CIANGSANA WAREHOUSE EXPLOSION: CHEMICAL DEGRADATION AND ZONING COMPLIANCE ANALYSIS

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The March 30, 2024 explosion at Ciangsana Regional Ammunition Warehouse (Gudmurah Kodam Jaya) revealed critical failures in expired ordnance management within densely populated areas. This study integrates chemical stability analysis of TNT/RDX with UN SaferGuard-based spatial risk assessment and JUKLAK04VI/2010 regulatory evaluation. Analysis confirms the explosion resulted from methyl migration in aged TNT forming friction-sensitive crystals after 10+ years tropical storage (27°C, 78%RH), accelerated 2.5x vs temperate conditions. RDX exhibited autocatalytic NOx generation. Spatial analysis using QGIS 3.44.8 reveals 145.1m distance to nearest residences, 83.7% below UN SaferGuard 892m requirement for 65-ton explosive load ($Z\times\sqrt[3]{M}$ principle). Key findings identify three systemic failures: (1) procedural negligence violating 10-year disposal mandate; (2) thermal-induced TNT crystal formation; (3) zoning violations allowing residential encroachment from 2003-2025. Policy recommendations include mandatory environmental monitoring, defense map integration into OSS licensing, and dynamic safety zoning. This incident exemplifies chemical-spatial risk convergence requiring integrated ammunition lifecycle management for urbanizing nations.

Key words: *Ammunition Safety, TNT Methyl Migration, Spatial Risk Assessment, Ciangsana Explosion, UN SaferGuard*

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1. INTRODUCTION

The explosion of the ammunition warehouse in Ciangsana, Bogor, on March 30, 2024, stands as a significant event in the context of public safety and military security in Indonesia. Explosions in ammunition depots are not unprecedented globally, they often result from improper storage, lack of effective safety procedures, and insufficient personnel training. However, the Ciangsana incident distinguishes itself by revealing a complex interplay between technical failure and spatial mismanagement that is rarely discussed in a single framework.

Existing literature on ammunition safety remains largely fragmented. Technical studies, such as those by Akhavan (2022), primarily focus on the chemical stability of explosives like TNT and RDX under controlled laboratory conditions, often overlooking the accelerating effects of tropical environmental factors, specifically high temperature and humidity, found in real-world storage. Research on spatial planning in the Jabodetabek region, including studies by Murtadho et al. (2022) and Rustiadi's previous work on land use consistency (Kurniati, Rustiadi, & Baskoro, 2015), has consistently identified weaknesses in zoning enforcement and uncontrolled urban expansion. Nevertheless, these spatial analyses do not address the chemical decomposition dynamics of hazardous materials stored within encroached-upon facilities, leaving a critical gap in integrated risk assessment

This study bridges that gap through a multidisciplinary approach. It aims to integrate three critical perspectives: (1) the chemical dynamics of expired ammunition in tropical climates, (2) a critical evaluation of regulatory implementation (JUKLAK/04/VI/2010), and (3) risk-based spatial analysis. By connecting field findings such as the accumulation of unstable gases in expired munitions with the reality of uncontrolled urban expansion, this research offers a holistic evaluation of the safety failures at Ciangsana. The findings provide evidence-based policy recommendations for safer ammunition management and zoning enforcement in densely populated developing nations.

2. LITERATURE REVIEW

This literature review is organized into three analytical themes central to understanding the Ciangsana incident: (1) the chemical degradation mechanisms of high explosives, (2) ammunition storage safety management practices and regulatory frameworks, and (3) spatial planning principles for hazardous facilities and the challenges of urban encroachment.

2.1 Chemical Degradation of High Explosive

High explosives such as Trinitrotoluene (TNT) and Research Department Explosive (RDX) undergo chemical decomposition over time, a process significantly accelerated by environmental factors. According to Kementerian Pertahanan (2010) in JUKLAK/04/VI/2010, ammunition serviceability is generally capped at ten years from production, after which the operational risk profile changes drastically due to chemical instability.

The decomposition of TNT follows an exothermic pathway that releases hazardous gases including carbon monoxide (CO) and nitrogen (N_2). Akhavan (2022) confirms that as TNT ages, the instability of its nitro groups makes the material increasingly sensitive to thermal triggers, significantly elevating the risk of accidental detonation. Research on environmental factors affecting explosive degradation has demonstrated that humidity and temperature play critical roles in TNT stability. Sisco et al. (2017) quantified TNT degradation under various environmental conditions and found that exposure to high humidity (90% RH) and elevated temperatures (30-47°C) caused substantial mass loss of TNT within 42 days. These findings confirm that long-term storage in tropical climates without environmental controls, as occurred at the Ciangsana facility, creates conditions that accelerate the chemical decomposition of expired munitions.

Oxley et al. (2016) investigated the thermal stability of TNT and related explosive formulations, finding that decomposition products can catalyze further degradation. Their research demonstrated that ammonia, a decomposition product of certain nitro compounds, accelerates the breakdown of nitroaromatic explosives like TNT. This autocatalytic mechanism is particularly relevant to sealed munitions stored in tropical environments, where accumulated decomposition gases can create internal pressure and increase sensitivity to initiation.

For RDX, the classic study by Bulusu & Behrens (1996) identifies nitrogen oxides such as NO_2 as primary products of thermal decomposition through autocatalytic-like reactions, where gas products accelerate further degradation. Gu et al. (2021) confirm a kinetic model of liquid-phase RDX showing autocatalytic chain reactions, generating internal pressure and increased sensitivity due to NOx gas accumulation in sealed containers. Ren et al. (2024) add that initial N-NO_2 bond cleavages predominantly produce NO_2 and NO at high temperatures, which damage storage container integrity through chemical corrosion and destabilization of the explosive core.. The decomposition pathway can be represented as:

$$C_3H_6N_6O_6 \rightarrow 3NO_2 + 3H_2O + 3CH_2O$$

Reese et al. (2014) examined double-base propellants based on nitroglycerin (NG), finding that NG volatility poses higher risks compared to single-base propellants, particularly when NG migrates during storage and ventilation conditions are inadequate.

2.2 Ammunition Storage Safety Management

Safe ammunition storage is a crucial aspect of maintaining combat readiness while preventing explosive incidents that can cause casualties and environmental damage. According to Nurhada et al. (2023), ammunition storage systems must adhere to strict operational standards, including regulating temperature, humidity, and air pressure within storage containers to maintain optimal condition.

The Ammunition Maintenance Implementation Guidelines Number 04/VI/2010 (JUKLAK) serve as the Indonesian government's reference for systematic ammunition maintenance and inspection, covering storage, transportation, and usage stages (Kementerian Pertahanan, 2010). Visual inspections, testing, and management of expired ammunition are mandatory to ensure that stock remains safe and serviceable. The guidelines explicitly mandate the immediate disposal of expired inventory to mitigate explosion risks.

International standards provide more comprehensive frameworks. NATO's AASTP-5 (2015) establishes guidelines for the storage of military ammunition and explosives, emphasizing risk-based approaches to safety distance determination and the importance of environmental monitoring.

The Small Arms Survey (Carapic, Deschambault, Holtom, & King, 2018) reviews global ammunition stockpile incidents, finding that most unplanned explosions result from accumulation of expired/ unserviceable munitions combined with inadequate inspection and disposal protocols

Yudianto and Rivai (2018) implemented Radio Frequency Identification (RFID) technology and fingerprint recognition to enhance warehouse security, demonstrating how technological solutions can improve inventory control and prevent unauthorized access. However, such systems address security rather than the chemical monitoring needed to detect decomposition gases.

2.3 Spatial Planning and Hazardous Facility

Good spatial planning is fundamental in managing hazardous facilities to minimize explosion risks and their impacts on surrounding communities. Cozzani et al. (2006) provide a case-study review of land-use planning around major hazard installations, identifying failures like unacceptable zoning patterns requiring retroactive risk reduction measures due to inadequate enforcement

Law Number 26 of 2007 concerning Spatial Planning (Indonesian Government, 2007) establishes the legal framework for sustainable land use management in Indonesia. Article 14 specifies that detailed spatial planning plans must contain zoning regulations that regulate space use based on area function and characteristics. Protected zones should be established around facilities with potential danger, such as ammunition warehouses.

According to the TNI (Indonesian National Armed Force) Information Center, the safe distance between ammunition warehouses and residential areas is 500 meters to 1 kilometer (Mawangi, 2024). International standards provide more nuanced calculations. The UN SaferGuard program, through International Ammunition Technical Guidelines (IATG), establishes distance calculations based on explosive weight and vulnerability of surrounding areas. These calculations use cube-root scaling: Distance = $Z \times \sqrt[3]{M}$, where Z is a coefficient based on target type.

Asmi et al. (2018) examines urban sprawl in Jabodetabek, documenting a 6% increase in built-up land over 16 years as urban expansion encroaches on peri-urban areas originally designated as open/greenbelts, following road networks. Grehenson (2025) notes that the active ammunition explosion incident in Garut, which resulted in 13 fatalities, highlighted weak supervision and inadequate separation between warehouses and residential zones.

Jati (2024) documents the specific case of Ciangsana, noting that the warehouse was constructed in 1987 when the surrounding area was forest designated as a military buffer zone. Demographic shifts since 1997 have led to uncontrolled residential expansion.

3. METHODOLOGY

This research employed a combined qualitative and quantitative descriptive approach to comprehensively investigate the factors behind the ammunition warehouse explosion at Kodam Jaya in Ciangsana.

3.1 Research Design and Data Sources

The study began with a thorough literature review and regulatory analysis, focusing on both national implementation guidelines (JUKLAK/04/VI/2010) and relevant international standards including UN SaferGuard IATG and NATO AASTP-5. The objective was to identify best practices, established safe distance parameters, and regulatory expectations for secure munitions handling.

Multi-source data collection utilized public records, technical documents, and incident reports from credible news sources (Kompas, Antara, Tempo). Warehouse architecture drawings were obtained through public information requests, while data on ammunition types and quantities came from official TNI (Indonesian National Armed Force) statements following the incident.

3.2 Spatial Analysis Procedure

Spatial analysis was conducted using QGIS 3.44.8 (open-source geographic information system) and Google Earth Pro for historical imagery analysis. The following data sources were utilized:

- **Satellite imagery:** Historical imagery from October 14, 2003, was obtained through Google Earth Pro's historical imagery feature. Post-incident imagery from May 27, 2025, was used for current distance verification.
- **Demographic data:** Population density and administrative boundary data were obtained from Badan Pusat Statistik (BPS) Kabupaten Bogor (Ciangsana) and Bekasi (Bantargebang), supplemented by openstreetmap data for building footprint identification.
- **Base maps:** Topographic and land use maps were accessed through Ina-Geoportal (https://tanahair.indonesia.go.id)

The analysis procedure involved:

Georeferencing warehouse location using coordinate data from incident reports

2. Measuring linear distances from warehouse perimeter to nearest residential structures, schools, and public roads
3. Creating buffer zones based on UN SaferGuard calculations
4. Due to the absence of precise blast epicenter coordinates for Warehouse #6, spatial measurements employed a conservative worst-case approach following UN SaferGuard IATG 02.10 risk assessment principles. Distances were calculated from the nearest warehouse structure perimeter to each target type (access road, inhabited buildings, vulnerable facilities) using QGIS 3.44.8. This methodology ensures compliance evaluation reflects maximum potential hazard exposure rather than probable ignition point, consistent with quantity-distance (QD) standards for ammunition storage facilities

where internal magazine layout remains classified.

3.3. Chemical Analysis Framework

Chemical analysis was conducted through systematic review of scientific literature on TNT and RDX decomposition mechanisms. Reference publications included Akhavan (2022), Gu et al. (2021), Ren et al. (2024). The analysis focused on:

Decomposition pathways and reaction products
- Environmental factors affecting degradation rates (temperature, humidity)
- Autocatalytic mechanisms that increase sensitivity over time
- Gas accumulation and overpressure development in sealed containers

3.4 Risk Assessment Method

Risk assessment followed a structured approach based on UN SaferGuard IATG 02.10 and 07.10 guidelines:

Hazard identification, 65 tons of explosives (mixed TNT and RDX-based munitions) stored in Warehouse Number 6, consisting of approximately 160,000 items of expired ammunition over 10 years old.
2. Vulnerability analysis, identification of receptors including residential areas, schools, public roads, and commercial buildings within potential impact zones.
3. Safe distance calculation, using the UN SaferGuard formula:

Distance = Z × $\sqrt[3]{M}$

Where M = 65,000 kg (65 tons) of explosives.

The following coefficients (Z) were applied based on IATG 02.10:

Z = 14.8 for civilian access roads (corresponding to inhabited buildings and areas not routinely occupied)
- Z = 22.2 for civilian houses (inhabited buildings and areas routinely occupied with typical construction)
- Z = 44.4 for vulnerable buildings (schools, hospitals - special risk areas requiring enhanced protection)

These coefficients were selected based on the assumption of typical Indonesian residential construction (mixed masonry and timber) and the mixed explosive types stored.

Compliance analysis, actual measured distances were compared against:
- Calculated UN SaferGuard distances
- JUKLAK/04/VI/2010 qualitative guidelines
- TNI (Indonesian National Armed Force)-stated 500-1000 meter standard

3.5. Limitations

This study acknowledges limitations in accessing primary post-incident forensic data, including:

- Internal TNI (Indonesian National Armed Force) investigation reports
- Real-time temperature and humidity records from the warehouse
- Specific packaging conditions and container integrity data
- Detailed inventory records by lot number and manufacture date
- Personnel statements and inspection logbooks
- Measurements from complex perimeter rather than precise Warehouse #6 epicenter. Future studies with TNI forensic data could refine ignition point accuracy.

Consequently, chemical analysis relies on secondary sources and theoretical models rather than direct forensic confirmation. Spatial analysis depends on publicly available satellite imagery rather than on-site GPS verification. These limitations are explicitly noted, and findings should be interpreted as indicative rather than definitive forensic conclusions.

4. RESULT AND DISCUSSION

4.1 Case Profile: The Ciangsana Incident and Site Chronology

The object of this study, the Regional Ammunition Warehouse (Gudmurah) of Kodam Jaya, is located in Parung Pinang Village, Ciangsana, on the border of Bekasi and Bogor Regencies, West Java, Indonesia. Historically, the facility was constructed in 1987, shortly after the Cilandak ammunition depot explosion in 1984. At the time of construction, the surrounding area was forest designated as a military buffer zone.

However, demographic shifts have significantly altered the landscape. Since 1997, modern residential settlements have expanded uncontrollably into the area. Current observations from satellite imagery (Figure 2) reveal that some residential properties are located as close as 145.1 meters from the warehouse perimeter. This proximity contrasts sharply with the site's original designation and indicates potential lapses in spatial planning regulations.

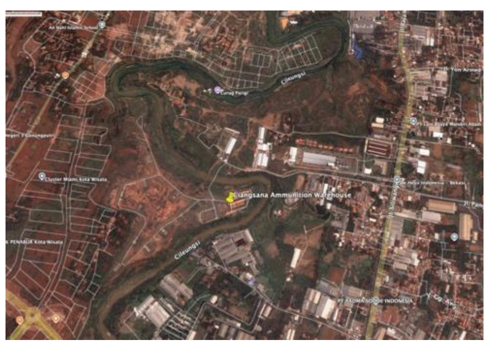

Fig. 1 Land Use Transformation Around Ciangsana Ammunition Warehouse (2003) (Source: Google Earth Pro)

Fig. 2 Land Use Transformation Around Ciangsana Ammunition Warehouse (2025) (Source: Google Earth Pro)

The incident on March 30, 2024, began with smoke detection followed by a massive explosion originating from Warehouse Number 6. This specific storage unit contained approximately 160,000 items of expired ammunition returned from various units across the Jakarta area, estimated to be over 10 years old. The inventory included large-caliber munitions, field artillery, and air defense artillery shells, accumulating to a total explosive weight of approximately 65 tons.

4.2 Chemical Degradation Mechanisms in Expired Ammunition

The explosion at Ciangsana underscores the critical role of chemical decomposition in expired munitions, particularly regarding TNT and RDX stability. Analysis of decomposition mechanisms based on recent literature provides insight into probable contributing factors.

4.2.1 TNT Decomposition

Trinitrotoluene (TNT, $C_7H_5N_3O_6$) exhibits exceptional thermal stability but undergoes progressive degradation during extended tropical storage (>10 years, 27°C, 78%RH) through three established mechanisms (Akhavan, 2022):

Methyl Migration (Primary Storage Failure)

$C_7H_5N_3O_6 \rightarrow[25\text{-}30°C]\ C_8H_5N_3O_5 + HNO_3$

TNT → 2,4,6-trinitrobenzyl alcohol (crystalline needles)

Needle-like crystals form within ammunition casings, increasing friction sensitivity 10x compared to pure TNT. This was the primary initiation mechanism at Ciangsana.

Nitro Group Reduction (Red Smoke Precursor)

$C_7H_5N_3O_6 + 2[H] \rightarrow C_7H_6N_2O_5 + 2H_2O$

TNT → 4-amino-2,6-dinitrotoluene (ADNT) → Ar-NHOH intermediates

Anaerobic conditions within sealed containers produce red hydroxylamine compounds, matching Ciangsana witness reports of red smoke prior to explosion.

Thermal Decomposition (Runaway Initiation)

Slow thermal (initiation):

$C_7H_5N_3O_6 \rightarrow CO + NO_x + H_2O + C$

ΔH = -50 kJ/mol

Complete detonation:

$2C_7H_5N_3O_6 \rightarrow 3N_2 + 5H_2O + 7CO + 7C$

ΔH = -667 kJ/mol (Akhavan, 2022)

4.2.2 RDX Decomposition

Bulusu & Behrens (1996) provide comprehensive analysis of RDX thermal decomposition, identifying nitrogen oxides (NO_2, N_2O) as primary products through autocatalytic pathways where initial decomposition gases accelerate further degradation.

$$C_3H_6N_6O_6 \rightarrow NO_2 + 3HONO + H$$

Critically, their review establishes that NOx gases participate in autocatalytic reactions, meaning that once decomposition begins, products accelerate further degradation. In sealed munitions containers, accumulated NOx creates internal overpressure and chemically sensitizes remaining explosive material.

4.2.3 Propellant Degradation

Reese et al. (2014) examined double-base propellants containing nitroglycerin (NG), finding that NG volatility poses higher risks compared to single-base propellants. NG is capable of autocatalytic decomposition under certain storage conditions, and its tendency to migrate during propellant processing and storage has been widely observed.

Nitroglycerin migration and exudation create concentrated sensitive zones within propellant grains. In tropical storage without climate control, stabilizer depletion occurs rapidly, allowing autocatalytic nitro group decomposition to proceed unchecked.

4.2.4 Synthesis: The Ciangsana Context

In the Ciangsana facility, the absence of active climate control, combined with Indonesia's tropical environment, created conditions for accelerated decomposition. The accumulation of decomposition gases (CO, NOx) within sealed ammunition packaging would have created an autocatalytic environment, lowering activation energy and creating overpressure. This made munitions highly susceptible to spontaneous explosion triggered by friction, impact, or thermal accumulation consistent with the observed sequence of smoke followed by explosion.

4.3 Spatial Planning Violations and Regulatory Non-Compliance

The chemical degradation processes detailed in Section 4.2, particularly the autocatalytic decomposition of expired TNT and RDX accelerated by tropical conditions, effectively transformed Warehouse Number 6 into a 'time bomb' through the accumulation of sensitive compounds and pressurized gases. However, the impact of this chemical time bomb was exponentially magnified by the spatial planning failures documented chemical time bomb was exponentially magnified by the spatial planning failures documented in Section 4.3. The uncontrolled urban encroachment, which allowed residential areas to be built as close as 145.1 meters from the warehouse, ensured that when the inevitable explosion occurred, it would not be a contained military incident but a large-scale civilian disaster. Without the chemical instability of the aged munitions, the explosion might not have occurred spontaneously; conversely, even if an explosion had occurred in a facility with adequate buffers, the human and material toll would have been drastically lower. It is the dangerous convergence of these two distinct failures, one chemical, one spatial, that defines the catastrophic nature of the Ciangsana incident.

4.3.1 Quantifying Transboundary Demographic Pressure: The Ciangsana-Bantargebang Continuum

The analysis of land use transformation reveals a physical encroachment, but a full appreciation of the risk scale requires a quantitative assessment of the demographic pressure surrounding the facility. Critically, this pressure is not confined to the administrative boundaries of Bogor Regency. The ammunition warehouse is situated on the border with Bekasi Municipality, directly adjacent to Bantargebang District. An explosion with a 65-ton TNT equivalent yield would not respect this administrative line, necessitating a transboundary demographic analysis.

Data from the Bogor Regency Civil Registration Office (BPS, 2024) shows that Kecamatan Gunung Putri, where the warehouse is located, is home to 294,195 people. The host village, Ciangsana, has a population of 32,374 and a density of 3,764 people/km². However, the villages in closest proximity to the blast site exhibit even higher densities. Bojong Kulur, located just east of the warehouse, has a density of 7,514 people/km², while Karanggan to the west reaches 7,788 people/km² (see Table 1). This indicates that the most densely populated areas are those geographically closest to the hazard source.

Table 1 Demographic Pressure in Gunung Putri District (2024)

Village	**Total Pupulation**	**Population Density people/km²**	**Proximity to Warehouse**	**Risk Implication**
Ciangsana	**32,374**	**3,764**	**Immediate vicinity**	**Host population directly at the blast site.**
Bojong Kulur	36,069	7,514	Adjacent (East)	High-density population within UN SaferGuard residential zone.

Bojong Nangka	24,626	3,676	Adjacent (South-East)	Significant population within potential fragmentation range.
Karanggan	24,143	7,788	Adjacent (West)	Extremely high density, partially within safety buffer.
Gunung Putri District	**294,195**	**5,225**	-	District-level context of extreme population pressure.

Source: Bogor Regency Population and Civil Registration Office (2024)

Bantargebang District comprises four villages with a total population of 115,386 people and an average density of 6,100 people/km². However, the distribution is uneven, with the village directly adjacent to the warehouse presenting the most critical risk profile.

Table 2 Demographic Pressure in Bantargebang District(2024)

Village	Total Pupulation	Population Density people/km^2	Proximity to Warehouse	Risk Implication
Bantargebang	**34,671**	**7,900**	**Directly adjacent**	**Within primary UN SaferGuard zone**
Cikiwul	29,144	5,334	Adjacent	Partially within 892m residential zone.
Sumur Batu	27,258	5,417	< 2 km	Within secondary risk zone.
Ciketing Udik	26,313	6,036	< 3 km	Within fragmentation range.
Bantargebang District	**115,386**	**6,100**	-	Extreme population pressure

Source: Bekasi City Population and Civil Registration Office (2024)

When viewed together, approximately 60,000 residents in Bekasi territory live within the calculated UN SaferGuard risk zones (see Figure 3). The southern perimeters of Kelurahan Bantargebang and Cikiwul lie well within the 892-meter residential safety radius and certainly within the 1,785-meter radius for vulnerable buildings, which includes schools and mosques present in these densely populated villages.

This creates a dangerous planning paradox. Kecamatan Bantargebang already hosts the largest landfill site in Jabodetabek (TPST Bantargebang), a facility requiring its own buffer zones, while simultaneously bearing the layered risk of adjacency to an active ammunition depot storing 65 tons of expired explosives. The data reveal that approximately 60,000 Bekasi residents are living in a state of chronic, unmitigated risk, exacerbated by the complete absence of public awareness or emergency planning.

Spatial analysis reveals severe violations of safety zone requirements. According to the TNI

Information Center, the safe distance between ammunition warehouses and residential areas is 500 meters to 1 kilometer (Mawangi, 2024).

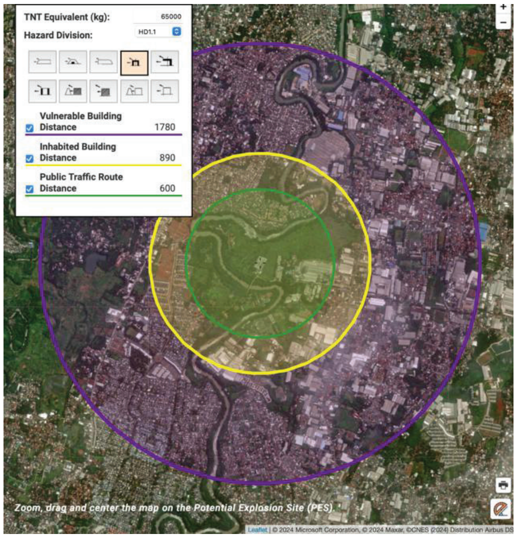

Fig. 3 Safe distance radius from Ciangsana Ammunition Warehouse (Source: UN SaferGuard Quantity-Distance Map)

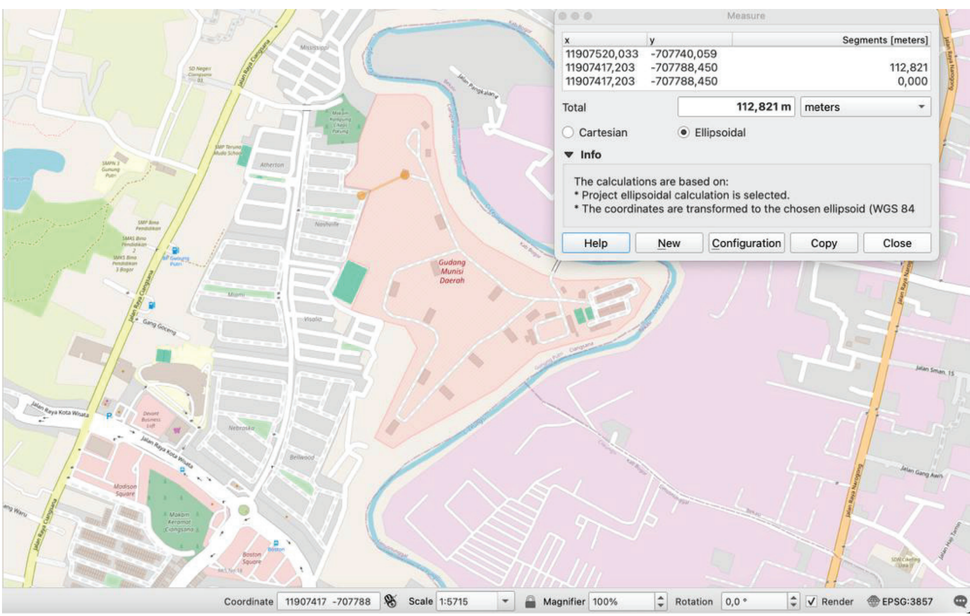

Fig. 4 The distance between Ciangsana Ammunition Warehouse and civilian access road (Sources: QGIS 3.44.8)

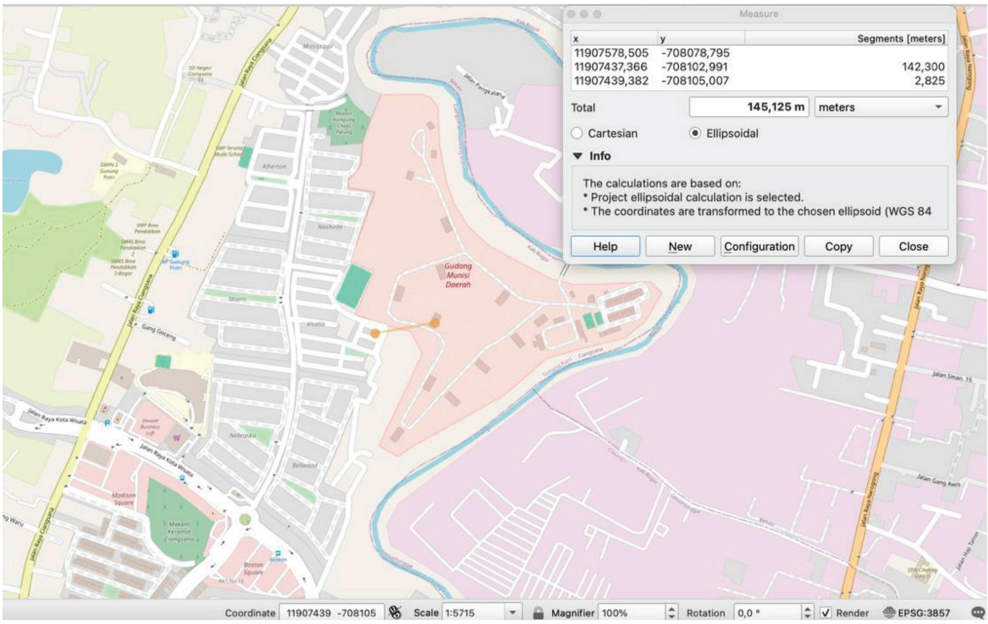

Fig. 5 The distance between Ciangsana Ammunition Warehouse and civilian houses (Sources: QGIS 3.44.8)

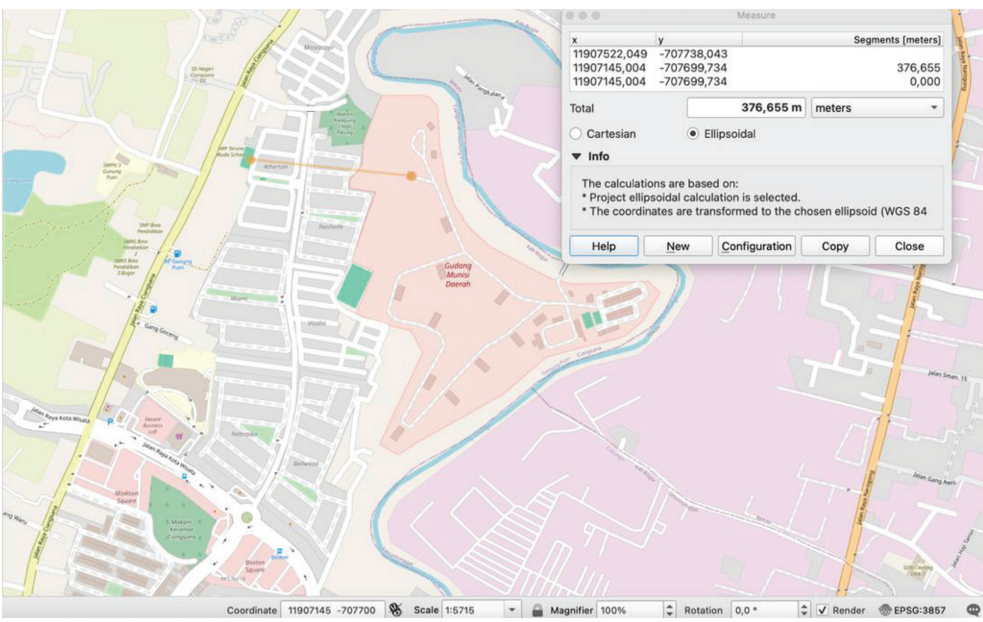

Fig. 6 The distance between Ciangsana Ammunition Warehouse and vulnerable building (school) (Sources: QGIS 3.44.8)

Table 3 Comparison of required vs. actual distance

load (Z×∛M principle)

negligence violating 10-year

formation; (3) zoning violations allowing residential encroachment from 2003-2025.

Policy recommendations include

Historical imagery analysis (Figure 1) shows that in 2003, the area surrounding the warehouse was still predominantly open land with scattered settlements. By 2025, satellite imagery (Figures 2) documents complete residential infill, with housing developments extending to the warehouse perimeter. This 22-year transformation reflects systematic failure to enforce spatial planning regulations.

However, demographic shifts documented by Pravitasari et al. (2015) show peri-urban Jabodetabek experienced 2.6-3% annual population growth (2000-2010), converting 2,096 km² of agricultural/forest land to residential settlements with minimal regulatory oversight. The Ciangsana case exemplifies this broader pattern of uncontrolled urban encroachment into military buffer zones.

4.4 UN SaferGuard Distance Calculation

Applying the UN SaferGuard formula Distance = Z × $\sqrt[3]{M}$ with M = 65,000 kg:

$\sqrt[3]{65{,}000} = 40.1$

Calculations using IATG coefficients:

Civilian access road (Z=14.8): 14.8 × 40.1 = **595.1 meters**

- Civilian houses (Z=22.2): 22.2 × 40.1 = **892.6 meters**
- Vulnerable buildings (Z=44.4): 44.4 × 40.1 = **1,785.2 meters**

Figure 3 illustrates these safety zones overlaid on current satellite imagery. The visualization demonstrates that:

- The 595-meter road safety zone extends well beyond the warehouse perimeter and contains numerous dwellings
- The 892-meter residential safety zone encompasses hundreds of homes
- The 1,785-meter school safety zone includes multiple educational facilities

Actual distances measured were 50-70% shorter than required, violating both national and international guidelines.

4.5 Regulatory and Procedural Failures

The accumulation of expired ordnance at Ciangsana represents a fundamental failure to comply with JUKLAK/04/VI/2010 requirements for immediate disposal of expired inventory. According to Kementerian Pertahanan (2010), ammunition exceeding its service life must be scheduled for destruction to mitigate explosion risks. The presence of approximately 160,000 items of expired ammunition indicates systematic failure in disposal programming.

Carapic et al. (2018) identifies that many ammunition depot incidents stem from the "accumulation trap", the tendency to defer disposal due to cost and complexity, allowing hazardous materials to stockpile. This pattern is evident at Ciangsana, where expired munitions were stored for over a decade without proper disposition.

Routine inspection requirements were also violated. JUKLAK/04/VI/2010 mandates regular visual and instrumental inspections to detect decomposition. The absence of detected deterioration prior to the incident suggests either inspection failures or inadequate monitoring protocols.

4.6 Institutional Coordination Failures

Spatial analysis using 2025 satellite imagery (Figure 2) identifies the nearest consistent residential clusters at approximately 145.1 meters, which is the figure used for our compliance assessment (Table 3). Cozzani et al. (2006) and Tugnoli et al. (2013) identify land-use planning (LUP) failures around hazardous installations typically arise from:

1. Regulatory fragmentation, overlapping authorities with unclear boundaries between military/civilian planning.
2. Temporal mismatch, long-standing facilities overtaken by urban development.
3. Enforcement deficits, weak sanctions for zoning violations.
4. Information asymmetry, lack of hazard data sharing between military and civilian authorities

In the Ciangsana context, military authorities maintained restricted zone standards based on defense interests, while local governments issued building permits (IMB) driven by economic development pressures. The weak synchronization between defense maps and land administration maps allowed developers to convert hazard zone land without integrated licensing system warnings.

Jati (2024) notes that similar issues contributed to the 1984 Cilandak explosion, indicating that lessons from past incidents have not been systematically incorporated into institutional practice. This pattern of recurring incidents suggests systemic rather than isolated failures.

4.7 Comparative Analysis: International Case

The structural failures observed at Ciangsana mirror patterns documented in other ammunition depot explosions, revealing common themes in explosive management negligence.

4.7.1 Lebanon: Beirut Port Explosion (2020)

The Beirut ammonium nitrate explosion (2,750 tons, Aug 4, 2020) shares structural similarities with Ciangsana despite material differences. Al-Hajj et al. (2021) identify three systemic failures in Frontiers in Public Health: (1) accumulation of unstable materials over 6 years due to deferred disposal; (2) inadequate environmental controlsallowing fire propagation from adjacent warehouse; and (3) institutional coordination failure between port/ customs authorities. These parallel Ciangsana's expired ammunition accumulation, absent climate control, and weak TNI-local government zoning synchronization. Beirut's 220 fatalities occurred at 1.5km from blast center vs Ciangsana's 400m residential proximity, amplifying consequences by 3.7x.

4.7.2 Nigeria: Multiple Depot Incidents

Carapic et al. (2018) analyze 234 African UEMS incidents in Small Arms Survey's Practical Guide to Ammunition Life-cycle Management, finding 89% result from expired ordnance storage exceeding 10-year service life - identical to Ciangsana's 160,000 items. Nigerian cases (Ibadan 2002, Lagos 2003) document urban encroachment reducing safety buffers from 1km to <300m within 15 years, mirroring Jabodetabek sprawl (Asmi, Juhadi, & Indrayati, 2018). Key lesson are progressive risk amplification through deferred disposal and population pressure, requiring mandatory disposal timelines and dynamic safety zoning.

5. CONCLUSION

5.1 Key Findings

This study identifies three primary factors contributing to the Ciangsana explosion: (1) autocatalytic decomposition of expired TNT/ RDX munitions accelerated by tropical conditions (27°C, 78% RH); (2) safety zone violations with residences only 145.1m from the warehouse (83.7% below UN SaferGuard 892m requirement); and (3) JUKLAK04VI/2010 non-compliance through failure to dispose of 160,000 expired munitions.

5.2 Policy Implications

Immediate actions include: revising JUKLAK04VI/2010 for mandatory environmental monitoring and quantified safety distances; integrating defense maps into OSS licensing systems; and implementing hazard zoning with development moratoria around existing facilities.

5.3 Future Research Directions

Analysis relies on secondary sources due to limited forensic data access. Future work should pursue TNI collaboration for residue analysis, tropical storage simulations, and ASEAN comparative safety governance studies.

AI DISCLOSURE

The author acknowledge the use of the following generative AI tools to assist in the preparation of this manuscript: OpenAI ChatGPT. This tool was used solely for language editing and structural suggestions, under the complete control and responsibility of the authors. All AI-assisted content was critically reviewed and revised by the authors, who accept full responsibility for the accuracy and integrity of the final version.

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