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Effect of Underground-Type Ammunition Magazine Construction in Respect of Civil and Military Coexistence

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Abstract: Recently, rapid urban development and changes in the national defense environment have required civil–military coexistence plans. In particular, this is an urgent issue for ammunition magazines, which have the widest range of military protection zones among military facilities because of the safety distance standard and their location at transportation hubs. In this study, fundamental research was conducted on underground-type ammunition magazines for the sake of the sustainable civil and military developments. First, the effects of reducing the safety distance for underground-type ammunition magazines, compared to that for ground-type ammunition magazines, were evaluated. Economic and environmental effects expected by substituting underground-type ammunition magazines for ground-type ammunition magazines were analyzed based on the results. Then, design methods of the underground-type ammunition magazine that effectively reduce the safety distance were suggested by performing numerical simulations. The installation of chambers at different depths and the application of technologies to reduce explosion pressure inside the chambers were discussed. Finally, an endowment and concession project method was analyzed based on the previous researches as the most efficient way of implementing the project of an underground-type ammunition magazine. It was concluded that research to specify design methods for underground-type ammunition magazines was urgently required to vitalize future underground-type ammunition magazine projects.

Keywords: civil and military coexistence; underground-type ammunition magazine; safety distance; numerical analysis on ground vibration; endowment and concession project; military facility

1. Introduction

Globally, conflicts between civil and military authorities have occurred consistently due to the attempts of the nation to civilian control, post-conflict operation toward other countries, etc. Therefore, many countries have performed various researches on civil–military relations to find political and economic directions for sustainable development in accordance with the results [1,2]. In particular, as a military presence in allied and conflict areas has become more common, many studies have been conducted on ways of mutual development of civil–military relations linked to peacekeeping and disaster support missions [3–5]. Recently, conflicts have frequently occurred over military facilities located in urban areas, especially in countries with a small national territory, such as the Republic of Korea [6,7]. Military facilities are constructed in a secluded place initially, as they utilize large sites for securing military protection zones. Over time, the infrastructure is expanded into the surrounding areas according to activities related to military facilities. Civil facilities are gradually increased accordingly, which leads to urbanization [8]. Then, military facilities become a serious impediment to urban development and economic activities, even though the urban areas were originally developed by the military. As a result, conflicts between military facilities and urban areas become unavoidable. Therefore, the military forces and private communities have been trying to find ways to establish a mutually sustainable relationship by turning the conflict into a win–win relationship [9–12].

Meanwhile, ammunition magazines require the widest range of military protection zones among military facilities by adhering to a conservative safety distance to prevent damage to buildings and infrastructures from accidental explosions [13,14]. In addition, ammunition magazines are generally located at transportation hubs for the timely distribution of ammunition during wartime. As a result, in places where social and economic activities are active, ammunition magazines are constantly requested to be relocated [15]. However, the relocation of ammunition magazines is not an easy consideration, since changes in the operational plan of commanding units and the necessity of a huge budget for the relocation project are unavoidable. Moreover, the management of the large military area has recently begun overloading the ammunition units. This is because the number of troops is being reduced owing to changes in the national defense environment. Nevertheless, the safety distance for ammunition magazines cannot be arbitrarily reduced because, although standards do not aim to prevent complete damage to facilities, they are required to avoid serious damage. That is, even if the facilities are built as per the safe distance standards, they may still be damaged to some extent in an accidental explosion. They may avoid serious damage, but some casualties may still occur. Therefore, researches on safety from the explosion of ammunition magazines have focused on identifying the propagation phenomenon of explosion pressure in order to establish a conservative safety distance. Sugiyama et al. analyzed the diffraction and reduction effect of explosion pressure when a barrier is installed through a small-scale experiment and numerical simulation [16]. Zhang et al. numerically evaluated the expansion, reflection, and diffraction of explosion pressure in the shelter [17]. In addition, many studies have been conducted to determine the shape of the blast wave, depending on the cause and phenomenon of the explosion [18,19]. However, researches on technologies that directly increase the safety of the surrounding asset and people by structural solutions are insufficient. Studies on ways to reduce internal explosion pressure by filling the facility with water and installing multiple vents were performed [20,21], but these methods are not applicable to ammunition magazines.

The technology to store ammunition magazines underground can address such problems. Underground-type ammunition magazines can reduce the safety distance by confining the impact arising from the accidental explosion (i.e., explosion pressures and fragments) inside the rock [22]. This is beneficial for both civilians and the military. The area required for ammunition units can be downsized in accordance with the reduced safety distance, while the secured land can be used for local developments such as road networks and industrial zones [23]. The guard operation would become easier even with downsized troops as the facilities and various structures are integrated [24]. Furthermore, underground-type ammunition magazines can be a good opportunity to enhance the effectiveness of the operation of ammunition magazines. Facilities based on the concept of management beyond the storage of ammunition are needed in the future because high-precision and high-performance ammunition is being developed rapidly. Smart technologies can be easily applied in the underground-type ammunition facilities with the integration of facilities and various structures. Thus, an underground-type smart ammunition magazine can be developed into a model for a newly suggested military facility, in line with the Fourth Industrial Revolution.

In addition, the underground-type ammunition facility can possess relatively larger storage chambers than the ground-type ammunition facility because of the increasing safety against accident explosion. Accordingly, the amount of concrete required for the construction of an underground-type ammunition facility can be significantly reduced, compared to that for a ground-type ammunition facility. The amount of CO_2 emissions generated during production, construction, maintenance, and demolition of concrete cannot be ignored from an environmental perspective. Therefore, several methods of calculating CO_2 emissions have been studied [25–27]. Based on the calculation methods, many studies are being conducted to reduce CO_2 emissions by developing precast concrete technologies or reducing the amount of concrete with reasonable design processes [28–30]. Environmental benefits in terms of CO_2 emissions are also expected when replacing ground-type ammunition magazines with underground-types since the amount of concrete consumed in construction can be reduced.

As bases for this argument, several progressing or completed construction projects for underground-type ammunition magazines have been reported in countries such as Singapore and the Republic of Korea [31]. However, even experts consider this type of facility unconventional as there are not enough studies and considerations of underground-type ammunition magazines yet. Moreover, the barriers to project promotion are quite high due to the insufficient construction cases worldwide and the excessive budget required for construction. Several projects have been significantly delayed in the Republic of Korea as reliable design results have not been drawn that abide by safety distance and ammunition storage standards. If accurate design results are not drawn, the military might end up violating safety standards or operating inefficient facilities, and local governments might not completely utilize the corresponding value or area of land. In this study, fundamental research was conducted for underground-type ammunition magazines for the sake of the sustainable civil and military developments. First, the effects of reducing the safety distance for underground-type ammunition magazines compared to that for ground-type ammunition magazines were evaluated. In addition, design methods for effectively reducing the safety distance were suggested by considering the concepts of the underground-type ammunition magazine and safety distance standard. Finally, the most suitable project promotion method for the underground-type ammunition magazine was presented by analyzing previous studies. Urgent issues for activating projects were discussed.

2. Safety Distance of Ammunition Magazines

2.1. Overview of Safety Distance Standard

The "safety distance" refers to the minimum separation distance required to protect people and surrounding properties from the risk factors (i.e., explosion pressure, fragments, thermal radiation, etc.) that accompany the accidental explosion of a chamber. The general concept of a safety distance is the same for each country; different safety distance standards are applied considering the characteristics by country. Most North Atlantic Treaty Organization (NATO) members comply with Allied Ammunition Storage and Transport Publication (AASTP) [32–34]. The United Nations (U.N.) follows the International Ammunition Technical Guideline, while the United States (U.S.) complies with the Department of Defense Explosives Safety Board (DDESB) 6055.9-STD [13,35]. The Republic of Korea prepared the "Instruction of Safety Control Standard for Ammunition and Explosion" based on the DDESB 6055.9-STD, and it has performed various explosion tests centered on the Agency for Defense Development to establish a reference equation for the safety distance in cooperation with the U.S. Department of Defense [14]. In this study, safety distance standards were analyzed by employing DDESB 6055.9-STD and Korea's "Instruction of Safety Control Standard for Ammunition and Explosion". However, details on equations, charts, and tables on the safety distance are not provided in this paper due to the security and nondisclosure contents.

The method for estimating the safety distance differs, depending on the risk factors of an accidental explosion. The military protection area must observe the maximum value among the estimated values of safety distance. The dominant risk factors vary, depending on the ammunition type, but in general the explosion pressure and fragments are dominant. Meanwhile, as the allowable risk level varies according to the objects of risk exposure, the safety distance also differs. The risk exposure objects considered in the current standards include inhabited buildings, public traffic routes, internal maintenance facilities, and nearby ammunition magazines. Figure 1 shows different types of safety distances, according to the risk factors and risk exposure objects.

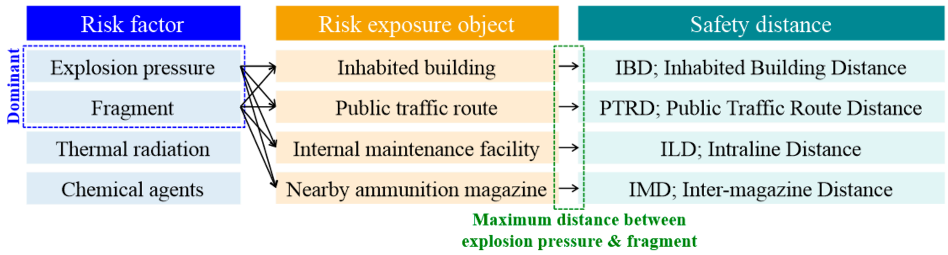


Figure 1. Safety distances according to risk factors and risk exposure objects.

In summary, the safety distances are classified into an inhabited building distance (IBD), public traffic route distance (PTRD), intraline distance (ILD), and inter-magazine distance (IMD), according to the risk exposure objects. The equation for calculating each safety distance also differs according to the risk factors. In general, a long safe distance is calculated for the risk exposure object with a small acceptable degree of damage. The IBD has the longest length among the safety distances, since an inhabited building has the highest vulnerable protection object (i.e., persons). Therefore, it is the main cause of civil complaints, owing to the extensive use of land. The order of the length in the safety distance standards is IBD, PTRD, ILD, and IMD.

The safety distance is calculated by multiplying the net explosion weight by a coefficient determined according to the risk exposure objects and risk factors, as seen in Equation (1). The coefficient was determined through a number of experiments and numerical analyses.

$$D = K \times W^{\frac{1}{3}}. \tag{1}$$

Here, D and K are the safety distance (m) and the coefficient, respectively, corresponding to the risk factors and risk exposure objects, and W refers to the net explosion weight (kg).

The dominant threat between explosion pressure and fragment can vary, depending on the composition and type of explosives. Therefore, the coefficient K in Equation (1) also depends on the composition and type of explosives. The coefficient for the explosion pressure is determined based on the minimum pressure to prevent damage to the risk exposure objects. On the other hand, the factors that affect the coefficient for the fragment are the impact energy and density in a certain area. However, fragments can be prevented through barriers. In addition, the underground-type ammunition magazines considered in this study have the effect of locking fragments by rock and tunnel passages. Thus, this study exclusively considered the threat of explosion pressure.

2.2. Effect of Reduction in Safety Distance of Underground-Type Ammunition Magazines

Unlike a ground-type ammunition magazine, an underground-type ammunition magazine has a feature in that the underground rock traps explosion pressure and fragments. Thus, underground-type magazines can significantly reduce the effects of explosion pressure and fragments, which are the two most dominant risk factors in ammunition. However, if the critical thickness of the chamber in the upward direction (i.e., the distance from the chamber to the ground surface) is unsatisfied, the ground over the top of the chamber may be ruptured, allowing explosion pressure and fragments to propagate to the surroundings. Thus, the critical thickness of the chamber in the upward direction is the minimum thickness to the degree that the ground surface will not be ruptured by an accidental explosion. Ammunition magazines can be classified as underground-type only if the critical thickness of the chamber in the upward direction is satisfied. The critical thickness of chamber in the upward direction is also calculated using Equation (1) by using different coefficients with other safety distances.

If the critical thickness of chamber in the upward direction is satisfied, there is no need to consider the safety distance for the explosion pressure and fragments, as they are trapped in the rock. However, the effects of explosion pressures and fragments that can burst out from the exit should be considered. Nevertheless, the safety distances necessary for explosion pressure and fragments that burst from exits are generally less than the safety distances of ground-type ammunition magazines if the entrance barricade is constructed. The safety distance for explosion pressure at the exit can be calculated by Equation (2). The safety distance for fragments at the exit is not necessary to consider after installing the entrance barricade.

$$D_E = K \times \frac{4A}{P}\left[\frac{(W/V_E)^{0.5}}{P_{so}}\right]^{\frac{1}{1.4}}. \quad (2)$$

Here, D_E and K are the safety distance at the exit (m) and the coefficient, respectively, corresponding to the risk factors and risk exposure objects. A and P are the minimum cross-sectional area (m^2), and the perimeter (m), respectively, at a distance of not more than five times the diameter of the exit from the exit. V_E is the volume of blast pressure through the inside of a tunnel (m^3), and P_{SO} is the acceptable incident pressure to risk exposure objects (Pa).

In addition, ground shocks occur in the underground-type ammunition magazine, owing to the explosion of the chamber besides the explosion pressure and fragments. Ground shock vibrates the surrounding structures, which can lead to structural damage or usability degradation owing to the relative movements of the ground and structures. Therefore, the maximum allowable velocity of ground particles should be specified according to the importance of the facilities and the safety distance should be calculated accordingly [36,37]. In other words, the coefficient K in Equation (1) for ground shock is determined based on the maximum allowable speed of the ground particles to ensure that risk exposure objects are not damaged. However, as this effect is less dangerous than the effects of explosion pressures and fragments, the safety distance can be much reduced. Furthermore, there is no need to consider the safety distance related to the ground shock for internal maintenance facilities and nearby ammunition magazines.

Finally, the chambers of the underground-type ammunition magazine should be sufficiently separated to prevent chain explosions in adjacent chambers. There are three cases in which a chain explosion can occur in an underground-type ammunition magazine:

1. A piece of rock from the wall surface in an adjacent chamber is crushed during explosion (i.e., scabbing), resulting in ammunition damage.
2. The explosion pressure that propagates through cracks in the rock damages ammunition.
3. The explosion pressure and fragments that propagate through the vehicle passage (i.e., tunnel) damage ammunition.

The explosion pressure and fragments propagating through the tunnel can be prevented by installing a blast door. In addition, if damage by scabbing is prevented, the explosion pressure does not propagate through cracks in the rock. In other words, the safety distance for preventing scabbing is the most dominant among the three cases explained above.

In summary, types of safety distances that should be considered in regards to the underground-type ammunition magazine are illustrated in Figure 2 according to risk factors and risk exposure objects. In addition, the considerations for calculating safety distances for underground-type ammunition magazines are summarized in Table 1 in comparison with ground-type magazines. The most dominant factors for determining the safety distance are summarized in Table 2, depending on the types of ammunition magazines. The total weight of ammunition that is generally stored in ammunition magazines and the compatibility group standards were considered, even though the details could vary depending on the ammunition type and risk rating. For the ground-type ammunition magazine, the risk by explosion pressure is the highest; thus, the IBD for the explosion pressure requires the longest safety distance. On the other hand, the explosion pressure that bursts out at the exit is the most dominant risk effect for the underground-type ammunition magazine. However, this effect usually affects the unit facilities of the ammunition corps, and it can be significantly reduced by changing the movement path of explosion pressure and the size of the chambers and exit cross-section or by installing various protective structures. Therefore, the riskiest factor for the underground-type ammunition magazine is the ground shock, and the IBD for this is the longest.

Table 1. Comparison of safety distance standards between ground-type and underground-type ammunition magazines.

Type	Risk Factor	Consideration
Ground-type	Explosion pressure and fragment	• Estimating distance according to net explosion weight and ammunition type • IBD, PTRD, ILD, and IMD according to risk exposure object
Underground-type	Explosion pressure and fragment at exit	• Estimating distance according to net explosion weight and pressure (or fragment) path • Reducing distance depending on installation of protective structures • IBD, PTRD, ILD, and IMD according to risk exposure object
	Ground shock (i.e., velocity of ground particle)	• Estimating distance according to net explosion weight and strength of ground • IBD and PTRD according to risk exposure object
	Explosion pressure and fragment from chamber	• Preventing by blast door
	Spall or pressure propagation through ground	• Estimating distance according to net explosion weight and strength of ground • Inter-chamber distance (ICD) (i.e., minimum thickness between each chamber)

Note: IBD = inhabited building distance; PTRD = public traffic route distance; ILD = intraline distance; IMD = inter-magazine distance.

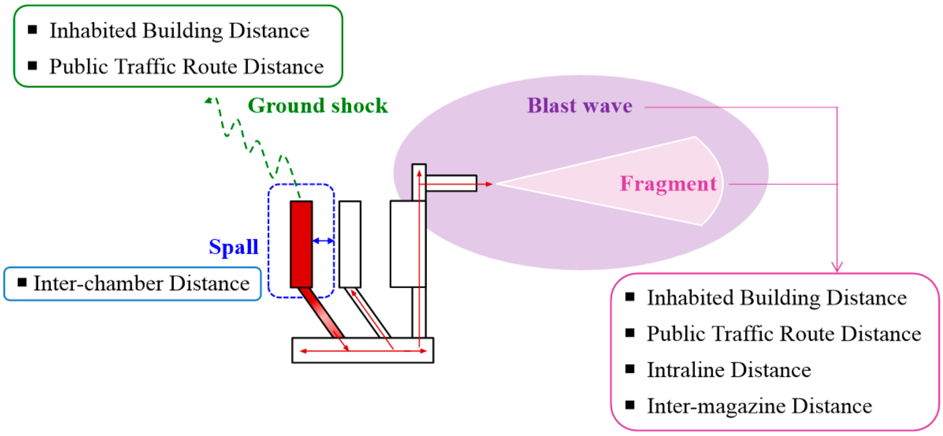


Figure 2. Schematic diagram of safety distances for an underground-type ammunition magazine.

Table 2. Dominant safety distance depending on ammunition magazine type.

Type	Dominant Safety Distance	Influential Factor
Ground-type	IBD for explosion pressure	net explosion weight, ammunition type
Underground-type	IBD for ground shock	net explosion weight, strength of ground
	IBD for explosion pressure at exit	net explosion weight, movement path of pressure

Note: IBD = inhabited building distance.

The amount of land that can be saved using an underground-type ammunition magazine relative to a conventional ground-type was evaluated by comparatively calculating the safety distance for the same net explosive weight. Figure 3 shows a graph comparing the IBD for the explosion pressure of the ground-type ammunition magazine and the IBD for the ground shock of the underground-type magazine. Figure 4 compares the other dominant safety distance of the underground-type magazine (i.e., IBD for explosion pressure at exit) with that of the ground-type ammunition magazine (i.e., IBD for the explosion pressure). Here, it was assumed that the exit of the underground ammunition magazine had 15 m of width and 7.5 m of height with an arch configuration, according to the construction cases. The tunnel from the chamber where the explosion might occur to the exit was set to be 300 m [38].

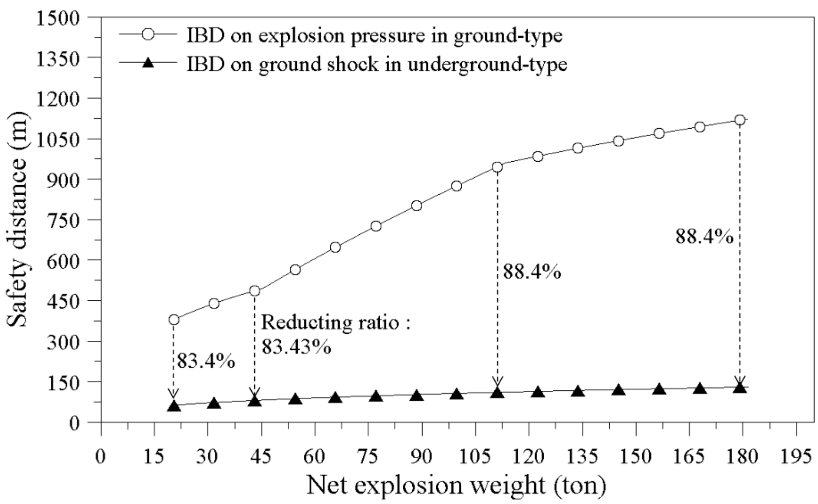


Figure 3. Comparison of dominant safety distances between ground-type and underground-type ammunition magazines (which are IBD for explosion pressure and IBD for ground shock, respectively).

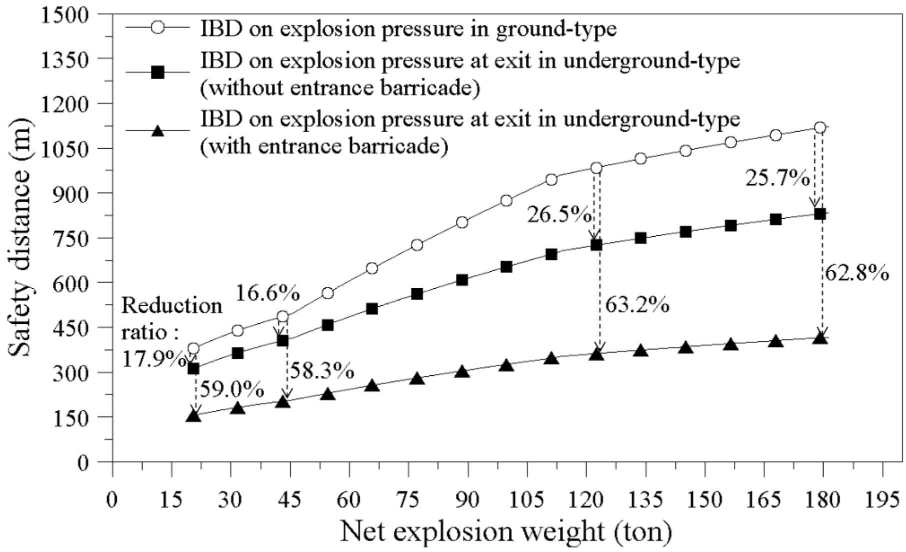


Figure 4. Comparison of dominant safety distances between ground-type and underground-type ammunition magazines (which are IBD for explosion pressure and IBD for explosion pressure at exit, respectively; considering the entrance with and without barricade).

Figure 3 shows that the underground-type ammunition magazine can reduce the IBD by up to 88.4% as compared to the ground-type. The degree of reduction in safety distance increased with an increase in the net explosive weight stored in the chamber, then maintained at 88.4% after 130 tons. This is because the damage from explosion pressure increases exponentially as the net explosive weight increases. Thus, the equation of the IBD for explosion pressure for ground-type ammunition magazine adopts a high safety factor for more than a certain net explosive weight. In contrast, the ground shock effect of the underground-type ammunition magazine does not take into account differential safety factors that depend on net explosive weight. In Figure 4, the differential safety factors are considered depending on net explosive weight in all equations, since both ground-type ammunition magazines and underground-type ammunition magazines represent safety distances for explosion pressure. However, the effects of explosion pressure can be reduced in the case of underground-type ammunition magazines by locking them in the ground formation. Therefore, the IBD reduction effect can be achieved by up to 25.7% without the installation of entrance barricades in the underground-type ammunition magazine. Only the entrance barricades must be constructed when designing underground-type ammunition magazines because the IBD reduction effect can increase to 62.8% by installing entrance barricades. As discussed before, however, the IBD for explosion pressure at the exit of underground-type ammunition magazines is not a significant cause of conflicts between the civil and military communities since it mostly affects the facilities of the relevant ammunition unit.

In this chapter, the safety distance standards of ground-type ammunition magazines and underground-type ammunition magazines were compared to each other. The reduction effects of the IBD, the most dominant safety distance, were directly compared. However, military protection zones of ammunition storage facilities are determined through the combination of several dominant safety distances. Therefore, the actual effect of the reduction in the military protection zones was assessed through an example in the next chapter.

2.3. Analysis of Economic and Environmental Effects of Underground-Type Ammunition Magazines

The effect of reducing the military protection zone of an underground-type ammunition facility compared to a ground-type ammunition facility was additionally analyzed by combining the various dominant safety distances indicated in Table 2. Based on the construction cases for an underground ammunition magazine, a total of 10 chambers were assumed to be installed in 15 m of width, 7.5 m of height, and 60 m length for arch configuration [38]. In this case, the total area for storing ammunition was 9000 m^2. It meant that a total of 20 ground-type ammunition magazines with an area of 450 m^2 were needed. The ground-type ammunition magazine with an area of 450 m^2 was assumed according to the standard specifications of the Republic of Korea. The specifications of the underground-type ammunition magazine and ground-type ammunition magazine considered in the example are shown in Table 3.

Table 3. Specification of ammunition magazines considered in example.

Type of Ammunition Magazine	Width (m)	Height (m)	Length (m)
Ground-type	12.0	8.0	37.5
Underground-type	15.0	7.5	60.0

Assuming that first-class ammunition with a total net explosive weight of 5,000,000 lb was stored, the underground-type ammunition magazines should store 500,000 lb per chamber. In the same way, the ground-type ammunition magazines should store 250,000 lb per magazine. Then, the IBD and the distance between each magazine (i.e., IMD for ground-type and ICD for underground-type ammunition magazines) were calculated, as shown in Table 4, according to the type of ammunition magazines. The IBD for explosion pressure at the exit in the underground-type ammunition magazines was calculated assuming that the tunnel from the chamber where the explosion might occur to the exit was 300 m. Entrance barricades were also assumed to be constructed. Consequently, the maximum military protection zone to be secured in ground-type and underground-type ammunition facilities are shown in Figure 5, based on the calculated safety distances.

Table 4. Safety distances of ammunition magazines in example.

Type of Ammunition Magazine	Type of Safety Distance	Value
Ground-type	IBD for explosion pressure	960.06 m
	IMD between side walls	24.00 m
	IMD between front and back walls	38.40 m
Underground-type	IBD for ground shock	140.31 m
	IBD for explosion pressure at exit	352.83 m
	ICD	60.48 m

Note: IBD = inhabited building distance; ICD = inter-chamber distance.

In Figure 5, ground-type ammunition magazines are arranged in 4 × 5 configurations, while underground-type chambers are placed in 2 × 5 configurations, assuming that a U-type tunnel is constructed. The military protection zones were conservatively calculated as about 85.16 km^2 for the ground-type ammunition facility and about 12.37 km^2 for the underground-type ammunition facility, respectively. The reduction effect of the military protection zone was about 85.47% when adopting underground-type ammunition magazines as a substitute for ground-type ammunition magazines. With a decrease in the safety distance, the secured land can be used for local development.

In addition to the site savings, the underground-type ammunition magazine can save on the amount of concrete used in construction, thereby reducing CO_2 emissions. In the above example, the amount of concrete was calculated to be 8166 m^3 and 6462 m^3 for ground-type and underground-type ammunition magazines, respectively, when assuming that both types had the same concrete thickness (i.e., 0.3 m for this example). If the weight of concrete per cubic meter is about 2.7 tons, about 4600 tons of concrete can be saved by constructing the underground-type ammunition magazines. The saving effect of concrete usage is 20.87%. A total of 14,500 tons of CO_2 emissions can be decreased by constructing underground-type ammunition magazines in the example, when considering that the CO_2 emissions per unit weight of ready-mixed concrete are 3.152 tons CO_2/ton (refer to Table 5) [39].

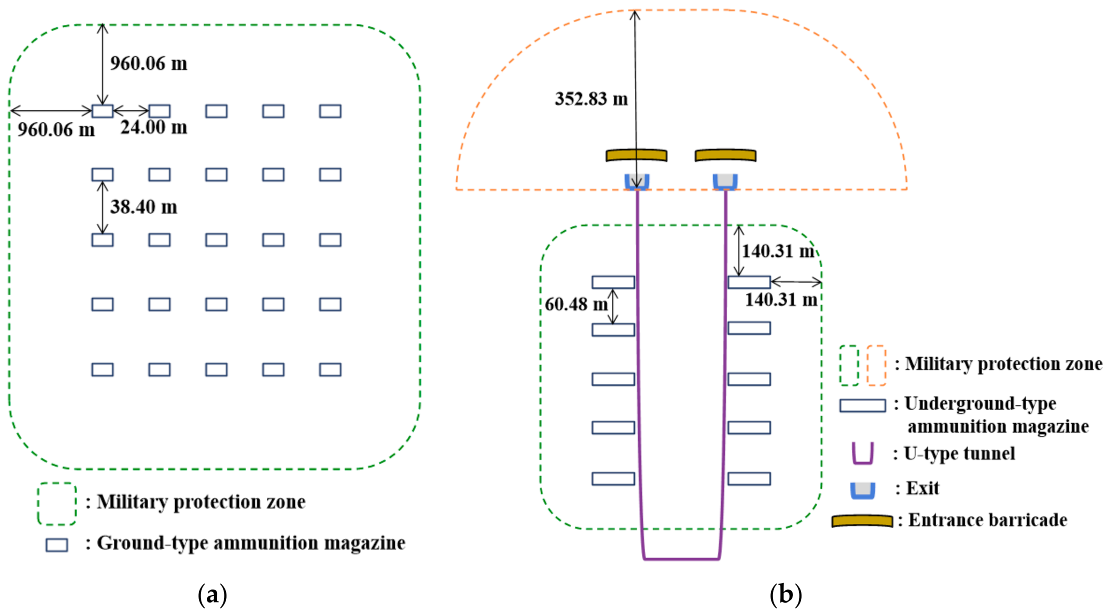


Figure 5. Military protection zones estimated in example. (**a**) Ground-type ammunition facility; (**b**) Underground-type ammunition facility.

Table 5. Amount of concrete usage and CO_2 emission of ammunition magazines in example.

Type of Ammunition Magazine	Volume of Concrete	Weight of Concrete	CO_2 Emission
Ground-type	8166 m^3	22,048 tons	69,495 tons
Underground-type	6462 m^3	17,447 tons	54,992 tons
Reduction effect	1704 m^3	4600 tons	14,502 tons

The reduction effect may be even greater considering the production of steel bars, curing, management, and demolition. The construction of underground-type ammunition magazines is an effective alternative technology that can greatly contribute not only to economic effects but also to environmental effects.

3. Design Strategy for Underground-Type Ammunition Magazines

3.1. Overview of Underground-Type Ammunition Magazines

Conventional underground-type ammunition magazines were originally constructed on a small scale for storing ammunition in rocky mountainous areas or caves to thereby protect it from aerial bombing during World War II and the US–Soviet Union Cold War era. Therefore, construction was undertaken without systematic design methods or safety distance standards. As a result of the decrease in risk following the end of the US–Soviet Union Cold War era, few countries have constructed underground-type ammunition magazines. Since the 1990s, countries with small amounts of land such as Singapore and the Republic of Korea have begun constructing underground-type ammunition magazines to efficiently utilize their land.

Singapore has been implementing a policy for constructing various facilities (such as sports grounds, shopping malls, department stores, etc.) underground due to limited land. They also constructed a large-scale underground magazine in 2007, considering that the safety distance of an underground-type ammunition magazine was significantly reduced, compared to that of a ground-type magazine. The underground magazine had large-scale chambers, each with a width of approximately 25 m and a length of approximately 100 m. In addition, protective structures to reduce the safety distance were also applied, such as a debris trap, expansion chamber, and exit barricade, etc. The required troops were reduced by approximately 20% with an automatic operation system. The ground area was reduced by approximately 4 km^2, as compared to that of a ground-type ammunition magazine of the same capacity, although the initial construction cost increased by approximately 15%. Consequently, the cost of the land was saved by approximately 90% [31]. The Republic of Korea studied an underground ammunition storage technique in a joint study with the U.S. in the early 1990s. From the study, various protective structures were developed to reduce the safety distance, such as debris traps, expansion chambers, and exit barricades. A schematic of developed protective structures is illustrated in Figure 6, and the effects of the structures are summarized in Table 6.

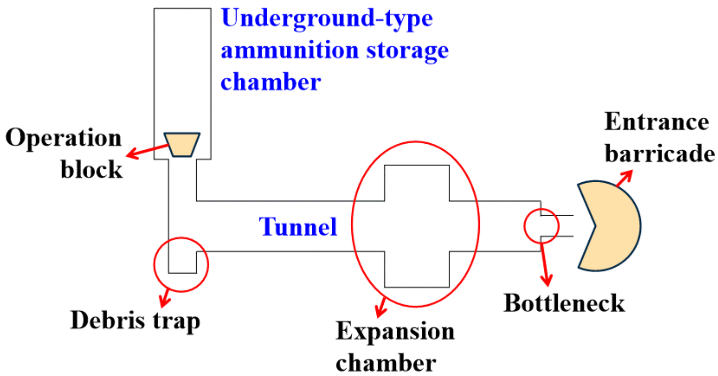


Figure 6. Schematic diagram of protective structures in an underground-type ammunition magazine.

Table 6. Effect of protective structures in an underground-type ammunition storage facility.

Structures	Effect
Entrance barricade	Reducing effect of explosion pressures and fragments in exit (i.e., reducing safety distance by 50% for explosion pressures and 100% for fragments, respectively)
Debris trap	Confining debris emitted from chamber by installing in opposite side
Expansion chamber	Reducing explosion pressures by increasing the cross-sectional area and confining debris
Operation block	Block that obstructs explosion pressure and fragments emitted from chamber
Bottleneck	Reducing explosion pressure that bursts out from exit by decreasing cross-sectional area of exit

In addition, an underground-type ammunition magazine was constructed for research purposes in the Republic of Korea. As a result, an underground-type ammunition magazine was evaluated to possess constant temperatures, fire insulation, weather-proof qualities, security, and operability and be light-proof, explosion-proof, and dust-proof, as well [24]. In 2015, underground-type ammunition magazines were constructed to reduce the military protection area because of the construction of a nearby road [38]. Besides the reduction effect of the military protection area, guards and management personnel could be downsized by constructing underground-type ammunition magazines. In addition, the transport time for the ammunition was significantly improved. However, some operational issues were identified regarding waterproofing, drainage, and ventilation. For example, tunnel lining was not installed as there was no systematic design method. Moreover, the project was not properly completed.

An analysis of construction cases for underground-type ammunition magazines shows that the levels of the elementary technologies are very high. However, the overall design technology for integrating them remains quite insufficient. For instance, insufficient numbers of chambers have been designed by adopting a simple design method, the ammunition weight-based method, without considering the transport and management of ammunition. Additionally, outdated private technologies such as a waterproof tent, etc., have been used. Above all, it is difficult to align opinions from civil and military experts, owing to the severe lack of construction cases, which is a great obstacle to project promotion. Above all, the safest and most conservative designs have been carried out because of insufficient construction cases, taking up a wide range of military protection zones. In other words, it is urgent to study ways to reduce the military protection zones, considering the increasing demand for the construction of underground-type ammunition magazines as well as the complementary development of civil and military interests. Therefore, technologies to reduce the safety distance in the underground-type ammunition magazine were provided by conducting a fundamental study on design methods for safely and efficiently constructing underground-type ammunition magazines.

3.2. Design Method for Reducing the Safety Distance of Underground-Type Ammunition Magazines

In this chapter, the method for efficiently implementing an underground-type ammunition magazine is presented in terms of reducing the safety distance. First, the method to arrange the chambers at different depths was examined. As the underground-type ammunition magazine has the advantage of utilizing ground with a deep depth, the safety distance can be further reduced on the plane by dividing the installation chamber into several floors. The current "Instruction of Safety Control Standard for Ammunition and Explosion" defines the ICD as the shortest distance between two adjacent chambers, i.e., the least rock thickness [14]. Therefore, if the depths of the chambers are separated as far as the ICD, it will be possible to construct chambers at different depths while abiding by the safety distance standard. In addition, the minimum allowable damages level defined by the ICD standard and the critical thickness of the chamber in the upward direction standard will be the same for the fracture of a wall or surface (refer to Table 7).

Table 7. Minimum allowable damage of ICD and critical thickness of chamber.

Safety Distance	Minimum Allowable Damage
Inter-chamber distance (ICD)	The minimum thickness required to prevent damage to ammunition by rock pieces caused by scabbing when special protective structures are not used
Critical thickness of chamber	The minimum distance from the natural rock surface of the chamber ceiling to the ground surface, that is, the thickness that must be maintained to prevent the ground surface above the chamber from being ruptured by the explosion inside the chamber

Here, both standards use the same reference equation. This indicates that the degree of the ground shock propagation for generating a ground rupture is the same in all directions when the chamber explodes. Therefore, if the minimum distance between chambers is established according to the ICD, regardless of the direction, it does not violate the safety distance standard.

To confirm this numerically, the ground shock propagating in all directions was analyzed through numerical analysis, by randomly applying the explosion pressure to the walls of the chamber. A finite element analysis program, GTS-NX, was used to simulate a dynamic analysis of the ground. The simulations were conducted in the following sequence: modeling of ground formation, eigenvalue analysis to determine the damping matrix used for a time history analysis, application of blasting load over time, and analysis of the ground vibration effects [40]. The shape of the chambers was assumed to be circular with a 12 m diameter. A random explosion pressure was uniformly applied to the walls. For each simulation, two chambers were modeled with a separation distance of 60 m at three-dimensional ground formation. Then, the degree of ground shock was evaluated when a chamber exploded by estimating the velocity of a ground particle at adjacent chambers located in upward, downward, and same depth directions. Therefore, a total of three cases were simulated as summarized in Figure 7. In Figure 7, the red dot indicates where the explosion of the chamber was simulated. The thickness of ground formation was set to be 400 m in all cases, and circular chambers were located in the center, each with a length of 60 m, as shown in Figure 8.

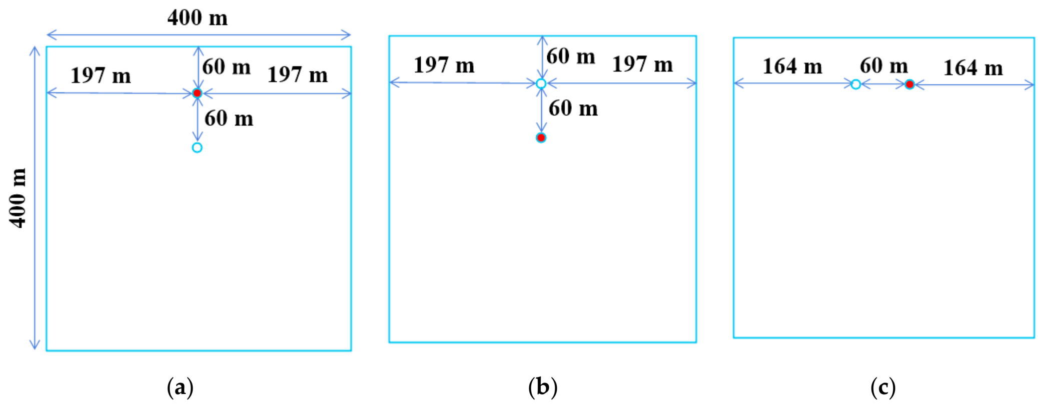


Figure 7. x-z coordinate of each simulation case for estimating ground shock effect to one chamber in explosion of another chamber: (**a**) effect of ground shock to adjacent downward chamber (Case 1); (**b**) effect of ground shock to adjacent upward chamber (Case 2); (**c**) effect of ground shock to adjacent chamber at same depth (Case 3).

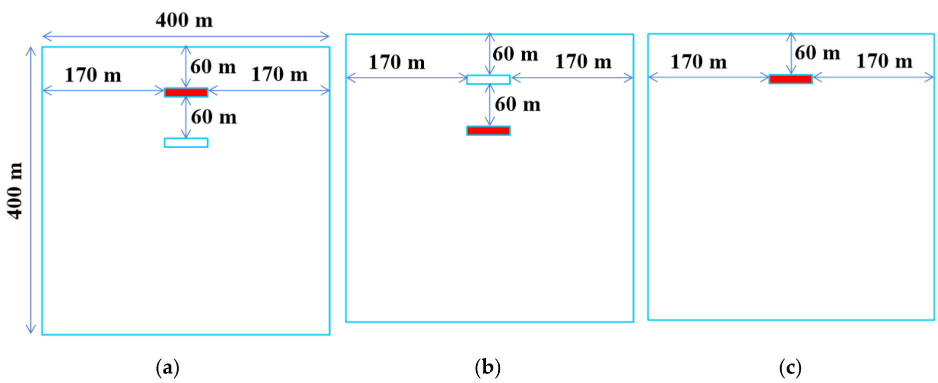


Figure 8. y-z coordinate of each simulation case for estimating ground shock effect to one chamber in explosion of another chamber: (**a**) effect of ground shock to adjacent downward chamber (Case 1); (**b**) effect of ground shock to adjacent upward chamber (Case 2); (**c**) effect of ground shock to adjacent chamber at same depth (Case 3).

A three-dimensional tetra mesh was created. As for the installation parts of the working surface of the blasting load, which required precise analysis, a dense mesh was set up by specifying the size of the edge. The general properties of bedrock in the Korean Peninsula were used for the properties of the solid layer in the numerical model (refer to Table 8).

Table 8. Dynamic properties of bedrock applied in numerical analysis.

Material Properties	Value
Unit weight (kN/m^3)	25.0
Cohesion (kPa)	13,000
Angle of friction (°)	35
Absorption (%)	0.5%
Dynamic shear modulus (MPa)	8000
Dynamic elastic modulus (MPa)	20,000
Dynamic modulus of volume change (MPa)	20,000
Poisson ratio	0.3

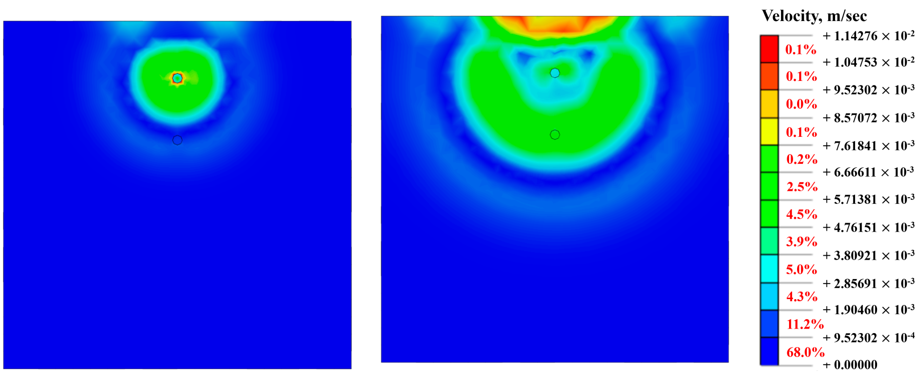
After modeling the chambers and ground formation, the eigenvalue analysis was performed by defining an elastic boundary with surface spring coefficients. The surface spring coefficients were calculated by Equation (3).

$$k = \frac{E}{30}\left(\frac{\sqrt{A}}{30}\right)^{-\frac{3}{4}} \quad (3)$$

Here, k is the surface spring coefficient of ground, E is the elastic modulus of ground (MPa), and A is the cross-sectional area (m^2).

Then, the natural periods of the first and second modes obtained from the eigenvalue analysis were applied to the numerical analysis. There is a possibility of significant errors when a normal-sized boundary is set in a dynamic analysis due to the reflection effect of a ground shock wave at the boundary. To address this issue, a viscous boundary was applied in the numerical model [41]. The viscous boundary was defined by applying the damping values for the x, y, and z coordinate directions at the boundary of the ground model. The applied damping values were estimated based on the absorption rate indicated in Table 8 (i.e., 0.005). Then, a linear time history analysis was performed. The total analysis time was set to 3 s, and the time interval was 0.0005 s.

The analysis results are shown in Figures 9–11 in the form of contours. The maximum velocities of ground particles measured in the separated chambers are summarized by the case in Table 9. The analysis results confirmed that the ground shock propagates circularly. The velocity of the ground particle is almost the same at the same separation distance. That is, the underground-type ammunition magazine can be constructed at different depths while applying the current safety distance standard as is for the ICD and IBD for the ground shock. However, if the shape of the chamber is not circular or the ammunition is unevenly stored on one side, the ground shock may not propagate circularly. In addition, if the properties of the ground are non-homogeneous or discontinuous planes such as joints, the propagation of the ground shock may be non-uniform. In these cases, an additional investigation will be required.



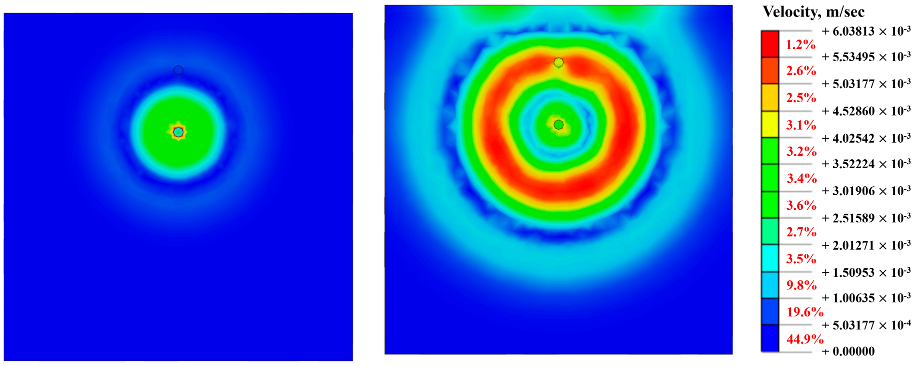
(**a**) (**b**)

Figure 9. Results of numerical simulation for velocity of ground particle in Case 1: (**a**) $t = 1.5 \times 10^{-2}$; (**b**) $t = 3.0 \times 10^{-2}$.

Table 9. Velocity of ground particle measured in separated chambers by case.

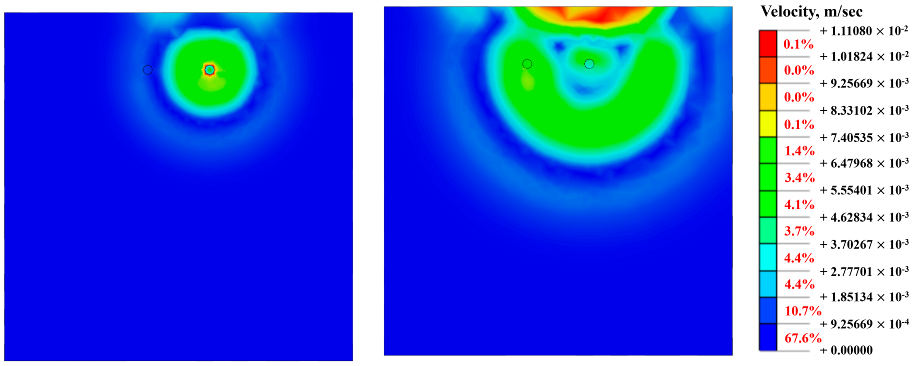
Case	Case 1	Case 2	Case 3
Velocity of ground particle	2.29 cm/s	2.37 cm/s	2.36 cm/s

Apart from arranging the chambers at different depths, the safety distance can be drastically reduced by applying technology to reduce the explosion pressure inside the chambers. Figure 12 is the result of estimating the velocity of ground particles at the same location by reducing the explosion pressure applied to the chamber wall under Case 1 conditions.



(**a**) (**b**)

Figure 10. Results of numerical simulation for velocity of ground particle in Case 2: (**a**) t = 1.5 × 10^{-2}; (**b**) t = 3.0 × 10^{-2}.



(**a**) (**b**)

Figure 11. Results of numerical simulation for velocity of ground particle in Case 3: (**a**) t = 1.5 × 10^{-2}; (**b**) t = 3.0 × 10^{-2}.

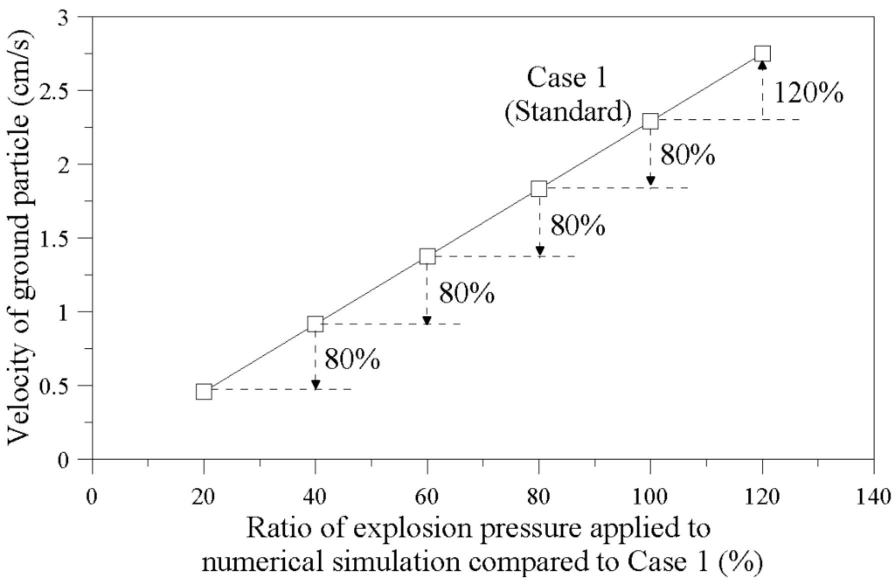


Figure 12. Reduction degree of ground particle velocity in accordance with decrease in explosion pressure applied at chamber wall.

As a result, the decreasing ratio of ground shock was proportional to the decreasing ratio of the explosion pressure occurring within the chamber. In other words, the safety distance can be reduced as much as the reduction of explosion pressure.

4. Strategy for Promoting Projects for Constructing Underground-Type Ammunition Magazines

In summary, it was concluded that the underground-type ammunition magazine could significantly reduce the safety distance as compared to a ground-type magazine. Futhermore, it has the potential for further reducing the safety distance by applying various design technologies. However, there are many delay factors in the project implementation of underground-type ammunition magazines because both military operational and initial construction cost aspects must be simultaneously considered. The military can adopt one of the business models shown in Table 10 for proceeding with the construction of underground-type ammunition magazines.

Table 10. Business models applicable for constructing underground-type ammunition magazines.

Business Model	Method
Endowment and concession project	Local government or public agency that has requested the relocation of military facilities constructs new facilities with its own budget and donates them to the military according to the causer pays principle. Then, in exchange for this, they develop an existing military facility area by obtaining a concession.
Special accounts project	The government pays the budget for the project.

The endowment and concession project method is the most suitable for an underground-type ammunition magazine construction project, relative to the special accounts project method, because the special accounts project is promoted with limits because of difficulties in securing finances [23]. The implementation process of an endowment and concession project is that a project implementer raises the required finances, selects the target site, donates alternative facilities, and receives the former military land. It is usually undertaken through a process comprising project approval, signing of a memorandum of agreement (MOA), licensing, design, construction and completion, and property disposal (refer to Figure 13).

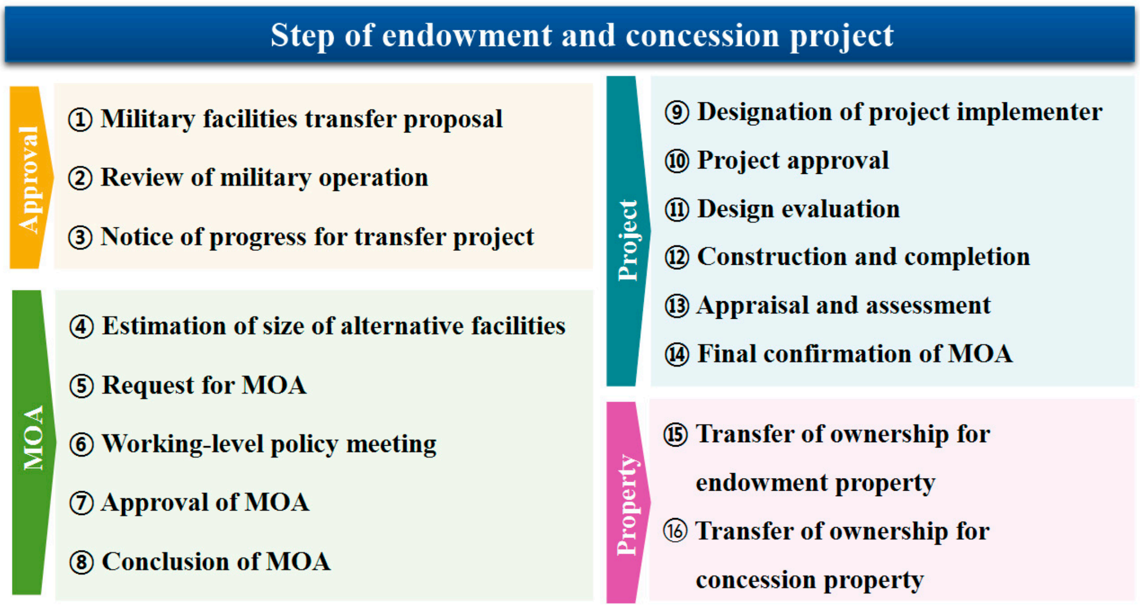


Figure 13. Process of endowment and concession project.

However, as many agencies are involved in pushing forward an endowment and concession project, complex interests frequently delay the project progress. In particular, when planning to relocate military facilities, in addition to general construction projects there is a need to consider various factors in accordance with the closure of military bases, such as local economic issues, domestic political impacts, conflicts with residents, real estate transfers of existing facilities, and achievement of military objectives, etc. Such delay factors in the project period cause issues such as increases in the project cost from the perspective of the project implementer, and the need to continue operating in poor and old facilities from the perspective of the military.

Therefore, a study was conducted to derive the potential risk factors affecting project delays, based on Delphi and analytic hierarchy process techniques [42]. According to this study, the first potential risk of the endowment and concession project was a requirement that exceeded the facility standards. From the perspective of the military, there was no choice but to discuss relocation with an emphasis on facility replacement for satisfying the operational and institutional functions of the current military facilities, even after their relocation. Accordingly, the military tended to make excessive demands, despite the imbalance between endowment and concession. In contrast, the local government or public agency hoped to proceed with the project so that the ratio of the endowment to concession approached equality, by considering the level of future development profit. As for facilities that do not have specific design methods, such as with the underground-type ammunition magazine, the opinion gaps can grow even wider. The second risk factor was design changes during construction and completion. The military should constitute a project management system separate from the project implementer to secure the quality of the military facilities. Therefore, there were frequent requests of additions, changes, etc., to the facilities during construction. Accordingly, if there is a design change of more than 10% of the scope of the originally planned project, the project may be delayed significantly.

Consequently, the key task in tackling delays in endowment and concession projects is to specify and standardize a design method suitable for an underground-type ammunition magazine. If there is a standard design method, there will be less disagreement between the military and project partners, resulting in less frequent changes in the design. However, in a situation where the demand for the underground-type ammunition magazine has not been longstanding and the construction cases remain insufficient, interest in developing design methods remains unfocused. Therefore, the most urgent consideration is to specify design methods and build databases for related technologies, to vitalize underground-type ammunition magazine projects.

5. Discussion

Nowadays, the national defense environment is constantly changing on account of rapidly shifting national policies, prolonged peace, and advancements in weapons systems. These changes constantly require civil–military coexistence plans on military facilities. Accordingly, the presence of defense facilities, which brings significant limitations to the social and economic activities, is becoming less acceptable. In particular, in the case of military facilities at risk of explosion, the establishment of excessive military protection zones and safety issues have caused great restrictions on civil and military coexistence. Therefore, many studies have been conducted in terms of political and institutional aspects. However, political and institutional measures cannot simultaneously solve both safety from the risk of explosion and site utilization for developing the local area. Recently, as threats from hydrogen energy stations and indiscriminate terrorists have increased, it is necessary to find solutions in terms of facilities and structures to prevent the risk of explosion in the city center. However, related research on them is still lacking.

Therefore, the construction of an underground-type ammunition magazine was proposed as a solution for the coexistence and sustainable development of both civil and military communities in this study. First, the expected reduction of the military protection zone was evaluated when constructing underground-type ammunition magazines by replacing ground-type ammunition magazines. The degree of reduction of the military protection zone was assessed by analyzing the safety distance standards and devising an example. As a result, the effect of reducing the military protection zone of an underground-type ammunition facility, compared to a ground-type ammunition facility, was estimated to be about 85.47%. This is assuming that a ground-type ammunition magazine took up an area of 200,000 m^2 for the military protection zones, and an area of approximately 170,940 m^2

could be utilized for other purposes, such as local development. By undergrounding the ground-type ammunition magazine, it is possible to maximize the efficiency of land use. Accordingly, in the Republic of Korea, a movement to build large-scale underground-type ammunition magazines is underway, with plans to build a "Smart Valley" using the saved land. The cost for constructing the underground ammunition magazines is expected to be approximately USD 1 billion. The economic ripple, however, is expected to reach approximately USD 6.5 billion, and more than 42,000 jobs are expected to be created [43]. Relative to the initial investment cost of underground-type ammunition magazines, the economic ripple effect will be quite substantial. In addition to the site savings, underground-type ammunition magazines can reduce 14,500 tons of CO_2 emissions produced, when constructing concrete in the example.

Next, design methods were proposed to further reduce the safety distance of underground-type ammunition magazines. First, the method of installing chambers at different depths was presented. The possibility of installation was determined based on the definition of the safety distance standard and numerical analysis results. Second, technologies to reduce the explosion pressure inside the chambers were suggested for effectively diminishing the ground shocks. In the parametric study with numerical simulation, the decreasing ratio of ground shock was proportional to the decreasing ratio of the explosion pressure occurring within the chamber. Of the methods of reducing the explosion pressure inside the chamber, an explosion-proof panel can be installed at the chamber wall. In addition, seismic vibration reduction devices can be installed to reduce damage caused by vibrations propagating to neighboring chambers when an adjacent chamber explodes.

Finally, an endowment and concession project method was proposed as a way to implement the underground-type ammunition magazine construction. However, it was determined through previous studies that the lack of design standards was the most significant risk factor for project delays. To vitalize future underground-type ammunition magazine projects, research to specify design methods for underground ammunition magazines is urgently required.

In this study, as the basic data for proceeding with the underground-type ammunition magazine construction, the effect of reducing the safety distance was analyzed. In addition, efficient design and project implementation methods were proposed. As a fundamental study, this paper presented only overall data in the general case and did not include specific details about the proposed design methods. Therefore, it will be necessary to apply a particular construction case in the future to verify the results of this study, and to carry out specific studies on constructability, economics, safety, and maintenance of detailed design methods.

6. Conclusions

In this study, a fundamental inquiry was carried out to find ways to develop civil–military mutual relations through the construction of underground-type ammunition magazines. The effects of reducing the safety distance through the construction of underground-type ammunition magazines were analyzed, and efficient design methods were proposed to further reduce the safety distance. With a decrease in the safety distance, the secured land can be used for local development. The reduced military facilities also decrease the amount of CO_2 emissions; thus, a significant environmental impact can be expected. Finally, a project plan suitable for underground-type ammunition magazines was analyzed. The results are summarized as follows.

1 The concept of safety distance for an ammunition magazine was analyzed. Then, the land-saving effect from using an underground-type ammunition magazine as compared with a ground-type magazine was evaluated, based on the safety distance standard. As a result, it was found that the IBD of the underground-type ammunition magazine could be reduced by about 88.4% on the ground shock effect and about 62.8% on the explosion pressure effect at the exit. In addition, the economic and environmental effects expected by substituting underground-type ammunition magazines for ground-type ammunition magazines were analyzed by devising an example. The effect of reducing the military protection zone was estimated to be about 85.47%. In addition,

14,500 tons of CO_2 emissions could be saved when constructing underground-type ammunition magazines in the example.

2 The basis for reducing the safety distance in the underground-type ammunition magazine was evaluated by analyzing the risk factors expected when an accidental explosion inside a chamber occurs. Then, design strategies for further reducing the safety distance in the underground-type ammunition magazine were provided. The method of installing chambers at different depths and using technologies to reduce the explosion pressure inside the chambers, such as explosion-proof panels, etc., were suggested.

3 As the most efficient way of implementing the project regarding the construction of underground-type ammunition magazines, an endowment and concession project method was recommended. Civilian organizations or governments can facilitate local development by obtaining a concession of part of the land located in a transportation hub from the ammunition corps, whereas the ammunition corps can operate the underground-type ammunition magazine by receiving a new facility with the value of the conceded land. However, the lack of design standards was evaluated as the risk factor for project delays.

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