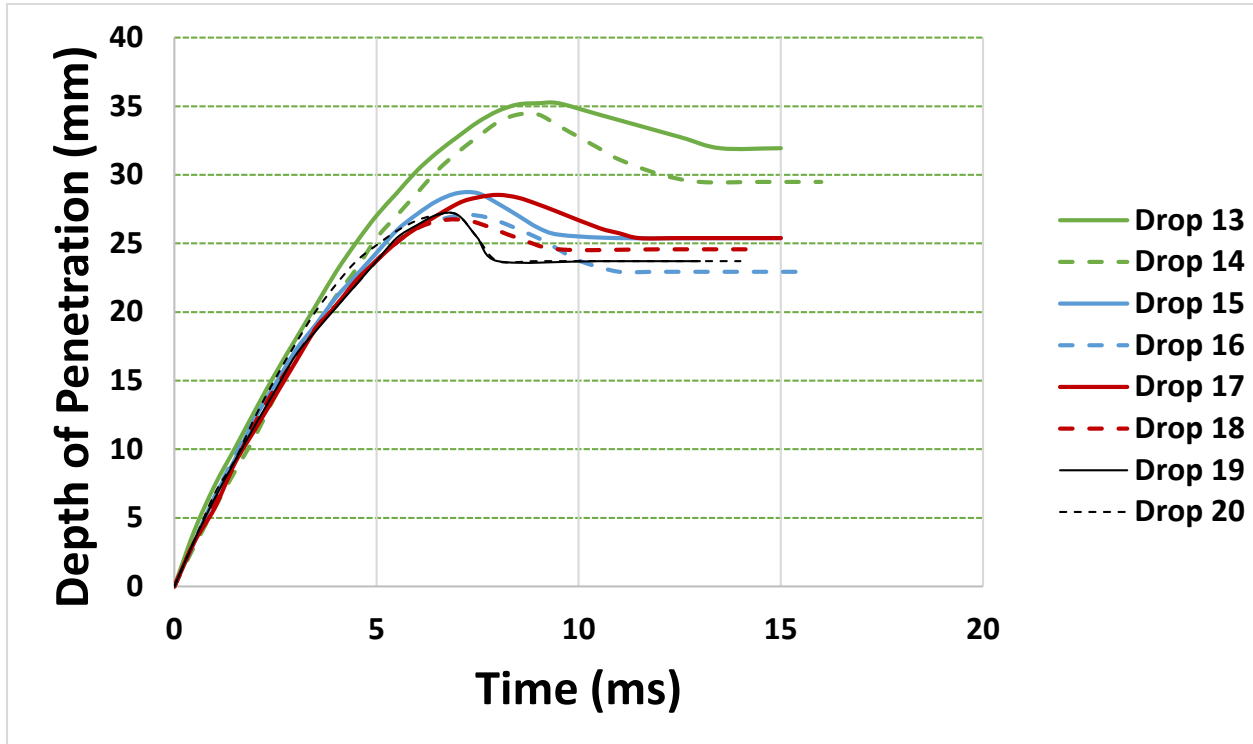


Fig. 13 Time history of DOP cylindrical setup

All graphs are qualitatively the same—that is, DOP increases rapidly to maximum DOP, rebounds, and stabilizes. The rate of increase from 0 to 3.0 ms is 5.23 mm/ms. The maximum DOP value ranges from 26.7 to 35.21 mm for times between 7.0 to 9.0 ms, respectively. Rebounding takes place for approximately 2.5–4 ms until leveling/stabilizing, varying per cylindrical drop. The duration of the rebound is substantially less than that of the rectangular drop tests. It is believed that the shorter duration of clay rebound is due to the global motion of the target. The clay, PVC, and wood are pushed downward approximately 3.46 mm, and the entire mass rebounds at a rate of 0.17 m/s.

Graphs of the percentage of rebound and rate of rebound versus drop number are shown in Fig. 14. The average percentage of rebound and mean value, 11.55% and 11.23%, respectively, is seen on the LHS of Fig. 14. The percentage of rebound is less than the rectangular configuration, but it cannot be determined how much it is influenced by the boundary or by the global motion.

The rate of rebound was calculated by finding the slope of the secant line (where the change in time is 100 μ s) at maximum DOP and maximum DOP plus 0.5 ms. Rate of rebound is between 0.40 and 1.63 mm/ms as shown on the RHS of Fig. 14. The average rate of rebound is 0.94 mm/ms, and the mean is 0.80. No overall conclusion can be drawn from the rebound rate for several reasons: global motion, the varying aim point of the dropper from test to test, and too few tests per modification.

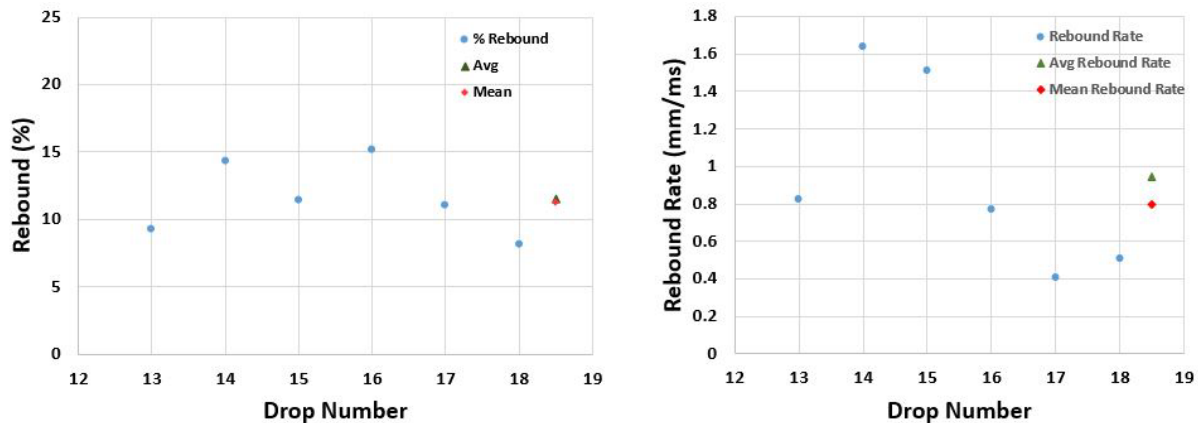


Fig. 14 Percentage and rate of rebound cylindrical drop tests

The data from the cylindrical drop tests should not be used for validation purposes or to modify models because of the global motion and its influence on the rebound of RP#1. It is believed that the cylindrical experiments can be redesigned to remove the global motion, in which case they could be useful in ascertaining boundary effects. It is recommended that more than two experiments per aim location be performed.

2.4 Discussion

Additional graphical analysis is presented in this section to investigate influences of temperature conditioning of the RP#1, timing of the DOP measurement from the end of the experiment, and storage of targets.

Figure 15 is a graph of DOP versus test number for all drop tests. The red and black dashed lines represent the minimum and maximum DOP; the blue and green data points correspond to the rectangular and cylindrical drop tests, respectively. The DOP measurements were taken of the crater depth (meaning after removal of the penetrator) by caliper.

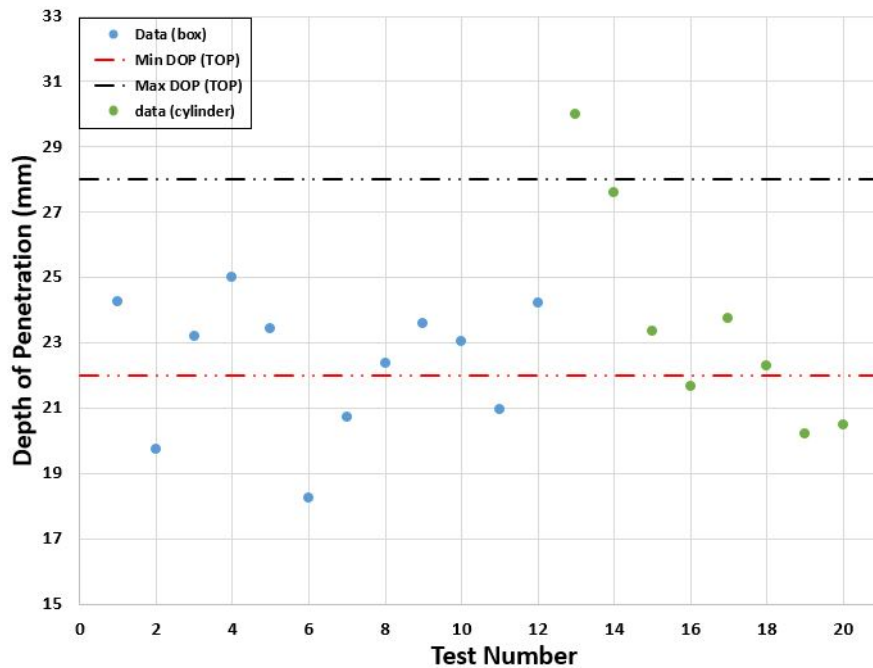


Fig. 15 Drop test DOP box and cylinder

Experiments producing DOP within 25 ± 3 mm are considered successful. The DOP of 8 of the 12 rectangular drop tests, and 4 of the 8 cylindrical drop tests, are acceptable, where Tests 19 and 20 are not used for analysis, as previously discussed. Of the 40% unusable, the DOP of 87.5% fell below the minimum measurement, with Test Number 4 above the maximum.

Variables in the specimen known to affect the behavior of RP#1 are temperature differences between the heat-treating room and the testing environment, working of the clay when packing and refilling craters may soften the material, storage time can harden the material, data collection timing, reheating, and the age of the clay (Tai et al. 2017).

Figure 16 contains graphs of the DOP versus temperature at time of testing and DOP versus time of measurement—that is, the interval of time between removal of

the clay from the heat-treating environment to the time of measurement of DOP with a caliper. The data points in blue and green are from the box and cylinder, respectively. The red and black dashed lines are the minimum and maximum DOP of a successful test. As expected, higher-temperature clay has a larger DOP, and lower-temperature clay has a smaller DOP. Temperatures in the range of $96^{\circ} \pm 2^{\circ}$ produced a 67% success rate. The DOP versus time of measurement graph indicates that obtaining the data in a timely manner is an influential factor.

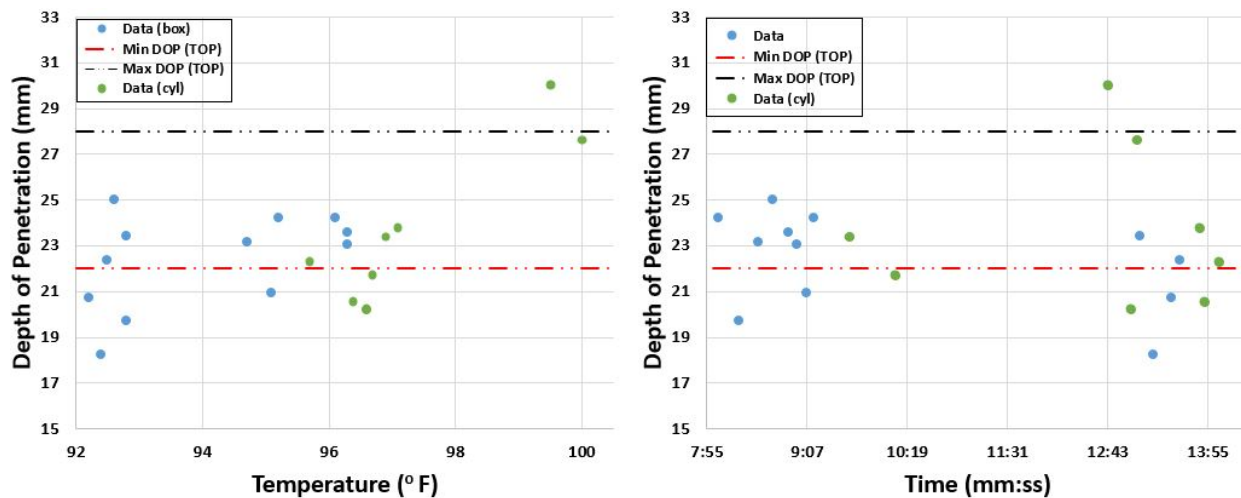


Fig. 16 DOP versus temperature and time interval

Both faces of the rectangular blocks of clay are used in the experiments, named “top” and “bottom”. Only the “top” face is used for cylindrical drop testing because the PVC is covered on the back end with a wooden disk in order to match impact testing conditions performed at ARL and TNO (van der Jagt-Deutekom et al. 2012; Schuster et al. 2018). For the purposes of the experiment, the “top” and “bottom” labels are used to differentiate between used and unused faces, not the manner in which it is stored in the temperature-controlled facility (that is, for hours between experiments or overnight). The graph in Fig. 17 shows DOP versus drop number, with blue circles for Box 1 and yellow for Box 2.

Rectangular blocks of clay stored in the temperature-controlled facility for hours or overnight showed that the clay face stored at the bottom of the block—Drops 1, 4, 5, 8, 9, and 12—had less DOP than that on the top of the block—Drops 2, 3, 6, 7, 10, and 11—due to hydrostatic pressure at the bottom-stored face.

The drop tests indicate that RP#1 is sensitive to many variables, including temperature, timing, heating, and storage. Redesign may not be possible to isolate the effects of the variables.

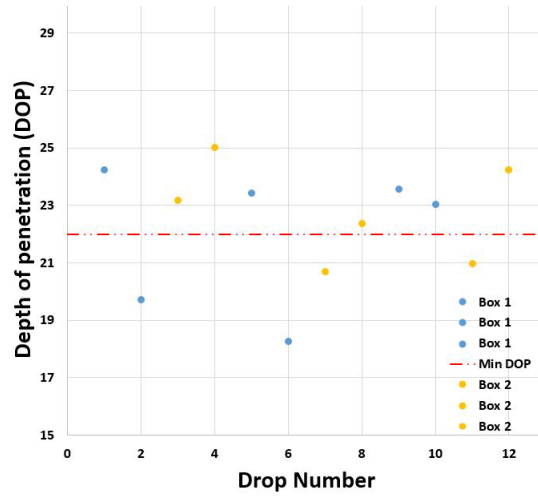


Fig. 17 Effect of storage on DOP

3. Side-Impact Tests

3.1 Setup

Twenty side-impact tests were performed: 16 in the rectangular setup and 4 in the cylindrical configuration. The dimensions of the rectangular block and cylindrical targets are the same as the drop tests, except the aluminum sides are removed from the rectangular block of clay prior to impact, similar to previous testing (Prather et al. 1977; Ivancik et al. 2017). A schematic of the side-impact experiments with dimensions is given in Fig. 18.

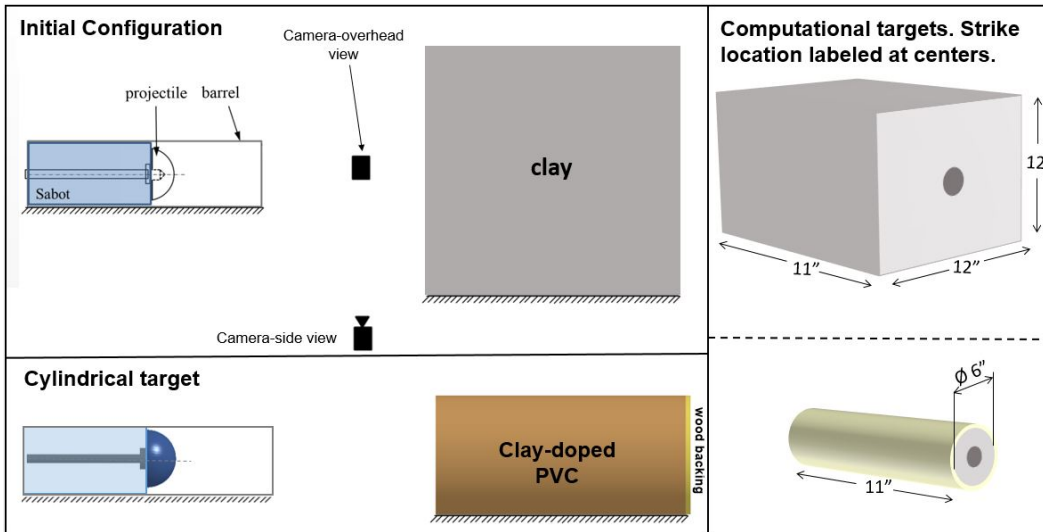


Fig. 18 Schematic of side-impact test for rectangular and cylindrical geometry

The rectangular configuration is initialized to model the Prather-type experiments of Ivancik. The rectangular block of clay has dimensions $12 \times 12 \times 11$ inches, where 11 inches is the depth, and 12×12 inches are the dimensions for the strike face of the clay target. The 11-inch sides are not confined. The projectile is a 200-g mass consisting of an 80-mm-diameter hemispherical striker with a 12.4-mm tail. The striker is Nylon 101, and the tail is Delrin. The velocity of the projectile is varied. The RP#1 in the cylindrical target is confined by a 3-inch inner radius PVC pipe with plywood backing material. The diameter of the clay is 6 inches, and the length is 11 inches.

The impactor cylindrical tail is marked every 10 mm, seen in the mid-upper part of Fig. 19, shown with and without sabots. The velocity is controlled by the gun shown on the LHS of Fig. 19. The target in the figure is a surrogate, used for calibrating purposes to ensure the impactor hits as close to the center of the strike face as possible. Before every impact test, drop tests are performed on each box to ascertain the condition of the RP#1. See Appendix D for calibration measurements performed prior to the impact tests. The lower RHS of Fig. 19 is an image of a calibration test with a dropper inset and surrounded by a red rectangle on the mid-LHS.

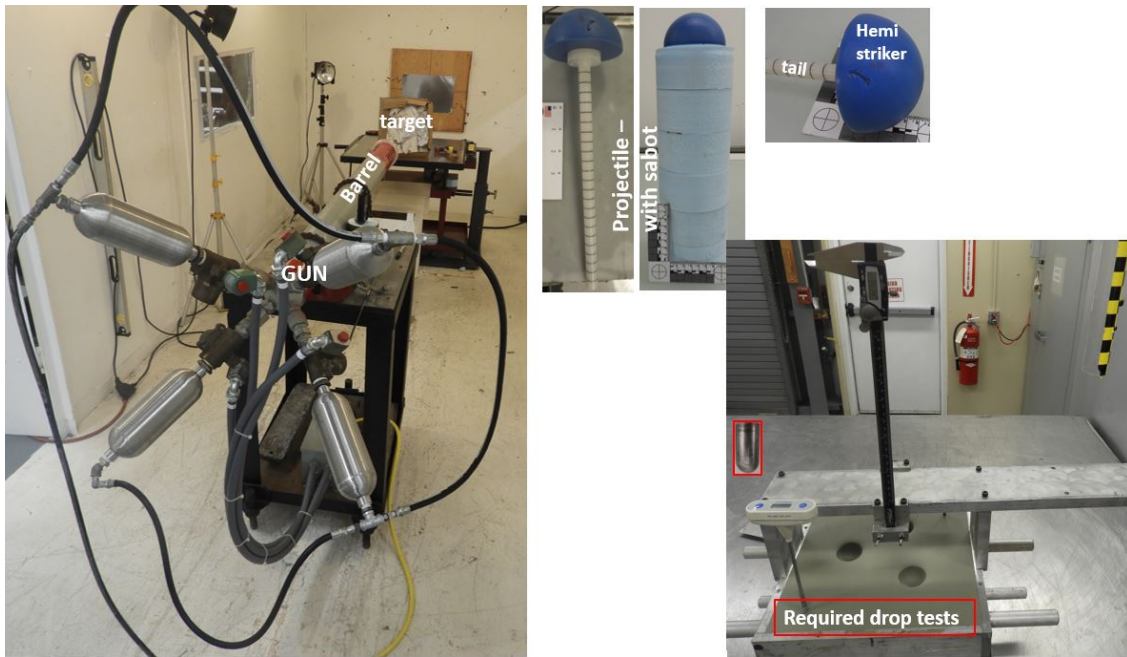


Fig. 19 Initial setup for impact tests

Similar to the Prather and Ivancik experiments, the block of RP#1 has free sides, and the bottom is motion-free due to a fixed 1-inch plexiglass plate behind it, seen in Fig. 20 on the upper RHS. The cylindrical target is kept in place with three wooden rectangular structures: one on each side of the cylinder and one of larger height at the back. The belt across the cylinder prevents the target from moving

upward upon impact; see Fig. 20, lower RHS and LHS. The impactor with sabot is loaded into the gun, and the gun has a stopper affixed at the exit of the barrel to stop the sabots, shown in Fig. 20 upper RHS.

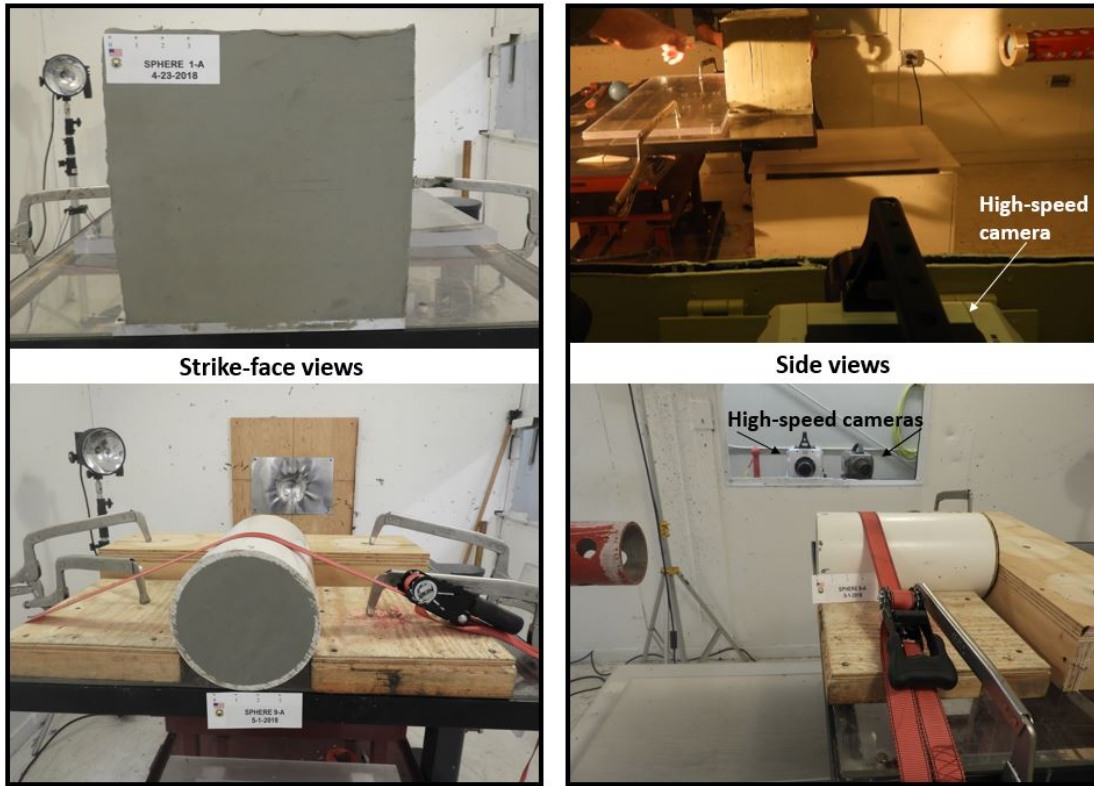


Fig. 20 RP#1 strike-face and side views

The evolution of the penetration and rebound was captured with a Phantom high-speed camera at 30,000 fps. The velocity of the impactor was varied for each impact test, ranging from 11.2 to 79.2 m/s. Maximum DOP was extracted from the high-speed camera, as was the time history of the DOP. Impact 1-A is not considered in the analysis because it was out of the FOV of the camera. The focus of the impact tests is to vary the impact velocity, study the effect on the time history of DOP, and examine rebound features, if any.

3.2 Rectangular Geometry

The evolution of an impact test for rectangular geometry is shown in Fig. 21, labeled a, b, c, and d. The sequence starts with a) initial contact, b) 0.333 ms, c) at maximum DOP, and d) after rebound. The sequence is from Impact 6-B, where the velocity is 65.96 m/s. The fragments seen in Fig. 21c are small chunks of clay that have broken off from the clay fold at the site of initial impact at Fig. 21b during formation of the crater. Impact 6-B does not demonstrate rebound. The hemispherical section of the impactor has penetrated far enough into the block that

the clay behind the hemisphere slightly closes, preventing rebound. Impacts with velocity 60 m/s and larger, therefore, do demonstrate measurable rebound.

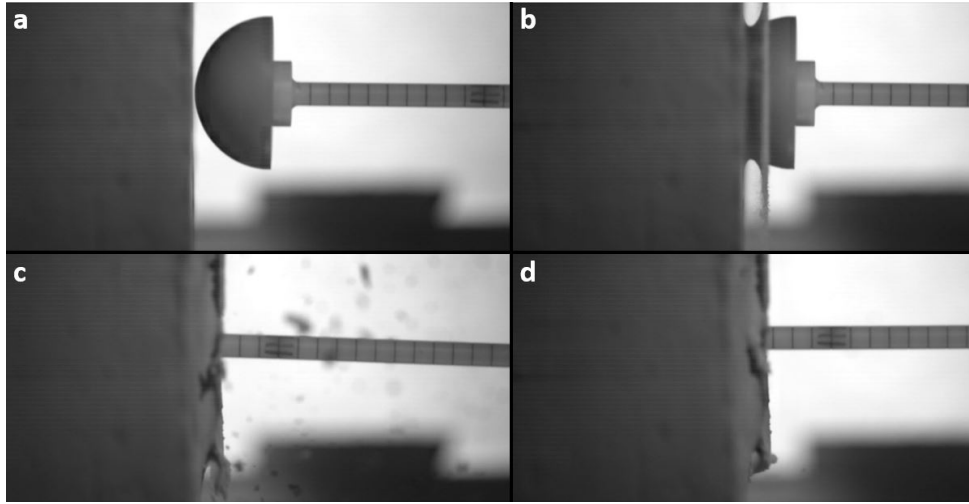


Fig. 21 Evolution of rectangular Impact 6-B

Appendix E shows a sequence of all impact tests at initial contact (Fig. E-1), at 0.333 ms (Fig. E-2), at maximum DOP (Fig. E-3), and after rebound (Fig. E-4). Impact 1-A, out of the FOV of the high-speed camera, is not considered in the analysis but is included in Appendix E for display purposes.

The stopper at the end of the barrel was either dislodged or out of place, and the sabots followed the impactor in two cases. The total yaw ranged from 0.40° to 5.19°. The impact velocity ranged from 11.18 m/s to 76.23 m/s. Table 1 lists impact test number, velocity (m/s), and notes about the flight history of the projectile that may influence the dynamics of penetration or are important features.

Table 1 Impact tests, velocity, and notes

Test	Velocity (m/s)	Notes	Test	Velocity (m/s)	Notes
1-A	11.18	Not used, test out of FOV	1-B	17.58	...
2-A	16.55	...	2-B	15.83	...
3-A	30.90	...	3-B	30.71	...
4-A	29.24	High total yaw: 3.46°	4-B	32.73	...
5-A	61.94	...	5-B	61.08	...
6-A	65.24	...	6-B	65.96	...
7-A	75.07	High total yaw: 3.59	7-B	72.79	Highest total yaw: 5.19
8-A	76.23	Stopper not in place, sabots followed, high total yaw: 3.65°	8-B	70.89	Stopper dislodge by sabots, sabots followed

The time history of the DOP was extracted from individual frames gathered by the high-speed camera at 30,000 fps. Time zero is set before penetration, and images were advanced in increments of 10 frames. See Fig. 22 for the calculated penetration distance for Impact 6-B. Every depth measurement starts at x_1 at the marker on the tail of the impactor (see figure top), advanced $n*10$ frames, where $n = 1, 2, 3, \dots, n_{terminal}$, and the second point is chosen at the marker on the tail, x_2 (see figure bottom). The PCC 2.5 software calculates the absolute value of the distance. All measurements were done by hand, two and three times for consistency. The error in measurements is the same as described in Section 2.2., except that the scale is different, shown on the LHS of Fig. 22.

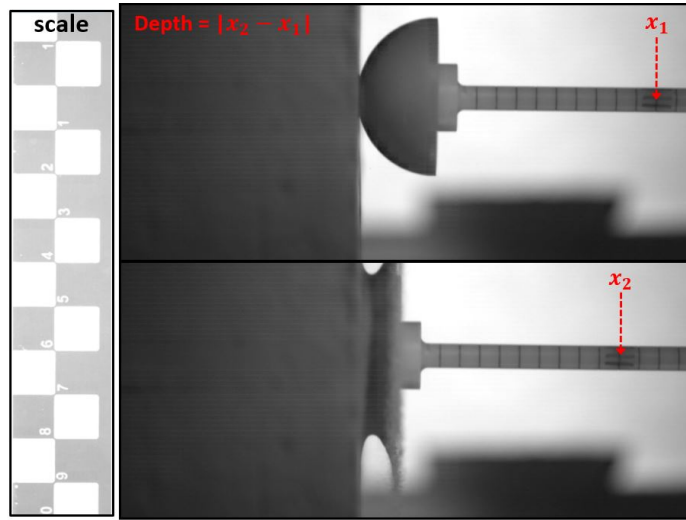


Fig. 22 Data extraction for time history of DOP rectangular impact

Graphs of the extracted time history of the DOP are shown in Fig. 23. There are 15 graphs; Impact 1-A is not included. The impact velocity ranges from 15.83 m/s (2-B, dashed green curve) to 76.23 m/s (8-A, dash gray). Curves are grouped together according to the proximity of the magnitude of velocity, see Fig. 23 legend. The curves are qualitatively the same: DOP increases rapidly to its maximum, rebounds, and stabilizes. Rates of increase are the same within velocity groups, maxima are close within a grouping, and rebound, when it can be extracted, takes place for 4.6 to 6.3 ms until stabilizing.

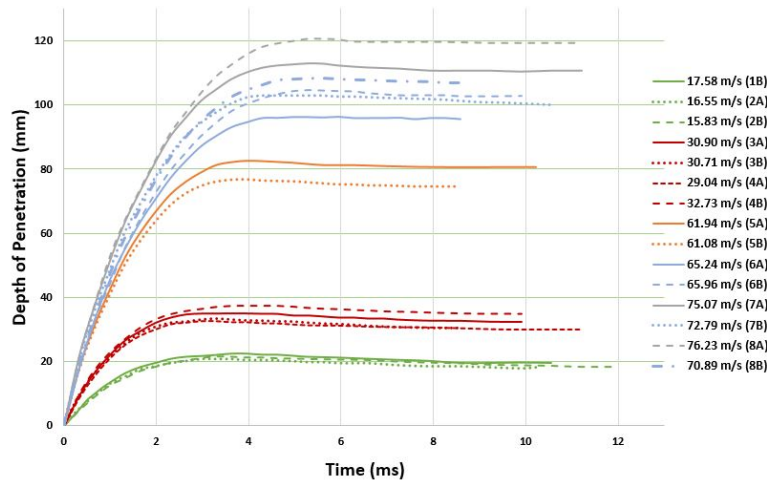


Fig. 23 Time history of DOP rectangular impact

A graph of the maximum DOP versus velocity is shown in Fig. 24 as blue circles, along with the minimum as a red triangle and maximum as a black triangle DOP from the Ivancik experiment study. The Ivancik measurements trend higher than the current study by approximately 10 mm, which is well outside the error associated with measurements taken from the Phantom high-speed camera for the current study. It is believed the difference in maximum DOP is due to manufacturing processes for RP#1 from the time of the Ivancik study to the present, Spring 2018.

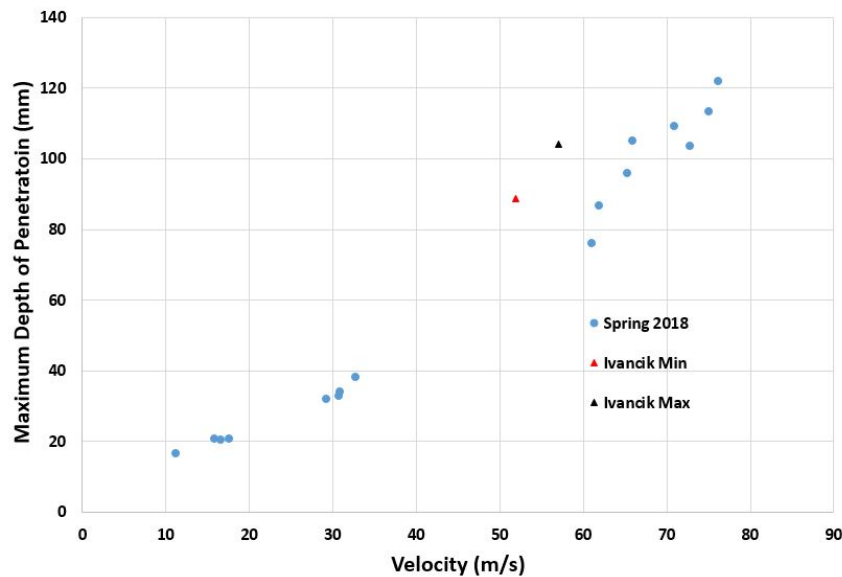


Fig. 24 Maximum DOP versus velocity

The tests that are off the trend are 4-B, 6-B, 7-A, and 7-B with impact velocities 32.73, 65.96, 72.79, and 75.07 m/s, respectively. It is possible that the total yaw for Impacts 7-A and 7-B, the highest for the rectangular impact tests, influenced the maximum DOP, producing lower penetration. However, the total yaw for Impacts

4-B and 6-B were among the lowest measured, and the calibration tests are all within the limits; see Appendix D. The maximum DOP for the outlying impact tests were off-trend from 2 to 4 mm, outside the range of error associated with extracting data from the high-speed camera.

Graphs in Fig. 25 show the percentage of total rebound and rate of rebound versus velocity. The percentage of rebound for tests with velocity 60 m/s and higher is between 0.75% and 3.5%. The values correlate with DOP (the clay behind the penetrator closes slightly, trapping it) and is not considered in analysis. The rebound rate for impact tests with velocities 60 m/s and higher is not measurable. The penetrator is trapped by the clay behind the hemisphere, makes an attempt to pull back but pushes forward and repeats. The percentage of rebound decreases exponentially with velocity (see dashed trend curve), where the coefficient on the variable is small, 0.036, shown in the equation inset of Fig. 25.

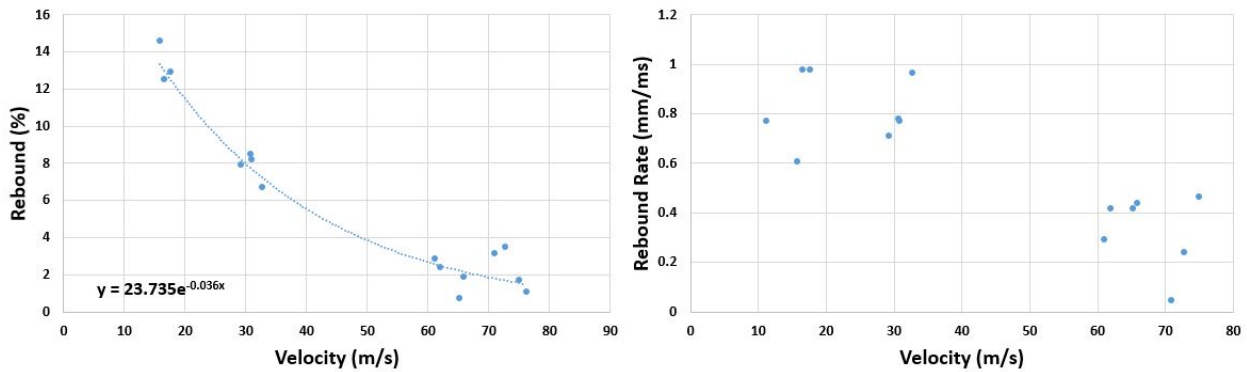


Fig. 25 Percentage and rate of rebound rectangular impact tests

The data from the rectangular impact tests demonstrate trends that warrant additional experiments at impact velocities. Rebound percentages and rates are not measurable at 60 m/s and larger.

A possible redesign of the impactor is to reshape it to a half ellipsoid with the major axis in the direction of impact and taper the back end to remove the sharp edge.

3.3 Cylindrical Geometry

The evolution of an impact test for cylindrical geometry is shown in Fig. 26, labeled a, b, c, and d. The sequence starts with a) initial contact, b) 0.333 ms, c) at maximum DOP, and d) final frame. The sequence is from Impact 9-A, where the velocity is 57.93 m/s. The fragments seen in Fig. 26c are small chunks of clay that have broken off from the initial contact at the clay seen in Fig. 26b during formation of the crater. Impact 9-A demonstrates minimal rebound because the clay closes behind hemisphere; therefore, 10-A, 11-A, and 12-A have no measureable rebound, as the impact velocities are 66.69 m/s, 70.47 m/s, and 78.67 m/s, respectively. After

reaching maximum DOP (Fig. 26c), the entire cylindrical configuration starts to move in the direction of the penetrator, demonstrated by comparing the location of the top of the PVC between Figs. 26b and 26d. The total movement is 10.48 mm from maximum DOP to final camera frame.

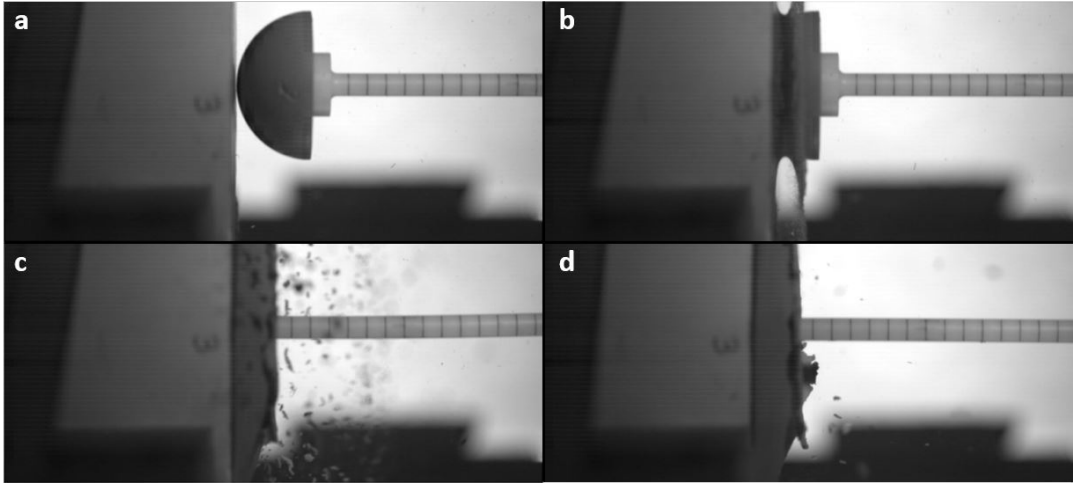


Fig. 26 Evolution of Cylindrical Impact 9-A

Appendix F shows a sequence of all impact tests at initial contact (Fig. F-1), at 0.333 ms (Fig. F-2), at maximum DOP (Fig. F-3), and at the final frame from the high-speed camera (Fig. F-4). Each of the cylindrical impact test target configurations moved during the experiment after reaching maximum DOP, continuing through the final frame from the camera. The stopper at the end of the barrel was either dislodged or out of place, and the sabots followed the impactor for Tests 11-A and 12-A. The total yaw ranged from 0.40° to 3.17° . The impact velocity ranged from 57.93 to 78.67 m/s. Table 2 lists impact test number, velocity (m/s), and notes about the flight history of the projectile that may influence the dynamics of penetration or are important features. There was no measurable rebound.

Table 2 Cylindrical impact tests, velocity, and notes

Test	Velocity (m/s)	Notes	Test	Velocity (m/s)	Notes
9-A	57.93	Lowest yaw: 0.40°	10-A	66.69	...
11-A	70.47	Stopper not in place; sabot followed	12-A	78.67	Stopper not in place; sabot followed; high yaw: 3.17°

The time history of the DOP was extracted from individual frames of the high-speed camera, 30,000 fps. Time zero is set before penetration, and images were advanced in increments of 10 frames. See Fig. 27 for the calculation of the penetration distance for Impact 12-A.

Every depth measurement starts in the middle of the diameter of the tail at the black pen markers shown on the tail of the impactor, see Fig. 43, top RHS, white oval, advanced $n*10$ frames, where $n = 1, 2, 3, \dots, n_{terminal}$. The second point is located horizontally from the first point, perpendicular to and at the top of the PVC, see Fig. 27, top LHS, white circle. The PCC 2.5 software calculates the absolute value of the distance. All measurements were done by hand, two and three times for consistency. Error in measurements is the same as described in Section 2.2, with the exception that the scale is the same used in Fig. 22 seen on the LHS of the figure. Every cylindrical experiment experiences global motion in the direction of the impactor, starting approximately 1.0 mm before reaching the maximum DOP, and continues to move until the end of data collection, a distance of approximately 10 mm from its initial location.

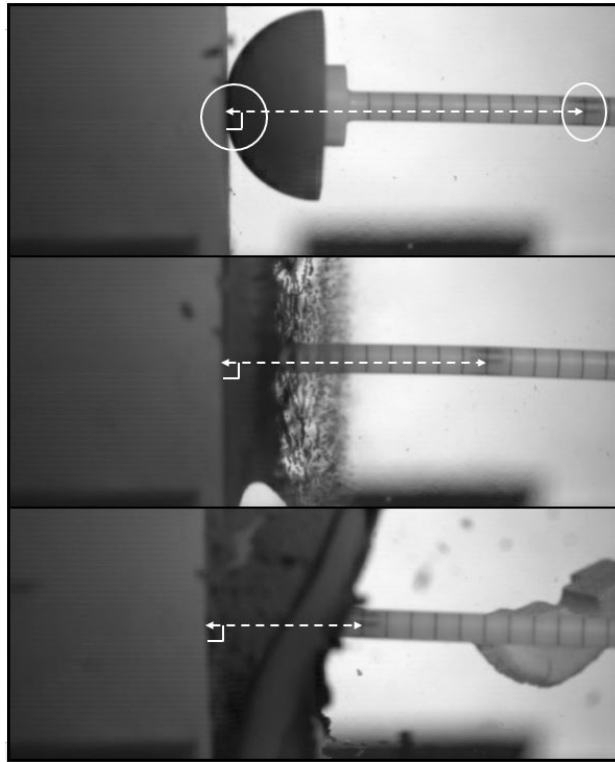


Fig. 27 Data extraction for time history DOP Cylindrical Impact 12-A

Graphs of the extracted time history of the DOP for the four cylindrical impact tests are shown in Fig. 28. The curves are qualitatively the same: DOP increases rapidly to its maximum, some rebound, and global motion of PVC. Early penetration rates increase with impact velocity but are the same within velocity groups for the

rectangular impact tests and diverge due to the effects of the PVC boundary. DOP maxima increase with impact velocity but are 22% to 25% less than the rectangular impact tests at the same velocity.

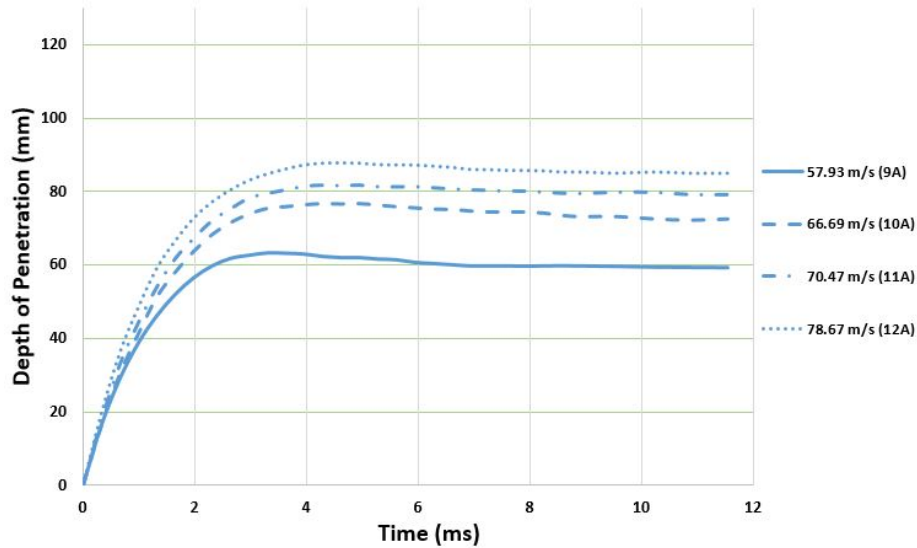


Fig. 28 Time history of DOP cylindrical impact

None of the cylindrical impact tests have measureable rebound, only instantaneous, before the penetrator is trapped by the clay behind the hemisphere and displays oscillatory behavior in the direction of the impact and rebound. The entrapment is more severe and occurs sooner in the cylindrical case than the rectangular due to the confinement by the PVC.

A notable difference between the rectangular and cylindrical configurations is extrusion of the clay at the PVC boundary. Figure 29 demonstrates the evolution of that behavior for Test 9-A, where the amount of extruded clay is 2.51 mm. The amount of extruded clay at the boundary for 10-A, 11-A, and 12-A is 5.40, 6.99, and 10.80 mm, respectively.

The extruded amount of clay at the sides of the PVC and the total amount extruded at the crater, or the height of crater from the top of the PVC, can be used to validate boundary conditions and material models for finite-element analysis. In addition, the initial timing of the formation of the extrusion is useful to assess credibility limits on the ARL and TNO experiments that have intermediary materials between a threat and the clay. That is, credibility in the data should end at the time the pressure wave reaches the PVC and rebounds. The speed of sound in clay is approximately 343 m/s and the radius of the cylinder is 3 inches, therefore the pressure front from the impactor should reach the PVC in approximately 0.222 ms. The images from the camera show that for Test 9-A the pressure wave reaches the PVC boundary at approximately 0.267 ± 0.033 ms. The timing corresponds with the approximate credibility limits, 0.250 ms, for the ARL experiments (Schuster et al. 2018).

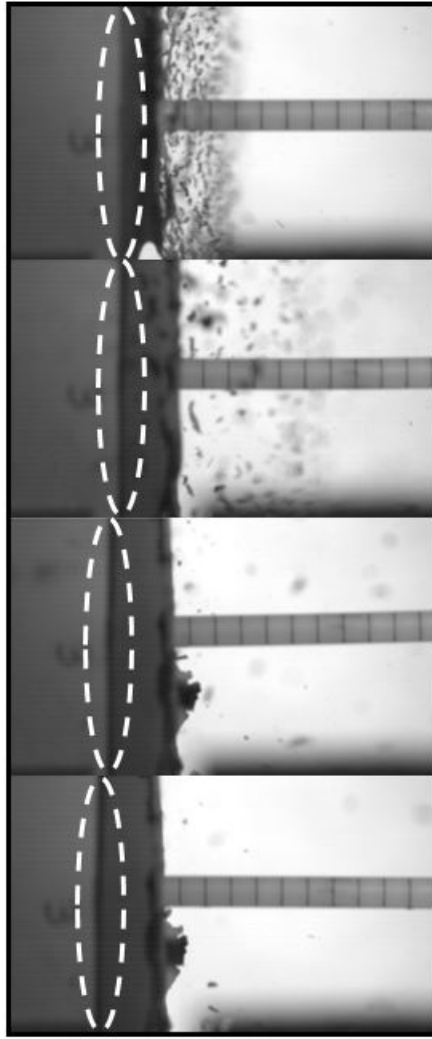


Fig. 29 Clay extrusion at PVC boundary

3.4 Discussion

A graph containing the four cylindrical and eight rectangular time histories of DOP is provided in Fig. 30. The eight rectangular tests are in the same impact velocity range as the cylindrical tests for comparison. Cylindrical curves are blue, and the rectangular are green with impact velocity labeled on the graph at the end of the time history curve.

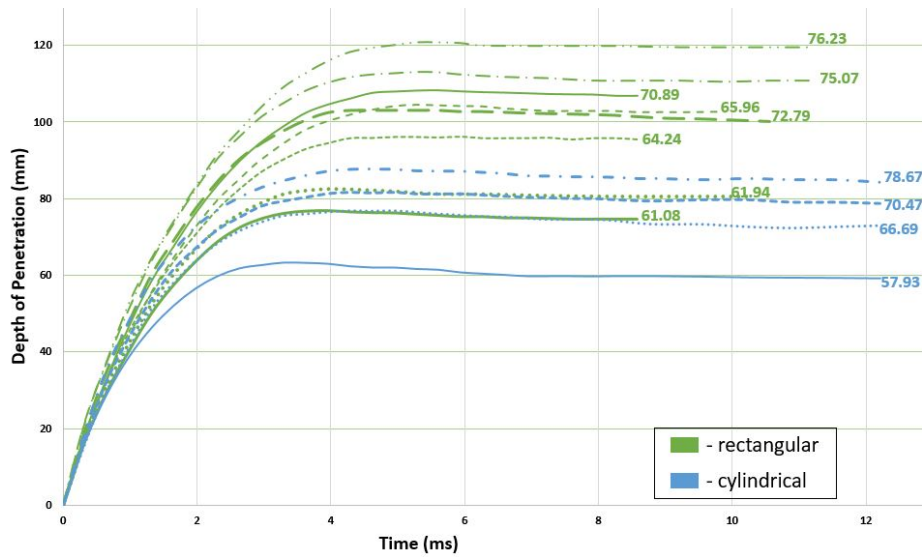


Fig. 30 Time history of DOP cylindrical and rectangular

Table 3 shows the type of impact test, where “Cyl” means cylindrical and “Rect” means rectangular, test number, velocity (m/s), and the amount of percentage lower the cylindrical maxima DOP are when compared with rectangular tests at a similar impact velocity. All cylindrical maxima DOP within the same velocity as the rectangular are lower by 24% to 27%, except 9-A, where the maximum DOP is 18% lower. For the outlying comparison within a similar impact velocity, that is, for 9-A and 5-B, the 5-B impact velocity is higher by 5.16%. The DOP of Test 9-A is 28.60% lower than 5-A, where the impact velocity difference is 6.5% higher.

Table 3 Cylindrical and rectangular DOP notes

Cyl	vel (m/s)	Rect	vel (m/s)	% lower	Cyl	vel (m/s)	Rect	vel (m/s)	% lower
9-A	57.93	5-B	61.08	18.00	10-A	66.69	6-B	65.96	26.55
11-A	70.47	8-B	70.89	24.35	12-A	78.67	8-A	76.23	27.35

The cylindrical impact tests show that the effect of the boundary is to decrease the maximum DOP and time history by approximately 26%.

4. Geometric Comparisons

Impact testing for BABT with clay backing material has generally been performed on rectangular blocks. The decision to change the target geometry to a cylindrical column of confined clay was to maximize the use of state-of-the-art X-ray technology to quantify the separation observed between a shoot pack and backing material. It had previously been understood that the crater formed within the

backing material was an imprint of the BFD; therefore, changing the target geometry was required to exploit new technology.

Figure 31 contains DOP versus time for eight impact experiments: four from the cylindrical geometry, shown as green curves, and four from the rectangular geometry, shown as dark blue curves. The style of curve—solid, dashed, dotted, dash/dot/dot—corresponds to similar impact velocities from each geometry. Within every velocity set, the time history of the DOP in the cylindrical case is less than the corresponding rectangular case. From initial contact to approximately 0.23 ms, the DOP history is the same. Therefore, the cylindrical target configuration does not provide an accurate representation of the dynamics of crater formation and is not credible after approximately 0.23 ms.

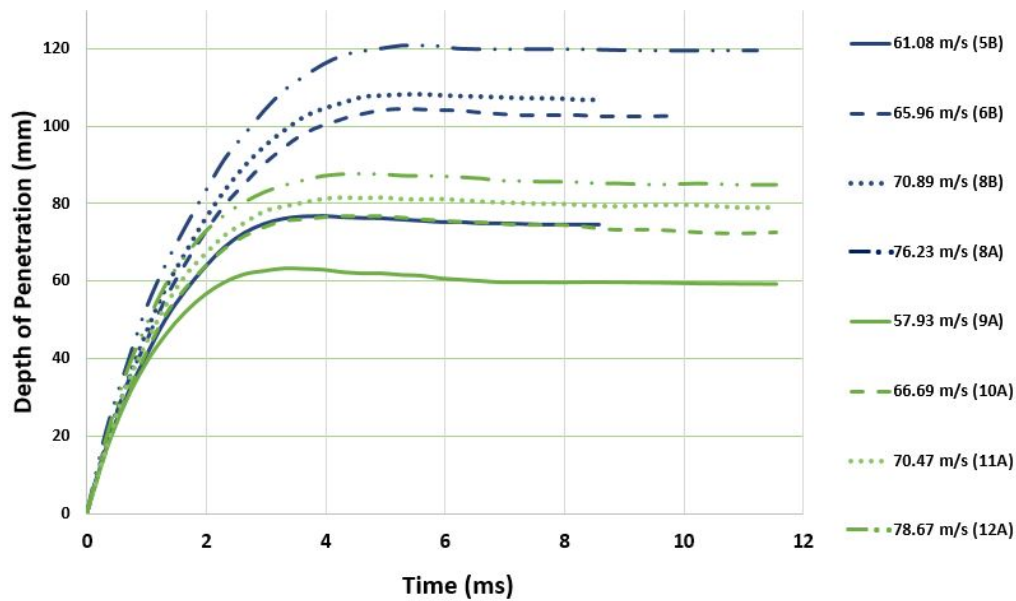


Fig. 31 DOP time history impact both geometries

Column drop testing is always performed prior to impact testing, and in this study additional drops were done to obtain points of validation for constituent models of clay. Column drop testing has historically been performed on rectangular blocks of clay, but for this study we also used cylindrical columns of clay.

Figure 32 contains DOP vs. time for four column drop tests: one from the cylindrical geometry, shown as a green, solid curve; and three from rectangular geometry, shown as blue curves in different styles. The rectangular drop tests 5, 9, and 10 were chosen because they met the ARL TOP requirement for final DOP. Cylindrical Drop 14 was chosen for the same reason as the rectangular cases but also because Drop 14 was aimed at the clay center.

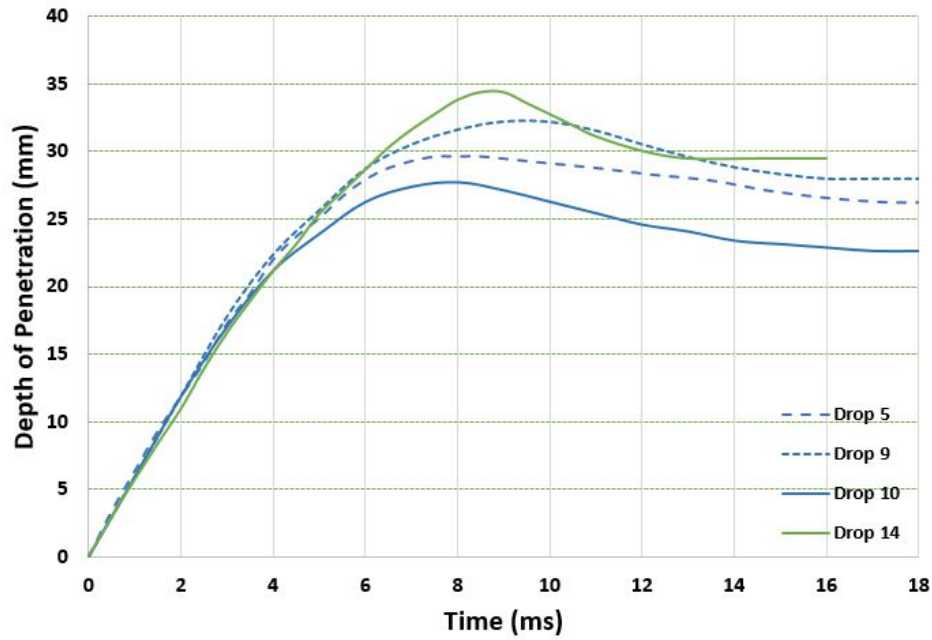


Fig. 32 DOP time history column drop testing both geometries

5. Summary and Conclusion

Prather-type side-impact testing and column drop testing of RP#1 were performed on both rectangular and cylindrical geometries to assess BABT at a variety of impact velocities, to assess the effects of the boundary in the cylindrical configuration, to calibrate and capture rebound of the RP#1, and to obtain validation points for constituent modeling. A time history of the DOP was collected by high-speed camera for both side-impact testing and column drop testing. The final DOP for column drop testing was also measured by caliper. Column drop tests were performed according to ARL TOP prior to each impact test.

Comparisons of side-impact testing between rectangular and cylindrical geometries showed that the presence of a stiff material confining the RP#1 has a dampening effect on the overall time history of the DOP, and the maximum DOP is significantly smaller in the cylindrical case. Column drop testing in both geometrical configurations showed rebounding of the RP#1 after reaching maximum DOP.

6. References

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Appendix A. Data Obtained for Drop Tests

Table A-1 contains the box (rectangular) and cylindrical drop test data. The rectangular drop tests are numbered 1–12. Two separate boxes were used, with top and bottom faces as targets. Cylindrical drop tests are numbered 13–20. There were two cylinders used, with only one face available as a target, as the other is confined by wood. The impact location on the clay face and the timing of impact after removal from the oven are recorded. The temperature and depth of penetrated are measured.

Table A-1 Data from rectangular and cylindrical drop tests

Drop #	Date	Target	Face	Location	Time	Temp (°F)	Depth (mm)
1	4/10/18	Box 1	Top	Center	8:04	95.2	24.24
2	4/10/18	Box 1	Bottom	Center	8:18	92.8	19.72
3	4/10/18	Box 2	Top	Center	8:32	94.7	23.18
4	4/10/18	Box 2	Bottom	Center	8:43	92.6	25.01
5	4/10/18	Box 1	Top	Center	13:06	92.8	23.44
6	4/10/18	Box 1	Bottom	Center	13:16	92.4	18.26
7	4/10/18	Box 2	Top	Center	13:29	92.2	20.70
8	4/10/18	Box 2	Bottom	Center	13:35	92.5	22.37
9	4/11/18	Box 1	Top	Center	8:54	96.3	23.58
10	4/11/18	Box 1	Bottom	Center	9:00	96.3	23.05
11	4/11/18	Box 2	Top	Center	9:07	95.1	20.96
12	4/11/18	Box 2	Bottom	Center	9:12	96.1	24.23
13	4/11/18	Cylinder 1	Top	Center	12:44	99.5	29.98
14	4/11/18	Cylinder 2	Top	Center	13:05	100.0	27.61
15	4/12/18	Cylinder 1	Top	Offset	9:38	96.9	23.35
16	4/12/18	Cylinder 2	Top	Offset	10:11	96.7	21.67
17	4/12/18	Cylinder 1	Top	Edge	13:50	97.1	23.73
18	4/12/18	Cylinder 2	Top	Edge	14:04	95.7	22.28
19	4/16/18	Cylinder 1	Top	Center	13:00	96.6	20.22
20	4/16/18	Cylinder 2	Top	Center	13:53	96.4	20.50

Appendix B. Images from Rectangular Drop Testing

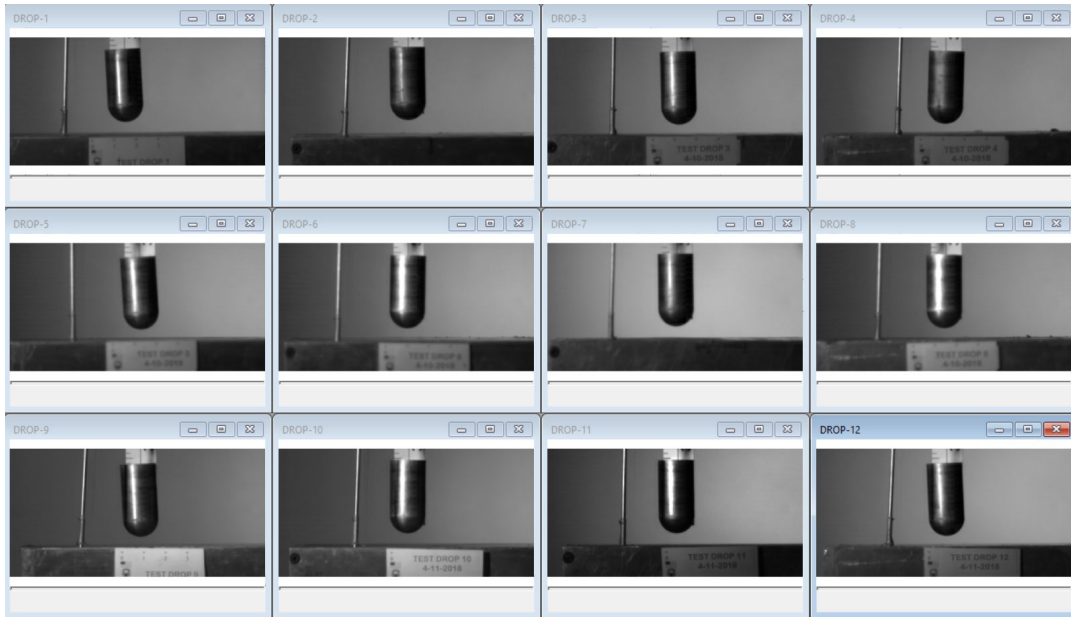


Fig. B-1 All rectangular drop tests before penetration

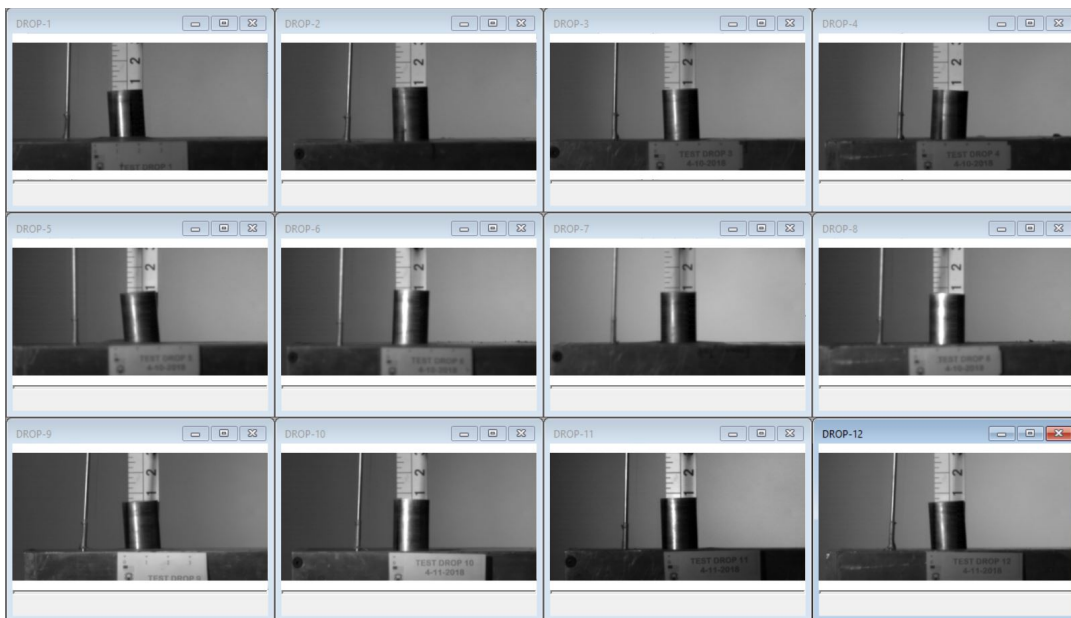


Fig. B-2 All rectangular drop tests at maximum depth of penetration

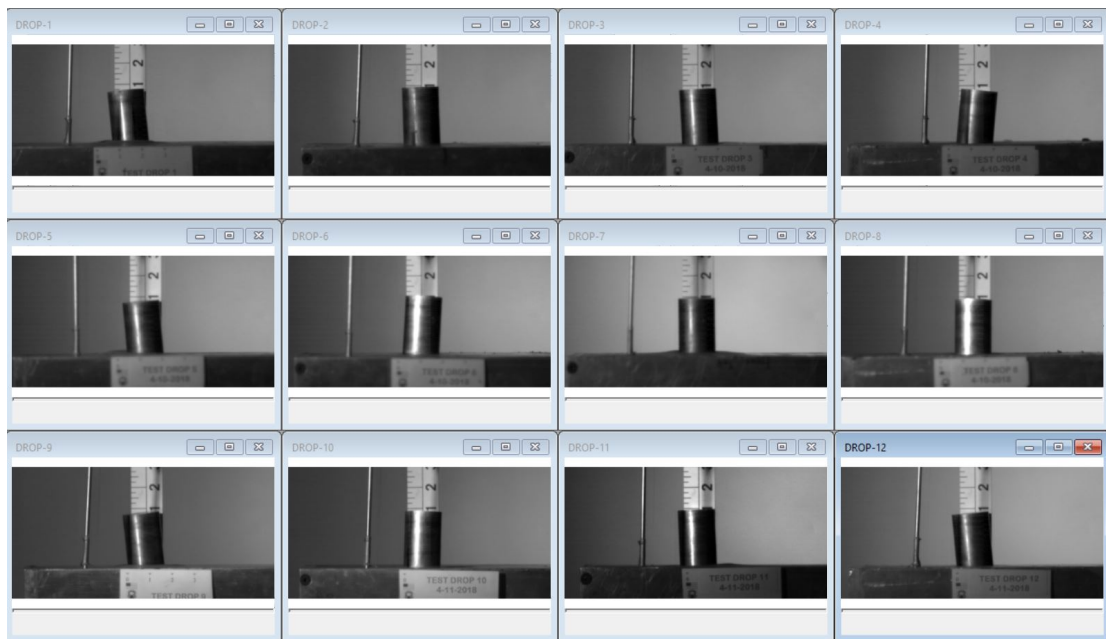


Fig. B-3 All rectangular drop tests end of rebound

Appendix C. Images from Cylindrical Drop Testing

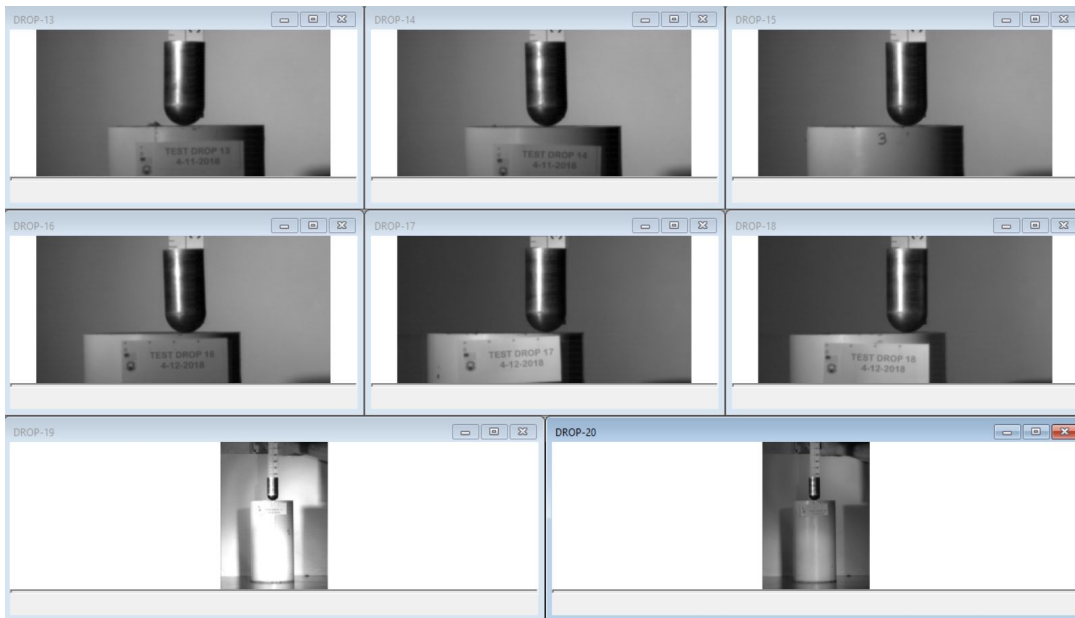


Fig. C-1 All cylindrical drop tests before penetration

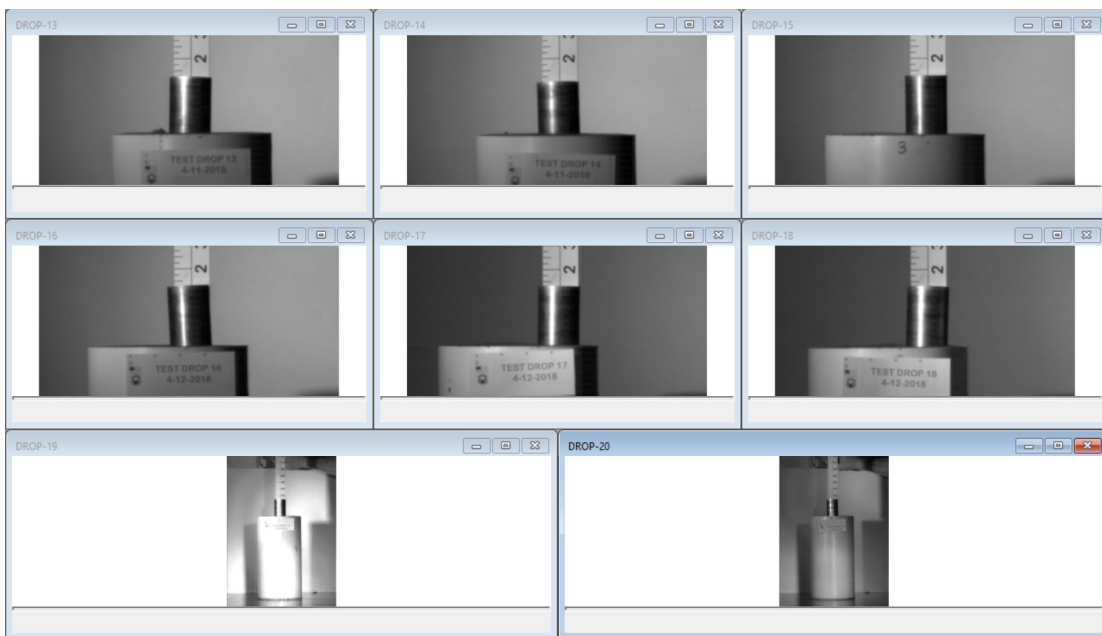


Fig. C-2 All cylindrical drop tests at maximum depth of penetration

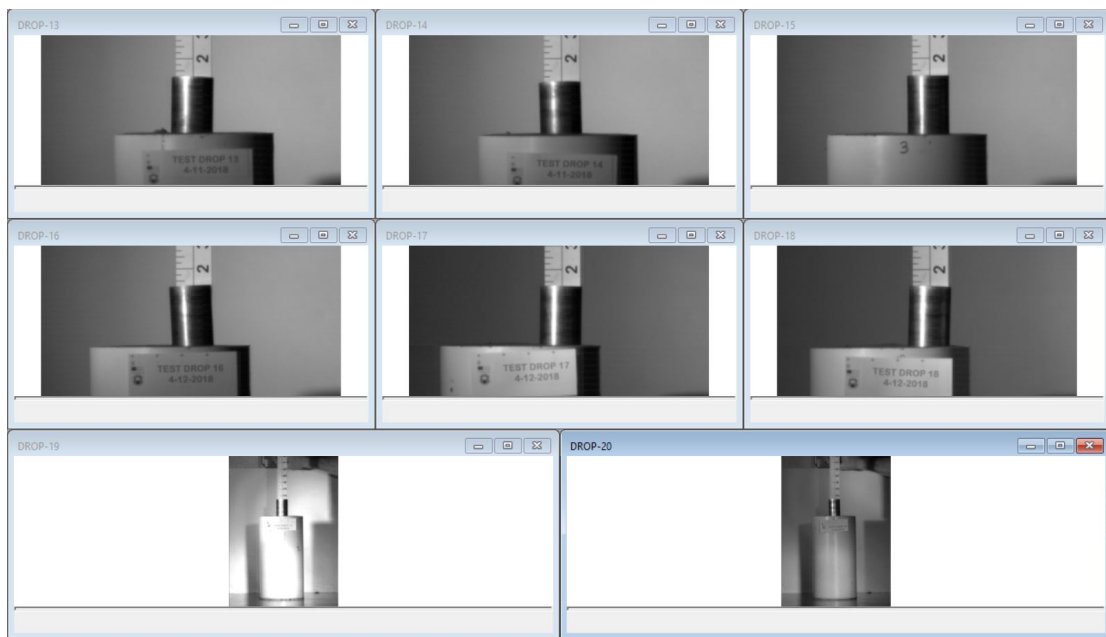


Fig. C-3 All cylindrical drop tests end of rebound

Appendix D. Data Obtained for Impact Tests

Tables D-1, D-2, and D-3 contain box (rectangular) impact test data for Faces A and B and cylindrical impact, respectively. The box geometry is numbered 1-A through 8-A and 1-B through 8-B, and the cylindrically confined clay target is numbered 9-A through 12-A. Two clay boxes and two cylindrical containers were used. The impact location for each test is the center of the clay box or cylinder, and the timing of impact after removal from the oven is recorded. The temperature and depth of penetrated are measured.

Table D-1 Data from Boxes 1 and 2 impact tests Face A

Clay #	Date	Target	Temp °F	Hum %	Shot: Face A							Calibration: Face A					
					Shot #	Time	Velocity ft/s	Depth mm	Yaw °	Pitch °	Tot Yaw °	Time	Temp 1 °F	Temp 2 °F	Drop 1 mm	Drop 2 mm	Drop 3 mm
1	4/23/2018	Box 1	73.9	35	1-A	13:53	36.67	16.61	0.35	3.39	3.40	13:32	96.1	97.9	27.02	27.83	27.31
2	4/24/2018	Box 2	69.1	39	2-A	9:07	54.29	20.51	-0.82	-0.72	1.09	8:49	94.1	96.1	24.41	23.72	22.70
3	4/24/2018	Box 1	70.0	42	3-A	10:19	101.37	34.06	1.38	-0.42	1.44	10:06	95.7	94.7	23.22	24.91	24.06
4	4/24/2018	Box 2	71.4	42	4-A	13:09	95.92	32.09	3.46	0.00	3.46	12:56	91.8	92.3	22.40	22.07	22.61
5	4/24/2018	Box 1	72.9	43	5-A	14:08	203.22	86.72	1.46	-0.57	1.57	13:56	94.6	92.8	23.89	23.22	24.18
6	4/25/2018	Box 2	68.0	60	6-A	8:11	214.04	95.90	-0.23	0.54	0.59	7:58	95.4	98.0	23.93	22.86	23.44
7	4/25/2018	Box 1	69.3	60	7-A	9:24	246.28	113.37	-2.08	-2.93	3.59	9:13	96.1	96.8	23.74	23.03	24.07
8	4/25/2018	Box 2	72.5	61	8-A*	14:08	250.09	121.94	-2.14	2.96	3.65	13:57	94.0	96.9	25.30	24.06	24.58

Table D-2 Data from Boxes 1 and 2 impact tests Face B

Clay #	Date	Target	Temp °F	Hum %	Shot: Face B							Calibration: Face B					
					Shot #	Time	Velocity ft/s	Depth mm	Yaw °	Pitch °	Tot Yaw °	Time	Temp 1 °F	Temp 2 °F	Drop 1 mm	Drop 2 mm	Drop 3 mm
1	4/23/2018	Box 1	73.9	35	1-B	14:21	57.68	22.15	-0.73	-1.95	2.08	13:37	96.5	98.1	25.87	27.24	26.10
2	4/24/2018	Box 2	69.1	39	2-B	9:19	51.93	20.85	-1.41	-0.25	1.44	8:54	93.7	95.3	25.71	23.64	23.58
3	4/24/2018	Box 1	70.0	42	3-B	10:30	100.77	32.74	1.55	-0.81	1.75	10:11	94.7	94.9	23.19	22.75	22.35
4	4/24/2018	Box 2	71.4	42	4-B	13:19	107.37	38.05	0.25	1.06	1.09	13:01	91.6	92.6	23.17	23.36	22.86
5	4/24/2018	Box 1	72.9	43	5-B	14:21	200.39	75.95	0.60	-1.02	1.18	14:00	92.4	93.8	22.78	22.09	22.18
6	4/25/2018	Box 2	68.0	60	6-B	8:23	216.40	105.02	-0.36	0.43	0.55	8:03	96.8	96.2	24.08	24.90	24.99
7	4/25/2018	Box 1	69.3	60	7-B	9:35	238.81	103.41	-0.43	5.17	5.19	9:17	96.8	95.5	22.27	22.06	23.13
8	4/25/2018	Box 2	72.5	61	8-B**	14:20	232.59	109.03	-0.71	1.66	1.80	14:01	95.3	94.7	24.82	23.66	25.07

Table D-3 Data from cylindrical impact tests

Clay #	Date	Target	Temp °F	Hum %	Shot: Face A							Calibration: Face A					
					Shot #	Time	Velocity ft/s	Depth mm	Yaw °	Pitch °	Tot Yaw °	Time	Temp 1 °F	Temp 2 °F	Drop 1 mm	Drop 2 mm	Drop 3 mm
9	5/1/2018	Cylinder 1	69.3	37	9-A	0.4	190.06	64.2	0.34	0.21	0.4	8:34	101.0	N/A	22.30	N/A	N/A
10	5/1/2018	Cylinder 2	70.0	39	10-A	0.4	218.81	80.68	0.24	0.63	0.67	9:22	102.8	N/A	24.00	N/A	N/A
11	5/1/2018	Cylinder 1	75.0	36	11-A*	0.6	231.2	89.73	0.78	-1.47	1.67	13:10	100.5	N/A	25.48	N/A	N/A
12	5/1/2018	Cylinder 2	75.6	36	12-A*	0.6	258.12	93.26	2.94	1.17	3.17	13:43	101.3	N/A	26.49	N/A	N/A

Appendix E. Images from Rectangular Impact Testing



Fig. E-1 All rectangular impact tests at initial contact

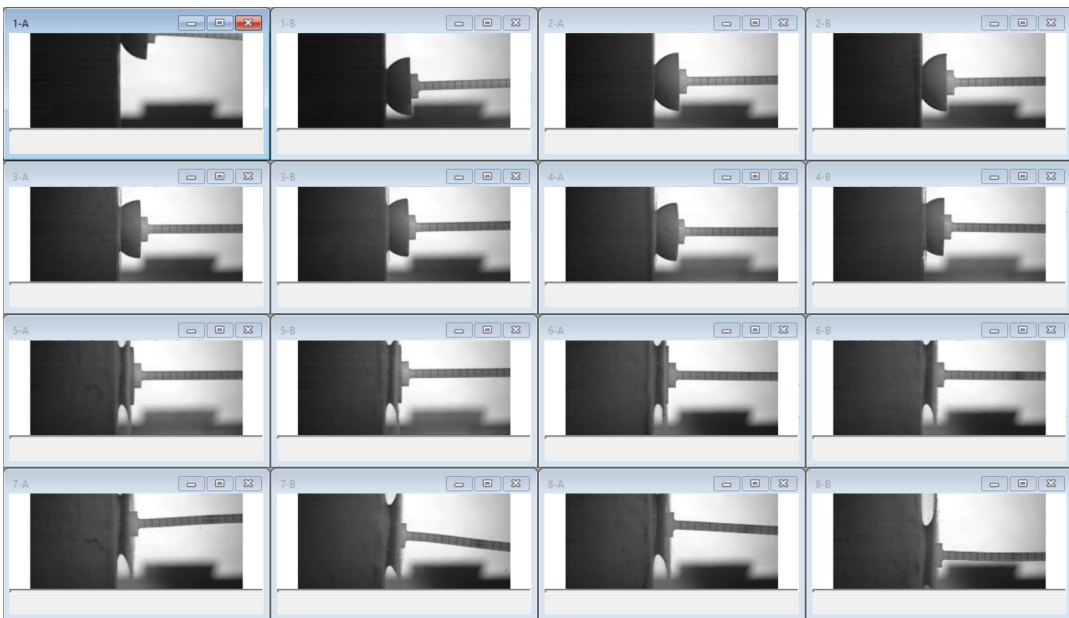


Fig. E-2 All rectangular impact tests at 0.333 ms



Fig. E-3 All rectangular impact tests at maximum depth of penetration



Fig. E-4 All rectangular impact tests after rebound

Appendix F. Images from Cylindrical Impact Testing

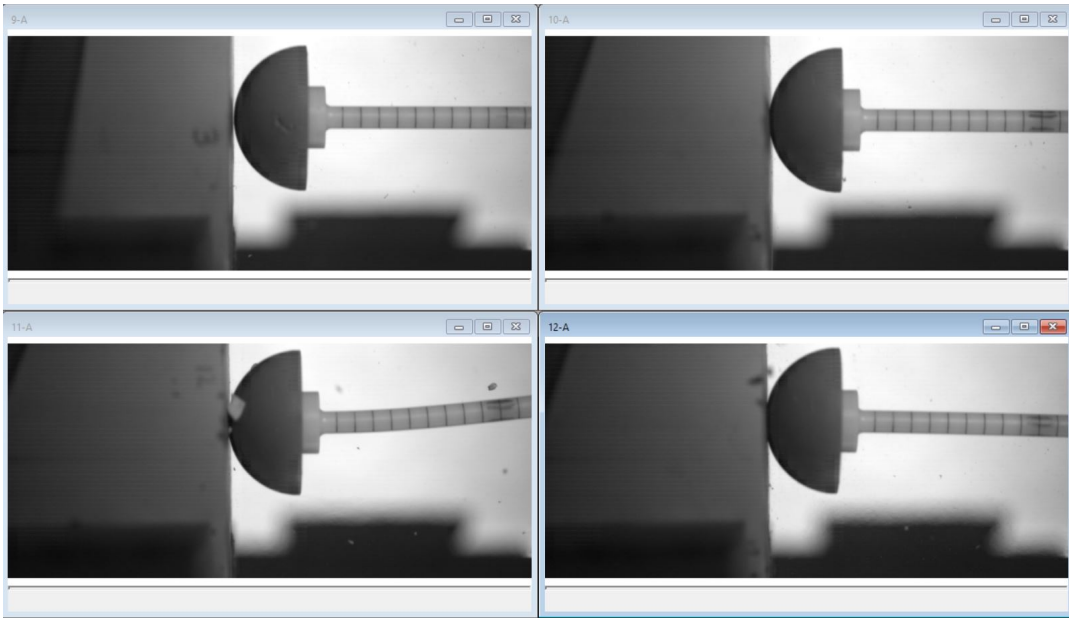


Fig. F-1 All cylindrical impact tests at initial contact

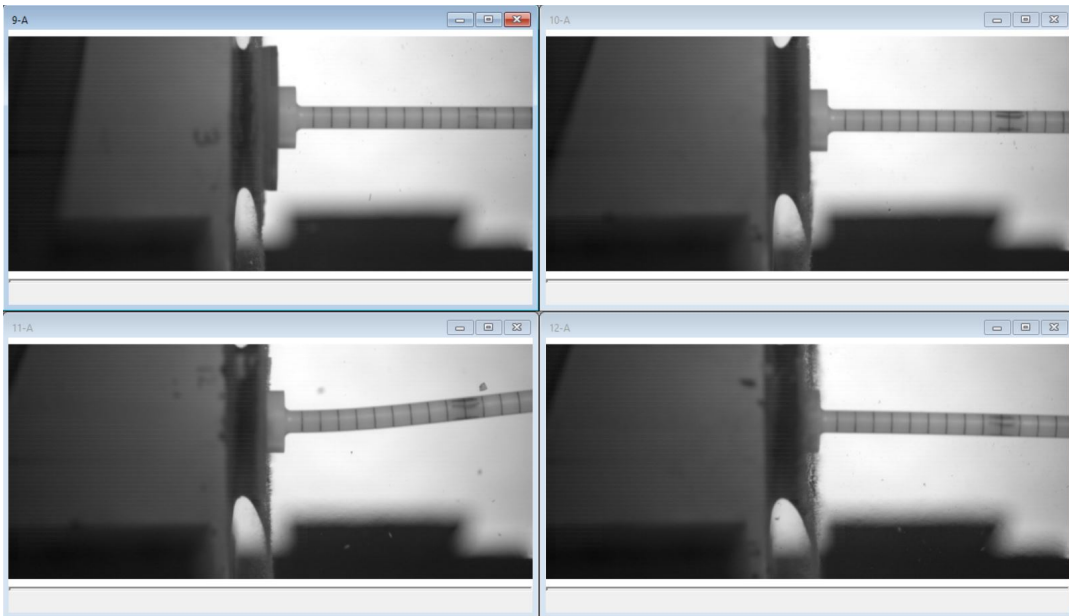


Fig. F-2 All cylindrical impact tests at 0.333 ms

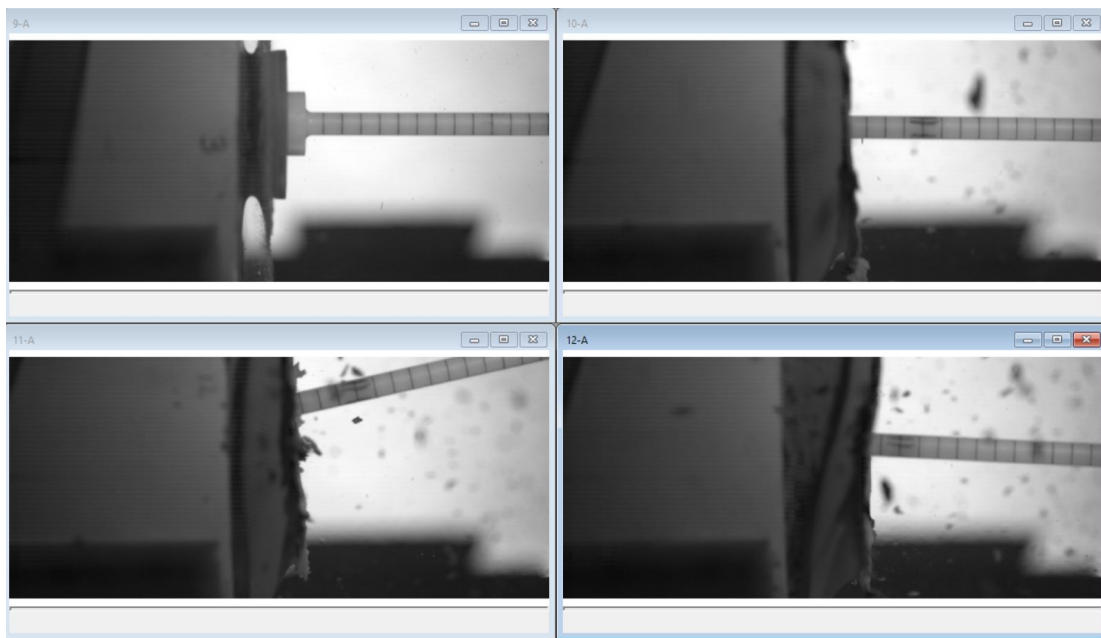


Fig. F-3 All cylindrical impact tests at maximum depth of penetration

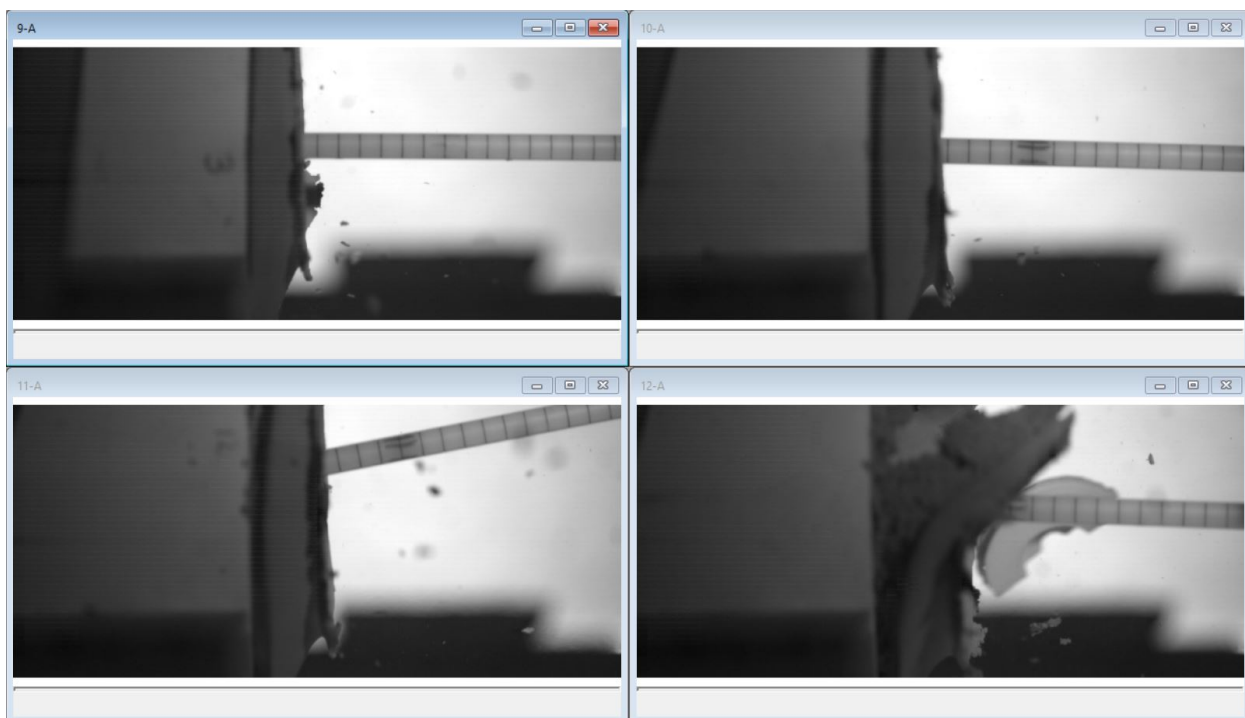


Fig. F-4 All cylindrical impact tests at final frame of high-speed imagery

List of Symbols, Abbreviations, and Acronyms

ARL	Army Research Laboratory
BABT	behind-armor blunt trauma
BFD	back-face deformation
CCDC	US Army Combat Capabilities Development Command
DOP	depth of penetration
FOV	field of view
fps	frames per second
LHS	left-hand side
PCC	Phantom Camera Control
PVC	polyvinyl chloride
RHS	right-hand side
RP#1	Roma Plastilina #1
TOP	test operating procedure

1 DEFENSE TECHNICAL
(PDF) INFORMATION CTR
DTIC OCA

2 CCDC ARL
(PDF) IMAL HRA
RECORDS MGMT
FCDD RLD CL
TECH LIB

1 GOVT PRINTG OFC
(PDF) A MALHOTRA

13 NATICK SOLDIER RSRCH
(PDF) DEV AND ENGRNG CTR M
G CARBONI
M CODEGA
D COLANTO
R DILALLA
B FASEL
J FONTECCHIO
B KIMBALL
J KIREJCZYK
M MAFEO
M MARKEY
J PARKER
D PHELPS
J WARD

3 PROG EXECUTIVE OFC
(PDF) SOLDIER
A FOURNIER
J MULLENIX
E BEAUDOIN

1 AUTO CELL PEO LAND SYS
(PDF) A PURTELL

2 OFFICE OF NAVAL RESEARCH
(PDF) T BENTLEY
K YANKASKAS

1 NAVAIR PATUXENT RIVER
(PDF) B SHENDAR

1 INST FOR DEFNS ANALYS
(PDF) Y MACHERET

6 MPMC DOD BLAST INJURY
(PDF) RSRCH PROG COORDINATING
OFC
R GUPTA
M LEGGIERI
R SHOGE
S HINDS
C STEELE
T PIEHLER

3 MPMC JTAPIC PRGM OFC
(PDF) F LEBEDA
W LEI
J USCILOWICZ

4 US ARMY AEROMEDICAL
(PDF) RSRCH LAB
F BROZOSKI
V CHANCEY
B MCENTYRE
D WISE

1 TARDEC
(PDF) R SCHERER

1 RDECOM HQ
(PDF) AMSRD PE
D RUSIN

1 EDGEWOOD CHEML AND BIOL
(PDF) RSRCH DEV AND ENG CTR
M HORSMON

1 OSD DOT&E
(PDF) J IVANCIK

50 ARL
(PDF) FCDD DAS LA
P BAKER
T STADTERMAN
P DISALVO
N EBERIUS
FCDD DAS LA
N ELDREDGE
M PERRY
FCDD DAS LBE
M MAHAFFEY
J GURGANUS
M COHEY
S COARD
FCDD DAS LBG
M ROTHWELL
F REYNOLDS
FCDD DAS LBS
R DIBELKA
FCDD DAS LBW
G DIETRICH
M ENDERLEIN
A KULAGA
K LOFTIS
W MERMAGEN
S SNEAD
R VANAMBURG
FCDD RLW
S SCHOENFELD

FCDD RLW PA
S BILYK
FCDD RLW PB
S ALEXANDER
T BAUMER
A BROWN
A DAGRO
A DILEONARDI
A EIDSMORE
B FAGAN
M GRAHAM
A GUNNARSSON
C HAMPTON
C HOPPEL
M KLEINBERGER
E MATHEIS
J MCDONALD
P MCKEE
K RAFAELS
S SATAPATHY
K THOMPSON
K WEAVER
T WEERASOORIYA
S WOZNIAK
T ZHANG
FCDD RLW PC
M FERMEN-COKER
FCDD RLW PD
J RUNYEON
FCDD-RLW-PE
P SWOBODA
FCDD RLW PF
N GNIAZDOWSKI
FCDD RLW P
R FRANCAERT