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Principles of Fortification Project Design: Considering the Effect of Ground Conditions

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Abstract

The advancement of military technology and the destructive power of modern weaponry have necessitated the development of strong fortifications. A fundamental design principle is the careful selection of the site, as geological and geotechnical factors significantly influence the propagation of shock waves and ground vibrations following an explosion. Additionally, the structure's design relies on various factors, including the desired level of security, the types of weapons involved, the topography of the area, and strategic as well as economic-technical considerations. This study aims to explore and enhance the geotechnical parameters and design principles in military fortification projects. When examining the history of fortifications in Greece, the Metaxa Fortification Line along the Greek-Bulgarian border stands out as the largest defensive structure ever constructed in the country. This monumental engineering project, was completed in just four years and was remarkably cost-effective for its time. It comprises 21 fortified complexes featuring numerous surface constructions and thousands of meters of underground corridors and shelters. The overall project integrated various elements, including road construction, tunneling, surface buildings, water supply, drainage, ventilation, lighting systems, and ditches. A crucial aspect of the design was the full utilization of the mountainous terrain and existing obstacles to maximize coverage and protection for the structures. Some of these forts remain intact today, serving as enduring evidence of the scale and significance of this fortification project.

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This paper presents a brief overview of this fortification achievement to highlight its innovations, which were pioneering for its time, employing techniques that have been adopted in modern fortification projects.

Keywords: *Military fortification construction, Military geology, Underground Shelters, Forts of Metaxas Line*

ΠΕΡΙΛΗΨΗ

Η πρόοδος της στρατιωτικής τεχνολογίας και η καταστρεπτική δύναμη των σύγχρονων οπλικών συστημάτων, επιβάλλει την ανάγκη κατασκευής σύγχρονων οχυρωματικών έργων και την ενίσχυση των ήδη υφιστάμενων. Βασικός κανόνας του σχεδιασμού είναι η κατάλληλη επιλογή εδάφους, καθώς τα γεωλογικά και γεωτεχνικά στοιχεία είναι αυτά που καθορίζουν σε πολύ μεγάλο βαθμό τη διάδοση του ωστικού κύματος και της εδαφικής δόνησης μετά από έκρηξη. Επιπλέον, η μορφή του δομήματος, εξαρτάται από το επίπεδο ασφαλείας, το όπλο σχεδιασμού, το τοπογραφικό ανάγλυφο, στρατηγικά και οικονομοτεχνικά κριτήρια. Σκοπός της παρούσας εργασίας είναι η διερεύνηση και εμβάθυνση των γεωτεχνικών παραμέτρων και αρχών σχεδιασμού στα στρατιωτικά οχυρωματικά έργα. Ανατρέχοντας στην ιστορία των οχυρωματικών έργων της Ελληνικής επικράτειας, η οχυρωματική Γραμμή Μεταξά, κατά μήκος των ελληνοβουλγαρικών συνόρων, μπορεί με ασφάλεια να χαρακτηριστεί ως το μεγαλύτερο οχυρωματικό έργο που έχει κατασκευαστεί ποτέ στη χώρα. Αποτέλεσε ένα τεράστιο τεχνικό έργο για την εποχή του, το οποίο κατασκευάστηκε σε μόλις τέσσερα χρόνια και με πολύ περιορισμένους οικονομικούς πόρους. Αποτελείται από 21 οχυρωματικά συγκροτήματα τα οποία διαθέτουν εκατοντάδες επιφανειακά έργα και χιλιάδες μέτρα υπόγειων στοών και καταφυγίων. Το συνολικό έργο συνδύαζε έργα οδοποιίας, σηράγγων, επιφανειακών έργων, ύδρευσης, αποχέτευσης, εξαερισμού, φωτισμού και τάφρων. Βασικό στοιχείο του σχεδιασμού, αποτέλεσε η πλήρης εκμετάλλευση του ορεινού ανάγλυφου και όλων των φυσικών εμποδίων, προκειμένου να επιτευχθεί η μέγιστη κάλυψη και προστασία των κατασκευών. Κάποια από αυτά τα οχυρά παραμένουν ακόμα και σήμερα ανέπαφα στο πέρασμα του χρόνου και αποτελούν ατράνταχτη απόδειξη του μεγέθους της κατασκευής του έργου. Στο πλαίσιο της παρούσας εργασίας πραγματοποιείται συνοπτική παρουσίαση του οχυρωματικού αυτού επιτεύγματος στην προσπάθεια ανάδειξης των καινοτομιών του, οι οποίες αποδεικνύονται πρωτοπόρες για την εποχή του, προσομοιώνοντας τεχνικές που έχουν υιοθετηθεί στα σύγχρονα οχυρωματικά έργα.

Λέξεις – Κλειδιά: *Στρατιωτικά οχυρωματικά έργα, Στρατιωτική γεωλογία, Υπόγεια καταφύγια, Οχυρά Γραμμής Μεταξά*

Introduction

Military land fortifications are construction techniques that have evolved in response to changes in warfare. Advances in military technology have significantly altered the nature of combat, prompting ongoing research into new and improved fortification methods. The destructive power of modern weapon systems, combined with advancements in nuclear energy, has underscored the vulnerabilities of traditional fortifications and created a need for stronger, contemporary structures. Furthermore, developments in material technology and construction methods offer opportunities to enhance the strength of both new and existing fortifications.

Fortification projects consist of both aboveground and underground constructions. The level of protection required depends on the operational needs. Underground structures are frequently used in fortifications because they offer substantial protection against military strikes. Additionally, these structures provide a high degree of concealment, making them less likely to be detected, especially when situated deep below the ground surface. Bondesan and Ehlen (2022) define military geoscience as the application of geology and geography to military operations. The importance of this application for the development of military projects became evident after World War I, which led to the introduction of military geology in military schools and was extensively utilized during World War II, particularly in Germany. Since then, interest in the academic field has increased significantly, resulting in numerous conferences being organized. In 2013, the International Association of Military Geosciences was founded to sponsor international military geoscience conferences worldwide. Military geoscientists, including civil engineers and geologists, apply their expertise to support military activities even during peacetime. They accurately assess soil parameters to understand the limitations of an operational environment, evaluate its potential for offensive or defensive actions, and make use of its natural resources. Geologists play a vital role in various construction projects, including the establishment of fortifications. Their responsibilities include locating and securing water supplies, digging tunnels and other underground structures, and identifying routes for roads, bridges, and temporary airfields. To support these efforts, they use essential tools such as topographic maps, aerial photographs, climate data, vegetation information, and details about the terrain's relief (Galgano & Rose, 2021).

The current review paper intends to highlight the necessity of geological research and knowledge in military construction sites. Engineering Geology has significantly contributed to this purpose, providing essential technical support and insight into the conditions of the operational terrain. As mentioned by Koukis (1985), having geologists in the field is particularly important, as they offer accurate assessments of soil parameters and a deeper understanding of the geological conditions in areas designated for military construction. To this extent, within the framework of this review, a brief presentation of the Metaxas Fortification Line is introduced. This impressive engineering project, remarkable for its era, was designed to fully utilize the mountainous terrain and natural obstacles. The overall project study was compiled by professors from the National Technical University of Athens in collaboration with army officers, introducing several technical innovations that were groundbreaking for Greece at that time, simulating techniques that have been adopted in modern fortification projects.

1.1 Types of Damage

The resistance of military structures is influenced by the threats they may encounter throughout their lifespan. The damage observed in fortifications after being attacked by conventional weapons is primarily attributed to Twisdale et al, (1994):

- projectile penetration into a structural element
- airblast shockwave and potential fragments, due to a projectile explosion in the air
- ground shockwave, due to projectile explosion inside the ground, close to the construction site

When a projectile strikes a target, it can either be destroyed or cause varying degrees of damage, ranging from minor effects to complete penetration of the structural element. Additionally, penetration may create a crater on the surface of the impact and cause spalling on the inner surface of the structure, particularly when concrete is used as the primary construction material (TM5-855-1, 1997). If the penetrating weapon contains explosive material, the airblast shockwave generated by the explosion must also be considered. When considering the other two types of damage, airblast shockwaves, and ground shockwaves, structures must be designed to withstand severe shock effects. The loads generated during these events can reach extremely high intensity. The medium through which the shockwave travels—whether air or ground—plays a crucial role in determining the pressure experienced by a structure. In homogeneous media like air, estimating pressure is relatively straightforward. In contrast, the characteristics of ground shockwaves are influenced by the properties of the terrain. Experimental findings have revealed that the amplitude of ground shockwaves in saturated soil can be up to twenty times greater than in the same soil under unsaturated conditions (Bukovalas et al., 2008).

1.2 Design weapon

The term "design weapon" refers to a launch and projectile system used to strike fortifications. It is important to note that the accuracy of the weapon depends on the characteristics of the launcher, while its destructive power is determined by the projectile's features. As the complexity of the calculations for weapon impact increases, the amount of information required about each weapon also grows. In practice, engineers utilize software that includes libraries with various types of projectiles for these calculations (Bukovalas et al., 2008).

2. SITE SELECTION

The design and layout of fortifications are heavily influenced by the characteristics of the area where the project will be implemented. Similar to civil engineering projects, military projects must consider several key factors during planning. These include the topography of the region, the prevailing geological and geotechnical conditions, and the construction methods to be used. Additionally, it's important to carefully evaluate the quality of geological and geotechnical data. This data is crucial as it affects the propagation of air blasts and ground shockwaves following an explosion, as well as providing coverage and concealment for the structures (Koukis, 1985).

The selection of a project location that enhances its lifespan is influenced by several factors, including operational requirements, weapon design, and the unique physical attributes of the proposed site. Leveraging local geological features can greatly minimize the risk of structural damage. Furthermore, natural barriers such as cliffs, steep slopes, rivers, trees, and marshy areas can impede access to fortifications and complicate their placement. When establishing a technical project, it is essential to analyse the prevailing geological conditions of the site and assess the soil parameters that will impact the construction. With the advancement of weapon system technology, there is an increasing necessity for underground defense structures to ensure high-level protection for personnel and equipment. The construction of underground structures requires detailed information about the foundation soil and the soil above it. For instance, if the ground is rocky, it is essential to know the type of rock, the thickness of the weathering zone, its compressive and tensile strength, ductility, and the stability of its roof and walls. Additionally, understanding soil conditions and its bearing capacity is crucial. All these parameters of the rock mass must be assessed in three dimensions to facilitate effective excavation, underpinning, cementing, proper ventilation, and moisture control (Koukis & Kynigalaki, 1983).

Constructing a fortification on high-quality rock significantly decreases the likelihood of being attacked from the sides and below, provided that projectiles and bombs can reach such angles. Moreover, tunnel fortifications built in solid rock are safeguarded against direct strikes. Subsurface investigations also assess the hydrogeological and geotechnical conditions essential for constructing bridges, tunnels, and buildings. In stiff formations like shale, limestone, or igneous rocks, the attenuation of ground shockwaves is much lower compared to soft soils. When construction occurs in saturated soil, particularly below the aquifer, the amplitude of ground shockwaves increases significantly. Generally, if an aquifer is close to the earth's surface, liquefaction can become a critical failure factor (Koukis & Kynigalaki, 1983).

3. GROUND SHOCKWAVES AND CRATERS

A possible projectile detonation within the ground can lead to two significant outcomes. First, it generates ground shockwaves due to the released energy. Second, it creates a crater, which represents an area of deformed ground. This type of explosion can seriously damage underground military facilities, potentially disrupting their constant operations, especially in critical constructions. In designing fortifications, the characteristics of the ground shockwaves produced by the detonation and penetration of the projectile should be considered, when it occurs near the structure (Bukovalas et al., 2008). Figure 1 illustrates possible firing positions of a projectile beneath the ground's surface (Danielson et al., 2000).

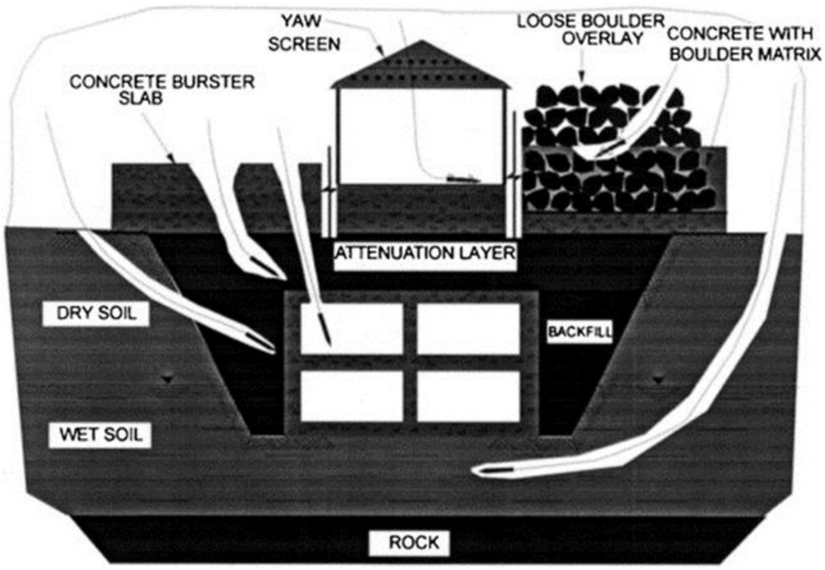


Fig. 1: Possible firing positions of a projectile beneath the surface of the ground (Source: Danielson et al., 2000).

The pressure experienced to a structure from a nearby explosion depends on the type of explosive used and the characteristics of the ground. The soil type influences how quickly vibrations travel through it. When estimating ground motion, several parameters should be considered (Bukovalas et al., 2008):

- Mass and type of explosives.
- Firing depth: To generate ground motion, the released energy must not escape into the air.
- Characteristics of Soil.

The soil conditions in the construction area greatly influence the intensity of ground vibrations and the characteristics of soil movement. The soil's response is determined by various factors, including the type and grain size of the soil material (such as sand or clay), its relative density, and its degree of saturation. Notably, when the degree of saturation exceeds 95%, the propagation of ground shockwaves becomes especially significant. For instance, when soil saturation increases, the maximum ground velocities can rise to 2-10 times higher (Bukovalas et al., 2008). Therefore, it is advisable to avoid constructing fortifications in saturated soils. Additionally, granular materials like sand and gravel are more suitable for use as backfill than clay. This is because granular materials dissipate ground vibration more quickly, leading to lower pressure (Koukis, 1985). A crater created by a ground explosion does not immediately threaten the fortification. However, it is crucial to consider this factor when designing fortifications, especially if the crater's size might compromise the structure's protective layer, making it vulnerable to impacts from other weapons. Additionally, in certain instances, the soil debris projected during the explosion could pose risks to both personnel and sensitive equipment involved in the project (Bukovalas et al., 2008). The shape of a crater formed by an explosion is influenced by several factors: the type of explosive used, the depth at which it detonates, the geological layers (stratigraphy), and the characteristics of the surrounding soil. In explosions occurring in rock or concrete, only specialized piercing weapons can reach the necessary depth to create a crater. In contrast, an explosion in loose and saturated sand can lead to local soil liquefaction, resulting in a wide and shallow crater (Koukis, 1985).

4. SOIL AND ROCK PENETRATION

When examining ground or rock penetration, it is crucial to consider the likely trajectory of the projectile and the depth it will reach in the soil. The penetration depth depends on several factors, including the type and shape of the projectile, its velocity, the angle of impact, and the stratigraphy and properties of the geomaterials. A high-speed impact, a vertical entry, and the presence of soft ground can significantly reduce ground stability. Additionally, well-consolidated gravels or coarse sand have much lower permeability compared to very soft clay, which should be treated as a flowable material in design considerations (TM5-855-1, 1997). Experimental findings indicate that when a projectile collides with granular soil material at low speed, and the density of the soil is similar to that of the projectile, the soil acts like a solid. In this case, the penetration depth of the projectile is nearly zero. On the contrary, when the projectile collides with granular material at high velocity, and the density of the projectile is significantly greater than that of the soil particles, the soil behaves like a liquid. In this scenario, the projectile can penetrate the soil as it would penetrate a viscous liquid (Goey et al., 2012). When impact occurs on rock, it is typically considered to be invulnerable. However, the subsequent crushing of the rock can alter its properties and strength. Additionally, the strength of the rock decreases as its porosity increases due to corrosion, and any cracks that form can significantly affect penetration depth. Other factors influencing the penetrability of a rock include its density, modulus of elasticity, and degree of disintegration. Meanwhile, the overall quality of the rock is determined by the presence of fractures and discontinuities within its structure (TM5-855-1, 1997). To protect important underground fortification structures from penetration and to reinforce existing structures, various protective measures are often implemented. These include the use of a concrete protection slab placed on an earth backfill where the work is embedded and/or the installation of layers of natural hard rock boulders over an artificial fill, typically made of gravel (Figure 2).

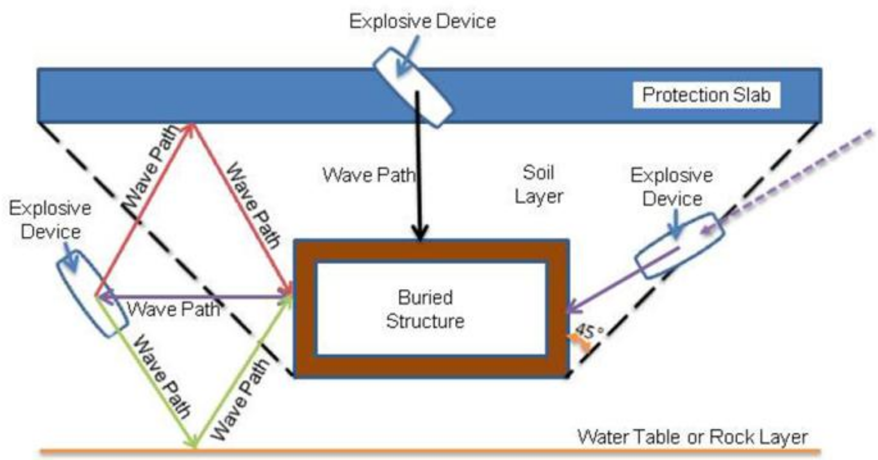


Fig. 2: Protection slab on earth backfill (Source: Chowdhury & Wilt, 2015)

The choice of the most suitable method depends on local conditions and the construction techniques used in the project. A combination of the two methods mentioned above can be employed, such as placing layers of boulders on top of a concrete burster slab. These protective measures aim to stop the trajectory of the targeted weapon. When a projectile attempts to penetrate the protective structures, it may either be destroyed, deflected, or diverted from its original course (TM5-855- 1, 1997). The dimensions and thickness of the pre-blast plate are determined by the distance required to effectively deflect the projectile, ensuring that the surrounding structure is not impacted by the shock wave generated when it is fired. The backfill material surrounding the project consists of friable quarry sand and gravel, which effectively dissipates the shock wave. Additionally, drainage measures must be implemented to prevent the gravel from becoming saturated with water. If the ground is saturated, the vibrations caused by the explosion may exceed the construction's ability to withstand them safely (Bukovalas et al., 2008).

5. TYPES OF FORTIFICATION STRUCTURES

Fortification structures are classified into three main types based on their construction methods (Bukovalas, 2008; see Table 1 for comparison):

Type I structures (Figure 3), are built on or very near the ground surface, making them safe from direct impact and penetration by the design weapon.

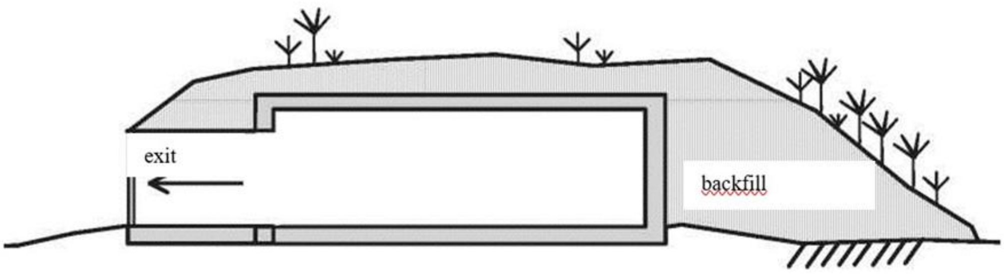


Fig. 3: Type I fortification (Source: Boukovalas, 2008)

Type II structures (Figure 4), are fortifications constructed using cut-and-cover methods, ensuring they are placed deep enough below the ground surface to withstand attacks from armor-piercing weapons. Additionally, protective measures are implemented, such as the construction of a pre-blast slab, which may or may not include layers of boulders for added defense.

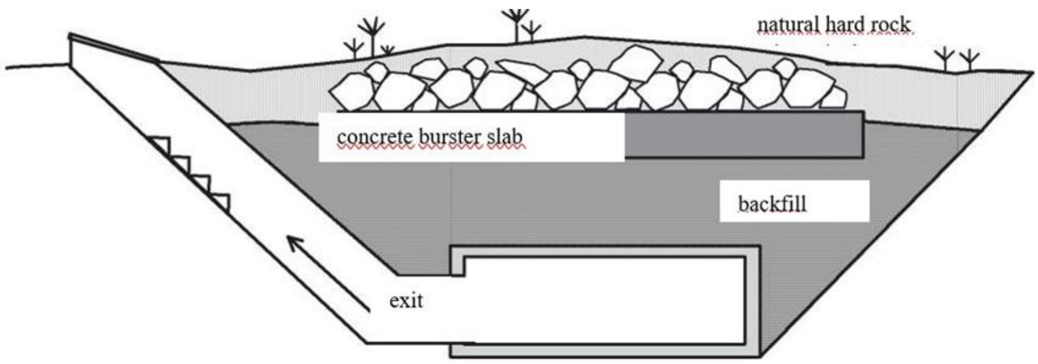


Fig. 4: Type II fortification (Source: Boukovalas, 2008)

Type III structures (Figure 5) are fortifications built as tunnels within rock masses. In this case, the protective zone is provided by the overlying rock mass, which safeguards the structure from attacks, even from high-penetration weapons. Furthermore, the project is nearly undetectable from both the ground surface and the air.

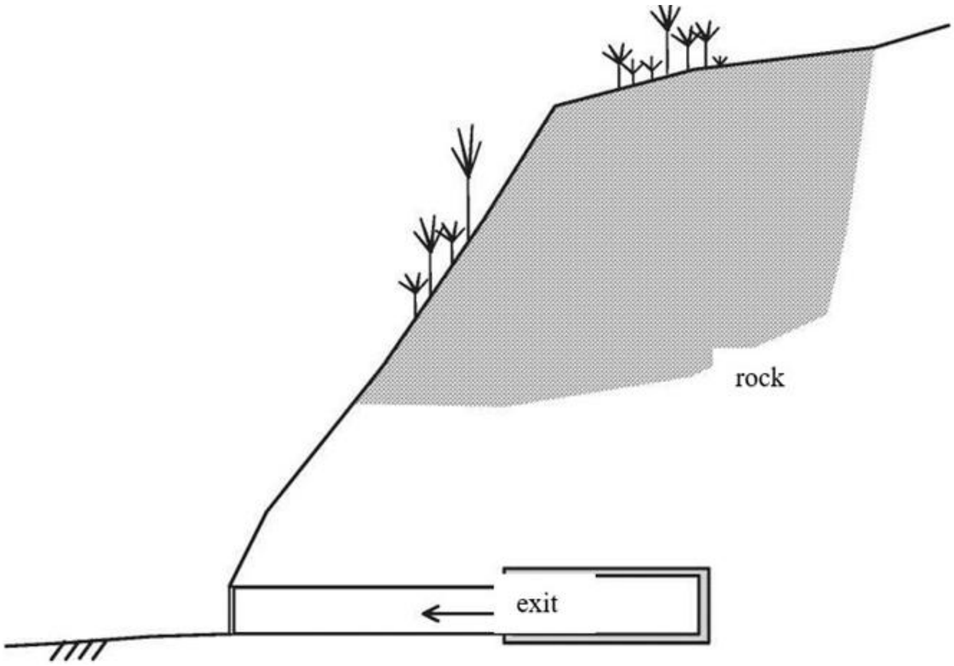


Fig. 5: Type III fortification (Source: Boukovalas, 2008)

Table 1: Advantages and disadvantages of the three types of fortifications (Bukovalas, 2008)

Type	Degree of Protection	Advantages	Disadvantages
I	low to medium	• low cost • simple construction	• decreased strength • decreased coverage
II	medium	• high strength • high coverage	• increased cost of excavation and overlay measures • need for specific inputs e.g. elevators
III	high	• immune • undetectable • no backfill required	• specific construction equipment required • increased costs of support measures in case of low-quality rock • difficult cleanup of entrances/exits after impact • the strength of the rock influences the design of the project

6. A LEGENDARY CASE STUDY - METAXA LINE FORTS (1936-1941)

Between the two world wars, fortification construction was widespread across Europe, and Greece was no exception. From 1936 to 1941, a series of fortifications were built along the northern mountainous border with Bulgaria, known as the "*Metaxas Line*" This line was named after the then-Prime Minister Ioannis Metaxas and represents the longest fortification line constructed in Greece during the 20th century (Kupka, 2001). The Metaxas fortification line was a significant technical undertaking for its time. This project involved not only hundreds of surface constructions and thousands of meters of underground galleries and shelters but also the challenges posed by difficult mountain terrains, harsh weather conditions, and the economic situation of the country during that period. The overall scope of the project included road construction, tunneling, surface works, water supply systems, drainage, ventilation, lighting, and trench excavation. A total of 21 fortifications were constructed exclusively by Greek engineers and laborers along a line approximately 350 kilometers long (Figure 6), all within just four years. Additionally, a road network totaling 174 kilometers was opened. The excavations, both underground and on the surface, totaled 900,000 square metres. The project included 650 surface works, 13,000 metres of underground shelters, and 24,000 metres of underground transportation corridors. In total, 180,000 cubic metres of concrete were prepared. The overall construction cost reached 1.50 billion drachmas (approx. 420 million euros present value), with 68.28% allocated to the contractor's work and 31.72% to materials and overheads (Tasios, 2002).

Fig. 6: Map of Metaxas Line Forts (Source: www.maphub.net)

The geology of the terrain along the Metaxa Line exhibits significant variation, as the alignment spans approximately 350 kilometers across three distinct geotectonic zones along the Greek-Bulgarian border: the Rhodope Massif, the Serbomacedonian Massif, and the Circum-Rhodope Zone. The mountainous and semi-mountainous regions within these zones are predominantly composed of massive metamorphic and plutonic rock formations—such as gneiss, marble, schists, granite, and rhyolite (IGME, Geological Map of Greece, 1983)—which provide advantageous conditions for the construction of fortifications and strategic defense against hostile incursions. So, the Metaxa Line incorporates a series of forts situated on rocky slopes and ridges, capitalizing on the natural strength and elevation of the terrain. Figure 7 offers a view of the Nevrokopi plateau (see map in Figure 6 for location) as seen from Fort Lisse.

Fig. 7: View of Nevrokopi plateau from Fort Lisse (Source: www.ww2wrecks.com, Photo by Miltiadis Dimitriadis)

6.1 Planning

One of the primary requirements during the planning stage of the projects was to optimize the natural defensive capabilities of the terrain where the fortifications would be constructed (Kupka, 2001). This meant the individual fortification structures needed to conform closely to the mountainous topography to minimize access routes and utilize natural barriers, such as marshlands and rivers. The goal was to reduce the reliance on artificial barriers along most of the fortification lines. Given the terrain conditions, it was extremely challenging, if not impossible, for enemy motorized units to navigate through Greek territory, especially since the road network had nearly vanished by that time. As a result, this objective was largely accomplished. During the initial planning of the projects, the officers at each fort assessed the level of resistance needed to withstand potential attacks. These resistance levels were based on the types of weapons that the attackers were believed to possess. Table 2 illustrates the necessary soil protective layers for underground fortifications, based on soil type, for four projectiles of varying calibers, each with different maximum penetration depths (GES/DIS, 1987). The type of soil and the thickness of the soil cover influenced the dimensions of the underground reinforced concrete structures. This was crucial to ensure that the underground spaces were fully shielded from projectiles penetrating the ground and to protect personnel from the strong ground vibrations caused by bombings. Notably, in rocky soil, the thickness was significantly less than that found in common or cohesive soils (GES/DIS, 1987).

Table 2: Soil thicknesses for the protection of underground fortifications, based on soil type and projectile caliber (GES/DIS, 1987)*.

Bullet Caliber (mm)	Common soil		Cohesive soils		Soft rock**		Semi-hard rock**	
	Penetration depth (m)	Landcover thickness (m)	Penetration depth (m)	Landcover thickness (m)	Penetration depth (m)	Landcover thickness (m)	Penetration depth (m)	Landcover thickness (m)
75	3,50	**5,10**	1,60	**3,10**	1,20	**2,55**	0,70	**1,85**
105	5,00	**7,35**	2,20	**4,35**	1,50	**3,50**	1,00	**2,60**
155	6,00	**10,00**	3,00	**6,60**	2,30	**5,65**	1,30	**4,10**
220	8,50	**14,50**	4,00	**9,45**	3,30	**8,00**	1,50	**5,75**

*comma is used as decimal point

** Semi-hard rock includes hard limestone, while soft rock encompasses chalk, marl, shale, and cobblestones.

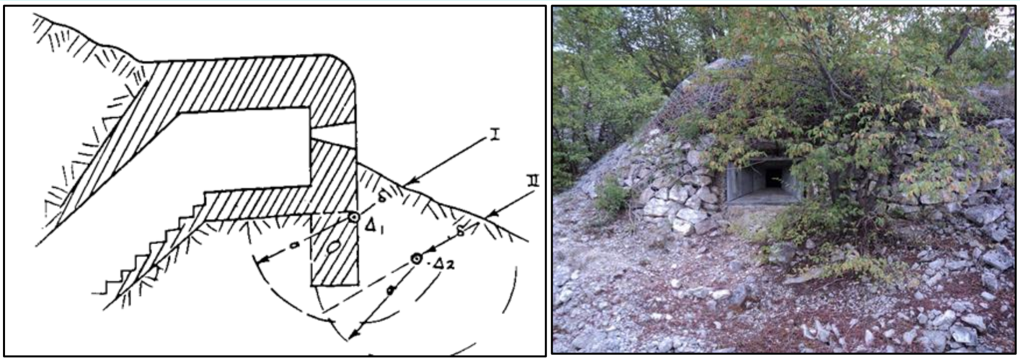
6.2 Construction Description

Each complex of fortifications was made up of a series of underground spaces connected by a complex network of galleries. These galleries led to surface firing and observation positions. Depending on their armament and intended purpose, the surface positions were categorized into searchlight canopies, observation posts, machine gun placements, mortar positions, grenade launcher sites, and locations for anti-tank and anti-aircraft guns (Girbatsis, 2024). The fortifications also featured anti-tank obstacles, such as ditches and reinforced concrete structures. The underground facilities were built to meet both the living needs of the personnel and support their mission. They included administration offices, a telephone center, ammunition depots, quarters for officers and gunners, a kitchen, an infirmary, food storage areas, sanitary facilities, water tanks, ventilation systems, and more. Each fort was designed to be self-sufficient in food, water, and ammunition for ten days (Girbatsis, 2018).

6.2.1 Permanent structures on the surface.

Both the surface structures that connected to underground galleries and the individual independent surface fortifications were constructed using reinforced concrete. The requirement for high concrete strength, ranging from 300 to 400 kg/cm^2, led to the use of special high-strength cement at concentrations between 400 kg/m^3 and 800 kg/m^3 on the outer side of the roof slabs in the surface works. In contrast, the typical practice up to that point used only 250 kg/m^3 of cement. The reinforcement of the structural elements for the surface works was based on the behavior of reinforced concrete under explosive loads, such as impact, penetration, and explosion. This topic regarding the behavior of concrete subjected to explosions was analyzed by the professors at the National Technical University of Athens, N. Kitsikis, P. Paraskevopoulos and A. Rousopoulos and represents a technical innovation, as it remains a subject of controversy today (Tasios, 2002).

The most significant innovation was the invention of fiber-reinforced concrete. This development involved reinforcing the surface structures of concrete with thin steel bars that are densely arranged in three dimensions and not interconnected. The foundation strengthening for surface works was considered necessary only in situations with a significant soil slope. This was to prevent the potential overturning or destruction of the project caused by the underground breach of a projectile beneath the project's floor. The strengthening was achieved by embedding the structure's front wall to an appropriate depth in the ground, ensuring that the floor remained outside the energy radius of the projectile's underground rupture (Figure 8) (GES/DIS, 1987). Due to the absence of a protective soil layer in the section of the project that was above ground, a decision was made to safeguard the descent to the shelters by replacing the missing soil layer with reinforced concrete. To facilitate this, a nomograph was utilized to determine how the thickness of the concrete coating would change during descent based on the thickness of the overlying soil. Figure 9 provides the relevant illustration accompanying this nomogram (GES/DIS, 1987).



(a) (b)

Fig. 8: (a) Reinforcement of foundation for surface construction (Source: GES/DIS, 1987), (b) Implementation of foundation reinforcement in a surface-level structure at Fort Lisse (Source: www.museumfinder.gr)

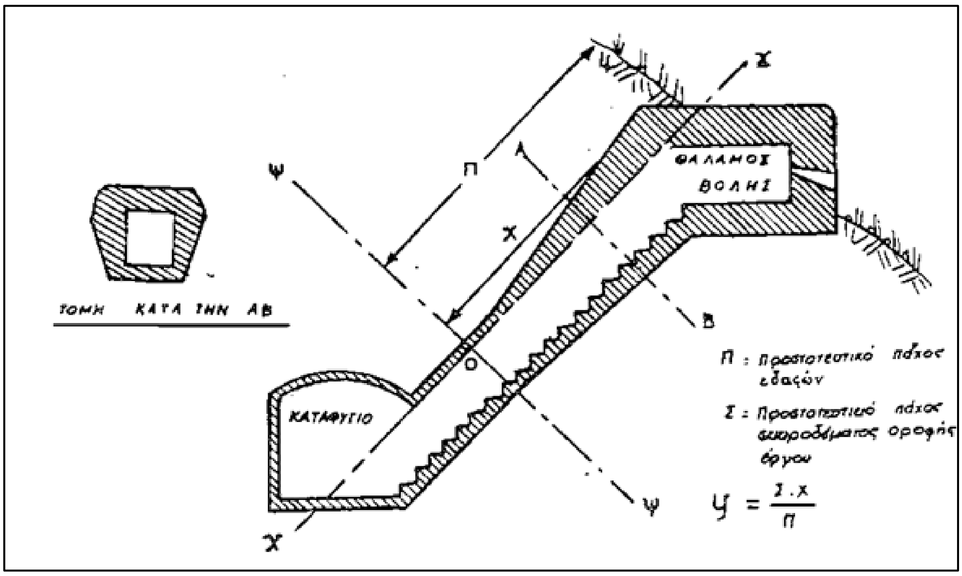


Fig. 9: Illustration from the specific nomogram showing how concrete coating thickness varies with the thickness of the soil above it (Source: GES/DIS, 1987)

6.2.2 Underground Constructions

All the underground areas of the fortifications of the Metaxa Line were constructed using conventional mining methods. The construction progressed in distinct sections (Figure 10). The excavation required precise carving of the arcades, both horizontally and spatially. To facilitate this, a detailed scale plan of the layout of the galleries and shelters was created at a scale of 1:200 (Kato Nevrokopi Municipality, 2018). The excavation process was guided by a speedometer, and the galleries were supported by rough timber ties. Each underground fortification system was accessed via stairs or inclined galleries, while vertical communication between the underground galleries and surface works was achieved through vertical and steep stairs.

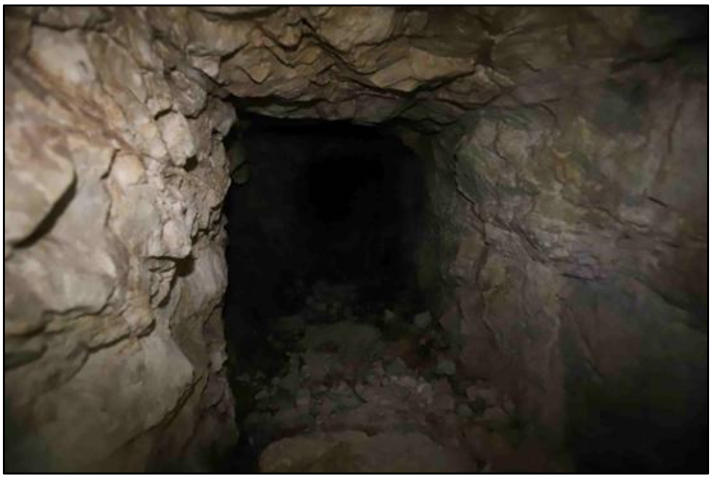


Fig. 10: Unfinished portico at Lisse Fort, constructed using conventional mining methods (Source: Personal file)

Mining began on the southern side of the hill that was to be fortified. After establishing a central corridor, several smaller corridors branched off, leading to the remaining underground spaces. The cross-sections of the structural elements in the underground works were much smaller than those in the surface works, as they were not exposed to direct impacts. The concrete used in the galleries contained 250 kg/m^3 of cement and 50 kg/m^3 of theraic earth. This combination was particularly beneficial for wet soils, as it enhanced the concrete's strength and improved its waterproofing properties. The incorporation of theraic earth represented another technical innovation in the construction of underground fortifications (Tasios, 2002). A galvanized sheet was used to cover the dome of the roof for waterproofing purposes. Additionally, stonework was incorporated between the cladding of the portico and the natural ground to ensure continuous water drainage. This water was then directed to a well located along the arcades (Kupka, 2001). Figure 11 displays an unfinished portico at Fort Rupel, where the cross-sections of the walls and the roof of the tunnel, approximately 20 cm thick, can be observed. It also illustrates the corresponding weights, the sheet metal sealing, and the rock that has been inserted between the tunnel lining and the ground to facilitate water drainage. In cohesive rocky soils, where there is no risk of collapse, the cross-sections of galleries and shelters have a rectangular shape with a semicircular roof. In contrast, in non-cohesive soils, the cross-section is oval, as this design is statically more resilient (Figure 12; Girbatsis, 2018). Additionally, the lining of underground galleries in cohesive soils is constructed with plain concrete, featuring structural elements that range from 0.15 to 0.20 metres in thickness. In non-cohesive soils, the thickness of the structural elements is typically 0.20 metres.

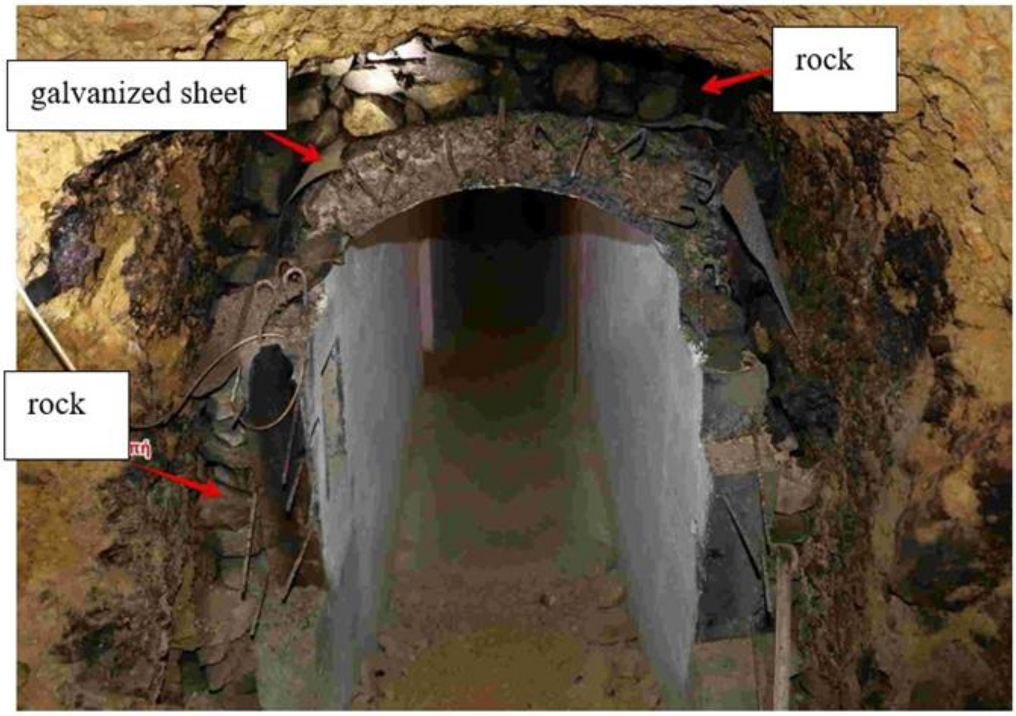


Fig. 11: Unfinished portico at Fort Rupel (Source: Personal file)

Fig. 12: Gallery sections based on the terrain (Source: G.E.S. poster at Rupel Fort)

7. CONCLUSIONS

A fundamental principle in defense operations is the careful selection of terrain and full utilization of its characteristics. The application of engineering geology has become essential in military operations, preparing technical geological studies in the field crucial for assessing soil parameters and interpreting the geological conditions of an area during the planning and construction of military projects. Geological and geotechnical factors significantly influence the propagation of shock waves and ground vibrations following an explosion. Additionally, exploiting the local terrain can help conceal and shield military structures. Overall, constructing fortifications in high-quality rock formations greatly minimizes the risk of damage from direct impacts. The construction of underground facilities is a common strategy in military projects due to the high level of protection they provide. Underground structures are less susceptible to direct hits and offer substantial cover, making them difficult to detect. Ground vibration during construction depends on various soil properties, such as type, grain size, relative density, and degree of saturation. Saturated soil can increase the risk of failure, which is why it is generally not advisable to undertake projects in areas with high water tables. The choice of construction method—whether above ground or underground—depends on factors such as the project's security requirements, the type of weapons involved, topographical features, and strategic or economic considerations. For projects requiring a high level of protection, tunneling in rock is preferred. For medium-protection needs, cut-and-cover methods are employed, while low to medium-protection projects can be constructed at or very close to the surface.

Finally, the Metaxas Fortification Line is the most iconic complex of fortifications in Greece and continues to be a subject of study due to the remarkable durability of its structures and the innovative construction techniques employed. A key aspect of the design was the effective use of the mountainous terrain and natural obstacles. The type of soil and its thickness above the underground structures significantly contributed to their protection and minimized ground vibrations from projectile explosions. Notably, in rocky areas, the thickness of the fortifications was considerably reduced compared to that in common or cohesive soils. Many of these forts remain intact today, and some parts are fully functional and open for visitors.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflict of interest regarding this publication.

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