SECURITY & DEFENCE QUARTERLY
https://securityandefence.pl/

Operations in subterranean systems: Terrain and weather variable

José Paulo Silva Bartolomeu

jpbartolomeu@gmail.com

https://orcid.org/0000-0002-0150-2884

Military University Institute, Portugal, R. Pedrouços 122, 1449-027 Lisboa, Portugal

Abstract

The overall objective of the research is to summarize tactical considerations, resulting from terrain and weather analysis, to support the preparation, planning and execution of subterranean operations. The study used the Grounded Theory for collection, analysis, and systematic treatment of data. The main data sources for the study consisted of purposive sampling from operations in subterranean systems and lessons learned from them. Two new sub-variables are now proposed to be included in terrain and weather variable from mission analysis model for subterranean operations: Subterranean system's location and accesses and subterranean system features. The key to finding subterranean systems is through terrain analysis, physical ground search, operational indicators, and intelligence products. The analysis of the features of the subterranean system and its mapping is critical for developing courses of action. Forces must be trained and equipped to manoeuvre and combat at short distances and poor visibility conditions. Surface access points and command and control bunkers usually are assessed as key terrain. Obstacles placed at intersections are excellent ambush sites. Accessing sophisticated structures requires specific techniques and equipment. Inside the subterranean systems, existing angles, barriers, walls, cavities, stairwells and other objects provide cover and concealment. Water can make it impossible to build subterranean systems, place obstacles, or even use them; droughts can "create" new avenues of approach. Clouds and fog difficult the detection of subterranean systems. The terrain and weather analysis model, the characteristics, and the tactical considerations presented, all combined, support the preparation, planning, and execution of operations in subterranean systems.

Keywords:

operations, tunnel, tactical, subterranean, terrain and weather

Article info
Received: 29 December 2019
Revised: 30 March 2020
Accepted: 31 March 2020
Available online: 14 April 2020
DOI: http://doi.org/10.35467/sdq/119946

Introduction

Subterranean systems (spaces or structures located beneath the ground) have been used recurrently by states, regular forces, irregular forces, terrorists, criminals and civilians throughout the history of mankind. Archaeological pieces of evidence from excavations at Troy show engineering units of King Sargon, ruler of Akkad between 2334 and 2279 BC, mining under enemy city walls (Springer, 2015).

The tactical value of subterranean systems has been exploited by several actors, in varied tasks, operations, and conflicts. They have been used to store water, equipment, weapons and ammunition, lodging, command and control (C2), weaken defensive structures, avoid obstacles at the surface, access inaccessible places by other means, achieve surprise and generate attacks, protection, gain time, production, and defence, and they also have been employed as routes of communication, prison, and hospital, among other uses (Richemond-Barak, 2018, pp. 3, 11, 42, 46; United States Army [USA], 2017b, pp. 1–1, 1–2; USA, 2019a, pp. 7–32, 7–34). Improvements in the capability to construct spaces and underground structures enhanced their usefulness and proliferation. Contenders with less strength or capabilities use these systems to gain freedom of action; state actors use them to hide and protect military capabilities. In the future, more conflicts will take place underground or at least incorporate elements of subterranean warfare, particularly when one party has aerial and technological superiority over another (Richemond-Barak, 2018, p. 53).

Subterranean systems have very specific characteristics and present significant challenges to fire, control, and force protection (USA, 2019a, p. 7–32). The identification of the subterranean system's location, features, and vulnerabilities, the communications and navigation, as well as assessment of the enemy, can all be very challenging. Models that reflect the main characteristics and effects of terrain and weather in operations in subterranean systems can be very useful to state operational requirements, build capabilities and draw up plans and orders.

Considering the relevance of this subject, the object of research selected for this study is the terrain and weather in subterranean operations. Data collection includes operations in subterranean systems in the contemporary age, in several regions of the World where wars and conflicts took place. Theoretical sampling and saturation delimited the number of operations analysed (Glaser and Strauss, 1967, pp. 61, 62, 111, 112). In relation to content, the study only addresses operations in subterranean systems at the tactical level.

The overall objective (OO) of the research is to summarise tactical considerations that result from terrain and weather analysis to support the preparation, planning and execution of subterranean operations. The following specific objectives (SO) were established to operationalise this objective:

SO1: Propose one terrain and weather analysis model for ground forces operating in subterranean systems;

SO2: Deduce the main characteristics and effects of terrain and weather variable in subterranean systems.

The objectives presented and the inputs from systematic collection and analysis of data during the investigation allowed the construction of the following central question (CQ): what tactical considerations that result from terrain and weather analysis should guide the preparation of ground forces to conduct operations in subterranean systems?

The study is organised in such a way that the second section begins after the introduction, where a theoretical and conceptual framework is made that describes relevant concepts for ground forces operating in subterranean systems. The third section describes the methodology and method adopted. The fourth section contains data and discusses the results for formulating theories and explanations for observed patterns. The fifth section sums up the tactical considerations that result from Terrain and Weather analysis, to support preparation of ground forces to conduct operations in subterranean systems. Finally, the main conclusions obtained in the study are listed.

Theoretical and conceptual framework

This section describes some structuring concepts for the theme under study. The review of the literature focuses on military operations, mission analysis terrain and weather variable, and subterranean systems categories. The analysis model adopted to conduct the research is also presented.

Military operations are complex, consisting of human endeavour (a clash of wills characterised by threat or application of force and violence), conducted in dynamic and uncertain environments (often among populations), and designed to achieve a political purpose (USA, 2019b, p. 1–1). An operation, according to NATO (2018, p. 91), consists of a sequence of coordinated military actions with a defined purpose. The publication *Operations (ADRP 3-0)* defines *operation* as a "sequence of tactical actions with a common purpose" (USA, 2017a, p. 1–7). "A tactical action is a battle or engagement employing lethal and nonlethal actions designed for a specific purpose" (enemy, terrain, friendly forces, or other entities) (USA, 2017a, p. 3–13).

Land operations occur across the entire expanse of the land domain focused on the destruction or dislocation of enemy forces or securing key land objectives that reduce the enemy's ability to conduct operations (USA, 2017a, p. 1–8). The land domain includes surface, subsurface and supersurface areas; "subsurface areas consist of areas below the surface area" (USA, 2019a, pp. 7–32, 8–1). The analysis of the mission variables - *mission, enemy, terrain and weather, troops and support available, time available, and civil considerations* (METT-TC) refines the leader's understanding of the situation and is essential for developing courses of action (COA) for a given operation (USA, 2016, p. A–2; Exército Português [EP], 2012, pp. 1–12, B–23, B–24; USA, 2017a, p.1–2; NATO, 2019, E–1). Terrain and weather analysis consist in collecting, processing, evaluating and interpreting geographical information on natural and man-made features, slope and elevation, soil conditions, and vegetation, on the impact of climate and weather on terrain, and their effects on the forces. At tactical level, analysts use the five military aspects of terrain expressed in the memory aid OAKOC – observation and fields of fire, avenues of approach, key and decisive terrain, obstacles, cover and concealment -, and the military aspects of weather - visibility, wind, precipitation, cloud cover, temperature, and humidity - to develop assessments (USA, 2016, pp. 10-5, A–3, A–4; EP, 2012, pp. 4–7, 4–8; USA, 2019a, pp. 4–5, 4–18, 4–19).

Subterranean systems are organised into three main categories: tunnels, natural cavities and caves; urban subsurface systems; and military purpose underground facilities (USA, 2017b, p. 2–1). Caves and natural cavities are formed by the erosion or dissolution of limestone and can be adapted for operational purposes. Urban subsurface systems include basements, catacombs (sometimes encountered in older sections of cities), civil defence shelters, underground garages, subway lines (which usually have electrified rails and power cables, and are located under main roads), mines, aqueducts, sewers (sanitary, storm, or combined system), passages and utility tunnels (NATO, 2017, p. 4–25; USA,

2017b, pp. 2–1, 2–2; USA, 2017c, p. 1–6; Richemond-Barak, 2018, p. 47; USA, 2019a, pp. 7–32, 7–34). These systems typically benefit from further protection resulting from surface constructions. In addition to being used by the population for day to day activities, they can also be used for illicit or military purposes.

Underground facilities are subdivided into shallow and deep facilities, which are known as "cut and cover" and '"deeply buried" (Sepp, 2000, p.14). Military purpose underground facilities have redundant power, water, ventilation, and communications infrastructure, blast doors, and protection against unauthorised access in the form of at least one, if not multiple barriers (doors, gates, hatches and framing, as well as the presence of any reinforcement to hinges and locking mechanisms) (USA, 2017b, pp. 2–2).

Shallow facilities represent most underground facilities and include underground silos and bunkers, usually are dug out, built, and then re-covered with the original earth ("cut and cover"). "They frequently have down ramps that provide access from the surface to the facility and may have thick, reinforced concrete walls and ceilings" (USA, 2017b, pp. 2–5).

Deep facilities are state facilities or military bases, constructed by tunnelling operations, settled deep below the surface or deep within mountains (have more than 20 m of overburden and are surrounded by solid rock), and are very difficult to detect (Sepp, 2000, pp. 5, 6, 7). These facilities are immune to attack by most weapons, are larger, better equipped, potentially containing dozens of rooms, multiple portals, and doors designed to prevent unauthorised access and/or protect against blast effects (including nuclear blast doors) (Sepp, 2000, p. 10; Richemond-Barak, 2018, pp. xviii, 52; USA, 2017b, pp. 2–1, 2–2, 2–4, 2–5). The structuring concepts are extremely relevant to the construction of the conceptual framework.

During the review of the literature, it was assessed that land operations occur in surface, subsurface and supersurface areas focused on the destruction or dislocation of enemy forces or securing key land objectives that reduce the enemy's ability to conduct operations. Land operations are conducted in dynamic and uncertain environments. Terrain and weather analysis is essential for developing COA. From the land operations perspective, subterranean systems can be organised into three main categories: tunnels, natural cavities and caves; urban subsurface systems; and underground facilities for military purpose. These categories incorporate very relevant features for this study and for conducting operations in areas below the surface area (subsurface); for this reason, a new sub-variable - subterranean system features – was added to the variable terrain and weather from the mission analysis model in use in Portuguese Army, USA, and NATO doctrines. The proposed analysis model in table 1 (Provisional model for terrain and weather analysis in subterranean systems) will be further refined due to the products obtained through data collection and analysis, as specified in Grounded Theory.

Table 1. Provisional model for terrain and weather analysis in subterranean systems

Dimension	**Mission variables**	**Sub-variables**
Land operations in subterranean systems	Terrain	Subterranean system categories and their features (dimensions, depth, type of construction, level of protection, purpose and vulnerabilities), observation and fields of fire, avenues of approach, key or decisive terrain, obstacles, and cover and concealment.
	Weather	Visibility, winds, precipitation, cloud cover, temperature, and humidity.

Source: Adapted from Portuguese Army (EP, 2012), USA (2016; 2017b; 2019) and NATO (2019) doctrines

The CQ focused the theoretical and conceptual framework and the building of a provisional model for mission analysis in subterranean systems, but this model requires consolidation and verification.

With CQ as a reference, and attending the defined SO, the following derived questions (DQ) were formulated:

DQ1: What Terrain and weather analysis model should be adopted by ground forces operating in subterranean systems?

DQ2: What are the main characteristics of terrain and weather in subterranean systems?

In order to answer to DQ1 it is possible to present the deduced analysis model as hypothesis; however, the verification of this hypothesis and the answer to DQ2 requires data analysis and an inductive generation of theories (Creswell, 2009, p. 70).

Methodology

This section describes the methodology followed and the method used in the research.

The methodology portrays steps that facilitate study understanding and results obtained while simultaneously allowing its replication in future investigations. The research strategy adopted is mixed, where the central premise is that of complementarity, which enables the collection, analysis and integration or relationship of qualitative and quantitative data (Creswell, 2009, p. 203). To build the theoretical and conceptual framework, which consists of a review of the literature and definition of the analysis model, deductive reasoning was adopted. A qualitative research method was adopted for collection and analysis of data, as well as for testing of existing theories. This allows the emergence of new ideas and theories (Bryman, 2012, p. 387), i.e., new ideas and theories for ground forces to conduct military operations in subterranean systems. As the results obtained with inductive reasoning alone do not always allow their generalisation or the replication of results to other contexts, iterative elements of deduction and abduction are incorporated again throughout the process (Charmaz, 2008, pp. 155–157; Bryman, 2012, pp. 26, 401).

Research privileges empirical observation and the contextual conditions in which phenomena occur to create theories, and relies on the Grounded Theory for the collection, analysis, and systematic treatment of data (Glaser and Strauss, 1967; Strauss, 1987). This research design exploits primary and secondary data sources, enhances research questions, and permanently combines research with data analysis, providing a rich and complete insight into subsurface operations. The method refers to the participants and procedure, data collection instrument(s) and data processing technique(s) used.

The main data sources for the study are the operations in subterranean systems and lessons learned from them. Because of the impossibility of using the entire universe of study (population), representative samples of the target population were selected (Fortin, 2003, p. 202). The deliberate choice of the samples is known as "purposive sampling" (Yin, 2016, p. 93). The subterranean operations were selected from the US Civil War, World War I, the 2nd Sino-Japanese War, the Korean Conflict, the Vietnam War, the Afghanistan War, and the recent conflicts in the Middle East (e.g., Turkey, Israel, Syria, Lebanon, Afghanistan and Iraq), and Tunisia. Samples included regular and irregular actors and these increased throughout the research due to the needs identified during data interpretation; and only stopped increasing when theoretical saturation was reached, i.e. when new data

no longer added value. The data research was done at the Military University Institute in Portugal, primarily on the Internet, with access to international sources.

Documentary and non-documentary techniques were used for data collection. Documentary techniques relied on written and unwritten instruments to access primary and secondary sources. The written instruments consisted of books, scientific articles, doctrinal publications, and newspaper articles; the unwritten instruments comprised photographs, images and videos. As a non-documentary technique, participant observation was adopted. In this case, the researcher was part of the community under study, as well as a Portuguese Army Officer and Land Military Tactics teacher, and thus had access to the perspectives of the people with whom he interacts and to the group discussions.

Manual techniques and word documents were used for data processing. A memo prepared from the sources consulted originated from each of the operations. Relevant data is extracted from the memos and coded manually. Subsequently, the memos were used to perform analyses for each type of operation by the proposed analysis model, and the results obtained and published. The most relevant features of the variable and sub-variables were compared with memos drawn from the US and NATO doctrines on the same theme. As a result of the discussion, theories and explanations were generated for the observed patterns, providing the answer to DQ2 and CQ.

Presentation of data and discussion of results

In subterranean operations, leaders analyse the same mission variables that they use in any land operation; however, they may have to do some critical thinking and "[a]dditionally, there is a high probability that the situation will be extremely unclear." (USA, 2017b, p. 3–3). Thus, seeking to contribute to the clarification of the situation during the mission analysis for conducting operations in subterranean systems, this section initially presents data for answering to DQ1. After the consolidation of the analysis model, together with data presented for the mission variable and sub-variables, theories and explanations for observed patterns are formulated, consisting of the main characteristics and effects of the terrain and weather variable in subterranean systems and providing the answer to DQ2.

Consolidation of the analysis model

The theoretical saturation obtained through the study confirmed the validity of the variable and sub-variables proposed in the provisional model of analysis. In addition, during data collection, the location and access to some categories of subterranean systems were identified as one of the major concerns of the forces (e.g., intelligence effort, search operations, and local security operations to deny location). This concern is also noted by several authors; here are some examples:

- "Tunnel detection demands extreme care and thoroughness on the part of friendly troops to locate hidden entrances or other evidence of their existence" (US Military Assistance Command, Vietnam [USMAC-V], 1966, p. 18);

- "Due to the concealed character of the tunnel, detecting it constitutes a major part of the operation" (Shapir and Perel, 2014, p. 53);

- "Detecting the tunnels is a very very difficult task" (Hecht, 2015);

"[S]earching for and finding underground facilities is the most important step in dealing with these targets" (Sepp, 2000, p. 15).

Given the collected data (presented in this section), corroborated by the aforementioned authors, it is assessed relevant to add a new sub-variable into the variable terrain and weather: Subterranean system's location and accesses. The data obtained also reflects the need to include the environmental factors (e.g., air quality, existence of animals or hazardous materials), slope and azimuth (especially in tunnels and sewers) in the analysis of the subterranean system features, as well as connections with other systems.

The theoretical coding given in table 2 is thus obtained, also providing an answer to DQ1.

Table 2. Model for Terrain and Weather analysis in subterranean systems

Dimension	Mission variables	Sub-variables
Land operations in subterranean systems	Terrain	Subterranean system's location and accesses, subterranean system categories and its features (dimensions, depth, type of construction, level of protection, environmental factors, slope and azimuth, connections with other systems, purpose and vulnerabilities), observation and fields of fire, avenues of approach, key or decisive terrain, obstacles, and cover and concealment.
	Weather	Visibility, winds, precipitation, cloud cover, temperature, and humidity.

Source: Adapted from Portuguese Army (EP, 2012), USA (2016; 2017b; 2019) and NATO (2019) doctrines

Subterranean system's location and accesses

During the American Civil War, at the Siege of Petersburg (1864), the earth removed from the tunnels was concealed in the vegetation at night and fires on the surface were made to conceal smoke rising from the ventilation system (Kinard, 1998, pp. 31, 32; Schmutz, 2009, pp. 55, 61).

During World War I, the progress of excavation work was often slowed by bombardments in the entrances of the galleries. French tackled this problem by constructing alternative concealed entrances (15 m back) (Jones, 2010, p. 64). The location of subterranean systems is not easy to determine, and their existence is kept a secret from enemy forces and, sometimes, friendly forces to reduce the chances of intelligence leakage (e.g., Australian offensive against Turkish lines in September 1916 [Jones, 2010, pp. 196–198]).

In the Korean War (1950-1953), false targets and disguised tunnel entrances were built on the surface, thus contributing to increased ammunition consumption by opposing forces (Herman, 2014).

In the Vietnam War, Viet Cong tunnels were very well camouflaged; entrances, bunkers and vents were very difficult to locate (USMAC-V, 1967, p. 17). The Americans used searching tactics and techniques to locate tunnels (USMAC-V, 1968, pp. 3, 4):

- A search area, with no more than 1000 m^2, was assigned to one rifle company;

- One rifle squad had a search team and a security team rotating periodically;

- Looking for tunnel entrance/presence indicators, i.e., small trails in the vegetation, fresh food or human faeces in the vicinity, worn places on the bamboo, slight depression in or around the bamboo clump, bamboo breathing tubes (the beaches and dunes were disguised in the middle of the cactus), or isolated individuals (USMAC-V, 1968, pp. 3, 4, 6–17);

- Dogs for detecting Viet Cong fighters hiding in tunnels and sappers penetrating US bases (USMAC-V, 1966, p.12; USMAC-V, 1967, p. 17).

After the Israeli strike on Iraq's Osirak nuclear reactor in 1981, Iraqi Armed Forces started to build the walls and roofs of structures before creating underground facilities and increased the use of deep shelters and tunnels to conceal satellites and reconnaissance aircraft (Cordesman, 2003, pp. 33, 106, 218). In the Gaza Strip, the main problem for IDF in subterranean operations between 1990 and 2014 was tunnel detection. After 1990, four different systems were used (geophone systems, sensors based on optical fibres, mapping changes in ground-generated infrared radiation, and microgravity measurements), but none of them succeeded (Shapir and Perel, 2014, pp. 53–54; Cohen *et al.*, 2017, p. 100).

During the Lebanon War in 2006, Israeli intelligence discovered a bunker and a tunnel system near the town of Maroun al-Ras, but the lack of coordination with the units on the ground (and the unmanned aerial systems) resulted in tactical failures and caused severe civilian casualties (Jensen, 2019, pp. 159, 160, 162). In 2014, due to the ineffectiveness of the airstrikes, IDF conducted "Operation Protective Edge" to locate and destroy tunnels. HUMINT and ground patrols proved to be efficient ways to locate tunnels. Entrances to cross-border tunnels are generally dug from underneath buildings (apartment houses, private family houses, or public facilities) in Gaza residential neighbourhoods closest to the border (e.g. the cross-border tunnel dug from the grounds of the Al-Wafa hospital on the outskirts of the Gaza neighbourhood of Shujayia, near the Israeli village of Kfar Aza approximately 3 km away, and another, still in the process of being dug, from the basement of a mosque in Khuza'a) (Hecht, 2015).

Tunnels exit points inside Israel were only dug in the last hours before being used by the attack-teams to prevent their detection (Hecht, 2015). Things that point to a tunnel being built include underground vibrations, motors, and digging sounds. Unusual truck/vehicle activity in an area, an out-of-the-ordinary amount of bags or barrels, electric wire, generators, a great number of people entering and not leaving for a long time at one particular site, people with muddy clothes, headlamps, candles, piping, and water pumps.

Visual signs of the presence of tunnels after the construction include depressions, collapsed terrain, air holes, ventilation shafts, steam or smoke rising from the ground, turned or managed soil, worn and cut vegetation, trails, fresh food, lone individual, sinkholes, human faeces, the scent of burning wood, and food being cooked in uninhabited areas. In urban areas, signs of the presence of subsurface systems include manhole covers, steam rising from the ground, existing flooring and construction materials in houses, businesses, and other structures not under construction. There are also operational indicators such as movement of enemy forces in a specific direction, sniper fire from areas with no avenues of withdrawal, enemy inflicting casualties at relatively long-range and withdrawing without decisive engagement or being detected by friendly forces (hit-and-run tactics), or failure of cordons to prevent infiltration or withdrawal of enemy forces. Civilian buildings such as religious houses, schools, hospitals, chicken houses, stables, latrines and private homes are used to hide tunnel entrances; false walls and floors, laid-out wires and hoses, and modified fans can also indicate the presence of tunnels.

Military purposed underground facilities are constructed and operated with enormous security and reserve measures by states; therefore, they are quite difficult to find. The construction of underground facilities and their internal layout can be masked by mining operations, construction of civil infrastructure, and by transporting the material away

from the site (USA, 2019c, p. 1–6). Indicators of the existence of deeply buried facilities include gravity perturbations, emergency exits, water and sewage hook-ups, ventilation shafts, and electrical power lines (above or below ground).

Subterranean system categories and its features

During World War I, rudimentary tunnels called "Russian sap" were widely used. They were dug to a depth of 25 to 50 cm, with a width of 80 cm at the base and 1 m at the top and between 1.60 m and 1.80 m high, had no timber supports, and had a hole for ventilation every 13.7 m (Jones, 2010, pp. 185, 187, 190). When used for supplies and casualty evacuation, their width often needed to be greater to allow two-way traffic (Jones, 2010, pp. 206, 207). The sophistication of the tunnels evolved rapidly during the war. French forces built the main tunnels from 35 m to 45 m long, from 1.30 m to 1.50 m high, and 1 m width (the British ones were from 1.47 m to 1.93 m high, and 84 cm width) to provide good monitoring and ventilation; for longer tunnels, dimensions were reduced to 80 cm and 65 cm. The depth used had to be sufficient to provide protection against artillery ammunition and enemy advances (between 4 and 20 m). Whenever explosions were made inside the mine, they had to ensure that the depth and load produced "camouflets" without craters, i.e. without creating further obstacles for assaulting forces on the surface. (Jones, 2010, pp. 40, 53, 60).

Wherever possible, tunnels were built in pairs, 15-20 m apart, but connected to increase ventilation (Jones, 2010, pp. 29, 51, 53, 209). Digging tunnels at lower altitudes than the target's altitude allowed the Germans to reach depths of 40 m, thus avoiding existing craters and detection by the French (e.g., in Vauquois, a mine of 16 500 kg was detonated at 35 m deep) (Jones, 2010, p. 61). In early 1918, the tunnels reached 95 m (Jones, 2010, p. 73). Evidence of the increasing sophistication of the tunnels can be seen in the "subways", of 2 m high and wide enough for two laden men to pass. Subways had electric lighting, plans of the subways placed at entrances and mid-way along, direction boards at the junctions, traffic checkpoints (Military Police) with a telephone connection and traffic light systems (to allow large flows of forces to quickly reach the front line when necessary), and, in some cases, tramways (Jones, 2010, pp. 225, 226). From mid-1917, the excavations were covered with 8 to 10 m of earth, reinforced with strong timber, and had at least two exits, wide and high enough to allow rapid exiting by the garrison (Jones, 2010, p. 245). The German mined dug-outs at Arras were all designed to a pattern; the stairways, supports, and the timber used in them resulted from replication in sawmills (Jones, 2010, p. 232).

The caves were of varying size, some could accommodate thousands of troops, and were provided with electricity, water, gas-proof doors, and tramlines. During the Battle of Arras (April 1917), the "Thompson's Cave" was able to accommodate 700 casualties on stretchers, had dressing and operating rooms, kitchens, and latrines (Jones, 2010, 230, 231). Cellars, catacombs, quarries, mines, aqueducts and sewers were some of the urban subsurface systems used (e.g., the British used a small boy to run telephone cable through the Arras sewers [Jones, 2010, p. 228]). Most underground facilities with a military purpose were shallow. German bunkers were quite comfortable, their dimensions and configuration varied depending on the terrain and nature of the soil, but in general they were 10 m long, 2 m wide, and 1.8 m high; they were cased with jointed beams of 8 cm thickness and covered with 5-6 m of earth (in 1917, they increased the thickness of earth to 7-8 m, especially in the case of command posts, medical or signals bunkers) (Jones, 2010, pp. 215, 222). Access to the shelters was from the trench, through a hole or staircase. In 1917, the Germans began to build shellproof concrete bunkers, sized to accommodate 18 soldiers, and to permit rapid evacuation to meet an attack (Jones, 2010, p. 245).

The nature of the soil (sand, rock, or clay) is very pertinent in tunnel construction (Jones, 2010, pp. 48, 54, 96). In Flanders, geological knowledge was very relevant for deep tunnelling, assessing water levels according to the time of year, and ensuring water supply (Jones, 2010, pp. 175, 245). In Vietnam, coastal areas featured sandy or clay soils; sandstone was found in this region and was excellent for tunnelling as it required no shoring up. Laterite, a reddish-brown, hard soil rich in iron oxide was also common in the region but was difficult to dig through but, on the other hand, provided good support for tunnels, trenches, and bunker pits (Rottman, 2006, p. 18). Vietnam tunnels used to have very different lengths and extents, from simple cave-like underground structures to multilevel systems many kilometres long and were built to withstand heavy air and artillery bombardment (USMAC-V, 1967, p. 17).

Most underground tunnels were used as hiding places, but some were used for active defence, with concealed firing positions. Common features among the tunnels in Vietnam were the camouflage of the entrances; traps, spike pits, and mines placed in the vicinities of the tunnels; booby traps placed inside the tunnels near the entrance, and false passages excavated to deceive the enemy; wooden lids used for tunnel entrances strong enough to support the earth covering them and to not fall in if accidentally stepped on. The earth removed from the tunnel was spread over the surrounding area and covered with leaves, grass, and twigs. The average tunnel size was of 0.6 m wide and 0.9 m high, with several hundred metres long and consisting of a main shaft, connecting corridors, multiple entrances, several air vents, and no lighting was installed. On the perimeter of areas with tunnels, Viet Cong units and guerrillas organised defensive positions to prevent or impede enemy troop movement into the area (USMAC-V, 1965; USMAC-V, 1966, p. 4).

Karez (subterranean irrigation systems) can measure several km-length and are used in several countries (e.g. Afghanistan) for operational activities (Grau and Jalali, 1998; Jones, 2010, p. 255). The typical cross-border tunnel in Gaza Strip was dug at a depth of approximately 20 m, 1.5 m wide, and 2 m high – a few were wider to enable heavier equipment to be moved through them; the entrances were approximately one metre; there were ventilation shafts dug every few hundred metres, sides and roof lined with concrete, and electricity and telephone wires; some had several branches and rooms for storing equipment or accommodation (Hecht, 2015).

In the Lebanon War (2006), Hezbollah's bunkers were 40 m deep, with a roof built of slabs of reinforced concrete 90 cm thick, and double blast doors designed to provide protection from destructive overpressure generated by IDF high-explosive munitions. Bunkers included firing positions, operations centres, medical facilities, weapons and ammunition stockpiles, ventilation and air conditioning, bathrooms with running water, and dormitories (Lambeth, 2011, p. 44, 45, 97, 156). Under the border between North and South Korea, one of the tunnels discovered measured 1.8 km long, 2 m high, and 2 m wide and ran through bedrock at a depth of 73 m below ground (USA, 2017b, p.1–1). North Korea also built a regimental airbase into a granite mountain (USA, 2017b, p.1–1). In Jordan (2018), on the border with Iraq and Syria, the Jordanian Army unearthed part of the Trans-Arabian Pipeline (Tapline) to prevent its use by the self-proclaimed Islamic State of Iraq and Syria (ISIS) and smugglers (Future for Advanced Research and Studies [FARS], 2018).

Deep underground facilities are usually much larger and have multiple barriers, e.g., some chambers of the North American Aerospace Defense Command (NORAD) are 18.44 m high, 13.7 m wide and 417 m long (USA, 1980, p. 7–7). Further power plants chambers, aqueducts, and tunnels' excavation dimensions, rock properties and reinforcement elements can be seen in detail in the Engineering Manual "Engineering and Design Rock Reinforcement" from Department of the Army U.S. Army Corps of Engineers (USA, 1980).

The data obtained allowed the three categories of subterranean systems described during the literature review to be validated: tunnels, natural cavities and caves; urban subsurface systems; and underground facilities for military use. By analysing data, it is possible to identify new underground spaces: pipelines and subterranean irrigation systems, to be included in the category of tunnels, natural cavities and caves; and underground quarries and transit systems, to be included in the category of urban subsurface systems. The subterranean system features analysis acknowledges that the subterranean systems used in operations have very diverse characteristics. Subterranean systems vary in dimensions, depth, type of construction (rudimentary or sophisticated), level of protection (the extent to which the facility has been hardened, and with what material), nature of the soil (properties suitable or not for construction; natural protection offered by the surface under which the system has been constructed), environmental conditions (air quality, dangerous animals, collapse hazard, and visibility), slope, azimuth, and purpose (original and operational). Furthermore, subterranean systems may have segments from different subcategories.

Observation and fields of fire

The subterranean systems effects evaluation on observation and fields of fire presents much more complexity than aboveground terrain, where the landscape often varies predictably, and intelligence gathering tools and techniques can be more effective.

The category of the subterranean system and its characteristics provide relevant inputs on effects evaluation on observation and fields of fire. Two more examples are given in Table 3.

Table 3. Limitations for observation and fields of fire

Subterranean System	Limitations for observation and fields of fire	References
Tunnel	Blind corners; random changes in direction and corners constructed with no less than a 60° angle and no more than a 120° angle (e.g., 2nd Sino-Japonese War [1937-1945] and Vietnam War [1964-1967]).	USMAC-V, 1967; Lrrp, 2008; Triolet and Triolet, 2011.
	Confined space (e.g., Vietnam War [1964-1967] and border between Lebanon and Israel).	USMAC-V, 1966, p. 4; Ahronheim, 2018.

Observation may be good in sophisticated tunnels, underground military bases, transit and subway tunnels; however, in rudimentary tunnels, sewer systems, irrigation systems and aqueducts, observation is probably limited due to lack of light. Yet, existing or other light sources can be deactivated or activated by any of the contenders. Audible observation will be limited if there is overpressure due to detonations or weapon discharges. Fields of fire limits are reduced significantly when changes of direction occur at small angles, as well as in confined spaces.

Avenues of approach

"Units should always assume that without control of the subterranean environment, the enemy has freedom of maneuver" (USA, 2019c, p. 1–6). Depending on the strength and depth of the above-ground defence, subterranean systems can be secondary or primary avenues of approach at lower tactical levels. Subterranean avenues of approach can lead to an objective or key terrain on subsurface or surface and became

a primary concern when used by threat forces. Subterranean terrain increases forces' possible COA. Forces (both attacker and defender) using subterranean terrain as avenues of approach have an advantage because they can develop numerous operations covered and concealed.

Manoeuvrability is a critical factor for using subterranean terrain since it is very restrictive and easy to defend or block. Sophisticated structures usually have a larger size and less restricted manoeuvre spaces. Some are large enough for tactical vehicles, trucks carrying ballistic missiles, or even used as aircraft hangars (Sepp, 2000, p. 1; NORAD, n.d.; Zhang, 2012; National Security Archive [NSA], 2013). Some tunnels, passageways and other spaces allow one or two soldiers to walk abreast. Sanitary sewers are usually too small for troop movement; however, storm sewers often permit forces to move beneath the combat to the surface behind the adversary (e.g. Polish resistance fighters against German forces in 1944 [Rossman, 1994]).

Key terrain

Key or decisive terrain analysis has to include the surface area. The seizure, retention, or control of surface access points usually gives a marked advantage to any of the forces in combat. For example, these points could prove critical in isolating the threat's ability to reinforce or resupply, preventing large numbers of troops leaving bunkers and defend on the surface or establishing a support by fire position to protect a breach force.

Possible key terrain in subterranean systems are C2 bunker, barriers blocking C2 bunker, and tunnel connected to C2 bunker (e.g., bunkers and tunnel networks used by Hezbollah in Lebanon in 2006 [USA, 2014, p. 11]). In sophisticated systems, the control rooms with panels that operate the entry portals, with maps and other relevant markings can also be key. Some terrain not assessed as key terrain for the force operating on the subterranean system may be key or decisive terrain for the force on the surface (e.g., machine gun nests and fortified positions [see table 4]); therefore, it is important for the planning to be integrated.

Table 4. Key terrain

Key terrain	Why?	References
Fort	Its destruction would disrupt enemy defence and enable assault by surface forces.	Schmutz, 2009, p. 1.
Machine-guns and observation posts, armoured shelters, exits of communication trenches, and centres of resistance.	Its destruction or control would disrupt enemy defensive system, affect morale, and create conditions to defeat or destroy the enemy or achieve objectives.	Jones, 2010, pp. 53, 68.

The whole subterranean system when tied to terrain providing tactical advantage or manoeuvre advantage can be assessed as key terrain for some echelons/forces. During the War of the Spanish Succession, in the siege of Turin (1706), tunnels were decisive for the city's Austrian/Savoyard defenders to withstand the French Army until reinforcements arrived to lift the siege (Jensen, 2019, p. 226). In Poland, during the Warsaw Uprising in 1944, the Warsaw municipal sewer system was key for the Polish resistance fighters against the German forces (Rossman, 1994). In megacities, "[v]ictory without butchery means employing deception, gaining support from inside, and preventing the enemy from using tunnels" (Jensen, 2019, p. 213). Tunnels can also be important symbols of resistance and key for development of information operations campaigns (e.g. Gaza Strip).

Obstacles

Assessment of a subterranean area as an obstacle depends on the unit mission. Due to the need to maintain the momentum of surface operations, the lack of capability to operate underground, or the high risk it poses, commanders may decide to bypass subterranean systems during the planning process. On the other hand, it could be assessed as being of great importance, requiring additional focus by friendly forces and added resources to overcome one or multiple barricades and obstacles outside of the subterranean system. Table 5 includes some examples of obstacles.

Table 5. Obstacles

Obstacle	When	References
Ditch (water-filled)	Middle age	Jones, 2010, p. 13; Springer, 2015.
Counter-tunnel	From ancient times to the present.	Illinois Central Railroad Company, 1909, pp. 73, 74; Short, 2004, pp. 4, 21, 22; Herman, 2014; Richemond-Barak, 2018, p. 8.
Wire obstacles	World War I	Jones, 2010, pp. 71, 99 e 100
Booby traps (grenades, spike traps, poison arrows, trip-wires, trap doors, and a variety of other means), and poisonous animals.	1937-1945 and 1964-1967 (Sino-Japanese War and Vietnam War).	USMAC-V, 1967, pp. 14, 15; Lrrp, 2008; J. and L. Triolet, 2011; Richemond-Barak, 2018, pp. 9, 10.
False side tunnels	1964-1967 (Vietnam War)	USMAC-V, 1967, p. 17.
Water (flooding the tunnels)	1453 (Turkey)	Crowley, 2005, pp.170–171; Feldman, 2008, p. 91; Philippides and Hanak, 2011, pp. 507–510.
Smoke and toxic smells		
Counter-tunnel		
Greek fire (incendiary weapon of flammable liquid)		
Fire in the wooden structures that supported the mines, resulting in cave-ins.		
Antitunnel system / Wall of Defense (“Obstacle”)	Since 2016 (Israel)	Fishman, 2017.
Anti-tunnel system / Deep water-canal	Tunisia (n.d.)	FARS, 2018.

Obstacles within a subterranean system limit mobility considerably and can be existing, inherent to the terrain (natural or man-made), or reinforcing/military (constructed, demolitions, mines, contamination or expedient), to extend or improve the effectiveness of existing obstacles.

Existing obstacles can be:

- Natural: large rocks, ravines, a large volume of water, soil features (e.g., hard rock or water-permeable soil), gaps and ditches, air supply limited, non-existent, or toxic;

- Man-made: gates, doors, walls, fences, but also water, or stairs (if using robots).

Reinforcing obstacles can be:

- Constructed: counter-tunnels, deep water-canals, ditches (water-filled), walls, false side tunnels, fencing, wire obstacles, tripwires, security or reinforced doors, false walls, and opening mechanisms and physical, electromechanical or biometric checkpoints;

- Demolitions: landslides, "camouflets", and craters;

- Mines;

- Booby traps (vary significantly based on geography, availability of materials, and technical sophistication of the force): improvised explosive devices (usually deployed near junctions and often operated by tripwires), nail boards, spike pits, grenades, poison arrows, and trap doors.

- Contamination: toxic gas, and smoke (subterranean systems prevent dispersion);

- Expedient: poisonous animals, water, foliage, fire, cement injection, rubble, debris, furniture, and other objects existing in the structure.

The classification of the obstacles is either protective and tactical. Protective obstacles are close to defensive positions and are key components of security operations. Tactical obstacles are employed to block, fix, disrupt, or turn the enemy's movement; these obstacles also impose additional losses in personnel, equipment, and time on the enemy.

Cover and concealment

The use of subterranean systems expands the physical battlefield and provides cover and concealment to its user against air and surface forces.

Inside the subterranean systems, depending on their characteristics, there may be barriers, walls, cavities (natural or man-made), stairwells and objects that can be used for cover and concealment; near C2 bunkers, limited corners and barriers provide cover and concealment; storm sewers and subway lines lack cover and concealment. The angles that exist in the systems provide cover and concealment. Gun-slits provide cover for defending forces. Surface infrastructures may be used to reinforce the coverage provided by subterranean systems. Darkness is a very relevant form of concealment. The existence of cover and concealment, including darkness, inside an underground system, favours the attacking forces. Some forces/groups may use civilians or civilian buildings as cover ("human shields") or concealment (Dershowitz, 2014; Hecht, 2015).

Weather

Water can make it impossible to build subterranean systems, place obstacles, or even use them (floods). For these reasons, precipitation and temperature are factors to take into account in the course of construction and while conducting operations (e.g., sewers fill rapidly during rainstorms and, though normally drained by electrical pumps, may overflow); melting snow may preclude the use of subterranean systems; cold may restrict the use of electrical equipment (see Jones, 2010, p. 67). Prolonged periods of drought and heat might result in opening new subterranean avenues of approach through some aqueducts and sewers. Urban areas may require extensive analysis in the presence of microclimates. Cloud cover and fog restrict visibility, making it difficult to detect subterranean systems and their entrances and to conduct airdrop operations for resupplying (used by logistic units where terrain or enemy limit access by ground transportation assets).

Tactical considerations

This section summarizes tactical considerations that result from terrain and weather analysis, to support preparing ground forces to conduct operations in subterranean systems, providing the answer to CQ. Evaluating the effects of terrain and weather in subterranean systems is substantially different from the evaluation on open terrain. The analysis of the military aspects of terrain (OAKOC) must be in the context of subterranean systems features.

Subterranean system's location and entrances

The first step during terrain analysis is to identify the environment (urban, desert, mountain, forest, etc.) where the force is going to operate, the assigned area and surrounding areas where our forces can influence the normal development of operations, or where something may affect operations.

Detection of subterranean systems demands extreme care and thoroughness to locate hidden entrances or other evidence of their existence. It's easier to detect a tunnel when it is being built than afterwards. Sensitive microphones must be close to the location of the tunnel to be effective; and yet, the sound of digging can be reduced by working slowly, using manual tools, or by other sounds in the area.

After the construction, the key to finding a tunnel system is through terrain analysis and physical ground search. Given the surrounding environment, the reconnaissance and search forces should consider other signs of the presence of tunnels. Experienced trackers and dogs can be very useful for reconnaissance and detection. Force also must look for operational indicators of subterranean systems (e.g., movement of enemy forces in a specific direction, sniper fire and hit-and-run tactics from areas with no avenues of withdrawal, failure of cordons to prevent infiltration or withdrawal of enemy forces). In urban areas, forces must identify buildings with basements and subterranean spaces (government, military, industrial, commercial, and residential). In these cases, intelligence acquired from other sources is highly relevant. Monitoring threat communications, exploring documents on the plans of the tunnels from threat headquarters, ask/pay the local population for information about tunnels, sewers, and construction projects are very relevant sources, as well as defectors, or infiltrating agents into the digging operations.

When the presence of tunnels has been determined, the area must be isolated and secured (including other entrances and exits) to protect friendly troops and prevent threat access to and egress from the systems. Smoke or explosions inside a tunnel can be useful for detecting new accesses from outside (and flush out anyone hiding in them). To determine deeply buried facilities, each location should use an integrated combination of blueprints, maps, aerial photographs, videos, geo-prospecting instruments (to measure electric, magnetic and gravitational fields, or sound waves), satellites (for thermal, multispectral, and infrared imaging of the facility and involving area), hydrology analysis tools, and human intelligence reports (resulting from covert agents, defectors, photographs, documents, and soil samples, among others).

Subterranean system categories and its features

The analysis of the features of the subterranean system and its mapping are critical to identifying information requirements, support the subsequent study of the military aspects of the terrain, and develop COA. In operations, forces must examine connections to the system, surface features and adjacent terrain (e.g., local businesses and residential

structures), distance from known blind spots and dead spaces on the surface to the system perimeter, storm/sewer drainage and ventilation systems, choke points (natural and man-made), and structure's susceptibilities to above-ground demolitions.

Systems with a high level of protection (e.g., deep underground facilities) usually require a considerable number of personnel as well as specialised breaching capabilities. Given the mission, proper analysis of the subterranean system's supporting infrastructure (ventilation, communication lines, satellite dishes or antennas, transportation, energy, storage facilities, water supply and waste disposal) may provide the Commander with vulnerable points or umbilicals for the system to operate. These points can be used as alternative entries and properly exploited may be sufficient for functional defeat without the force having to enter the structure.

Observation and fields of fire

Forces must be trained and equipped to combat at short distances and poor visibility conditions; in case of contact with the threat, audible observation must be protected.

Avenues of approach

During the planning process, leaders must balance the advantage of developing operations covered and concealed vs limited manoeuvrability (terrain very restrictive and easy to defend or block).

Whenever subterranean systems have tunnels, pipes or culverts large enough to facilitate foot (crawling, standing, two men or more side by side) or vehicular movement, an analyst must prepare avenues of approach, or mobility corridor overlays. Overlays should show their size, orientation and, if possible, prioritisation based on the probability of use. Using overlays, analysts must layer surface terrain on top of subterranean terrain to see how forces using both terrains can manoeuvre against opposing forces effectively. The consequences of progression denial in any of the selected avenues of approach and identified alternative avenues of approach must be assessed.

Most movement techniques are similar to the ones used in urban areas, but some hallways can be even longer and narrower requiring the force to move in a column. In this case, soldiers must reduce space between them to maximise ballistic shield protection. The use of robots also must be maximised.

Key terrain

Key terrain analysis must include the subsurface and surface areas. Surface access points and C2 bunkers usually are assessed as key terrain in subterranean operations. Subterranean systems can be assessed as decisive terrain.

Obstacles

Obstacles placed at intersections provide great ambush sites, and standing water in tunnels presents excellent camouflage for booby traps and anti-personnel mines set on likely routes. Accessing sophisticated structures requires specific techniques and equipment, which may be manual, ballistic, mechanical, explosive or thermally cut.

In operations, if not using subterranean systems and there isn't any intention to destroy or neutralise them, entry points must be sealed and early warning devices and obstacles employed (e.g., wire, heavy weights, or tack-welding).

Cover and concealment

Inside the subterranean systems, attacking forces can use existing angles, barriers, walls, cavities, stairwells and other objects for cover and concealment. Whenever possible, the first man must use a ballistic shield for cover, especially in storm sewers, subway lines, and other subterranean system lacking cover and concealment. Darkness is also a very relevant form of concealment. Gun-slits and other objects can provide cover for defending forces.

Weather

Forces must assess the impact of precipitation, temperature and droughts on the operations (e.g., flooding hazard and new subterranean avenues of approach), as well as cloud cover and fog restrictions on visibility during detection and airdrop resupplying operations.

Conclusion

Historically, states, civilians, regular forces, irregular forces, terrorists, and criminals have used subterranean systems as a means to conduct operations. Improvements in the capability to construct spaces and underground structures enhanced its usefulness and proliferation.

In the future, more conflicts will take place in subsurface areas or at least incorporate subterranean warfare elements. Urban subsurface areas are more extensive, conventional, accessible, and have features favourable to forces conducting offensive, defensive, and security operations. Caves in mountains, karez in deserts, and tunnels in forests and border regions will continue to be largely used in asymmetric war tactics and insurgencies. Deeply buried facilities in the mountains will continue to be used by states to cover and conceal military capacities and secret programmes. Models reflecting the main characteristics and effects of Terrain and Weather in operations in subterranean systems can be very useful to state operational requirements for developing capabilities and theorising concepts and doctrine to support the planning process.

The research strategy adopted for this study is mixed, combining the collection, analysis and integration or relationship of quantitative and qualitative data. To build the theoretical and conceptual framework, which consists of literature review and definition of the analysis model, it was adopted using deductive reasoning. A qualitative research method was adopted for collection and analysis of data; as the results obtained with inductive reasoning alone do not always allow their generalisation or the replication of results to other contexts, iterative elements of deduction and abduction were incorporated again throughout the process. Research privileges empirical observation and the contextual conditions in which phenomena occur to create theories, and relies on the *Grounded Theory* for collection, analysis, and systematic treatment of data. The main data sources for the study consisted of purposive sampling from operations in subterranean systems and lessons learned from them.

The theoretical saturation obtained through the study confirmed the validity of the variables and sub-variables proposed in the provisional model of analysis. Additionally, forces have been assessed to have difficulties in detecting some subterranean systems. For this reason, a new sub-variable was added into the variable terrain and weather: subterranean system's location and accesses. The data obtained also reflected the need to include the environmental factors slope and azimuth, as well as connections with other systems in the analysis of the subterranean system features. The theoretical coding given in Table 2 is thus obtained, also providing an answer to DQ1. Ground forces operating in subterra-

nean systems should adopt the terrain and weather analysis model shown in table 2. The same model provided the categories and sub-categories for data analysis and assessment of the main characteristics of Terrain and Weather in subterranean systems, which were assessed and presented during section 4, providing an answer to DQ 2. Some of the most relevant are discussed here.

A subterranean system's location and entrances: the location and entrances to subterranean systems are not easy to determine; their existence is kept a secret from enemy forces and, sometimes, friendly forces to reduce the chances of intelligence leakage. Indicators of tunnel building include sounds and unusual activity in the area. After the construction, the best indicators are terrain, enemy activity and intelligence products.

Subterranean system categories and its features: subterranean systems vary in dimensions, depth, type of construction, level of protection, nature of the soil, environmental conditions, slope, azimuth, and purpose. The features of subterranean systems reduce the effectiveness of infantry, sniper, artillery and air attacks, as well as air and satellite surveillance, or even intelligence agencies, chemical, and/or nuclear attacks.

Observation and fields of fire: in most cases, observation and fields of fire in underground systems are limited to short distances and poor visibility, as well as favouring the defensive forces; if there is contact with the threat, audible observation may be affected.

Avenues of Approach: forces using subterranean terrain as avenues of approach have an advantage because they can develop numerous operations covered and concealed. Manoeuvrability is a critical factor for using subterranean terrain since it is very restrictive and easy to defend or block.

Key terrain: the seizure, retention, or control of surface access points usually provides a marked advantage to any of the forces in combat. Some terrain not assessed as key terrain for the force operating on the subterranean system it may be key or decisive terrain for the force on the surface.

Obstacles: obstacles within an underground system limit mobility considerably. Protective obstacles are close to defensive positions and are key components of security operations. Tactical obstacles are employed to block, fix, disrupt, or turn the enemy's movement; these obstacles also impose additional losses in personnel, equipment, and time on the enemy. Subterranean systems can be assessed as obstacles.

Cover and concealment: subterranean systems provide cover and concealment to users against air and surface forces. Inside the subterranean systems, there may be barriers, walls, cavities, stairwells and objects that can be used for cover and concealment; near C2 bunkers, limited corners and barriers provide cover and concealment; storm sewers and subway lines lack cover and concealment. Some forces may use civilians as "human shields".

Weather: water can make it impossible to build subterranean systems, place obstacles, or even use them; droughts can "create" new avenues of approach. Cloud cover and fog restrict visibility, making it difficult to detect subterranean systems and resupply forces by airdrop.

The tactical considerations in subterranean systems, resulting from terrain and weather analysis, were assessed and presented during section 5, providing an answer to CQ. Some of the most relevant are discussed here.

The analysis of the military aspects of terrain (OAKOC) must be in the context of subterranean systems features.

Subterranean system's location and entrances: detection of a subterranean system during construction is easier than afterwards. After being built, the key to finding it is through terrain analysis, physical ground search, operational indicators, and available intelligence products.

Subterranean system categories and its feature: analysis of the features of the subterranean system and its mapping, as well as the connections to the system, surface features and adjacent terrain, are critical to identifying information requirements, support the subsequent study of the military aspects of the terrain, and develop COA. Systems with a high level of protection usually require a substantial number of personnel as well as specialised breaching capabilities. Given the mission, proper analysis of the subterranean system's supporting infrastructure may provide the Commander with vulnerable points.

Observation and fields of fire: forces must be trained and equipped to combat at short distances and poor visibility conditions; in case of contact with the threat, audible observation must be protected.

Avenues of Approach: during the planning process, leaders must balance the advantage of developing operations covered and concealed vs limited manoeuvrability.

Key terrain: key terrain analysis must include the subsurface and surface areas. Surface access points and C2 bunkers usually are assessed as key terrain in subterranean operations. Subterranean systems can be assessed as decisive terrain.

Obstacles: obstacles placed at intersections are excellent ambush sites. Accessing sophisticated structures requires specific techniques and equipment. In operations, if not using subterranean systems and there isn't intention to destroy or neutralise them, entry points must be sealed and early warning devices and obstacles employed.

Cover and Concealment: inside the subterranean systems, forces can use existing angles, barriers, walls, cavities, stairwells and other objects for cover and concealment. Whenever possible, the first man must use a ballistic shield for cover.

Weather: based on recent weather patterns and soil features, analysts should be aware of the potential for flooding conditions and other effects on the structure, assess potential avenues of approach resulting from droughts, and cloud cover and fog effects on visibility during detection activities, as well as on resupplying by airdrop operations.

To conclude, the terrain and weather analysis model, the characteristics and the tactical considerations presented, all combined, support the preparation, planning, and execution of land operations in subterranean systems. Developing models for other mission variable analysis is recommended for future studies on operations in subterranean systems.

Funding

This research received no external funding.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Ahronheim, A. (2018) 'IDF Hezbollah tunnel-destroying material discovered in Lebanon', *Jerusalem Post*, 27 December, Available from: https://www.jpost.com/Arab-Israeli-Conflict/Conquer-the-Galilee-IDF-reveals-Hezbollahs-tunnel-attack-strategy-575616 (Accessed: 9 September 2019).

Bryman, A. (2012) *Social Research Methods*. 4.ª ed. Oxford: Oxford University Press.

Charmaz, K. (2008) 'Grounded Theory as an emergent method', in Hesse-Bilber, S. N. and Leavy, P. (eds.), *Handbook of emergent methods*. New York, NY: The Guilford Press, pp. 155–172.

Cohen, R. S., Johnson, D. E., Thaler, D. E., Allen, B., Bartels, E. M., Cahill, J., Efron, S. (2017) *From Cast Lead to Protective Edge: Lessons from Israel's Wars in Gaza*. Santa Monica, Calif: RAND Corporation.

Cordesman, A. H. (2003) *The lessons of the Iraq War: main report.* Washington, DC: Center for Strategic and International Studies.

Creswell, J. (2009) *Research design: Qualitative, quantitative and mixed methods approaches*. 3th edn. Los Angeles: Sage.

Crowley, R. (2005) *Constantinople: The Last Great Siege1453*. London, England: Faber and Faber Limited Bloomsbury House.

Dershowitz, A. M. (2014) 'Terror Tunnels: The Case for Israel's Just War Against Hamas', *Gatestone Institute*, 12 September, Available at: https://www.gatestoneinstitute.org/4695/hamas-terror-tunnels (Accessed: 9 September 2019).

EP. (2012) *Operações (PDE 3-00).* Lisboa: EP.

Feldman, R. T. (2008) *Tha fall of Constantinople.* Minneapolis: Twenty-First Century Books.

Fishman, A. (2017) 'What is Israel doing about the Gaza tunnels today?', *ynetnews.com*, 03 July. Available at: https://www.ynetnews.com/articles/0,7340,L-4931788,00.html (Accessed: 12 September 2019).

Fortin, M. F. (2003) *O Processo de Investigação: da concepção à realização*. Loures: Lusociência.

FARS (2018) *How Threats Posed by Tunnels Escalated in the Middle East*, Available at: https://futureuae.com/ar-/Mainpage/Item/3871/severe-risks-how-threats-posed-by-tunnels-escalated-in-the-middle-east (Accessed: 9 September 2019).

Glaser, B. and Strauss, A. (1967) *The discovery of Grounded Theory: Strategies for qualitative research*. New York: Aldine de Gruyter.

Grau, L. W. and Jalali, A. A. (1998) 'Underground Combat: Stereophonic Blasting, Tunnel Rats and the Soviet-Afghan War', *Foreign Military Studies Office,* Available at: https://community.apan.org/wg/tradoc-g2/fmso/m/fmso-monographs/200606 (Accessed: 10 September 2019).

Hecht, E.(2015) *The Tunnels in Gaza: Testimony before the UN Commission of Inquiry on the 2014 Gaza Conflict*. Available at: https://www.mideastdig.com/wp-content/uploads/2017/01/testimony.pdf (Accessed: 04 October 2019).

Herman, A. (2014) *Notes from the underground: the long history of tunnel warfare.* Available at: https://www.hudson.org/research/10570-notes-from-the-underground-the-long-history-of-tunnel-warfare (Accessed: 21 October 2019).

Illinois Central Railroad Company (1909) *Siege and defence of Vicksburg and the Vicksburg National Military Park*. Available at: https://babel.hathitrust.org/cgi/pt?id=loc.ark:/13960/t2h712n3k;view=1up;seq=41 (Accessed: 10 September 2019).

Jensen, B. M. (2019) *Complex terrain: megacities and the changing character of urban combat*. Quantico, Virginia: Navy, Marine Corps University Press.

Jones, S. (2010) *Underground Warfare 1914-1918*. South Yorkshire: Pen & Sword Military.

Kinard, J. (1998) *The Battle of the Crater: Civil War campaigns and commanders.* Texas: Mcwhiney Foundation Press.

Lambeth, B. S. (2011) *Air Operations in Israel's war against Hezbollah: learning from Lebanon and getting it right in Gaza.* Santa Monica, CA: RAND Corporation.

Lrrp. (2008) Tunnel Warfare - Vietnam Experience [Web log post]. Available at: https://lrrp2.wordpress.com/2008/07/12/tunnel-warfare-vietnam-experience/ (Accessed: 13 September 2019).

NATO. (2017) *Urban Tactics: Edition A Version 1 (ATP-99)*. NATO Standardization Office.

NATO. (2018) *Allied Land Tactics: Edition B Version 1(ATP-3.2.1).* NATO Standardization Office.

NATO. (2019) *Tactical Planning for Land Forces: Edition A Version 1 (AAP-28).* NATO Standardization Office.

NORAD. (n.d.) *Cheyenne Mountain Complex [Online page]*. Available at: https://www.norad.mil/About-NORAD/Cheyenne-Mountain-Air-Force-Station/ (Accessed: 13 September 2019).

NSA. (2013) *Underground Facilities: Intelligence and Targeting Issues.* Available at: https://nsarchive2.gwu.edu/NSAEBB/NSAEBB439/ (Accessed: 4 October 2019).

Philippides, M. and Hanak, W. K. (2011) *The Siege and the Fall of Constantinople in 1453: Historiography, Topography, and Military Studies*. Farnham: Ashgate Publishing Limited.

Richemond-Barak, D. (2018) *Underground Warfare.* New York: Oxford University Press.

Rossman, J. (1994) In the Warsaw Sewers. *Zeszyty Historyczne*, No. 109. Paris: Instytut Literacki. Available at: http://www.warsawuprising.com/paper/warsaw_sewers.htm (Accessed: 15 September 2019).

Rottman, G. (2006) *Viet Cong and NVA Tunnels and Fortifications of the Vietnam War (Fortress 48)*. New York: Osprey Publishing.

Schmutz, J. F. (2009) *The Battle of the Crater: A Complete History*. North Carolina: McFarland & Company, Inc.

Sepp, E. M. (2000) *Deeply Buried Facilities. Implications for Military Operations (Occasional Paper No. 14).* Air War College, Alabama.

Shapir, Y. and Perel, G. (2014) Subterranean Warfare: A New-Old Challenge. In: A. Kurz, and S. Brom (Ed.), *The Lessons of Operation Protective Edge* (pp. 51–57) Tel Aviv: Institute for National Security Studies. Available at: https://www.inss.org.il/publication/subterranean-warfare-a-new-old-challenge/ (Accessed: 04 October 2019).

Short, N. (2004) *Germany's West Wall: The Siegfried Line* (Fortress 15). S.l.: Osprey Publishing.

Springer, P. J. (2015) 'Fighting under the earth: the history of tunneling in warfare'. *Foreign Policy Research Institute.* Available at: https://www.fpri.org/article/2015/04/fighting-under-the-earth-the-history-of-tunneling-in-warfare/ (Accessed: 9 September 2019).

Strauss, A. (1987) *Qualitative analysis for social scientists*. New York: Cambridge University Press.

Triolet, J. and Triolet, L. (2011) *La guerre souterraine: Sous terre, on se bat aussi*. Paris, France: Perrin.

USA (1980) *Engineering and Design Rock Reinforcement*. Washington DC: Department of the Army.

USA (2014) *Subterranean Environment: Tunnel to Victory, the 2006 Lebanon War.* Fort Leavenworth: Complex Operational Environment and Threat Integration Directorate.

USA (2016) Commander and Staff Organization and Operations (FM 6-0). Washington DC: Department of the Army.

USA (2017a) *Operations (ADRP 3-0)*. Washington DC: Department of the Army.

USA (2017b) *Small Unit Training in Subterranean Environments (TC 3-21.50).* Washington DC: Department of the Army.

USA (2017c) *Urban Operations (ATP 3-06/ MCTP 12-10B)*. Washington DC: Department of the Army.

USA (2019a) *Intelligence Preparation of the Battlefield (ATP 2-01.3).* Washington DC: Department of the Army.

USA (2019b) *Mission Command: Command and Control of Army Forces (ADP 6-0).* Washington DC: Department of the Army.

USA (2019c) *Subterranean Operations (ATP 3-21.51)*. Washington DC: Department of the Army.

USMAC-V. (1965) *Lessons Learned no. 45: Viet Cong Turmels* Available at: http://cgsc.contentdm.oclc.org/cdm/singleitem/collection/p4013coll11/id/1535/rec/1 (Accessed: 2 October 2019).

USMAC-V. (1966) *Lessons learned no. 56: operations against tunnel complexes*. Available at: http://cgsc.contentdm.oclc.org/cdm/singleitem/collection/p4013coll11/id/1491/rec/1 (Accessed: 2 October 2019).

USMAC-V. (1967) *Counterinsurgency Lessons Learned no. 61: Salient Lessons Learned*. Available at: http://cgsc.contentdm.oclc.org/cdm/singleitem/collection/p4013coll11/id/1422/rec/1 (Accessed: 2 October 2019).

USMAC-V. (1968) *Techniques for Detecting, Neutralizing and Destroying Enemy Tunnels*. Available at: https://apps.dtic.mil/dtic/tr/fulltext/u2/683375.pdf (Accessed: 3 October 2019).

Yin, R. K. (2016) *Qualitative Research from Start to Finish*. 2nd edn. New York: The Guilford Press.

Zhang, H. (2012) China's Underground Great Wall: Subterranean Ballistic Missiles. *Belfer Center*. Available at: https://www.belfercenter.org/publication/chinas-underground-great-wall-subterranean-ballistic-missiles (Accessed: 2 October 2019).