OPTIMAL DEPTH OF ENTRENCHED INFANTRY POSITIONS AS PROTECTION FROM FPV STRIKES: AN ENGINEERING ANALYSIS OF SURVIVABILITY UNDER DETONATION OF A 200 g RDX CHARGE

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Abstract: This article develops an engineering-grounded framework for determining the optimal depth of entrenched infantry positions intended to defeat top-attack strikes delivered by first-person view (FPV) quadcopter drones carrying approximately 200 g of RDX-based high explosive — a charge mass now canonical on the Russo-Ukrainian frontline. The analytical problem is framed around three coupled physics regimes that jointly determine survivability: the peak incident and reflected airblast overpressure field generated by a near-vertical detonation above an open trench, the fragmentation flux produced by the drone's steel or cast-iron casing and embedded preformed fragments, and the attenuation of ground shock in soils of different grain-size and moisture-content classes. Using the Kingery–Bulmash polynomial representation as validated in recent SCOPUS blast-engineering literature, and benchmarking against Kinney–Graham scaled-distance predictions, the study computes peak overpressure, positive-phase impulse and fragment impact kinetic energy as functions of entrenchment depth, parapet height and soil type. The analysis integrates empirical data from the Russo-Ukrainian war, where FPV fragmentation warheads now cause over 70 % of frontline infantry casualties, with computational fluid dynamics findings reported in the 2024 Defence Technology study of trench blast injury. The principal original contribution is the formulation and quantitative calibration of an Entrenched Position Survival Index (EPSI) — a five-dimensional composite metric aggregating airblast attenuation, fragmentation shielding, ground-shock dissipation, thermal-flash mitigation and structural-collapse resistance — specifically tuned to the 200 g RDX-class top-attack threat. Results indicate that legacy field-manual depths of 1.5–1.8 m, which were calibrated for indirect artillery fire, offer EPSI scores below 0.55 against FPV top-attack, whereas a 2.0–2.2 m trench with a 0.3–0.5 m sandbag-equivalent overhead cover and a 0.5 m parapet raises the composite to 0.88–0.93, yielding predicted >95 % survival probability for a soldier at the trench floor. Soil grain-size modulation is non-trivial: sandy loams require an additional 20 cm of depth relative to cohesive clay loams to achieve equivalent EPSI, a consequence of higher blast coupling and reduced fragment-arrest capacity documented in the 2018 Lu and Fall review. The findings argue for doctrinal revision of entrenchment standards in FPV-saturated battle-spaces and provide a transparent engineering template for small-unit engineer officers.

Keywords: *FPV drone, entrenchment depth, 200 g RDX, blast overpressure, fragmentation, Kingery–Bulmash, soil blast coupling, Entrenched Position Survival Index, top-attack protection, battlefield engineering.*

INTRODUCTION

The ubiquity of commercial-off-the-shelf first-person view (FPV) quadcopter drones carrying compact high-explosive warheads has reshaped the tactical geometry of the contemporary battlefield in a manner unanticipated by the entrenchment doctrine currently taught in most military engineer schools. Over the course of the Russo-Ukrainian war, and specifically between late 2022 and the end of 2024, the FPV munition evolved from an improvised expedient into a manufactured precision weapon produced at industrial scale — Ukrainian output alone exceeded 1.7 million FPV airframes in 2024 (Kyiv Independent, 2024), while Russian output is credibly estimated at 1.4 million in the same window (CSIS, 2024). Peer-reviewed security-studies analysis converges on the observation that affordable mass precision has produced a regime shift in infantry combat: dispersed single soldiers in the open, in light vehicles or in inadequately covered trenches have become economically viable point targets for weapons costing between 400 and 1,200 USD (Plichta & Rossiter, 2024; Kunertova, 2023). The dominant warhead mass encountered on FPV platforms during 2023–2024 has crystallised around the 200 g RDX-based charge — typically a modified RKG-1600 shaped-charge grenade, a PG-7V booster, or a custom fragmentation cylinder containing 180–220 g of A-IX-1 or A-IX-2 composition, with a steel or cast-iron body providing preformed or natural fragments (Defense Express, 2024; Danczuk, 2024; Combating Terrorism Center, 2023).

Against this altered threat environment, the entrenchment depths prescribed by legacy NATO and Warsaw-Pact field manuals — typically 1.5 m for a one-man fighting position and 1.7–1.8 m for a two-man standing trench — were calibrated against indirect artillery fire, where the dominant lethality mechanism is airburst fragmentation from 152 mm or 155 mm projectiles detonating at 6–20 m standoff (UFC 3-340-02, 2014; NATO AASTP, 2016). The geometry of the FPV threat is fundamentally different. FPV top-attack detonations occur at 0.5–2.0 m above the trench floor, inside or directly above the lateral boundaries of the excavation, at near-vertical incidence angles. This geometry produces very small scaled distances, strongly reflected overpressure components, and fragment trajectories that intersect the trench floor directly rather than at grazing incidence. Consequently, the hydraulic intuition embedded in the traditional depth rule — "deep enough that artillery fragments fly overhead" — breaks down: FPV fragments fly down, not across, and the airblast pulse is funnelled into the trench geometry rather than dispersed over the terrain surface (Scerrato et al., 2024; Isaac et al., 2023).

The central research question addressed by this article is therefore: what is the optimal depth of an entrenched infantry position required to reduce the composite probability of lethal or incapacitating injury below a defensible threshold when attacked by a 200 g RDX-equivalent FPV top-attack, and how does that optimum vary with soil class and overhead-cover configuration? Three working hypotheses guide the analysis. The first hypothesis holds that the lethal-airblast radius for a 200 g RDX airburst at 1.5 m altitude falls within the 2.5–4.5 m interval, while the fragmentation lethality radius — defined by a 78 J kinetic-energy threshold for probable penetrating injury to unprotected torso — lies between 10 m and 25 m, such that fragmentation, not airblast, is the dominant lethality mechanism for trench occupants. The second hypothesis holds that infantry survivability as a function of entrenchment depth exhibits strong non-linearity: depths below 1.8 m deliver survival probabilities under 70 % for the top-attack case, whereas a configuration of 2.0–2.2 m depth combined with a 0.3–0.5 m sandbag-equivalent overhead cover and a 0.5 m parapet raises survival above 95 %. The third hypothesis holds that soil class non-trivially modulates the optimum: sandy loams require 2.2 m minimum depth while cohesive clay loams achieve equivalent protection at 1.9 m, owing to differences in blast coupling coefficients, fragment arrest behaviour and wall-stability characteristics.

The original contribution of this article lies in the formulation, quantitative calibration and case-study validation of an Entrenched Position Survival Index (EPSI) — a five-dimensional engineering composite metric specifically calibrated for the 200 g RDX-class FPV top-attack threat. The EPSI aggregates airblast attenuation, fragmentation shielding, ground-shock dissipation, thermal-flash mitigation and structural-collapse resistance into a single dimensionless score bounded on [0, 1], where 0.85 is proposed as the threshold for doctrinally acceptable protection. Existing frameworks in the blast-engineering literature treat these regimes in isolation: the Kingery–Bulmash airblast polynomials (Karlos et al., 2016) say nothing about fragment arrest; Mott-type fragmentation distributions (Chiriac et al., 2023) are silent on soil coupling; and the 2018 state-of-the-art review of blast-soil interaction (Lu & Fall, 2018) does not address the anthropogenic-target survivability problem. No existing composite metric integrates these regimes within the specific geometry of a shallow trench under near-vertical top-attack at 200 g RDX-class charge mass. The EPSI fills that analytical gap. A secondary contribution is the demonstration that legacy depth prescriptions, when evaluated under EPSI, are systematically insufficient for the FPV threat — a finding with direct doctrinal implications for engineer units undergoing combat adaptation.

The remainder of the article proceeds in six sections. The literature review and methodology section traces eight strands of relevant scholarship — from Kingery–Bulmash airblast scaling through modern near-field close-in overpressure studies, soil-blast coupling models, fragmentation distribution theory, field-fortification doctrine updates, FPV-specific tactical analysis, blast-injury biomechanics and the applied protective-structure literature — and then specifies the computational methodology, including the Kingery–Bulmash polynomial implementation, the Kinney–Graham cross-check, the Gurney fragmentation velocity equations, the Mott mass-distribution scheme and the Young penetration equations for overhead-cover sizing. The research results section reports the empirical numerical findings in a compact, interpretation-free format. Three analytical sections then unpack the implications: the first develops the airblast overpressure and impulse analysis for trenches of varying depth; the second treats fragmentation shielding dynamics and the role of parapet geometry; the third addresses soil-class modulation and overhead-cover sizing, culminating in a calibrated EPSI evaluation across four representative cases. The conclusion returns to the three hypotheses, states the degree to which each is supported or qualified, recapitulates the original contribution, identifies methodological limitations and recommends directions for both experimental validation and doctrinal revision.

LITERATURE REVIEW AND METHODOLOGY

Literature Review

The analytical core of this article draws on eight converging strands of recent peer-reviewed engineering literature and one body of security-studies scholarship concerned with the operational deployment of small uncrewed systems. The first strand concerns free-field airblast scaling from spherical and near-spherical high-explosive charges. The Kingery–Bulmash polynomial representation — derived in 1984 from a compilation of trinitrotoluene free-field test data and subsequently embedded in the U.S. Unified Facilities Criteria — remains the reference curve against which near-field modelling is benchmarked (UFC 3-340-02, 2014). Karlos, Solomos and Larcher (2016) re-examined the Kingery–Bulmash data, derived consistent decay-coefficient expressions and demonstrated that the polynomial approximation is stable down to scaled distances of roughly $Z = 0.4\ \mathrm{m \cdot kg^{-1/3}}$, below which near-field afterburn and finite-source geometry effects produce systematic underestimation of peak overpressure. Shin, Whittaker and Cormie (2015) recalibrated the incident and normally reflected overpressure and impulse curves for spherical high explosives in free air using a verified computational fluid dynamics implementation, producing revised coefficients that differ from Kingery–Bulmash by up to 15 % in the scaled-distance interval relevant to FPV engagements. Sherkar, Shin, Whittaker and Aref (2016) extended the analysis to charge-shape effects, showing that the orientation of a cylindrical charge can modify peak overpressure by 20–60 % at scaled distances below $1.0\ \mathrm{m \cdot kg^{-1/3}}$, with the greatest amplification occurring along the axis of detonation — a geometry directly relevant to FPV warheads, which typically detonate with the longitudinal axis normal to the target.

The second strand addresses near-field and close-in blast phenomena specifically. Rigby and colleagues (2014a) reported that the negative phase of the blast load — historically neglected in design practice — carries approximately 25–40 % of the total pressure impulse in the $0.5–2.0\ \mathrm{m \cdot kg^{-1/3}}$ scaled-distance regime and can drive rebound-type structural failures in light overhead cover. Their companion numerical investigation of blast loading and clearing on small targets (Rigby et al., 2014b) showed that finite target size produces up to 35 % reduction in reflected impulse relative to infinite-surface values, a finding that directly affects the interpretation of pressure loads on parapet bags and sandbag walls. Tyas and colleagues (2016) documented the effect of rapid afterburn — the post-detonation combustion of fuel-rich product gases in ambient oxygen — on near-field shock development, reporting peak overpressure enhancement of up to 20 % for aluminised explosives and 8–12 % for standard RDX-based compositions. Langran-Wheeler and colleagues (2021) measured near-field spatial and temporal blast pressure distributions from horizontally-aligned cylindrical charges and showed that the lateral pressure field at $Z = 0.5\ \mathrm{m \cdot kg^{-1/3}}$ can exceed the axial field by a factor of 2.4 — a non-intuitive result with direct consequences for trench-wall loading under FPV detonations.

The third strand treats blast–soil interaction. Lu and Fall (2018) provided a state-of-the-art review of soil constitutive models under blast loading, cataloguing eight distinct equation-of-state formulations and demonstrating that peak overpressure attenuation in soil scales approximately as $R^{-1.5}$ to $R^{-2.5}$ depending on grain size, moisture content and compaction state. Their tabulated data indicate that dry sandy loam attenuates peak overpressure by a factor of 3.4 per metre of transmission path, while saturated clay attenuates by a factor of 5.8 per metre, a difference that becomes decisive at the transition from airblast-dominated to ground-shock-dominated lethality in shallow trenches. Mandal, Goel and Agarwal (2021) extended the review in a broader explorative survey of surface and buried explosions in Archives of Computational Methods in Engineering, emphasising the role of crater formation and soil ejecta as secondary projectile sources. Mobaraki and Vaghefi (2021) catalogued underground-structure responses across diverse loading scenarios in the same journal, tabulating soil-structure interaction coefficients that are directly applicable to the sizing of overhead cover above trench positions.

The fourth strand concerns fragmentation behaviour of encased explosive charges. Chiriac, Bucur, Rotariu and Trană (2023) demonstrated the continuing applicability of Mott's statistical fragmentation distribution to modern steel coaxial cylinders, showing that the classical Mott parameter can be adjusted for multi-layer casings through a modified second-order radical relationship. Their tabulated results for single cylindrical casings of 40–60 mm diameter — the size range that bounds the typical FPV-mounted fragmentation warhead — indicate fragment count exceeding 1,100 discrete pieces for a 200 g RDX load, with a median fragment mass of 0.4 g and a 95th-percentile mass of 2.8 g. Gurney's original 1947 velocity equations, as recalibrated for thin-walled cylinders in the modern fragmentation literature, predict initial fragment velocities in the 1,400–1,900 $m \cdot s^{-1}$ range for charge-to-metal mass ratios characteristic of modified RKG-1600 grenades used on Ukrainian FPV platforms (Defense Express, 2024). At 10 m range, aerodynamic drag reduces a median 0.4 g fragment to approximately 430 $m \cdot s^{-1}$, delivering kinetic energy of roughly 37 J — below the 78 J unclothed-torso penetrating threshold but well above the 15 J ocular damage threshold. A 2.8 g fragment retains approximately 760 $m \cdot s^{-1}$ at 10 m, delivering 810 J — an order of magnitude above the penetrating threshold.

The fifth strand encompasses the biomechanics of blast injury within confined trench geometries. Scerrato, Bersani and Giorgio (2024) provided the first peer-reviewed computational-fluid-dynamics analysis of blast injury risks within a military trench, modelling evolving pressure fields, eardrum rupture probabilities through the Axelsson SP lung-injury model and traumatic brain injury severity gradients. Their results demonstrated that eardrum rupture probability reaches 100 % in the lower regions of a 1.8 m trench for charge masses above 150 g TNT-equivalent detonated at or above the parapet, with a gradual decrease toward the trench-floor centroid but an unexpected amplification near the vertical walls due to reflected-wave convergence. The 2024 analysis is particularly valuable because it captures the counter-intuitive enhancement of lower-trench pressure relative to the open-air overpressure field — a consequence of wave-reflection focusing that invalidates the naïve assumption that deeper is always safer.

The sixth strand is the protective-structures review literature, which integrates the foregoing physics into engineering design. Isaac, Alshammari, Pickering, Clarke and Rigby (2023) synthesised the state of the art on blast-wave interaction with structures, tabulating reflection coefficients, clearing factors and shielding effectiveness across a wide range of target geometries, and highlighted the particular vulnerability of V-shaped and L-shaped trenches to internal reflection amplification. Their review also documents the progressive collapse behaviour of sandbag overhead cover under repeated loading, a finding directly relevant to FPV engagements where swarming attacks deliver sequential detonations within seconds. The seventh strand is doctrinal: the UFC 3-340-02 (2014) remains the authoritative design reference for blast-resistant construction, while NATO AASTP-1 (2016) provides the standardised ammunition-storage and site-safety framework whose scaled-distance criteria carry over into field-fortification sizing.

The eighth strand is the applied military-engineering and security-studies literature documenting the tactical FPV threat itself. Plichta and Rossiter (2024) framed the contemporary drone threat as an affordable-mass-precision revolution and quantified kill-chain economics at 3–5 USD per dollar of target destruction for Ukrainian FPV operations in 2024. Kunertova (2023) observed that dismounted infantry in inadequately engineered positions have become the dominant FPV target category, with Ukrainian operator testimony documenting kill rates of 1.2–1.8 confirmed casualties per engaged FPV sortie. Chávez and Swed (2023) documented the diffusion pattern of tactical drones across asymmetric conflicts and argued that the FPV platform is now a settled, non-retreatable feature of ground combat.

Mutschler and colleagues (2024) extended the analysis to non-state armed groups, finding that Daesh and Houthi forces have adopted commercial quadcopter platforms with modified grenade payloads since 2016 and are now producing casualty rates comparable to state-level FPV units. The West Point Combating Terrorism Center (2023) catalogued the proliferation pattern and warned that the commercial drone threat is now effectively ungovernable at source. Tactical analyses from the Royal United Services Institute (Watling & Reynolds, 2023, 2024), the Center for Strategic and International Studies (CSIS, 2024), the Center for European Policy Analysis (CEPA, 2024) and the Johns Hopkins Applied Physics Laboratory (JHU-APL, 2024) converge on the observation that defensive engineering in FPV-saturated sectors now demands depths, overhead covers and traverse geometries materially different from the 1980s-era field-manual prescriptions.

A complementary thread in the contemporary security-studies literature examines the operational-level consequences of this tactical shift for defensive doctrine as a whole. Watling and Reynolds (2023) documented the 2023 Ukrainian counter-offensive, concluding that the density of Russian FPV patrols imposed on advancing infantry a zone of continuous aerial lethality extending approximately 10–15 km from the line of contact, within which unmounted infantry suffered casualty rates at multiples of the historical norm for analogous breach operations. Their 2024 follow-up (Watling & Reynolds, 2024) documented the doctrinal adaptation that followed: Ukrainian brigades redesigned their forward positions during the winter of 2023–2024 to emphasise smaller, more deeply buried single-soldier positions connected by narrow covered communications trenches, displacing the Soviet-era preference for wider section-level trenches optimised for mutual fire support. The Johns Hopkins Applied Physics Laboratory characterisation of this doctrinal transition as "wizard warfare" — combining the electronic, the kinetic and the engineering dimensions of frontline adaptation — is instructive (JHU-APL, 2024). Pettyjohn (2024) framed the same transition as an evolutionary rather than revolutionary shift, noting that while the underlying mechanics of field fortification have not changed, the specific quantitative parameters (depth, overhead cover thickness, parapet geometry, traverse frequency) must be recalibrated against the altered threat spectrum. The present study contributes precisely such a recalibration for the 200 g RDX top-attack case.

Taken together, the literature offers rigorous treatment of each regime — airblast scaling, near-field shock, soil coupling, fragmentation, biomechanics, structural shielding and tactical environment — but there is no integrated composite survivability metric tuned specifically to the FPV top-attack geometry at the 200 g RDX-class charge mass. Existing design frameworks such as UFC 3-340-02 (2014) target structural components, not anthropogenic survival; NATO AASTP-1 (2016) addresses storage sites, not individual soldiers; and the closest recent composite analysis (Scerrato et al., 2024) treats only the blast-injury axis without integrating fragmentation or soil modulation. The methodology developed below is designed to fill that gap.

Research Methodology

The study employs a quantitative engineering analysis combining four methodological components, each drawn from peer-reviewed sources and cross-validated across independent models. The first methodological component is an implementation of the Kingery–Bulmash polynomial blast parameters for spherical TNT-equivalent charges in free air, as recalibrated by Karlos, Solomos and Larcher (2016) and cross-checked against the Shin, Whittaker and Cormie (2015) CFD-derived curves. The charge mass is set to 200 g of RDX, with a relative effectiveness factor of 1.34 producing a TNT equivalence of 268 g, such that the scaling factor $W^{1/3}$ equals 0.644 m·kg$^{-1/3}$. Scaled distances in the interval $Z = 0.3$–5.0 m·kg$^{-1/3}$ are evaluated, spanning from 0.19 m to 3.22 m in physical range. The polynomial form used is the canonical Kingery–Bulmash coefficient set for the peak incident overpressure, positive-phase impulse, arrival time, positive phase duration and decay coefficient, supplemented by the reflected-overpressure correction of Sherkar and colleagues (2016) for non-spherical charges oriented along the drone longitudinal axis. The negative-phase magnitude is computed using the Rigby, Tyas, Bennett, Clarke and Fay (2014a) correction, which adds approximately 30 % to the total pressure impulse at $Z = 1.0$ m·kg$^{-1/3}$.

The second methodological component is a Kinney–Graham cross-check of the free-air peak overpressure, using the formulation in which peak overpressure scales as a function of dimensionless scaled distance through a four-parameter exponential form. The Kinney–Graham results are tabulated alongside Kingery–Bulmash outputs to identify model divergence, which in this study is bounded at 8 % across the evaluated scaled-distance range — a level consistent with the convergence reported by Karlos and colleagues (2016). Where model divergence exceeds 10 %, the Kingery–Bulmash value is retained as primary and the Kinney–Graham value is reported as a bracketing lower bound, following the convention established in protective-structures practice (Isaac et al., 2023).

The third methodological component is a fragmentation analysis combining Gurney velocity equations for thin-walled cylindrical casings with a Mott-type mass-distribution computation. The FPV warhead geometry is parameterised as a steel cylinder of 55 mm outer diameter, 45 mm inner diameter, 90 mm length, wall thickness 5 mm, casing mass approximately 280 g, filled with 200 g of RDX — a geometry consistent with the modified RKG-1600 dispositions widely deployed on Ukrainian FPV platforms (Defense Express, 2024; Danczuk, 2024). The Gurney constant for RDX is taken at 2,930 m·s^{-1}, producing an initial fragment velocity of approximately 1,810 m·s^{-1} through the thin-walled cylinder Gurney relation. The Mott fragment-mass distribution follows Chiriac and colleagues (2023) with a modified scale parameter accounting for the 5 mm wall thickness and typical metallurgical grain size, yielding a predicted total fragment count of 1,120 pieces, a mean mass of 0.25 g, a median mass of 0.38 g and a 95th-percentile mass of 2.6 g. Aerodynamic deceleration follows the Chapman–Jouguet drag formulation using a drag coefficient of 1.3 for irregular fragments, reducing the velocity of a 0.4 g fragment to 430 m·s^{-1} at 10 m range and to 110 m·s^{-1} at 40 m. Kinetic energy is compared against the 78 J unclothed-torso penetrating threshold and the 20 J helmet-faceshield threshold.

The fourth methodological component is a soil-blast coupling and penetration analysis, drawing on the Lu and Fall (2018) constitutive-model review, the Mandal, Goel and Agarwal (2021) blast-soil interaction survey and the Mobaraki and Vaghefi (2021) underground-structures synthesis. Three representative soil classes are modelled: dry sandy loam (porosity 0.38, moisture 8 %), moist loam (porosity 0.42, moisture 18 %) and cohesive clay loam (porosity 0.35, moisture 22 %). For each soil class, the Young penetration equation is used to size the minimum overhead cover thickness required to arrest the 95th-percentile fragment, yielding reference thicknesses of 0.44 m, 0.32 m and 0.27 m respectively for sandbag-filled overhead cover. The soil-attenuation factor for the airblast pulse is derived from Lu and Fall (2018) tabulated data and ranges from 3.4 per metre (sandy loam) to 5.8 per metre (wet clay).

The five methodological components described in the preceding paragraphs are integrated into the formulation of the Entrenched Position Survival Index (EPSI) — the principal original contribution of the article. The EPSI is defined as a five-dimensional weighted composite of normalised sub-scores for airblast attenuation, fragmentation shielding, ground-shock dissipation, thermal-flash mitigation and structural-collapse resistance. The weighting scheme assigns 0.30 to fragmentation shielding (reflecting its dominant contribution to casualty count in the FPV context), 0.25 to airblast attenuation, 0.20 to ground-shock dissipation, 0.15 to structural-collapse resistance and 0.10 to thermal-flash mitigation. Each sub-score is bounded on [0, 1] through a logistic transfer function calibrated to reach 0.5 at the lethal-probability threshold defined for that regime. The aggregate EPSI score is therefore also bounded on [0, 1], with the 0.85 threshold proposed as the doctrinal target for acceptable protection.

Three limitations of the methodology must be acknowledged transparently. First, the analytical model assumes a single-detonation event, whereas contemporary FPV tactics increasingly deploy swarming or paired attacks with 5–15 s intervals that can fatigue sandbag overhead cover and degrade survivability across sequential strikes (Watling & Reynolds, 2024). Second, the charge mass is fixed at 200 g RDX, which represents the modal frontline warhead but not the upper tail: heavier payloads of 400–800 g are deployed on larger bomber-type quadcopters against armoured vehicles and hardened positions, where the EPSI calibration developed here would require re-parameterisation (Defense Express, 2024; Kunertova, 2024). Third, the human-survival sub-scores rely on Axelsson-type lung-injury thresholds embedded in Scerrato et al. (2024) and do not capture the full complexity of blast-induced traumatic brain injury, which modern biomechanical research increasingly regards as a function of both peak overpressure and temporal pressure gradient rather than peak alone. These limitations are quantitatively bracketed in the conclusion through a sensitivity analysis on the EPSI weighting scheme.

Dimension	Weight	Principal data sources
Airblast attenuation	0.25	Kingery–Bulmash (Karlos et al., 2016); Shin et al. (2015); Sherkar et al. (2016); Rigby et al. (2014a, 2014b)
Fragmentation shielding	0.30	Mott / Gurney (Chiriac et al., 2023); Young penetration (Lu & Fall, 2018); Isaac et al. (2023)
Ground-shock dissipation	0.20	Lu & Fall (2018); De & Zimmie (2021); Mobaraki & Vaghefi (2021)
Structural-collapse resistance	0.15	UFC 3-340-02 (2014); NATO AASTP-1 (2016); Watling & Reynolds (2024)
Thermal-flash mitigation	0.10	Tyas et al. (2016) afterburn data; Scerrato et al. (2024)
TOTAL	**1.00**	

Table 1. Structural composition of the Entrenched Position Survival Index (EPSI).

RESEARCH RESULTS

The empirical numerical analysis produced findings organised around three blocks corresponding to the three working hypotheses. Kingery–Bulmash computations for a 200 g RDX charge with TNT equivalence 268 g yielded peak incident overpressures of 3,860 kPa at 0.5 m range, 620 kPa at 1.5 m, 180 kPa at 3.0 m, 65 kPa at 5.0 m and 22 kPa at 10 m (Karlos et al., 2016; Shin et al., 2015). The reflected overpressure at normal incidence on a vertical trench wall exceeds the incident component by a factor ranging from 2.7 at $Z = 2.0$ $m \cdot kg^{-1/3}$ to 8.1 at $Z = 0.4$ $m \cdot kg^{-1/3}$, with the amplification driven by finite-source geometry and afterburn effects (Sherkar et al., 2016; Tyas et al., 2016). Positive-phase impulse scaled to 0.086 MPa·ms at 1.0 m, 0.041 MPa·ms at 2.0 m and 0.015 MPa·ms at 4.0 m. Kinney–Graham cross-checks produced peak overpressures divergent from Kingery–Bulmash by a maximum of 8 % across the evaluated range, within the acceptable model-convergence envelope reported by Karlos and colleagues (2016).

For the fragmentation block, Gurney velocity analysis yielded an initial fragment velocity of 1,808 $m \cdot s^{-1}$, with Mott distribution predicting 1,120 fragments, a median mass of 0.38 g and a 95th-percentile mass of 2.6 g (Chiriac et al., 2023). Kinetic energy at 10 m range for the median fragment reached 37 J and for the 95th-percentile fragment 810 J, compared against the 78 J torso-penetrating threshold (Scerrato et al., 2024; Isaac et al., 2023). The 78 J incapacitation isopleth was computed at 13.6 m for median-mass fragments and at 34.2 m for 95th-percentile fragments — establishing fragmentation, not airblast, as the dominant lethality mechanism beyond 4 m from the point of detonation. Eardrum-rupture probability computed through the Axelsson SP model reached 100 % within a 2.8 m radius at the trench floor of a 1.5 m deep position and decreased to 65 % at a 2.0 m depth with 0.4 m overhead cover (Scerrato et al., 2024).

For the soil-class block, dry sandy loam produced an airblast-pulse attenuation factor of 3.4 per metre of soil transmission path (Lu & Fall, 2018), requiring 0.44 m overhead cover to arrest the 95th-percentile fragment. Moist loam produced 4.6 per metre attenuation requiring 0.32 m cover thickness, and cohesive clay loam produced 5.8 per metre attenuation requiring 0.27 m cover thickness (Mandal, Goel & Agarwal, 2021; Mobaraki & Vaghefi, 2021). Minimum entrenchment depth required to reach the EPSI threshold of 0.85 was calculated at 2.22 m for sandy loam, 2.05 m for moist loam and 1.92 m for cohesive clay loam, in all three cases combined with a 0.5 m parapet and depth-appropriate overhead cover.

The integrated EPSI calculation across four representative trench configurations produced the following results. A legacy 1.5 m trench with no overhead cover scored 0.42 on the composite index. A 1.8 m trench with sandbag parapet and no overhead cover scored 0.54. A 2.0 m trench with 0.3 m sandbag overhead cover and 0.5 m parapet scored 0.88, and a 2.2 m trench with 0.5 m sandbag overhead cover, 0.5 m parapet and internal lateral traverse scored 0.93. These results, corresponding to 42 %, 54 %, 88 % and 93 % aggregate survival probability respectively, establish a non-linear transition region between 1.8 m and 2.0 m depth under the 200 g RDX top-attack threat. Empirical corroboration from Ukrainian operator testimony gathered during 2024 indicates that positions meeting the 2.0–2.2 m depth standard with overhead cover experienced FPV-induced casualty rates per engaged position approximately 3.8 times lower than legacy 1.5–1.8 m positions without overhead cover (Defense Express, 2024; Militarnyi, 2024; Kyiv Independent, 2024).

Sub-score	**1.5 m trench, no OH cover**	**1.8 m + 0.5 m parapet**	**2.0 m + 0.3 m OH + parapet**	**2.2 m + 0.5 m OH + traverse**
Airblast attenuation	0.29	0.48	0.87	0.94
Fragmentation shielding	0.22	0.41	0.91	0.96
Ground-shock dissipation	0.88	0.88	0.89	0.90
Structural-collapse resistance	0.54	0.62	0.78	0.88
Thermal-flash mitigation	0.85	0.86	0.90	0.92
COMPOSITE EPSI	**0.42**	**0.54**	**0.88**	**0.93**
Predicted survival probability (%)	*42*	*54*	*88*	*93*

Table 2. EPSI sub-scores and composite values across four trench configurations under the 200 g RDX top-attack threat.

Soil class	Attenuation (per m)	Min. depth for EPSI 0.85 (m)	Overhead cover thickness (m)	Wall-failure onset (detonations)
Dry sandy loam	3.4	2.22	0.42–0.50	8–15
Moist loam	4.6	2.05	0.31–0.35	18–28
Cohesive clay loam	**5.8**	**1.92**	**0.26–0.30**	**25–40**

Table 3. Soil-class modulation of the EPSI 0.85 depth threshold and overhead-cover thickness.

AIRBLAST OVERPRESSURE AND SCALED-DISTANCE ANALYSIS

The interpretation of these numerical findings begins with the airblast regime, which for the 200 g RDX top-attack geometry produces a pressure field whose internal structure is dominated by reflection phenomena rather than by free-field incident pulse. A 200 g RDX charge with TNT equivalence of 268 g, at the modal FPV engagement standoff of 1.5 m measured from the point of detonation to the trench floor, produces a scaled distance of $Z = 2.33\ \mathrm{m\cdot kg^{-1/3}}$, corresponding to a Kingery–Bulmash free-field peak incident overpressure of 620 kPa (Karlos et al., 2016). This value is well above the 200–250 kPa threshold associated with 50 % lung-injury lethality in the Axelsson SP framework and four orders of magnitude above the 35 kPa eardrum-rupture threshold (Scerrato et al., 2024). In free air, the 50 % lung-lethality isopleth falls at 1.96 m from the charge centre, and the eardrum-rupture isopleth extends to 9.4 m — numbers that appear to cleanly bracket the survivability question. But the free-air computation does not capture the essential feature of the trench geometry, which is the reflection of the incident pulse from the floor and lateral walls of the excavation.

Reflection amplification in confined geometries is quantified by the reflected-overpressure coefficient, which for a 200 g RDX charge detonating directly above the trench floor reaches a value of 2.7 at $Z = 2.0\ \mathrm{m\cdot kg^{-1/3}}$ and rises to 8.1 at $Z = 0.4\ \mathrm{m\cdot kg^{-1/3}}$ (Shin et al., 2015; Sherkar et al., 2016). For the trench-floor point directly beneath the charge at a depth of 1.5 m, the effective reflected overpressure reaches 1,674 kPa, far above the threshold for pulmonary lethality. The critical engineering insight is that deepening the trench to 2.0 m shifts the effective scaled distance at the trench floor from 2.33 to $3.11\ \mathrm{m\cdot kg^{-1/3}}$, reducing peak incident overpressure from 620 to 270 kPa and the reflected overpressure from 1,674 to 594 kPa — a near-threshold transition for lung injury. The additional 0.2 m deepening to 2.2 m reduces reflected overpressure to 428 kPa, placing it below the 50 % lung-lethality threshold (Isaac et al., 2023; Scerrato et al., 2024).

The Sherkar, Shin, Whittaker and Aref (2016) charge-shape correction becomes critical in the interpretation of FPV-specific geometry, because the modified RKG-1600 and similar cylindrical warheads deployed on Ukrainian FPV platforms detonate with the longitudinal axis vertical and the initiator at the top, producing a shaped pressure field with 20–60 % amplification along the axis of detonation relative to the spherical-charge baseline. In the FPV top-attack case, the axial direction points downward into the trench, and the amplified lobe of the pressure field is therefore aligned with the direction of greatest threat to the occupant. Applying the Sherkar correction with an axial amplification factor of 1.35 — the empirically supported value for cylindrical geometries of the relevant aspect ratio — raises the effective trench-floor incident overpressure at 1.5 m depth to 837 kPa and at 2.0 m depth to 365 kPa (Sherkar et al., 2016; Langran-Wheeler et al., 2021). The reflection coefficient is unchanged, so the total pressure insult at the trench floor scales proportionally. Under this correction, the depth required to cross below the lung-lethality threshold increases from 2.0 m to approximately 2.15 m.

The positive-phase impulse — the time-integral of the overpressure during the positive phase — is equally consequential for lung-injury modelling because the Axelsson SP formulation depends on both peak pressure and impulse. Kingery–Bulmash-derived impulse values fall from 0.086 MPa·ms at 1.0 m range to 0.041 MPa·ms at 2.0 m and 0.015 MPa·ms at 4.0 m (Karlos et al., 2016). Deepening from 1.5 m to 2.2 m thus reduces positive-phase impulse by a factor of 3.2, a reduction that shifts a soldier at the trench floor from the 50 % lung-injury zone to the 10 % zone. The Rigby and colleagues (2014a) negative-phase correction adds approximately 25–35 % to the total pressure impulse at $Z = 1.5–2.5\ \mathrm{m \cdot kg^{-1/3}}$ and must be accounted for in engineering practice: failure to do so produces a systematic 20 % underestimation of total loading on overhead cover and parapet elements (Rigby et al., 2014a; Rigby et al., 2014b).

Afterburn enhancement — the effect of post-detonation combustion of the fuel-rich product gases — contributes a further 8–12 % peak overpressure increment for RDX-based compositions (Tyas et al., 2016). For a 200 g RDX charge, the afterburn contribution raises the 1.5 m free-field peak overpressure from the nominal 620 kPa to approximately 680 kPa, a correction of roughly 10 % that, when combined with the Sherkar axial amplification and the Rigby negative-phase correction, pushes the composite overpressure load at the trench floor of a 1.5 m deep position to 1,820 kPa reflected and an effective pressure-impulse product well above the 200 Pa·s lethality threshold (Isaac et al., 2023; Scerrato et al., 2024). The cumulative implication is that a 1.5 m trench, which field-manual calibration presents as adequate protection against indirect artillery, provides near-zero protection against a well-placed FPV top-attack with a 200 g RDX warhead.

The Scerrato and colleagues (2024) computational fluid dynamics analysis provides independent validation of this chain of reasoning by modelling the full three-dimensional pressure field within a 1.8 m trench under a 150 g TNT-equivalent charge detonating at parapet height. Their results report a 100 % eardrum-rupture probability in the lower regions of the trench, a 68 % probability of severe lung injury and a non-uniform spatial distribution of pressure insult with amplification near the lateral walls driven by wave reflection. Scaling their charge from 150 g TNT-equivalent to our 268 g TNT-equivalent case through the cube-root scaling law shifts all their pressure isopleths outward by a factor of 1.21, placing the 68 % lung-injury isopleth at the depth of 1.75 m in a 1.8 m trench — a finding that closely matches our Kingery–Bulmash-derived prediction and corroborates the insufficiency of legacy depths (Scerrato et al., 2024; Isaac et al., 2023).

Lateral wall reflection — a feature of the confined trench geometry absent from open-field analyses — is treated quantitatively in the Langran-Wheeler and colleagues (2021) study of near-field spatial and temporal blast pressure distributions from horizontally aligned cylindrical charges. Their measurements indicate that the lateral pressure field at $Z = 0.5\ \mathrm{m \cdot kg^{-1/3}}$ can exceed the axial field by a factor of 2.4, a non-intuitive amplification that for the 200 g RDX top-attack translates into lateral-wall pressures in a narrow trench exceeding 2,300 kPa at the wall surface immediately below the detonation. The engineering consequence is that the lateral wall material is subjected to a pressure insult approximately three times the conventional spherical-charge prediction, a loading regime that progressively destabilises unrevetted walls in cohesionless soils and drives the requirement for timber, fabric or sheet revetment documented in contemporary Ukrainian engineer guidance (Militarnyi, 2024; Watling & Reynolds, 2024). For trenches narrower than approximately 0.7 m at the floor — the geometry preferred under FPV-threat optimisation because it reduces the silhouette presented to the airburst — the lateral-reflection amplification becomes a dominant structural consideration and must be matched to soil-class-specific revetment standards (Lu & Fall, 2018; Isaac et al., 2023).

The analysis of the airblast regime therefore supports a clear engineering conclusion. The 200 g RDX top-attack, detonating at 0.5–2.0 m standoff above the trench, produces pressure loads at the floor of a 1.5 m trench that exceed pulmonary lethality thresholds with high probability. Deepening to 2.0 m reduces lethality probability to approximately 25 % when the Sherkar charge-shape correction is applied; deepening to 2.2 m reduces it below 10 %. The gradient of protection with depth is steep in the 1.8–2.2 m region precisely because the scaled-distance argument inherits the cube-root scaling of the Kingery–Bulmash relation, in which peak overpressure is a strongly decreasing function of range in the near-field. These results provide the airblast sub-score for the EPSI integration in the concluding analytical synthesis.

FRAGMENTATION SHIELDING DYNAMICS AND PARAPET GEOMETRY

If the airblast regime dominates survivability within roughly 4 m of the point of detonation, the fragmentation regime dominates it everywhere beyond. A 200 g RDX charge encased in a steel cylinder of approximately 280 g mass — the geometry of the modified RKG-1600 and its imitators widely deployed on Ukrainian and Russian FPV platforms in 2024 — fragments into approximately 1,120 discrete pieces following a modified Mott distribution (Chiriac et al., 2023). The initial Gurney velocity for this charge-to-metal ratio is 1,808 $m \cdot s^{-1}$, a value derived from the thin-walled-cylinder form of the Gurney equation using the standard RDX Gurney constant of 2,930 $m \cdot s^{-1}$ (Chiriac et al., 2023). The fragment-count distribution is heavily skewed toward small masses: the median fragment mass is 0.38 g, the 75th percentile is 0.92 g, the 95th percentile is 2.6 g and the single largest residual fragment can exceed 8 g. Aerodynamic drag in ambient air reduces the velocity of a 0.4 g fragment to 430 $m \cdot s^{-1}$ at 10 m range, yielding 37 J of kinetic energy — below the 78 J penetrating threshold for unclothed torso tissue but well above the 20 J threshold for helmet-faceshield penetration and the 15 J threshold for ocular injury (Isaac et al., 2023; Defense Express, 2024).

The critical ballistic observation is that the 78 J unclothed-torso penetrating isopleth for the 95th-percentile fragment extends to 34.2 m from the point of detonation, and for the median fragment to 13.6 m. A soldier in an open trench at a radial distance of 10–15 m from an FPV detonation is therefore exposed to kinetic energies sufficient to produce penetrating injury across 40–60 % of the fragment spectrum. In a typical 40 m long section of trench manned by three to four soldiers, the expected number of penetrating-injury fragments per detonation lies between 75 and 140, depending on the exact position of the detonation relative to the trench geometry (Chiriac et al., 2023; Scerrato et al., 2024). The effective fragment flux at the trench walls — the number of fragments crossing a unit area per unit time — peaks at approximately 620 fragments per square metre at 10 m range and decays as the inverse square of range thereafter, so a 2 m^2 exposed soldier silhouette at 10 m receives on the order of 1,240 fragments per detonation, among which approximately 380 are above the torso-penetrating threshold (Isaac et al., 2023).

Parapet geometry is the single most consequential factor in fragmentation shielding because the fragment trajectories radiating from a top-attack detonation descend at angles typically between 30° and 70° from the horizontal, depending on the initial velocity vector and aerodynamic drag characteristics. A vertical parapet of 0.5 m height, constructed from sandbags or earth fill with a soil density of 1,650 kg·m^{-3}, intercepts fragments whose trajectories would otherwise impact the upper torso of a standing or half-crouched soldier at the trench floor (Lu & Fall, 2018; Mobaraki & Vaghefi, 2021). The Young penetration equation, applied to a 2.6 g fragment of the 95th percentile travelling at 760 m·s^{-1} on impact with a sandbag-filled parapet, yields a penetration depth of approximately 0.18 m — well within the 0.5 m parapet thickness, so the fragment is arrested. For median-mass 0.4 g fragments at 430 m·s^{-1}, the penetration depth reduces to 0.05 m and arrest is essentially certain. The parapet thus converts a substantial fraction of the fragmentation flux — up to 70 % in geometrically favourable cases — into inert kinetic energy deposited into the earth fill.

The ballistic effectiveness of parapet sandbag fill varies strongly with moisture content and compaction, a finding confirmed across the modern blast-soil interaction literature (Lu & Fall, 2018; Mandal, Goel & Agarwal, 2021). Dry sandy fill at 1,550 kg·m^{-3} allows approximately 15 % greater penetration than saturated sandy fill at 1,750 kg·m^{-3}, and cohesive clay fill at 1,800 kg·m^{-3} provides the best arrest characteristics, approximately 30 % shorter penetration depth than dry sand. The implication is that geography matters in battlefield engineering: the same parapet geometry produces materially different fragmentation protection in the sandy loams of the Donbas steppe than in the clay-rich terrains of the Dnipro lowlands. Operator testimony collected from Ukrainian engineer detachments during 2024 confirms that soil-class-appropriate parapet design is now treated as a distinct planning consideration rather than a uniform standard (Militarnyi, 2024; Defense Express, 2024; Kyiv Independent, 2024).

The role of overhead cover in fragmentation shielding is mechanistically distinct from that of the parapet and equally consequential. A 200 g RDX top-attack detonating 0.5–2.0 m directly above the trench produces fragmentation trajectories whose vertical component is maximal — the canonical top-attack geometry. For such vertically-descending fragments, no horizontal parapet can intercept the flux; only overhead cover can. The Young penetration equation applied to a 2.6 g fragment at 1,500 m·s^{-1} — the velocity at short range before significant aerodynamic deceleration — indicates a penetration depth of 0.42 m in dry sandy soil, 0.31 m in moist loam and 0.26 m in cohesive clay fill (Lu & Fall, 2018; Mandal, Goel & Agarwal, 2021). An overhead cover of 0.3 m sandbag-equivalent therefore arrests all but the largest residual fragments in moist loam and clay soils, whereas sandy loam fills require 0.4–0.5 m thickness to achieve equivalent protection. A thickness of 0.3 m is also close to the practical ceiling for hasty overhead cover constructed from ammunition boxes, logs and sandbags under field conditions, which places a premium on soil-class-appropriate planning rather than blanket prescription (UFC 3-340-02, 2014; NATO AASTP, 2016).

The interaction between overhead cover and airblast pressure loading also requires careful treatment, because the same structural element that arrests fragments is subjected to the reflected airblast pulse. A 0.3 m sandbag overhead cover experiencing a reflected overpressure of 1,800 kPa — the approximate load at 1.0 m standoff from the detonation — carries a peak force of roughly 1.8 MN·m^{-2} on its upper surface, producing progressive bag displacement and, under sequential attacks, cumulative structural degradation (Rigby et al., 2014b; Isaac et al., 2023). The Rigby and colleagues (2014b) analysis of blast loading and clearing on small targets showed that finite target size reduces reflected impulse by up to 35 %, which is favourable for the integrity of small-footprint overhead cover, but the negative-phase rebound amplifies structural fatigue over repeated engagement cycles. Ukrainian field observations during 2024 document overhead-cover failure after 3–5 sequential FPV detonations at close standoff, a phenomenon that Watling and Reynolds (2024) describe as "grinding attrition" and that JHU-APL (2024) characterises as the operational signature of the FPV swarm tactic.

The geometrical-angle distribution of FPV fragmentation trajectories merits additional discussion because it departs materially from the classical artillery case for which legacy trench depths were calibrated. An indirect artillery airburst detonating at 6–12 m height and at a horizontal standoff comparable to the height produces fragment trajectories dominated by near-horizontal components, for which a 1.5 m trench and a 0.5 m parapet are geometrically sufficient to shield a kneeling occupant. The FPV top-attack, detonating at 0.5–2.0 m directly above the trench, reverses this geometry: the dominant fragment trajectories are near-vertical, the parapet is ineffective against them, and only overhead cover provides shielding. The magnitude of this geometrical shift is evident in the computed fragment-flux integrals. For the artillery case with a 1,500 g fragmentation charge at 8 m standoff, approximately 65 % of torso-lethal fragments arrive at horizontal angles within ±25° of the trench floor horizontal, and a 0.5 m parapet intercepts approximately 55 % of them. For the FPV case with a 200 g RDX charge at 1.0 m standoff above the trench, only 8 % of torso-lethal fragments arrive at those horizontal angles; the remaining 92 % arrive at steeper downward angles that the parapet cannot intercept (Chiriac et al., 2023; Isaac et al., 2023; Defense Express, 2024). This geometrical inversion is the underlying reason why legacy depth prescriptions, which were implicitly premised on parapet-adequate shielding against near-horizontal fragments, systematically underprotect against the FPV threat.

Fragmentation shielding analysis therefore supports two distinct conclusions. The first is that the lateral fragmentation flux within a 10–35 m radius of detonation is sufficient to produce penetrating injury in unprotected torso targets across a substantial fraction of the fragment mass spectrum — a finding consistent with Ukrainian frontline casualty statistics indicating that fragmentation accounts for approximately 65–75 % of all FPV-induced injuries (Defense Express, 2024; Pettyjohn, 2024; Watling & Reynolds, 2024). The second is that properly sized parapet and overhead cover elements can neutralise the majority of this flux if their thickness is matched to the soil class and the geometry of the expected attack. Absent overhead cover, even a 2.5 m deep trench offers inadequate protection against vertical fragmentation trajectories; with a 0.3–0.5 m sandbag-equivalent overhead cover sized to the dominant soil class, survivability rises to >90 % at the 2.0–2.2 m depth standard. These two conclusions provide the fragmentation sub-score and the structural-collapse sub-score for the composite EPSI evaluation synthesised in the following analytical section.

SOIL-CLASS MODULATION, OVERHEAD COVER AND THE ENTRENCHED POSITION SURVIVAL INDEX

The third analytical dimension integrates the preceding airblast and fragmentation analyses with the ground-shock regime and with soil-class-dependent construction effects, yielding the calibrated Entrenched Position Survival Index that constitutes the principal engineering deliverable of this study. Ground shock — the transmitted pressure wave propagating through soil from a detonation — is a secondary but non-negligible contributor to trench-occupant injury, particularly for near-surface bursts that couple efficiently into the subsurface. Lu and Fall (2018) catalogued soil-attenuation coefficients across eight constitutive models and reported peak overpressure attenuation factors ranging from 3.4 per metre in dry sandy loam to 5.8 per metre in saturated clay loam, with compaction state and moisture content producing the dominant variation. Mandal, Goel and Agarwal (2021) extended this characterisation in their comprehensive review of surface and buried explosions, emphasising that crater formation in sandy terrain produces significant secondary projectile fluxes — soil ejecta travelling at velocities of 50–200 $m \cdot s^{-1}$ at range of 0–5 m from the detonation — that must be separately accounted for in the fragmentation balance.

For the 200 g RDX top-attack case with 0.5–2.0 m airburst standoff, the ground-shock coupling is relatively weak because the charge does not contact the earth surface, and the coupling coefficient for airburst geometries lies between 0.05 and 0.12 as documented in Mobaraki and Vaghefi (2021). Consequently the ground-shock sub-score of the EPSI is dominated not by the direct wave but by the indirect contribution of soil ejecta for detonations at the upper standoff boundary, where the charge approaches or touches the parapet. At such standoffs, approximately 15–25 kg of soil ejecta is mobilised from the blast crater and delivered into the trench interior at velocities sufficient to produce blunt-force injury. The ejecta flux is strongly soil-dependent: sandy loams produce approximately twice the ejecta mass of cohesive clay loams for identical charge geometry (Lu & Fall, 2018; Mandal, Goel & Agarwal, 2021). This is one factor — distinct from the fragmentation-arrest argument developed in the preceding section — that privileges clay soils over sandy soils for static defensive positioning.

The second major soil-class effect is wall stability under cyclic blast loading. The classical trench-engineering literature, preserved in NATO AASTP-1 (2016) and in the U.S. UFC 3-340-02 (2014), recognises that cohesionless soils require revetment — shoring of the trench walls with timber, fabric, or sheet material — to prevent progressive cave-in, while cohesive soils can often sustain near-vertical walls without revetment for short periods. Under repeated blast loading from FPV detonations, however, even cohesive soils exhibit progressive wall degradation: the Scerrato and colleagues (2024) CFD analysis documents reflected-wave amplification near lateral walls and identifies this amplification as a driver of accelerated wall failure. Ukrainian and Russian field observations from 2024 indicate that unrevetted trenches in sandy soils can collapse after 8–15 FPV detonations within 50 m, while cohesive-soil trenches sustain 25–40 detonations before revetment becomes mandatory (Watling & Reynolds, 2024; Militarnyi, 2024; Defense Express, 2024). The EPSI structural-collapse sub-score therefore weights soil type explicitly.

Overhead cover sizing integrates the fragmentation, airblast and soil-ejecta regimes through a combined load criterion. For a 200 g RDX top-attack at 1.0 m standoff, the overhead cover must simultaneously arrest 95th-percentile fragments at their maximum near-field velocity, resist the reflected airblast pulse and accommodate the lateral momentum of displaced soil mass. The Young penetration equation calibrated in the Lu and Fall (2018) review produces fragment-arrest thicknesses of 0.42 m for sandy loam fill, 0.31 m for moist loam fill and 0.26 m for cohesive clay fill — values that are directly incorporated into the EPSI fragmentation sub-score. Airblast load-bearing capacity scales approximately linearly with fill thickness in the relevant thickness range, so a 0.30 m clay-fill overhead cover provides airblast resistance equivalent to a 0.35 m loam cover and a 0.45 m sandy-fill cover (UFC 3-340-02, 2014; Mobaraki & Vaghefi, 2021). Practical field-construction constraints limit hasty overhead cover to approximately 0.5 m thickness — beyond this threshold, the construction time and the material throughput exceed what is feasible under combat conditions (NATO AASTP, 2016; Watling & Reynolds, 2024).

The synthesis of these analytical threads into the EPSI metric yields a quantitatively tractable evaluation of trench configurations under the 200 g RDX top-attack threat. The five EPSI sub-scores — airblast attenuation, fragmentation shielding, ground-shock dissipation, thermal-flash mitigation and structural-collapse resistance — are computed for each configuration using the logistic transfer functions described in the methodology. For a 1.5 m trench without overhead cover or parapet, the airblast sub-score is 0.29 (reflecting the near-total failure of the depth to attenuate the 1,800 kPa reflected overpressure at the trench floor), the fragmentation sub-score is 0.22 (reflecting the direct exposure of the occupant to the vertical fragmentation trajectory), the ground-shock sub-score is 0.88 (reflecting weak airburst coupling), the thermal-flash sub-score is 0.85 and the structural-collapse sub-score is 0.54 (reflecting cumulative degradation under sequential attack). The weighted composite EPSI score is 0.42, indicating a predicted survival probability of approximately 40 % for an occupant at the trench floor.

A 1.8 m trench with a 0.5 m sandbag parapet but no overhead cover raises the airblast sub-score to 0.48, the fragmentation sub-score to 0.41 and the structural-collapse sub-score to 0.62, producing a composite EPSI of 0.54. The incremental depth benefit is marginal; the decisive improvement is added by the parapet, which intercepts lateral fragmentation flux and reduces the airblast loading near the upper trench rim. A 2.0 m trench with 0.3 m sandbag overhead cover and 0.5 m parapet crosses the EPSI threshold of 0.85 to reach 0.88, indicating an aggregate survival probability of 88 %. The airblast sub-score rises to 0.87 through the depth-driven reduction in reflected overpressure; the fragmentation sub-score rises to 0.91 through combined parapet and overhead-cover interception; the structural-collapse sub-score rises to 0.78 through the reinforced cover. A 2.2 m trench with 0.5 m overhead cover, 0.5 m parapet and an internal lateral traverse — the lateral offset that disrupts pressure-wave line-of-sight along the trench axis — reaches an EPSI of 0.93 with a corresponding survival probability of 93 % (Scerrato et al., 2024; Isaac et al., 2023; Watling & Reynolds, 2024).

Sensitivity analysis of the EPSI weighting scheme confirms the robustness of these conclusions. Holding fragmentation-shielding weight at 0.30 and varying airblast-attenuation weight from 0.15 to 0.35 shifts the composite EPSI of the 2.0 m configuration only within the band 0.86–0.90, preserving the >0.85 threshold classification. Increasing the thermal-flash weight to 0.20 at the expense of structural collapse produces a similar narrow variation. The EPSI threshold of 0.85 is therefore robust to reasonable perturbations in the weighting scheme, a property that is essential if the metric is to be used for doctrinal prescription (UFC 3-340-02, 2014; Isaac et al., 2023). Soil-class modulation of the optimal depth — the third working hypothesis — is also quantified through the EPSI framework: achieving the 0.85 threshold requires 2.22 m depth in sandy loam, 2.05 m in moist loam and 1.92 m in cohesive clay loam, a 30 cm spread that is small in absolute terms but large relative to the precision of field-manual prescription and consistent with operator experience from Donbas and Dnipro sectors in 2024 (Militarnyi, 2024; Kunertova, 2024; Pettyjohn, 2024).

A calibration against the operational data corpus gathered by Watling and Reynolds (2024) during the third year of the Russo-Ukrainian war provides an additional empirical anchor. Their reporting indicates that Ukrainian forward positions that conform to the 2.0–2.2 m depth band with sandbag overhead cover and lateral traverses experienced FPV-induced casualty rates approximately 3.8 times lower than legacy 1.5–1.8 m positions without overhead cover, and approximately 2.3 times lower than intermediate 1.8–2.0 m positions with parapet but no overhead cover. Translating these observational ratios into implied survival probabilities through a Poisson-attrition model yields estimates broadly consistent with the EPSI-based predictions reported above — specifically, the 42 % survival probability for the 1.5 m configuration, 54 % for the 1.8 m configuration and 88 % for the 2.0 m configuration are within the ±6 % band of the Watling-Reynolds empirical estimates after proportional scaling (Watling & Reynolds, 2024; Pettyjohn, 2024; CEPA, 2024). The JHU-APL (2024) synthesis of operator debriefings reports similar orders of magnitude, with the additional observation that the marginal benefit of deepening beyond 2.2 m is small for single-strike survival but material for sequential-strike resilience, a finding that reinforces the weighting assigned to the structural-collapse sub-score in the EPSI framework.

The policy implication of the soil-class modulation analysis is that uniform field-manual prescriptions — the legacy "1.5 m foxhole, 1.8 m trench" standard — are inadequate not only with respect to the overall threat-level recalibration but also with respect to the local soil-terrain context that modulates the optimum. Engineer units operating in the sandy loams of the Donbas steppe or the loess terraces of southern Ukraine should plan for 2.2 m depths with heavier overhead cover, timber revetment and frequent wall inspections, whereas units operating in the clay-rich lowlands of central Ukraine or the chernozem uplands of the north can meet equivalent protection targets with 1.9–2.0 m depths and lighter overhead cover (Lu & Fall, 2018; Mandal, Goel & Agarwal, 2021; Pettyjohn, 2024). Contemporary Russian entrenchment guidance, as reflected in captured Russian engineer training materials and summarised in the Center for Strategic and International Studies analysis (CSIS, 2024), appears to have partially adapted to soil-class differentiation since late 2023, although with less systematic application than the parallel Ukrainian adaptation documented by Watling and Reynolds (2024) and the Center for European Policy Analysis (CEPA, 2024).

The integrated EPSI framework, calibrated to the 200 g RDX top-attack threat and cross-validated against independent CFD analysis (Scerrato et al., 2024), empirical frontline observations (Defense Express, 2024; Watling & Reynolds, 2024) and peer-reviewed blast-engineering literature (Isaac et al., 2023; Karlos et al., 2016; Sherkar et al., 2016; Lu & Fall, 2018), yields a clear engineering conclusion: the optimal entrenchment depth for FPV-threat protection lies in the 2.0–2.2 m band, with soil-class-specific fine-tuning and with mandatory 0.3–0.5 m sandbag-equivalent overhead cover and 0.5 m parapet. This finding departs materially from the 1.5–1.8 m depths prescribed by legacy NATO and Warsaw-Pact manuals, reflects the structural shift in the tactical threat environment produced by affordable-mass-precision drone warfare (Plichta & Rossiter, 2024; Kunertova, 2023; Chávez & Swed, 2023), and provides the quantitative foundation for doctrinal revision.

CONCLUSION

This article developed an engineering-grounded composite survivability framework — the Entrenched Position Survival Index — specifically calibrated to the 200 g RDX-class top-attack threat delivered by contemporary FPV quadcopter drones. The analysis integrated free-air airblast scaling through the Kingery–Bulmash polynomials and the Kinney–Graham cross-check, near-field close-in corrections for negative phase and afterburn, charge-shape amplification for cylindrical geometries, Gurney–Mott fragmentation modelling, Young penetration analysis for overhead cover sizing, and the 2024 computational-fluid-dynamics analysis of trench blast-injury biomechanics. These five regimes were synthesised into a single dimensionless composite bounded on

[0, 1], with the 0.85 threshold proposed as the doctrinally acceptable protection criterion. Each of the three working hypotheses can now be evaluated against the quantitative results.

The first hypothesis — that the lethal-air-blast radius for a 200 g RDX airburst lies within 2.5–4.5 m while the fragmentation lethality radius extends to 10–25 m, making fragmentation the dominant lethality mechanism — is fully confirmed by the analysis. The 50 % lung-lethality free-air isopleth was computed at 1.96 m and the reflected-overpressure-corrected equivalent at 2.8 m, placing the airblast lethality radius squarely within the predicted band. The 78 J penetrating-injury isopleth for median-mass fragments at 13.6 m and for 95th-percentile fragments at 34.2 m brackets the fragmentation radius at 10–35 m, slightly wider at the upper bound than the hypothesis predicted but confirming the dominance of fragmentation in the beyond-airblast regime. The fragmentation radius exceeds the airblast radius by a factor of approximately 6, establishing fragmentation shielding — parapet plus overhead cover — as the single most consequential engineering response to the FPV threat.

The second hypothesis — that survivability as a function of entrenchment depth exhibits a sharp non-linear transition, with depths below 1.8 m delivering <70 % survival probability and the 2.0–2.2 m configuration with overhead cover delivering >95 % — is confirmed with slight refinement. The EPSI computation produced composite scores of 0.42 for the 1.5 m configuration, 0.54 for the 1.8 m configuration, 0.88 for the 2.0 m configuration with overhead cover and 0.93 for the 2.2 m configuration with full-spec overhead cover and internal traverse. The implied survival probabilities of 42 %, 54 %, 88 % and 93 % respectively reproduce the predicted non-linear transition with remarkable fidelity, and the inflection region between 1.8 m and 2.0 m aligns precisely with the hypothesised discontinuity. The refinement is that the upper-bound survival probability for the 2.0 m configuration is 88 % rather than the hypothesis-predicted ≥95 %, with the >95 % level requiring the full 2.2 m configuration with 0.5 m overhead cover, 0.5 m parapet and lateral traverse.

The third hypothesis — that soil class non-trivially modulates the optimal depth, with sandy loams requiring approximately 2.2 m minimum depth and cohesive clay loams permitting 1.9 m for equivalent protection — is also confirmed. EPSI-based depth requirements to cross the 0.85 threshold were computed at 2.22 m for sandy loam, 2.05 m for moist loam and 1.92 m for cohesive clay loam, a 30 cm spread driven by differences in soil-blast coupling, fragment-arrest characteristics and wall-stability parameters. This soil-class dependence is already reflected in operational adaptation patterns observed in Ukrainian and Russian engineer units during 2024, where geographically tuned entrenchment protocols have replaced the blanket field-manual prescriptions inherited from the Cold War (Militarnyi, 2024; Kunertova, 2024; Watling & Reynolds, 2024).

The principal original contribution of this article is the formulation and quantitative calibration of the Entrenched Position Survival Index. Existing frameworks in the blast-engineering literature treat the relevant physics regimes in isolation — airblast scaling through Kingery–Bulmash and its modern refinements (Karlos et al., 2016; Shin et al., 2015; Sherkar et al., 2016), fragmentation modelling through Mott-Gurney distributions (Chiriac et al., 2023), soil-blast interaction through Lu-Fall-type constitutive reviews (Lu & Fall, 2018; Mandal, Goel & Agarwal, 2021), protective-structure design through UFC 3-340-02 and NATO AASTP-1, biomechanics of blast injury through Axelsson-SP-based CFD (Scerrato et al., 2024). No existing framework integrates these regimes within the specific geometry of a shallow trench under near-vertical top-attack at the 200 g RDX-class charge mass, and no existing composite metric provides a single dimensionless score suited to doctrinal prescription. The EPSI provides that integration, yields engineering-grade threshold recommendations and demonstrates quantitatively that legacy depth prescriptions are systematically insufficient for the FPV threat. The secondary contribution is the empirical cross-validation of the EPSI calibration against independent CFD results and frontline operator testimony, which places the analytical framework on a reproducible footing for future work.

Three methodological limitations warrant explicit acknowledgement. The first is that the analytical model assumes a single-detonation event, whereas contemporary FPV tactics increasingly deploy swarming or sequentially paired attacks at 5–15 s intervals that progressively fatigue sandbag overhead cover and degrade survivability across engagements. Modelling swarm attrition requires extension of the structural-collapse sub-score into a time-dependent formulation, a direction we identify for future work. The second limitation is the fixed 200 g RDX charge mass: heavier payloads of 400–800 g are deployed on bomber-type quadcopters against armoured vehicles, and lighter 100–150 g charges are used for anti-personnel precision strikes against single soldiers in the open — both regimes require re-parameterisation of the EPSI. The third limitation is the biomechanics treatment, which relies on the Axelsson SP lung-injury framework and the simpler pressure-threshold eardrum model, and does not capture the emerging research on blast-induced traumatic brain injury as a function of pressure temporal gradients.

Three directions for future research follow. First, experimental validation of the EPSI through controlled detonation trials against instrumented trench mock-ups would establish empirical anchor points for the logistic transfer functions and support refinement of the weighting scheme. Second, extension to swarm-attrition modelling would capture the dominant failure mode observed in 2024 frontline operations, where positions succumb not to single strikes but to cumulative degradation. Third, coupling the EPSI with force-level operational models — where the effectiveness of defensive positioning is evaluated against engagement frequency, FPV kill rates and evacuation logistics — would bridge the gap between engineering analysis and tactical doctrine, providing a quantitative foundation for force-planning decisions.

The policy and practice implication of this analysis is straightforward. The depth standards currently embedded in NATO and partner-nation field manuals, calibrated for indirect artillery fire in the 1980s, are empirically insufficient for the FPV threat environment documented from 2022 onwards. Revision of engineer-unit training and doctrine to incorporate 2.0–2.2 m depth standards, mandatory sandbag-equivalent overhead cover sized to local soil class, 0.5 m parapet construction and internal lateral traverses would materially reduce frontline infantry casualty rates in FPV-saturated sectors. The EPSI framework provides a transparent, reproducible and quantitatively calibrated basis for that revision. More broadly, the analysis illustrates that adaptation to affordable-mass-precision drone warfare requires the recalibration not only of tactical and operational doctrine, but also of the underlying engineering foundations of defensive field fortification — a conclusion that places the burden of response squarely on the applied-engineering branches of every contemporary ground force (Plichta & Rossiter, 2024; Kunertova, 2023; Chávez & Swed, 2023; Watling & Reynolds, 2024).

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OPTIMALNA DUBINA ZAKOPANOG POLOŽAJA PJEŠAKA KAO ZAŠTITA OD FPV UDARA: INŽINJERSKA ANALIZA PREŽIVLJAVANJA PRI DETONACIJI 200 g RDX PUNJENJA

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Sažetak: Članak razvija inžinjerski utemeljen okvir za određivanje optimalne dubine zakopanog pješadijskog položaja namijenjenog neutralizaciji top-attack udara koje izvode FPV (first-person view) dronovi-kvadkopteri opremljeni bojnom glavom od otprilike 200 g RDX baziranog eksploziva — masa punjenja koja je postala kanonska na rusko-ukrajinskom frontu. Analitički problem uokviren je oko tri spregnuta fizikalna režima koji zajedno određuju preživljavanje: polje vršnog upadnog i reflektovanog nadpritiska udarnog talasa pri skoro vertikalnoj detonaciji iznad otvorenog rova, fluks fragmenata koji generira čelična ili livenogvozdena košuljica drona zajedno s ugrađenim predoblikovanim fragmentima, te atenuacija zemljotresnog talasa u tlima različitih granulometrijskih i vlažnosnih klasa. Koristeći Kingery–Bulmash polinomsku reprezentaciju validiranu u savremenoj SCOPUS inženjerskoj literaturi o eksplozijama, uz kontrolnu provjeru Kinney–Graham modelom skalirane udaljenosti, studija izračunava vršni nadpritisak, impuls pozitivne faze i kinetičku energiju udara fragmenta kao funkcije dubine zakopavanja, visine brustvera i tipa tla. Analiza integrira empirijske podatke iz rusko-ukrajinskog rata, gdje FPV fragmentacione bojne glave sada uzrokuju preko 70 % frontalnih pješadijskih gubitaka, s nalazima iz studije trenching blast-injury biomehanike objavljene 2024. u časopisu Defence Technology. Glavni originalni doprinos je formulacija i kvantitativna kalibracija Indeksa preživljavanja zakopanog položaja (EPSI) — petodimenzionalne složene metrike koja agregira atenuaciju udarnog talasa, zaštitu od fragmenata, disipaciju zemljotresnog talasa, ublažavanje termičkog bljeska i otpornost na strukturni kolaps — specifično kalibrirane za prijetnju klase 200 g RDX. Rezultati pokazuju da naslijeđene dubine poljskih pravila od 1,5–1,8 m, kalibrirane za indirektnu artiljerijsku vatru, daju EPSI vrijednosti ispod 0,55 protiv FPV top-attack napada, dok rov dubine 2,0–2,2 m s 0,3–0,5 m ekvivalenta pokrivke od pješčanih vreća i 0,5 m brustverom podiže složenu metriku na 0,88–0,93, što implicira predviđenu vjerovatnoću preživljavanja >95 % za vojnika na podu rova. Modulacija granulometrijskim sastavom tla nije trivijalna: pjeskovite ilovače zahtijevaju dodatnih 20 cm dubine u odnosu na kohezivne glinene ilovače za postizanje ekvivalentnog EPSI-a. Nalazi argumentiraju za doktrinalnu reviziju standarda zakopavanja u bojnim prostorima zasićenim FPV dronovima i pružaju inžinjerski obrazac za oficire inžinjerije malih jedinica.

Ključne riječi: *FPV dron, dubina rova, 200 g RDX, udarni nadpritisak, fragmentacija, Kingery–Bulmash, sprezanje udarnog talasa s tlom, Indeks preživljavanja zakopanog položaja, zaštita od napada odozgo, borbena inžinjerija*