Slope Stability, Performance and Berm Design of Small Arms Ranges for the Canadian Armed Forces

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Abstract. The soil berm stop butt used to arrest bullets behind targets of Canadian Armed Forces Small Arms Ranges (SAR) infrastructure presents a geotechnical opportunity for optimization. Existing pre-emptive monitoring of the berms over the past decade has established multiple modes of failure. Previously, the initiation for remediation was assessed against a fixed amount of bullet impacts. Using qualitative and quantitative metrics, the deterioration of the soil berm can be assessed over time. The results of this research will be used to optimize and critique, for improvement, the design and use of SARs in an area-wide, national approach. Using LIDAR scanning, the effects of long-term, repetitive ballistic loading will capture the stability of standard soil-clay slopes. Some key characteristics of SAR stop butts including usage, material gradation, surface tunnelling, bullet penetration depth and environmental considerations will be monitored to assess their feasibility as threshold catalysts for routine maintenance of the berm.

Keywords: Optimization of Berm Design · Small Arms Ranges · Performance of Range Berms due to Impact

1 Introduction

Canadian Armed Forces (CAF) Small Arms Ranges (SAR) berms are, in most cases, at least wartime dated (Fig. 1) geo-infrastructure singularly designed towards one aim, the continued safe training of marksmanship by reducing the unnecessary risk and hazards of bullets and shrapnel ricochet in a training environment. From a geotechnical point of view, the effective use of soil berms as a stop butt poses a multi-pronged non-trivial problem set of significant complexity. As we will discover, there are many characteristics to be monitored and assessed to ensure optimization of the berm over its lifecycle.

As permanent safety infrastructure used in all of CAF training range conditions, the design of this pile of dirt aims to safely arrest and expend all kinetic energy of bullets with minimal impact to its structural stability over an extended period and subjected to repetitive ballistic loading. They are designed and constructed according to standards for *all land-based ranges, training areas, training facilities of DND and non-DND (*D-RTAM, 2010*).* This allows the effective training of military, police, corrections, and other shooting at competitive and recreational levels all having equally high standards of

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Fig. 1. RCAF Aerial Imagery CFB Kingston's SAR (RP OPS, 1965 & 1948)

safety. While the overarching designs have not varied much since their original emplacement, innovation has caused the design manual to be continuously updated as relevant innovation is proposed; although not every range is brought up to speed uniformly.

To frame the scope of the research, the primary focus is to assess stop butts used in training of small caliber handheld personal sidearms of the pistol and rifle variety smaller than machine guns. Although smaller 25-m pistol range berms are also commonly used, this study focused on a 600-yard range to include the standard service rifle rounds (SAR was designed in the imperial system of units and confirmed through measurements). Access to the Canadian Forces Base, Kingston, Ontario, 600-yard SAR was the principal location of all scans and soil testing.

While new procurement initiatives continue to develop and are uniquely tested at significantly higher cost in R&D than existent soil berm infrastructure, the problem remains; what do we do with the in-place significant soil geoworks across Canada. This ultimately was the original question from which our aim was derived: what are the contributing factors to range failure attributed to the soil berm?

2 Objectives/Aim

In the process of optimizing a pile of soil using a data driven technical approach, there are many aspects to consider. Some of the key geotechnical metrics of the berm design that are being assessed are berm performance and deterioration due to range use and weathering, O&M, structure, and contamination. The objectives of this research are therefore to affect positive optimization where possible and inform future designs in the construction manuals and operational lifecycle policy.

Assessing characteristics and providing berm-based recommendations may prove to be more pertinent given the vast array of climactic conditions and localized in-situ soils found domestically and internationally where CAF designed stop butt berms exist.

3 Methodology

To effectively assess the berm, various key structural concepts of soil slope and berm science were outlined against a literature review of previous studies and corporate SAR knowledge of failure points. This outlined the feasibility of establishing relevant tangible metrics that can be assessed and monitored. Subsequently, qualitative, and quantitative assessments were used to measure in- situ conditions of the 600-yard SAR. Although these results are not meant to be representative of all possible range- berm-soil-climate conditions across Canada, they may provide additional confirmation of default design standards and O&M procedures. If any eccentricity exists, it could provide a useful basis for the optimization of this berm as well as provide the basis to critique, for improvement, the design standards of SARs.

Equally important is the emplacement of continuous long-term monitoring and instrumentation plans for the berm. These monitoring programs can be used in parallel to assess other SARs domestically and abroad to define their geographically localized climatic and soil-based implications where these are used under CAF SAR conditions as a common factor.

In addition to the instrumented numerical measurements, this study has equally received Royal Military College of Canada's Research Ethics Board approval to conduct subject matter expert interviews to acquire corporate knowledge about the berms. The use of these anonymous technical interviews has been crucial in the "*where to look*" stages of review as well as the shared knowledge of future projects and research. The importance of non-quantifiable data has proven to be worthy of the effort required to acquire it. Questions such as: how to define a safe berm on a shooting range, how much risk is acceptable, have standards changed, how often are clean ups required and performed, etc., are a significant and genuine data set that take time and effort to assess.

3.1 RMC Green Team Data

Equally important is the meta-analysis of data collected over the past 10+ years for 150 sites in various conditions across Canada by *RMC's Green Team.* The data included SAR intrinsic characteristics (such as topography, proximity of firing range to surface water bodies, surficial geological and hydrogeological information, climatic information) as well as historical use of facility, ammunition type allowed on-site and current usage data (i.e. number of bullets shot on-site). This information has been organized in a risk matrix with a view to providing a risk ranking of the SAR regarding their respective intrinsic and current usage profiles (Skordaki & RMC Green Team, 2009; 2016; Skordaki & Vlachopoulos, 2017a; b; Skordaki & Vlachopoulos, 2018). The RMC Green Team SAR reports and publications have been a trove of data guiding the CAF's recent improvements and modernizations of SARs in a prioritized fashion.

4 Key Concepts

To start the optimization process, we need to accept that the design is the minimum combination of structural specifications that would accommodate the average unidirectional shooting conditions across a wide spectrum of geographical conditions. Deviations

Fig. 2. CFB Kingston 600-Yard SAR (LeBlanc, 2021)

from the design are engineered and approved on a case-by-case basis accommodating the localized conditions. Local soil mixes will have been favoured during the build of these berms and variation has been observed.

Important to note is that it would be feasibly impossible to construct a berm of sufficient size to stop all possible deliberate and accidental trajectories and reach 100% effectiveness. The objective of the berm is to actively arrest most rounds accurately fired within an acceptable error of the targeted area of fire. Passive measures enforced by range staff such as an extensive evacuated safety footprint behind the berm and the use of individual lanes, deliberate controlled simultaneous firing and weapon barrel control, limit the outlier ballistic trajectories. Ultimately the berm prevents 100% of bullets from being an unnecessary hazard in a training situation.

4.1 Berm Described

A standard stop butt soil berm is made up of an unspecified proportion of sand and clay mix and local soil. While the exact mix is not defined, the construction manual design includes statements which delineate maximum penetration depth of a bullet as well as *no stones or other hard fragments that could cause danger through ricochet* (D-RTAM, 2010). The berm characteristics are defined to initially construct the de facto stop butt model but left open ended so that any situational variation can be accommodated. However, the science behind many of the tangible design characteristics is not included. Contrary to most foundation problems, a stop butt berm should remain stable despite continuously disturbing the surface soil. The impact media aims to absorb and dissipate through plastic deformation both thermal and kinetic energy while retaining a consistent structure (Fig. 2).

We would be remiss not to mention the berm is used both in thawed and frozen conditions year-round. And although unconfirmed without completely digging it up, the berm should be isolated from the soil beneath it by a geo membrane or clay liner mitigating some of the contaminant mobility risk making it a clear boundary conditions for modelling purposes.

4.2 Structural Design

In summary, the berm's height and width are factors of the maximum straight line ballistic trajectory angles from the firing line where the shooters are positioned. Specifically, the

CFB Kingston stop butt contains approximately 10 000 m^3 of fill which is exposed to all weather conditions and used year-round. Controlled vegetation and root systems have taken hold in the berm over time and do provide a measure of stability to the slope. The cross-sectional design remains unchanged throughout the berm.

4.3 Innovative Technology

There have been many innovative designs trialed across many SARs such as steel bullet traps, overhead baffles, vertically hardened or self-healing/shock absorbing concrete surfaces. These options are not included in the optimizations as they become cost prohibitive for large scale replacement of all in situ CAF SARs (Bolduc and St- Jean, 2017).

Of future interest will be the green initiatives which could be used to improve existing range conditions. The use of green ammunition as well as uniformly sized healing rubber chunk media instead of soil are being trialed at various ranges across Canada. Their progress towards potential optimization of the berm is being monitored and will be elaborated on once results are commercially available.

4.4 Bullet Catcher

Within the last 5 years, implementation on the berm of wood framed 3.5 m squared boxes filled with 6 m^3 poorly graded non-uniform silty-sand media. The fill material selection was likely due to the higher drainage and lesser risk of compaction and tunneling. This raised sandbox, commonly referred to as a bullet catcher (BC) is installed to reduce the impact effects of bullets on the berm itself, thereby increasing its lifespan. Additionally, while remediation is a loosely defined concept with individualized local contract standards for SARs, the use of a separate media than the berm material reduces the maintenance effort required to sieve bullets and fragments as well as to refill any tunneling effects resulting from continued use.

4.5 Slope Angle

The ideal frontal berm slope angle and thus the impact angle of a bullet is an intriguing component of this research. While an insignificant curvature of the ballistic trajectory at short distance due to gravity exists, which would bring the bullet's impact slightly closer to normal to the surface, the angle difference is negligible at this range. The forward sloped surface of the berm therefore defines the impact angle of the bullets. A naturally upwards facing angle on the berm both allows the bullet to penetrate the soil and in the event of a ricochet, sends the bullet upwards and preferably further to the rear of the range vice back towards the shooters.

It is very specifically indicated in the design manual to operate with an impact surface of not less than 605 mils or 34 ° from the horizontal plane. Additionally, a ±1 ° change as caused by tunneling is cause for immediate repairs (D-RTAM, 2010). However, some American range designs call for a minimum of 45 ° as preferred slope of impact is 1 to 1 or steeper (Wilcher, 2012) and M.M. Dillon & Co Ltd's original engineered drawings for this specific 600-yard range require a minimum 2:1 slope equivalent to 26 °.

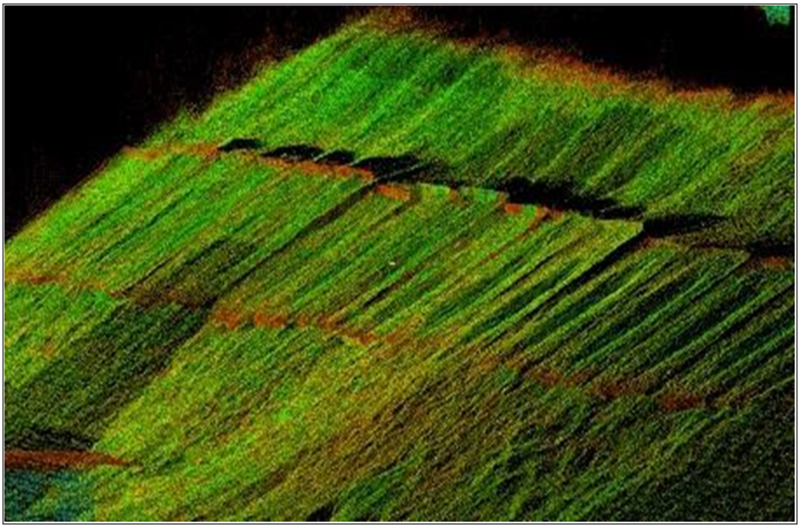

Fig. 3. LIDAR data point cloud (LeBlanc, 2021)

4.6 Berm Slope

A previous study conducted (Bolduc and St-Jean, 2017) concluded that the berm slope displayed a triple partitioned angle in cross-section. To date, we have attributed this mass wasting process of the berm construction materials to a combination of weathering, material selection as well as bullet impact since there is a very coincident correlation between the location of the slope changes and the impact area of most rounds given the steepest slope above the BC, and the gentlest slope in Fig. 3.

As a macro assessment of the berm, the use of Laser Imaging Detection And Ranging (LIDAR) technology has been instrumental to develop a baseline model of the berm reaching mm precision (±0.005 m total error on entire berm overlay) which will be used in conjunction with open source cloud compare software to overlay and indicate the changes over time of the infrastructure. This monitoring should be continued periodically over time to ensure precision and accuracy in determining when change occurs correlated to berm use. There has been some aerial lidar data provided by Geo Ontario of the range surface from as early as 2009. Ideally the scans will be taken at regular intervals.

On a micro assessment, higher fidelity scans concentrated on the BC fill media will be used before and after a range event to determine the void space created by tunneling. This data would be used to extrapolate predictively the number of rounds that can be fired against the specific fill media before manual raking would be required to maintain the bullet catcher. Additionally, we will be looking at the angle of surface that will be cause by mass wasting inside the bullet catcher as a factor of safety within the 34 ± 1°.

4.7 Lane Usage

The current berm model is guided by a tangible 100 000 rounds per lane of user recorded bullet impacts before assessment for some form of remediation should be initiated. To maintain currency, the average soldier will need to shoot ~800 rounds every year

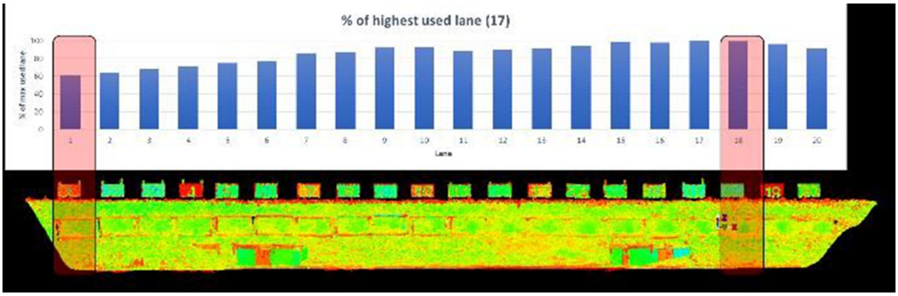

Fig. 4. Distribution of rounds by lane as a factor of the highest use lane (CFB Kingston, 2019)

although some of which can now be done on simulated indoor virtual trainers (DAT, 2007). However, if we approximate even 200 live rounds per person-year, there are well over 5 M rounds fired from the service rifle by the regular force's component of the Army branch of the CAF for minimum currency alone. This excluded all other forms of small arm's training at higher levels as well as different weapon systems including pistols or other rifles. This would mean that as an absolute minimum, full remediation of 50 lanes, or approximately 3-5 SARs a year should be completed just to keep the Regular Army minimally qualified on one service rifle.

Additionally, SAR lanes are often used non uniformly due to ease of access, relay size, target spacing and distribution, which sometimes prevents lanes besides each other to be used simultaneously, contributing to an uneven distribution of berm wear in some cases seeing up to 40% variation between the highest and lowest use lane in 2019 (Fig. 4). This leaves a large gap to optimize between remediating all lanes when the first one reaches the maximum threshold vice allowing lanes to exceed the maximum while waiting for the lower use lanes to meet the minimum; a lane-based approach may ensure a uniform standard of maintenance is applied across the berm. This leaves room to optimize a new threshold that is uncoupled from bullets per lane.

This opportunity factor allows partitioned bullet effects between high and low use lanes in relative comparison. In concert with the control pile of bullet catcher fill material situated off the berm, we can extrapolate what are effects due to weathering, and the remaining effects are characteristic of bullet wear on the berm. If we could develop metrics uncouple from usage and instead focused on measurable stability, environmental considerations, in- situ soil properties or structural design changes over time, we may be able to propose a more relevant maintenance schedule.

4.8 Bullet Penetration

In line with numerous conventions on warfare, the CAF uses highly standardized NATO bullets (made of various metals) placed in brass cartridges which house the explosive powder and provide the increased pressure which ejects the bullet from the barrel of the weapon. In Table 1, we observe that despite being almost twice the width (5.56 mm vs 9 mm), the pistol round is only about a third of the impact energy of a smaller rifle round due to the conservation of kinetic energy.

The effects of bullet penetration on the berm are noteworthy, but the equal and opposite reaction on the bullet is also interesting. The larger bullets tend to stay intact

Table 1. Open-source summary of NATO Bullets

Weapon	Caliber (NATO Std in mm)	Bullet Weight (g)	Speed (m/s)	Energy (J)
C7A2 Rifle	5.56 × 45	4.02 (62 gr)	922	1700
Browning Hi Power Pistol	9 × 19	7.45 (124 gr)	380	600

Fig. 5. Impacted shrapnel and bullets sizes (LeBlanc, 2021)

whereas the smaller higher velocity bullets disintegrate on impact. This leaves shrapnel of various sizes situated in the soil. If a berm had been used purely for pistol rounds, and using the threshold limit per lane, this would be equivalent to ~1000 kg of metals per lane accumulated before a cleanup is required. Practically there are not that many intact 9 mm found relative to total shrapnel pieces, which indicate there are significantly more micro shrapnel content mobilized in each lane (Fig. 5).

4.9 Forward Slope Surface Soil Testing Program

To determine the performance of the berm soil as well as the BC sand as impact media, a testing program was developed to look initially at the particle distribution at incremental depths on the berm.

4.9.1 First Round of Sampling

The first round of soil testing compared separate samples taken at 5 incremental 10 cm depths of the sand media in the center of the bullet catcher of the highest use lane. The soil was tested in the fall and after a rain event without any further shooting to give ample opportunity to settle naturally. The depth increments allowed measurements from

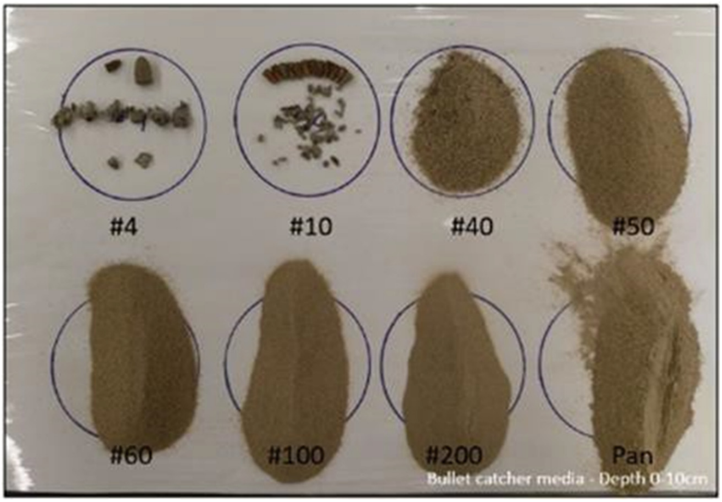

Fig. 6. Soil distribution of a 500 g sample by sieve gradation (LeBlanc, 2021)

surface to the geomembrane mesh that separated the BC media from mixing with the berm at ~50 cm depth. This was repeated with 5 samples from the lowest use lane. Additionally, one sample of the sand taken from the control pile which is stored offset from the berm and used to periodically augment the BC for a total of 22 sieve tests. In each case, the samples were oven dried until a WC change of less than 0.05% was reached between two measurements. The samples were then mixed, and two randomized sub-samples were prepared using 500 g each (Fig. 6).

Using standard calibrated sieves and a modified ASTM standard D422 due to having to subtract the substantial weight of metal fragments retained in sieves >#4 and #10 all data correlated well, and gradation curves were matching in all cases except for the initial drop attributed to the amount of metal or organic material in the larger sieves. It is important to note that despite contacting ASTM, the soil gradation standard was withdrawn at the time of testing with no replacement yet issued.

The results of this testing program indicated that the gradation of the soils varies by depth proportionately to the use of the soil. As you can see in Fig. 7 the % fines content retained on sieve #200 varied significantly from 6 to 14%. However, the fines decreased following the same curve, proportionately to the lane usage until it reached the expected maximum depth of penetration of the bullets at 25–30 cm where the gradations of the high use, low use, and control sand all matched at 6%. This proposes that the fill media is significantly impacted by a higher use.

4.9.2 Second Round of Sampling

Several components of the first round were then adapted. The second round focused on a single moderate use lane centrally located on the berm which was included in the overlap of rifle and pistol rounds use. The methodology closely resembled that of round one except for the addition of counting all fragments retained in the sieves as well as the

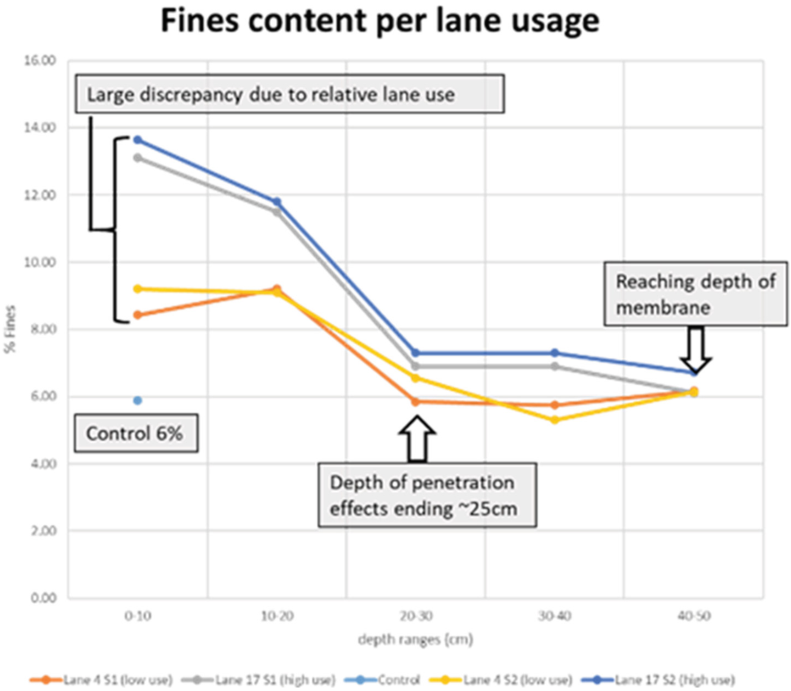

Fig. 7. Results of first round soil testing (LeBlanc, 2021)

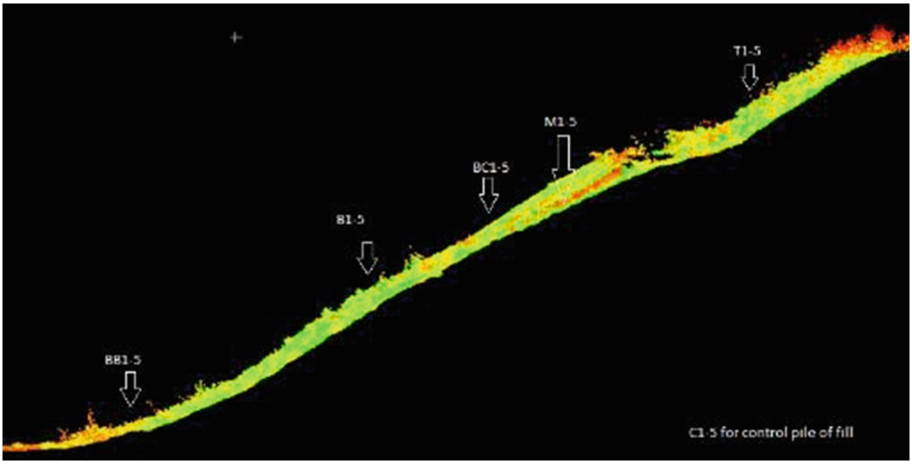

Fig. 8. Cross section of berm forward slope (LeBlanc, 2021)

WC drying time. Additionally, using the same 5 different depth increments this second round took samples from 5 different locations on the same cross-section of the berm plus the control pile.

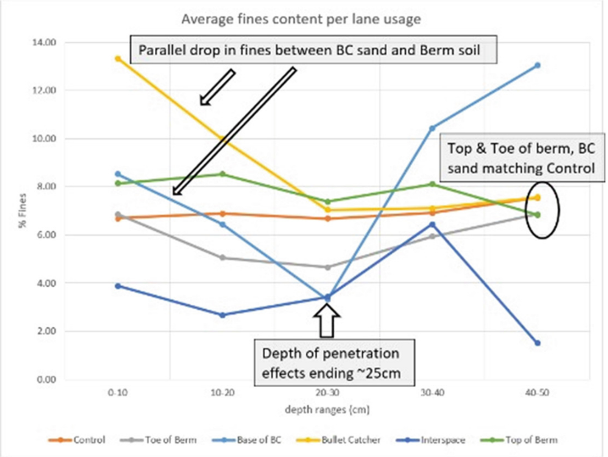

Fig. 9. Results of second round soil testing (LeBlanc, 2021)

These locations accounted for the toe of the berm, immediately below the BC, the BC itself (to confirm previous data), the interspace between BC (at the same elevation as the samples from inside the box) and the top of the berm as per Fig. 8. Each location and depth were doubly sampled to confirm gradation for a total of 60 tests. The first of each sample used the same ~500 g metric, but the second was reduced to ~300 g as there were some large % retained and there was concern that too much retained could be withholding smaller particles from passing. The largest absolute difference for any two measurements at the two sample sizes was 2.52% with the average variation at less than 1%.

The results of this round of testing are significantly more interesting. Across the entire depth of the control sand, we again see ~7% fines consistently, validating our previous results. The bullet catcher sand media performs exactly as it did in round one with significant fines at the surface ~13% and as soon as they reach the depth of maximum penetration, they drop to match the control sand (Fig. 9).

From this point onwards we are discussing the berm's sand clay mix soil and not just BC sand fill media, however, some depth similarities are observed. The top of berm is consistently above the % fines of the control sand, which is expected as few rounds or shrapnel are present. Therefore, there is minimal change of soil in depth. Suspecting this is the closest to a control of the berm material sampled so far, we expect any variation to be mostly because of weathering. If this is the case, we anticipate that the starting point of fines for the surface layer of the base of the bullet catcher is the same. However, while the fines content of this sample descent almost exactly in parallel to the drop of bullet catcher sand, once reaching the maximum depth of penetration, it takes an unexpected sharp increase in fines content. This also matches the pattern of the interspace sample which then also sharply increases at the 25–30 cm depth before separately dropping again. A few hypotheses arising from these patterns would suggest that the fines content of the berm structure is performing similarly to the sand of the BC media initially, but past the maximum penetration depth, the soil may in fact be settled as per conventional

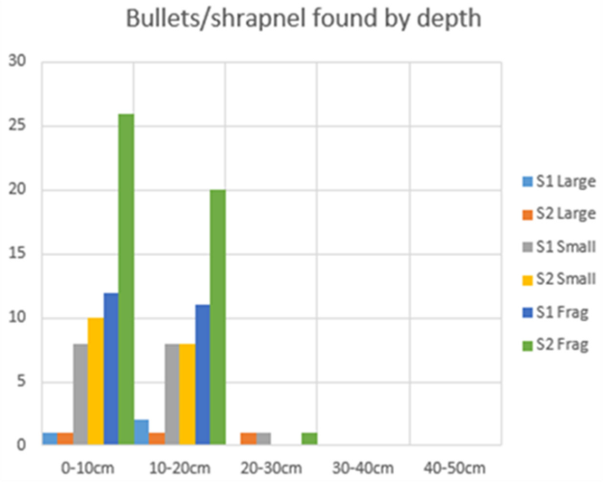

Fig. 10. Bullet fragments found by depth (LeBlanc, 2021)

soil gradation theory. The only unexplained divergent point is the sudden drop at 30–40 cm depth of the interspace berm sample.

In a subsequent round of testing, a control sample of the berm material taken on the far side of the berm subjected simply to weathering as well as depth testing of the berm should extend, without damaging the geomembrane, further than the 50 cm depth to confirm the sudden rise and drop in fines contents for the bottom of BC and interspace material. This may encourage more use of geomembranes for soil stability or may determine simple outlier anomalous samples.

Further lab testing will be required to complete the hydrometer testing to differentiate silts and clay contents of the BC and berm soils as well as Atterberg limits to determine plasticity and liquidity index. Ideally this will enable us to compare compression energy requirements to bullet energy expenditure where the sum should cancel each other.

The maximum penetration depth of the BC fill material was confirmed using monitoring all shrapnel filtered above sieve #10. As we observe in Fig. 10, there is a sharp decline of any large fragments found in the 20–30 cm depth and none found any lower.

4.10 Environmental

The next testing step is the soil metal content testing program which includes sampling and lab analysis for metal particulates at various depths, on high and low use lanes for concentration comparison. Specifically, >100 g samples will be taken at three depths (0–10 cm, 30–40 cm, 60+ cm) and lab-analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Optical Emission Spectrometry (ICP-OES) to determine the concentrations of ten metals, namely Pb, Cu, Zn, Ni, Cr, Sb, Bi, Sn, W, and Hg.

The results of this testing program are significant as we suspect that higher use lanes will contain more metal particulates and highest concentrations should be found at surface level contrary to normal sand settling theories. We suspect that the mobilization of metals will occur relative to the concentration of fines due to increased surface area per the soil testing program. This cross-sectional model of metal concentrations in the berm is important because a correlation to the fill media may offer an optimization opportunity to suggest a new metric to determine the maximum usage of a shooting lane uncoupled from a fixed value cap of bullets per lane. Additionally, if there are significant spikes in concentration below the bullet catcher, we will know that spillover is present and problematic and remediation efforts should look at whole of impact berm and not just impact media within the BC box. To show a control, we will be testing the peak and backslope of the berm which are subjected to weathering only.

Soil contamination is therefore a critical component of the berm's long-term performance. The proximity to subterranean water and distance to surface water is constantly being monitored for concentrations as this range falls on crown property and there is no shortage of surface water drainage problems year-round.

5 Results and Conclusion

To accurately assess the lifecycle characteristics of a berm, measurable data requires long term consistent monitoring to present valid results. In some cases, these results can be extrapolated to different SARs. However, there is a definite need for expanding the scope of instrumentation and analysis of berms before optimization can occur. Research must encompass the different conditions both climactic and reflective of construction standards, materials available and frequency of intended usage.

We have examined the safety justifications for and the scale of the geotechnical problem set. From the key concepts and subsequent testing and analysis included within this paper, we have developed on the concept of impact surface media properties, effects of weathering and settling, bullet and usage effects, environmental considerations as well as different methods to approach developing quantifiable and qualitative metrics to monitor the stop butt berm. All these factors should be considered when critiquing the design, construction, O&M and lifecycle of the berm. Ideally one of these metrics will be able to propose a new threshold limit to initiate berm remediation uncoupled from total rounds fired. Although local climactic and material availability will be the prevailing influence on the selection of berm and BC media, there is room to make every CAF SAR variant across Canada and internationally more efficient.

Moving forward, this berm knowledge could be practically applied to build better berm models for protective structures based entirely on unrestricted soil berms which may be useful when playing in a sandbox around the world.

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