

Israel Border Security Threats: Soil Tunnels

Kenneth R. Olson¹, Pam Olson², Elaine Wagner²

¹Department of Natural Resources and Environmental Sciences, College of Agricultural, Consumer, and Environmental Sciences, University of Illinois, Urbana, USA

²Independent Researcher, Urbana, USA

Email: krolson@illinois.edu

How to cite this paper: Olson, K.R., Olson, P. and Wagner, E. (2025) Israel Border Security Threats: Soil Tunnels. *Open Journal of Soil Science*, 15, 361-387.

<https://doi.org/10.4236/ojss.2025.156016>

Received: May 12, 2025

Accepted: June 2, 2025

Published: June 5, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Soil tunnels, on the Israeli borders with Gaza, Egypt, West Bank, Syria, and Lebanon have a long history of use for warfare, as invasion pathways, smuggling, and storage of rockets, missiles and ordnance and are causes of serious political tension between the countries. The primary objectives are to: 1) assess the soil and geological materials, climate, bedrock, permanent water table and flooding conditions that exist on the Israel border to determine where earthen soil tunnels could be successfully created, 2) assess the use by Hamas of soil tunnels during the October 7, 2023 invasion of Israel, 3) document the new Israel Defense Force (IDF) understandings, culture, and approach to categorizing, blocking, and destroying the Gaza tunnels, and 4) apply IDF lessons learned on the Israel-Gaza border to southern Lebanon-Israel border where Hezbollah has built a vast soil tunnel network. Soil tunnel construction and destruction often has adverse environmental and human health impacts on the Israeli border landscape.

Keywords

Israel, Borders, Soil Tunnels, Gaza, Syria, Lebanon, Israel Defense Forces, Hezbollah, Hamas

1. Introduction

For more than 2,500 years soil tunnels have been used in warfare and smuggling. Initially tunnels were utilized to attack fortresses that were underlain by unconsolidated (non-bedrock) soil materials (**Figure 1**). Later tunnels provided housing and served as smuggling corridors. Modern warfare soil tunnels are the pathways used to move troops (**Figure 2**), weapons and supplies to the other side of a border or wall for surprise attacks. Most of the soil tunnels are placed in easy-to-dig



Figure 1. Entrance to a soil tunnel dug by the Palestinians under the Syria and Israel border.

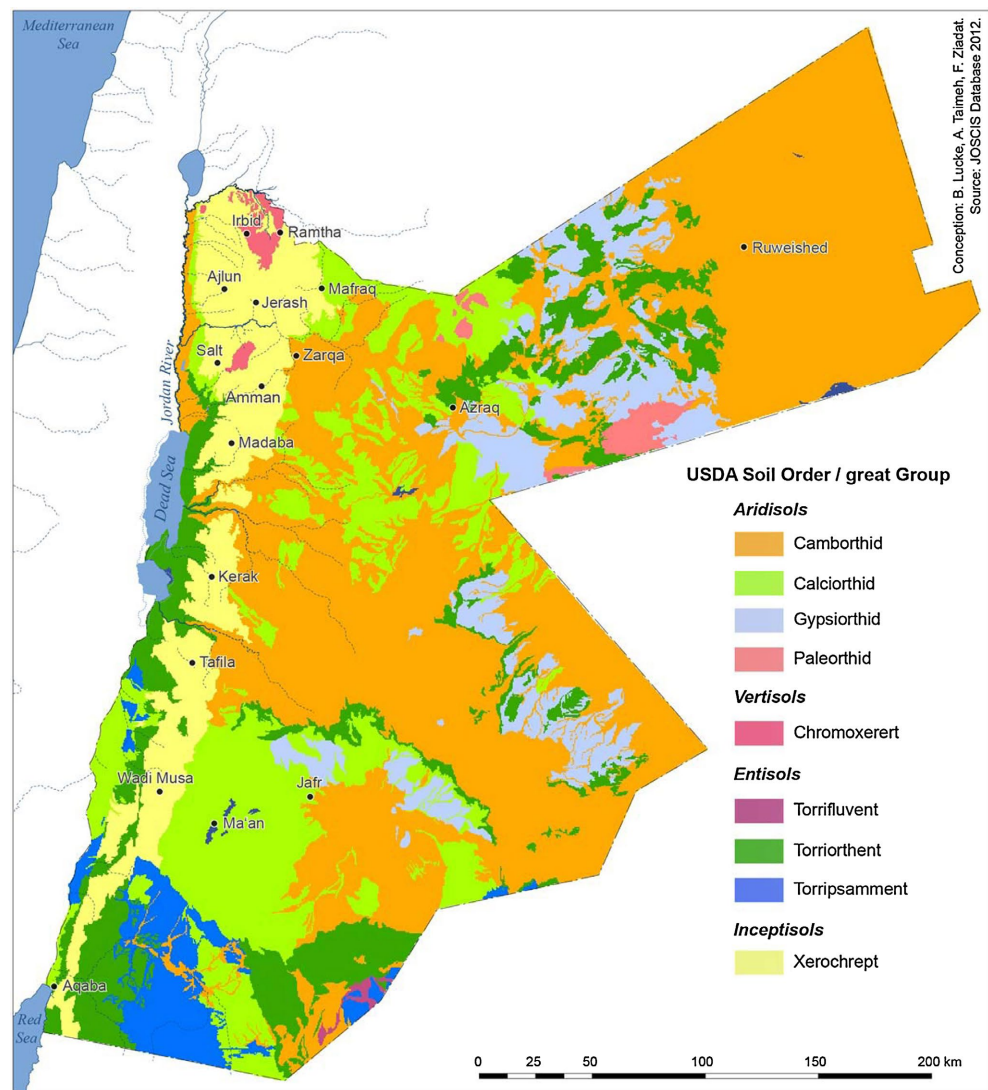


Figure 2. Jordan soil map. Photo Credit: Lucke, B., Tamell, A. and Ziadat, F.

unconsolidated soil materials that have a low water table and are not subject to flooding. Eventually, machinery was used to drill through bedrock permitting deeper and longer tunnels for troop movement or smuggling. However, when drilling through bedrock under international borders, the process created both noise and vibrations which were often detected by the enemy. Once discovered the tunnels were often collapsed by blowing up the tunnel, injection of gas, filling with water (**Figure 3**) or wastewater, or inserting barriers [1]. A series of case studies will be examined with the goal of determining soil and site criteria required to permit successful tunneling. The most restrictive soil and geologic conditions will be identified and potential mitigation methods used to overcome the site restrictions will be documented. Israel's history with warfare or smuggling issues along their borders (**Figure 4**) necessitates identifying areas most likely to be undermined by soil tunnels. In the case of Israel most of their borders are susceptible due to favorable arid climate, soils, and geology. An exception is the international border with Jordan where soil tunnels would be vulnerable to Jordan River flooding. Israel Defense Forces (IDF) and border patrol will need to continue to monitor the noise and vibrations, to identify future soil tunnel locations.

The primary objectives are to: 1) assess the soil and geological materials, climate, bedrock, permanent water table and flooding conditions that exist on the Israel border to determine where earthen soil tunnels could be successfully created, 2) assess the use by Hamas of soil tunnels during the October 7, 2023 invasion of Israel, 3) document the new Israel Defense Force (IDF) understandings, culture, and approach to categorizing, blocking, and destroying the Gaza tunnels, 4) apply IDF lessons learned on the Israel-Gaza border to southern Lebanon-Israel border where Hezbollah has built a vast tunnel network, 5) utilize pioneering and advanced underground warfare skills learned by IDF in Gaza to conduct raids into the Hezbollah tunnels along the Israel's northern border with Lebanon and 6) apply lessons learned by IDF on how to liberate areas in Lebanon underlain by soil tunnels. The environmental impact of the creation and destruction of soil tunnels is never included in the initial military analysis. The military strategy and

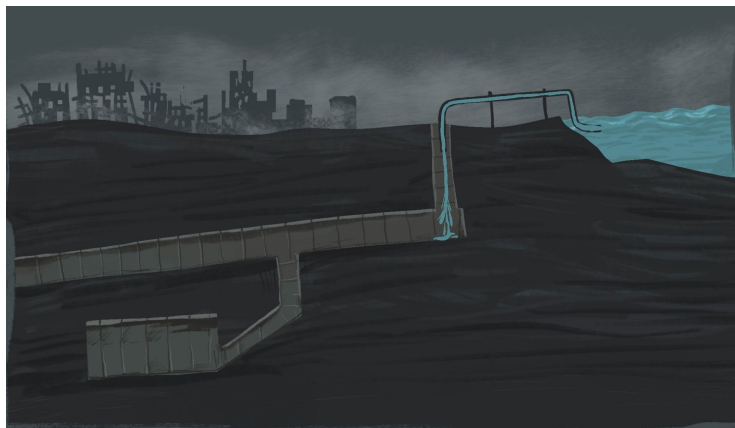


Figure 3. Drawing of sea water being pumped into soil tunnels. Photo Credit: In the public domain.



Figure 4. Middle East map showing the location of the tunnels between Egypt and Gaza Strip, Gaza Strip and Israel, Lebanon and Israel and Syria and Israel. Map by Mic Greenberg. Published with copyright permission from the Editor of the Open Journal of Soil Science.

need to win the war are always the priority and collateral damage to the environment can take decades to document, if ever. Soil tunnel construction and destruction often has adverse environmental and human health impacts on the Israeli border landscape.

2. Location Description—Israel Soils

The geology of Israel and Jordan includes igneous and metamorphic crystalline basement rocks from the Precambrian. These bedrocks are overlain by a lengthy sequence of Pleistocene sedimentary rocks that are overlain with sand dunes, alluvium, and playa deposits [2]. An important part of Israel's [2] soils (**Figure 5**)

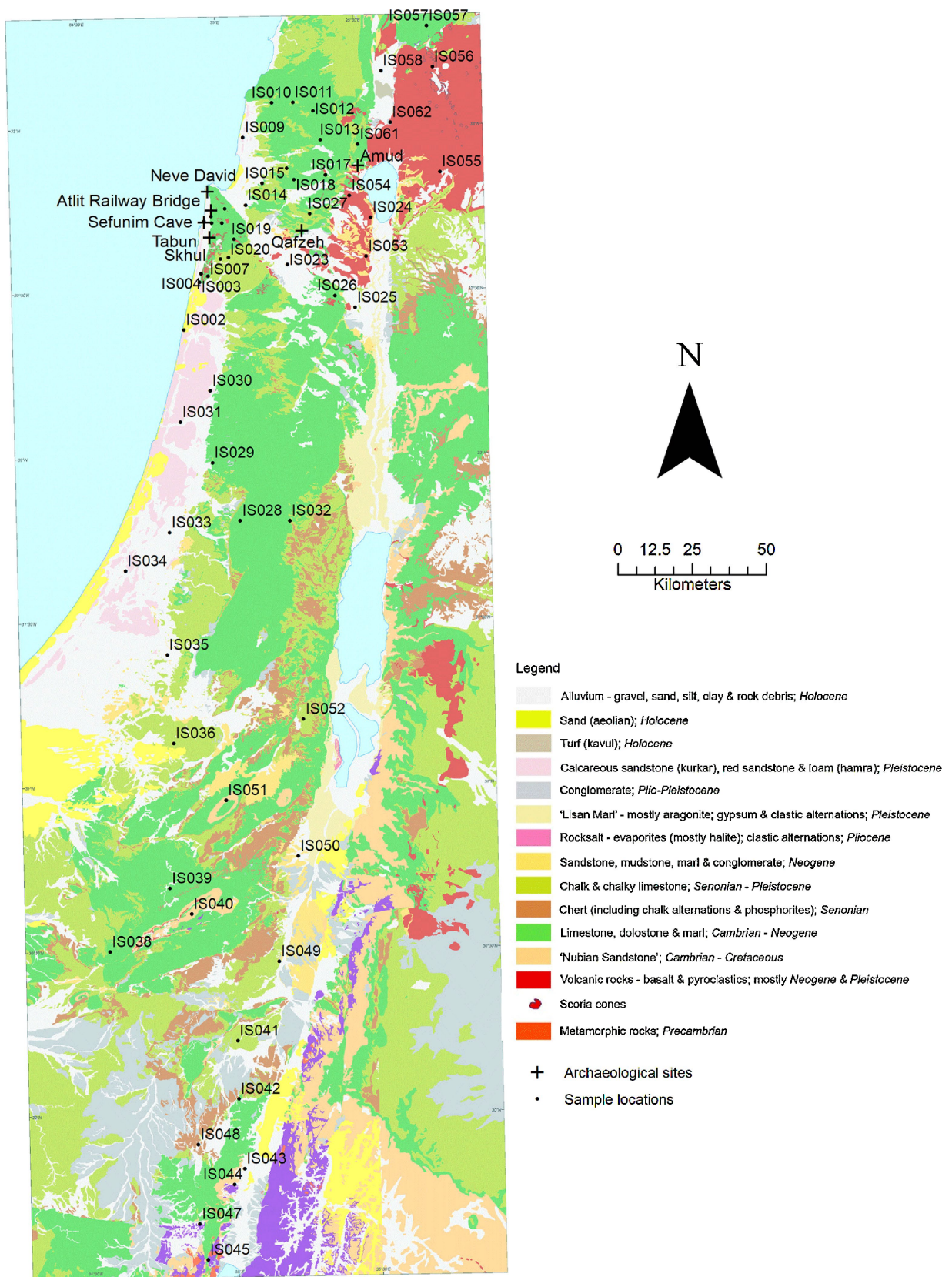


Figure 5. Israel soils (lithological) map. Sampling locations overlain on lithological map. Photo Credit: Sneh and Rosensaft, JOSCS Data base.

formed in limestone or basalt. These soils have a red color (Terra Rossa or Red Mediterranean Soil in old classification systems; Vertisols and Inceptisols orders due to their high clay and oxides contents in the newer USDA Soil Taxonomy).

After the formation of the Jordan Rift Valley [3] soil genesis indicates that they were influenced by a sequence of climatic changes. Slope, erosion by water, and colluvial activities have played a most significant role in their formation. The presence of deep soils, with high clay content rich in oxides and clay films, indicate that the soils were formed in a more humid climate. This is soil genesis theory is supported by buried paleosols in the steppe and desert. These areas have an average annual rainfall of less than 30 mm. However, the genesis of Terra Rossa is not completely known. These soils could either have been derived from bedrock, from aerosols, or formed by metasomatic processes [3].

Lucke *et al.* [3] noted “*Soil fertility generally varies from one soil order to another. The most fertile soils are those of the Inceptisols and Vertisols, due to their high clay content and high cation exchange capacity. However, these soils suffer from low organic matter and nitrogen contents, and sometimes iron, zinc, and phosphorus deficiency due to high carbonate content. The Vertisols induce physical stress on plant roots due to cracking which is driven by swelling and shrinking as a result of moisture variations. Therefore, they are suitable only for field crops, while trees are not recommended. Slopes are often covered by Xerorthents, which are generally shallow soils and recommended for forest plantation. Even if irrigation water is available, Aridisols in the dry regions pose various problems for cultivation that result from high carbonate, gypsum, or salt contents. Entisols are difficult to cultivate as well because they are dominated by sandy, gravelly, stony, or shallow substrate*” [3].

3. Results

3.1. Lebanon’s Land of Tunnels on the Israel Border

A report released by the Alma Center [4] [5], which researches security challenges to Israel from Lebanon and Syria (**Figure 4**), exposed “*what it described as a large-scale inter-regional Hezbollah tunnel system in different parts of Lebanon. The tunnel system is designed to move personnel and weapons around and out of the sight of the Israel Defense Forces. Some of the tunnels are large enough for pick-up trucks with multi-barrel rocket launchers—like the one used by Hezbollah to fire on Israel in 2021—to move tens of kilometers underground, according to the report, meaning that the truck can fire on Israel, vanish into a tunnel, and re-emerge tens of kilometers away*” [5]. The network of tunnels connects the Beqaa area, with Hezbollah’s central headquarter and logistical operational rear base (**Figure 2**), to Southern Lebanon, according to the report.

Lappin [5] estimated “*the cumulative length of all the tunnels can reach up to hundreds of kilometers. Like Hamas tunnels, the Lebanese tunnels contain underground command and control rooms, weapons and supply depots, field hospitals and shafts used to fire a wide range of rockets and missiles. The shafts open for a*

short period of time for the purpose of firing their armament and are then immediately shut down for the purpose of reloading the hydraulic launcher with new ordinance”.

“After the Second Lebanon War of 2006, Hezbollah, with the help of the North Koreans and the Iranians, set up a project forming a network of ‘inter-regional’ tunnels in Lebanon, a network significantly larger than the ‘Hamas’ metro (Hamas used Iranian and North Korean knowledge to build its tunnels as well). It is not merely a network of offensive and infrastructure local tunnels, in or near villages, it’s a network of tens of kilometers of regional tunnels that extend and connect the Beirut area (Hezbollah’s central headquarters) and the Beqaa area (Hezbollah’s logistical operational rear base) to southern Lebanon (which is divided into two staging areas named by Hezbollah ‘the lines of defense’)” [5].

Beeri [6]¹ called this inter-regional tunnel network “*Hezbollah’s Land of the Tunnels*”. Various reports indicate that in the late 1980s, and even more so after the Second Lebanon War (2006), North Korean advisors significantly assisted Hezbollah’s tunnel project. Beeri [6] found that “*Hezbollah, inspired and supported by the Iranians, saw North Korea as a professional authority about tunneling, based on the extensive North Korean experience (Figure 6) that had accumulated in building tunnels for military use since the 1950s. Hezbollah’s model is the same as the North Korean model: tunnels in which hundreds of combatants, fully equipped, can pass stealthily and rapidly underground. It’s two types of tunnels we’re talking about: offensive tunnels and infrastructure tunnels. While in Israel, professional officials believed that breaking rocks in the mountainous areas of the Galilee on the Israeli Lebanese border can be very difficult if not impossible, but the tunnels excavated between the two Koreas (north and south), were excavated in a mountainous terrain, which is considered even more rugged and solid than the terrain in the Galilee region. As it turned out, at least six Hezbollah offensive tunnels built and excavated into Israeli territory for many years, with the inspiration and support of North Korea and Iran, were exposed by the IDF in December 2018 as part of Operation Northern Shield*” [6].

¹Disclaimer: Verifying the information in reference 6 from independent sources that are top secret, and classified is not possible during a war. The alleged roles of Iran and North Korea in funding, sharing engineering technology and building the soil tunnels between Lebanon and Israel and Syria and Israel were documented with references [5]-[8]. However, both Iran and North Korea deny involvement in the funding, equipment manufacturing, engineering and tunnel construction under the Lebanon-Israel border. The fact that tunnel technology used by Hamas along Gaza border with unconsolidated parent material could not work in consolidated (solid bedrock) parent materials. Therefore, Hezbollah either had to fund, design, manufacture tunnel boring equipment and utilize the equipment to soil tunnels through consolidated (solid bedrock) parent material, or it had to have had external support and assistance. North Korea had previously created soil tunnels under the DMZ to invade South Korea using such engineering techniques to bore through consolidated (solid bedrock) parent material and would be a possible source of the required technology. Also, Iran has a long history of creating tunnels through and into mountains using mechanical equipment. These tunnels have been used for highways and storage of nuclear material. The construction of soil tunnels by both North Korea and Iran are well documented in the published literature. However, since both Iran and North Korea deny any involvement in the funding, design, manufacturing, engineering and construction of tunnels under the Lebanon-Israel border we decided to publish this disclaimer. Hopefully, after the war ends these reference 6 claims can be validated or discredited.



Figure 6. Soil tunnels through bedrock in Korea DMZ.

Olson and Speidel [4] determined “*The Iranian-backed Hezbollah used a pioneering tunnel system in south Lebanon (Figure 3) during its 34-day war with Israel in 2006. It also prepared for another conflict with its old enemy, Israel, by creating an advanced tunnel network on Israel’s northern border. This reputedly includes assault tunnels far into the Jewish state, just like Hamas’s infiltration tunnels into Israel’s southern desert*”.

“*The network, much of which appeared to have been carved out of the rock with pneumatic drills, included prayer rooms, sleeping quarters and electrically powered fans to keep the air circulating through the underground system. It was a city under the city. Israel’s military has been seeking ways to counter this old-new form of warfare, which has redefined the concept of the front line, but has not come up with a foolproof system. These tunnels could be constructed in an arid climate with a low permanent water table. The parent material is unconsolidated and overlies bedrock which can be excavated with power drills*” [4].

Olson and Speidel [4] reported “*Hezbollah built a vast network of advanced tunnels (Figure 2) along the Lebanon border with Israel for use in a future war and using them to conceal tens of thousands of rockets aimed at the Jewish state. The group has built a sprawling underground array of tunnels, bunkers, and surveillance outposts along the border with Israel, which it manned at peak readiness for battle*”.

“*The soil tunnels were highly advanced, with durable concrete, a 24-hour power supply via underground generators, a ventilation system to prevent damaging military equipment and a web of secondary escape shafts in case of attack. The tunnels housed tens of thousands of rockets ready for launch and were wrapped individually in protective materials to preserve them*”.

“*Hezbollah was constantly surveying the Israeli border area with electronic equipment as well as observation posts equipped with night-vision technology. Tunnel construction was said to be continuing around the clock, using primitive means rather than advanced machinery to avoid detection by Israeli surveillance*”

[4].

Miller [7] found “*Most of the weapons have been transferred to Lebanon through war-torn Syria, coming from Hezbollah’s key allies, the Syrian government and Iran. Tunneling in the rocky terrain of the Lebanon-Israel border is much tougher than in the sandy unconsolidated ground along Gaza’s border. Geologists suggested tunneling in the rocky terrain of southern Lebanon was not as difficult as it appeared. A cross-border tunnel hundreds of meters long can be dug in six months. The arid climate and low water table allowed soil (Aridisols) tunnel construction. These soil tunnels were blocked and/or blown up*” [7].

Regarding the Lebanese tunneling network project Beeri [6] suggested “*that it began before 2006, but there is no doubt that it gained significant momentum after that year. The tunnel project is the result of close cooperation between North Korea, Iran, which paid for the project and supported it, and Hezbollah. The triangle of cooperation between these three entities goes back to the 1980s. Since 2006, North Korean advisors significantly assisted Hezbollah’s tunnel project. Hezbollah, inspired and supported by the Iranians, saw North Korea as a professional authority about tunneling, based on the expansive North Korean experience that has accumulated in building tunnels for military use since the 1950s*” [6].

A report released by the Alma Center [5] stated “*In 2018, the IDF exposed six offensive Hezbollah cross-border tunnels excavated into Israeli territory. Their discovery spelled the end of the concept held by some in Israel that the challenge of breaking rocks in mountainous areas as in Lebanon was a serious barrier to Hezbollah tunnel building. A second type of tunnel network, described as local infrastructure tunnels, is located within and near the Shi’ite villages that act as Hezbollah’s staging areas. But the report exposed a new, third type of tunnel, which it called ‘inter-regional tunnels of enormous magnitude, spanning at least tens of kilometers’ across Lebanon*” [5].

Beeri [6] said “*In 2008, we uncovered an indication from a Christian Lebanese information source, describing a big project by Hezbollah in whole areas of Southern Lebanon, which began east of Sidon*”. He then “*described getting access to eyewitness accounts from local residents who were stopped by Hezbollah from entering certain areas. They didn’t understand why Hezbollah was stopping them. What they could see was what resembled industrial work, sand, digging, concrete in the area. But nothing was being built above ground. They saw Iranians and foreign nationals that they later realized were North Koreans*”.

Later, Alma obtained a map of Southern Lebanon divided up into polygon shapes, and within them, circles. Beeri [6] said IDF asked “*Could this be some sort of sketch of a route of a military system? A tunnel system?*” IDF connected the eyewitness reports of the digging and the fortification work that could not be seen overground and the map [6]. According to eyewitness reports, the Hezbollah carried out fortification work in those geographical areas using large quantities of construction materials. The work was carried out by a Korean company under the

supervision of an Iranian Revolutionary Guard Corps officer. While the actual construction was conducted by Hezbollah's Jihad Construction Foundation, the report, named a North Korean company, called Korea Mining Development Trading Corporation (KOMID), as the company doing the work.

The Jihad Construction Foundation reportedly received assistance from companies that acted as civilian cover for the construction of the long tunnels. One of the suspected companies, said Beerli, is the “*Beqaa for Construction and Contracting*” company. The company was set up in 2005 under the auspices of Iran's Islamic Revolutionary Guards Corps. Until 2013, it was headed by Major General Hassan Shateri, a senior IRGC officer who was mysteriously killed in Syria in 2013. It is highly likely that Shateri was responsible for carrying out Hezbollah's tunneling project in Lebanon” according to the Alma report. It sketched out the route of one tunnel, stretching 45 kilometers south of Beirut, east of Sidon, in an area of Southern Lebanon that Hezbollah describes as its “*second line of defense*” against a potential Israeli ground maneuver. Ultimately, the tunnels enable the secretive movement of Hezbollah's forces and weapons.

The IDF have their own long history of dealing with tunnels, especially cross-border tunnels. Hamas and Hezbollah have used cross-border tunnels in the past to conduct surprise attacks on IDF outposts or small patrols in a bid to kidnap Israeli soldiers [8]. This led to the IDF to develop advanced detection, mapping, and navigating capabilities, as well as—in an emergency such as a soldier being taken back into a tunnel—the tactics to follow an enemy underground.

In 2018, Israel pumped wet cement into cross-border Hezbollah tunnels along the northern border with Lebanon. The exact number of metric tons of wet cement required for a single tunnel, while not publicly reported, was substantial. This tactic may block tunnels under the right circumstances, but it is not practical where there are a lot of tunnels to address.

Spencer [8] found “*The IDF have already taken their new understanding, culture, and approach to tunnels to another theater in southern Lebanon, where Hezbollah also built a vast tunnel network of hundreds of miles and which is referred to as the ‘Land of Tunnels’.* The 98th Paratroopers Division, with its pioneering and advanced underground warfare skills, was one of the first units to conduct raids into the Hezbollah tunnels found along Israel's northern border.”

3.2. Syria and Israel Border

Olson and Speidel [4] determined “*The Syrian conflict has moved subterranean warfare to the forefront and provided a physical link to these tactics that go back to ancient times. Most of Syria's modern cities are built on layer after layer of ancient structures. The city of Aleppo, for example, is believed to have been continuously inhabited since the Copper Age, around 6000 BC, and Damascus was an urban center 2000 years before Julius Caesar. British archaeologists concluded in 2009 that remains of 20 Roman soldiers unearthed in a tunnel beneath the town's ramparts had been killed in a clash with the invading Persians seeking to*

dig their way into the fortress. Persians, in about 256 AD, may have been an earliest user of chemical warfare—pumping in a poisonous mix of burning sulfur crystals and bitumen that killed the Romans in minutes. In 2019 the Kurds found three major ISIS soil tunnels and cave complexes on the Turkey border with Syria”.

“Fighters of the Islamic Front rebel group blasted the large Syrian Army base at Wadi al-Deif in Idlib province in March 2014 from an unexpected quarter [4]. They detonated an estimated 60 mt of explosives stacked at the end of an 850-m tunnel the Syrian’s had spent weeks digging. The huge explosion, which killed dozens of Syrian officers and blew an entire hillside hundreds of meters into the air. While barbaric it did demonstrate a successful use of tunnels as a military tactic” [4].

Across the Middle East, it seems that everyone is going underground again [5] [6] [9]-[11], including Hamas, Hezbollah, and ISIS. Iran has constructed extensive nuclear facilities in underground bunkers and inside mountains to protect them from potential Israeli or US air strikes [5].

Olson and Speidel [4] found *“even the Syrian regime was tunneling. The Jaysh al-Islam coalition released a documentary that revealed a self-contained underground complex constructed in the bowels of Damascus under the Harasta quarter for Syrian President Bashar Assad and his inner circle. It included an intelligence center and chemical decontamination chambers. According to the Pentagon’s Joint Improvised-Threat Defeat Organization, there have been more than 50 major tunnel bombings occurring in Syria and Iraq as insurgent groups resorted to a primitive combat strategy to counter the technological superiority of the state military forces”.*

“Some of the bombings have been pulverizingly powerful. The March 4, 2015, tunnel bombing of the Syrian Air Force headquarters in Aleppo was so strong that it was registered as a 2.3-magnitude earthquake by the European-Mediterranean Seismological Center west of the city. There had never been such an intense network of tunnels as there is in Syria. It started in Homs in 2012. Military analysts estimate that the Syrian rebel groups have dug between 500 and 1000 tunnel systems. The environmental impact of the creation and bombing of the soil tunnels is never included in the analysis. It can take decades, if ever, for the impact of the soil tunnels and subsequent bombings to be documented”.

“ISIS has built extensive networks under cities it had conquered to evade round-the-clock air strikes by the United States and its allies and used tunnels to pump oil from captured fields, a key source of funding. Approximately 30 or 40 tunnels were found inside Sinjar, an Iraqi town captured by the jihadists in 2014 and retaken in November 2015 by the Kurdish” [4].

3.3. Israel and Gaza Border Tunnels

In May 2021, Israel Defense Forces (IDF) exposed to Hamas’ huge network of tunnels in the Gaza Strip, nicknamed by the IDF the “*Hamas Metro*”. Major Tal

Beeri [6], head of the research department at Alma and former member of the IDF said “ *Hamas didn’t invent tunnels. Usually, Hamas is the last in the food chain when it comes to new tools used by the radical axis. The discovery of the tunnel network in Gaza leads to the conclusion that this has been happening in Lebanon for a long time. The Iranians and North Koreans are mentors for both organizations. Hamas are the ones copying here. Hezbollah are usually the pioneers. So, imagine what is happening in Lebanon now*”.

During the 2014 Israel-Gaza conflict, Israel launched a ground offensive into Gaza (Figure 7) with the primary goal being to fully destroy the cross-border tunnels (Figure 8). In total 31 tunnels were found and destroyed during the weeks the Israel Defense Forces (IDF) were in Gaza [4]. On August 11, 2014, the IDF announced they had successfully tested a system that could be used to detect these tunnels. This new system apparently uses a combination of sensors and special transmitters to locate underground tunnels. The IDF expected development at a cost of \$0.5 billion US and was deployed by 2015.



Figure 7. Israel launched a ground offensive into Gaza in 2014 to find soil tunnel entrances. Photo Credit: Times of Israel.com.



Figure 8. Soldier walking inside a re-enforced Gaza tunnel. Photo Credit: Times of Israel.com

In 2105 Israel destroyed an earthen tunnel dug by Hamas from Gaza into Israeli territory, dealing a substantial blow to one of the main strategic assets in the Islamic militant group's arsenal. It was the second cross-border tunnel detected by the Israeli military using new technologies and they destroyed both of these tunnels. Israeli officials have predicted the end of the cross-border threat from such tunnels. The decision was made to incapacitate the tunnel despite the current tensions over Jerusalem [12]. During the 2014 Gaza war, several Israeli soldiers were ambushed and killed by militants who emerged from underground tunnels. The Israeli authorities claim the tunnels violate Israeli sovereignty and threaten civilians living in the border area.

The latest tunnels to be destroyed extended hundreds of meters into Israeli territory, according to the military, and ended in open farmland (Figure 9) about two kilometers from the nearest Israeli village [10]. Israel had invested heavily in trying to thwart the tunneling. Israel recently went public with its plans for a subterranean barrier using virtual-reality systems to simulate fighting in tunnels and is training troops in mock-ups of maze-like underground networks. Historically, Israel destroyed the earthen tunnels by bombing them. Up to a dozen Islamic Jihad militants were killed in the tunnel's collapse and two Hamas militants were rescued.



Figure 9. Moving sheep through a Gaza soil tunnel. Photo Credit: National Geographic.

In Gaza, Hamas has been confounding the Israelis for years with an elaborate labyrinth of tunnels (Figure 10) for infiltrating fighters into the Jewish state, launching rockets or sheltering commanders during combat. This has triggered three controversial invasions of the densely populated coastal strip. In Operation Protective Edge (Figure 11), the incursion in summer 2014, Israel destroyed 32 Hamas tunnels, but Palestinian sources said Hamas has more than 1000 people working underground building a new network. The tunnels were dug into deep soils (Alfisols, Inceptisols and Aridisols) underlain by unconsolidated parent material having a low water table. The border area is in an arid climate. There are few rocks and little bedrock below the soil surface.



Figure 10. An Israeli soldier overlooking an uncovered Palestinian tunnel in the Gaza Strip during Operation Protective Edge, 2014.



Figure 11. Photograph of a Palestinian tunnel shaft uncovered by the Israel military during Protective Edge, 2014. Photo Credit: Times of Israel.com.

Spencer [8] noted “*Before the 2023 war against Hamas in Gaza, the Israel Defense Forces (IDF) were one of the most prepared militaries in the world for underground warfare. The IDF were the only army to have a full brigade-sized unit dedicated to training, manning, equipping, researching, developing new technologies and tactics, learning, and adapting solely for underground warfare. Still, the challenges they faced early in their campaign in Gaza, many of which they struggled initially to overcome, speaks to the incredible complexity of subterranean warfare. Their responses to these challenges signal a paradigm shift in modern approaches to underground warfare.*”

“*One of the main reasons the IDF were unprepared for Gaza’s underground spaces was simply that no military had faced anything like it in the past—not even Israeli ground forces. The IDF faced a Hamas military organization that had spent over fifteen years engineering the infrastructure of an entire region—to include*

over twenty major cities—for war, with the group’s political-military strategy resting on a vast and expensively constructed subterranean network under Gaza’s population centers. The Hamas underground network, often called the “Gaza metro,” includes between 560 and 720 kilometers of tunnels and bunkers at depths ranging from just beneath apartment complexes, mosques, schools, hospitals, and other civilian structures to over 60 m below the land surface. There are estimates of over 5000 separate shafts leading down into Hamas subsurface spaces. In past wars, where underground environments were used, the tunnel networks were subordinate to the surface and were not built solely under population centers mostly to be used as massive human shields.”

“IDF investigations and captured Hamas documents produced reports that it took Hamas a year to dig one kilometer of standard tunnel at a per-kilometer cost of \$275,000. Several factors—size, type, and function, for examples—can raise the costs well beyond that of a standard mobility tunnel. The variety of tunnels in Gaza makes it difficult to estimate the underground network’s overall cost, but Hamas reportedly spent \$90 million to build just three dozen tunnels in 2014, and some analysts place the network’s total cost at over \$1 billion.”

“On October 7, 2023, the IDF had a brigade of special operations forces engineers, the Yahalom unit, fully equipped with technologies and tactics to accomplish the full range of underground warfare tasks, from detecting, securing, and mapping tunnels and bunkers to exploiting, clearing, neutralizing, and destroying them. This unit has spent decades researching, developing, testing, and purchasing technologies to overcome the challenge of military operations underground. This work includes a decade-long anti-tunnel cooperation and exchange program between Israel and the United States to jointly develop technologies and tactics that address the challenges of underground warfare. The IDF also has a robust military working dog program, the Oketz unit, that includes dogs trained for operating in subterranean spaces.”

“IDF units like Yahalom had plenty of work to do to prepare for underground warfare. Soldiers need special equipment to breathe, see, communicate, navigate, breach obstacles, and even shoot underground. Almost every piece of their standard military equipment designed for the surface will not work once they enter the subsurface. Line-of-sight and satellite-enabled technologies—including navigation, communication, and drones—are rendered useless. Night-vision goggles that rely solely on ambient light will not work in an environment where there is none. A blast from a weapon or explosive detonated in enclosed underground spaces can cause harmful pressures and blast injuries making it dangerous to even fire a personal weapon if the soldier is not wearing the proper protective gear” [8].

At the beginning of the IDF operations against Hamas in Gaza after the October 7 attack, the IDF targeted many bunkers and tunnels with precision-guided bunker-busting munitions [8]. These strikes were based on intelligence regarding the locations of tunnels, their purpose and value to the enemy, their contents, considerations about the presence of hostages or civilians, and other factors.

Once the ground campaign began, the IDF knew they would be encountering a lot of tunnels. They task-organized squad-sized elements of Yahalom to as many maneuvering units as possible. The force that entered Gaza rapidly learned how to identify visual indicators of tunnel shafts, such as markings on buildings, the presence of infrastructure needed in the tunnels for power or ventilation, and other identifying features [8].

Once a shaft was located, it was generally secured and then Yahalom was called forward to investigate it. Even identifying a shaft was dangerous and time-consuming. The IDF lost five soldiers in early November 2023 from a booby-trapped tunnel entrance [8]. Hamas's use of booby traps outside and inside their tunnels was pervasive. In some cases, Hamas tunnels were built with improvised explosive devices embedded into the walls. This allowed Hamas fighters to arm and then leave their booby-trapped tunnels quickly.

If a shaft was determined to be a tunnel it was carefully interrogated, mapped, and searched. Many advanced technologies were used in this process, including drones and robotic devices designed to work underground [8]. In some cases, military working dogs with cameras mounted on their backs were deployed, but the risk of losing dogs to booby traps made this tactic rare. During this time, Israel continued to be reluctant to send troops underground and only did so after tunnels were searched for potential dangers.

In fighting Hamas defenders, the IDF immediately faced enemy brigades, battalions, and companies that each had tunnel networks supporting their operations [8]. In northern Gaza, the IDF had weeklong battles over single neighborhoods because of Hamas's ability to pop in and out these networks and avoid decisive engagement.

In one attempt to combat Hamas's use of their tunnels, the IDF procured and deployed what is reported to be at least five industrial pumps (Figure 3) to push thousands of cubic meters of water per hour into the tunnels to literally flush Hamas fighters out of them. The flooding had minimal impact. One IDF officer [8] said, it took two weeks for a small Hamas tunnel to fill before the IDF finally saw Hamas fighters on the surface where they could be targeted. Due to the tunnels' porous concrete lining, the water simply drained out of them. Some tunnels were even built with drainage holes in them, while in others blast doors complicated the process. Flooding had little impact and was too time-consuming to use as a primary method to force Hamas fighters out of their tunnels. And ultimately, flooding would not destroy a tunnel.

The more the IDF engaged with the Hamas tunnel network, the more they adapted. Stopping for every suspected tunnel shaft and waiting for Yahalom to investigate severely slowed the momentum of maneuvering forces. Many of the suspected shafts were simply wells, civilian infrastructure, or other types of tunnels [8]. The IDF quickly realized they had to push some of the specialized knowledge of Yahalom lower and to general-purpose soldiers. The regular IDF soldiers began to become proficient at dealing at least with shaft identification,

site securing, and initial investigations.

The IDF began to realize that in many areas, the tunnels were a system of systems. Each Hamas company, battalion, and brigade had its own networks of tunnels that factored into how they would fight and move around. Some of these networks connected to each other while others were separate [8]. Once the IDF were able to focus intelligence efforts on determining the classification and architecture of a tunnel system in a specific area or neighborhood, their success in finding and dealing with tunnels significantly increased.

The IDF also developed a typology of Hamas tunnels. Some Hamas tunnels were tactical, such as small-unit tunnels that ran from building to building giving Hamas fighters the ability to hold specific terrain. Some were more operational as they connected different battalions or brigades to each other or provided operational mobility—like the two kilometer-long tunnels running underneath the river basin of central Gaza to connect the region’s northern and southern portions [8]. What to do about a specific tunnel and the urgency of action could be determined by proper identification of the type of tunnel that had been encountered.

Despite the IDF adaptations, a challenge remained: that of Hamas forces using the tunnels for their defensive operations as long as they could and then simply lining the tunnels with booby traps as they fell back to different tunnels [8]. The tunnels gave Hamas the ability to control the initiative of most battles in Gaza.

Spencer [8] identified “*One Israeli commander refused to allow Hamas fighters to control the initiative by using their tunnels. When the war in Gaza began, Brigadier General Dan Goldfus—a veteran of the Shayetet 13 unit, a naval special operations unit—commanded the elite 98th Paratroopers Division. In late November 2023, with some of the IDF’s best armor, artillery, and engineer units added to its paratroopers and commandos, the division was deployed into Hamas’s strongpoint city of Khan Yunis in southern Gaza. The city was considered to be the ‘center of gravity’ of Hamas’s military forces.*”

“*General Goldfus learned from what the other IDF divisions had encountered in northern Gaza but also oversaw a rapid learning initiative to study the Hamas tunnels in Khan Yunis. He had his soldiers study the details of each tunnel, traveled into the tunnels with his soldiers, and had soldiers collect on how Hamas protected certain tunnels. He also used his unique connections in the IDF and Israel’s intelligence service to develop what might be called all-source intelligence about types and locations of tunnels as well as other trends in Khan Yunis. Eventually, the division built the confidence that it understood the enemy’s tunnel network.*”

“*General Goldfus developed a plan to enter Hamas’s tunnels without Hamas knowing his soldiers were there. This was unlike any IDF unit’s approach to tunnels in Gaza yet. His plan was briefed to his superiors for approval. He was given the approval to take the calculated risks that other units had not to that point. He then started sending his special operations forces, engineers, and others into un-cleared tunnels at the exact same time he was maneuvering on enemy forces on*

the surface.”

“IDF special operations forces, commandos, and others were equipped with all the specialized equipment needed to breathe, navigate, see, communicate, and shoot underground. General Goldfus’s division headquarters refined the ability to control forces moving underground with the tempo of the surface forces. Incrementally, the division refined its tactics to the point its soldiers were conducting raids with separate brigades attacking on the surface while more than one subterranean force maneuvered on the same enemy underground.”

“For the first time in the modern history of urban warfare, General Goldfus and his soldiers were conducting maneuver warfare simultaneously incorporating the surface and subsurface in dense urban areas. They had turned tunnels from obstacles controlled by the defending enemy into maneuver corridors for the attacker.”

“More importantly, through General Goldfus’s leadership and his soldiers’ adaptations, innovations, and hard work, the division began to transform the IDF’s culture toward underground warfare. Its tactics were spread to other units, along with the understanding that the old culture of avoiding tunnels was no longer the IDF’s approach. The new culture of a deeper understanding of—and, in some cases, using—the enemy’s tunnels to facilitate maneuver warfare with simultaneous maneuver on the surface and subsurface is unlike that of any other military in modern history” [8].

One of the few feasible methods to eliminate a tunnel, used historically and validated by modern case studies, is to place explosives through the full length of it [8]. This is what Israeli forces have been doing in Gaza, but they quickly ran into scaling and resourcing problems.

Israel has a couple of explosive options. One of these is injecting liquid TNT into tunnels. This involves drilling holes into the tunnel at 650-foot intervals—and requires twelve tons of explosives per kilometer [8]. An alternative is methodically placing explosives along the inside of cleared tunnels. Reports show that to demolish just one kilometer of tunnel requires fifteen metric tons of TNT placed inside the tunnel. The amount of TNT needed for tunnels Israeli forces discovered in Gaza quickly exceeded their supplies of liquid or military-grade explosives like composition C-4. They therefore primarily relied on a field-expedient method of using both their own stockpile as well as captured Hamas explosives designed for other uses such as antitank mines to string together along tunnels.

The harsh reality is that there is likely not enough supply of explosives or enough time to destroy all the tunnels in Gaza. To find all the tunnels and then destroy them would potentially take years [8]. The IDF seem to be focusing limited resources on destroying the tunnels that provided Hamas with the most military value to survive or conduct attacks against Israel.

The IDF also developed advanced tunnel-striking capabilities with a wide variety of bunker-busting munitions. In the 2021 Operation Guardian of the Walls, the IDF believed they had destroyed ninety six kilometers of Hamas tunnels in

Gaza. Captured documents show that after this 2021 operation, the Hamas leadership authorized \$225,000 to install more blast doors in tunnel segments to protect against IDF bunker-busting munitions collapsing more of the tunnel beyond the point where the bomb directly strikes. Hamas also increased production of handbooks showing their fighters how to survive and fight in tunnels [8]. In general, the IDF culture before 2023 was marked by the belief that tunnels should be dealt with by specially trained forces and that regular troops should only be sent underground as a last resort.

3.4. Gaza and Egypt

The Gaza Strip smuggling tunnels are passages that have been created under the Philadelphi Corridor, a narrow strip of land, 14 km in length, situated along the border between the Gaza Strip and Egypt (Figure 5). After the Egypt-Israel Peace Treaty of 1979, the town of Rafah on the southern Gaza Strip was split by this Corridor. One part is in the southern part of Gaza, and the smaller part of the town is in Egypt.

The first recorded discovery of a tunnel by Israel was in 1983, after Israel had withdrawn from the Sinai [13]. The border, redrawn in 1982 after the Egypt-Israel Peace Treaty, divided Rafah into an Egyptian and a Gazan part. The tunnels used to start from the basements of houses in Rafah on one side of the border and end in houses in Rafah on the other side [14] [15]. After Israel withdrew from Gaza in 2005, the Philadelphi Corridor was placed under the control of the Palestine Authority until 2007. When Hamas seized power in 2007, Egypt and Israel closed borders with Gaza [15].

In 2009, Egypt began the construction of an underground barrier to block existing tunnels and make new ones harder to dig. In 2013-2014, Egypt's military destroyed most of the 1200 tunnels which were used to smuggle food, weapons and other goods into Gaza [7]. The blockage of the Gaza Strip caused a shortage of certain basic products, especially construction materials, fuel, some consumer articles, and medicines and medical supplies. Import restrictions, including of basic building materials, have led to the proliferation of tunnels under the border with Egypt. As Israel limited the Palestinian freedom of movement, the tunnels were the only way to move to and from Gaza.

The tunnels were used to smuggle a wide range of goods, including fuel, gas, cement, construction materials, raw materials, pesticides, seeds, agricultural tools, preservatives, packaging material, spare parts, livestock (Figure 9), zoo animals, food, medicines, clothes, car parts, building supplies, weapons and luxury items in general. Initially, the tunnels were used for moving consumer goods and medicines. During the First Intifada (1987 to 1993), some secret tunnels were utilized by militant groups to bring in arms and money [13].

Smuggling fuel through the tunnels had been the primary source of fuel for Gaza's only power plant. Electricity is needed for the desalination of drinking water. After Egypt demolished hundreds of tunnels in 2013 and Israel closed the

Kerem Shalom Crossing, a shortage in fuel caused the shutdown of the power plant. Increased fuel shortages and high prices, due to the intensified anti-tunnels measures by the Egyptian el-Sisi regime, halted the functioning of sewage treatment facilities in Gaza in 2014. Untreated wastewater was pumped into the Mediterranean, causing serious environment pollution and swimming prohibition at the beaches.

According to an article by Nicolas Pelham [13] in the *Journal of Palestine Studies* (IPS), child labor was employed in the smuggling tunnels with the justification that children were more “nimble.” Despite calls from human rights groups, the Gaza government has not completely stopped using child labor. Pelham reported that at least 160 persons, including children, have been killed in the tunnels.

Contractors operating from basements of houses or an olive grove were able to dig under the border at depths of up to 30 m and reaching up to 800 m in length. Many tunnels are of generally high quality of engineering and construction—with some including electricity, ventilation, intercoms, and a rail system—they are still very dangerous and are prone to cave-ins. The openings to many tunnels are found within buildings in or around Gaza’s southernmost city of Rafah [15]. Israel has destroyed hundreds of homes along the Gaza-Egypt border to enlarge the buffer zone, asserting that they were used to hide smugglers’ tunnels.

In late 2009 Egypt started construction of a subterranean barrier to curb the use of smuggling tunnels. In 2010, the Mubarak regime sprayed toxic gas into the tunnels, killing four Palestinians. In 2011, Egypt sealed a series of smugglers’ tunnels between its border and the Gaza Strip. In 2013, the Egyptian military shut down the smuggling tunnels connecting Sinai and Gaza by flooding them with sewage. On 11 September 2015, the Egyptian Army pumped water (Figure 3) from the Mediterranean Sea into the tunnels. Several Palestinian factions condemned the flooding of the border with sea water because it posed a serious threat to environment and ground water. By August 2014, the Egyptian Military destroyed 1659 smuggling tunnels [12]. The border area was in an arid climate with a deep and well-drained soil (Aridisols). The water table was low, and tunnels were dug through unconsolidated and consolidated parent material (Figure 12). These soil tunnels were blocked, blown up, or flooded with water and sewage.

From 2013 to 2019, Egypt used sewage and seawater to collapse primitive Hamas smuggling tunnels along its border with Gaza. As discussed earlier, however, this did not work on the more sophisticated tunnels found inside Gaza.

3.5. West Bank Soil Tunnels

After years of hearing about the tunnel threat in the North and South, now the residents of the Seam Zone fear the threat has expanded to the eastern front. Dr. Daphne Richemond-Barak, an expert in the field, explains in an interview with *Maariv* why this is nothing less than an oversight [16]. The Seam Zone area is made up of towns that lie between separation markers in the West Bank (walls,

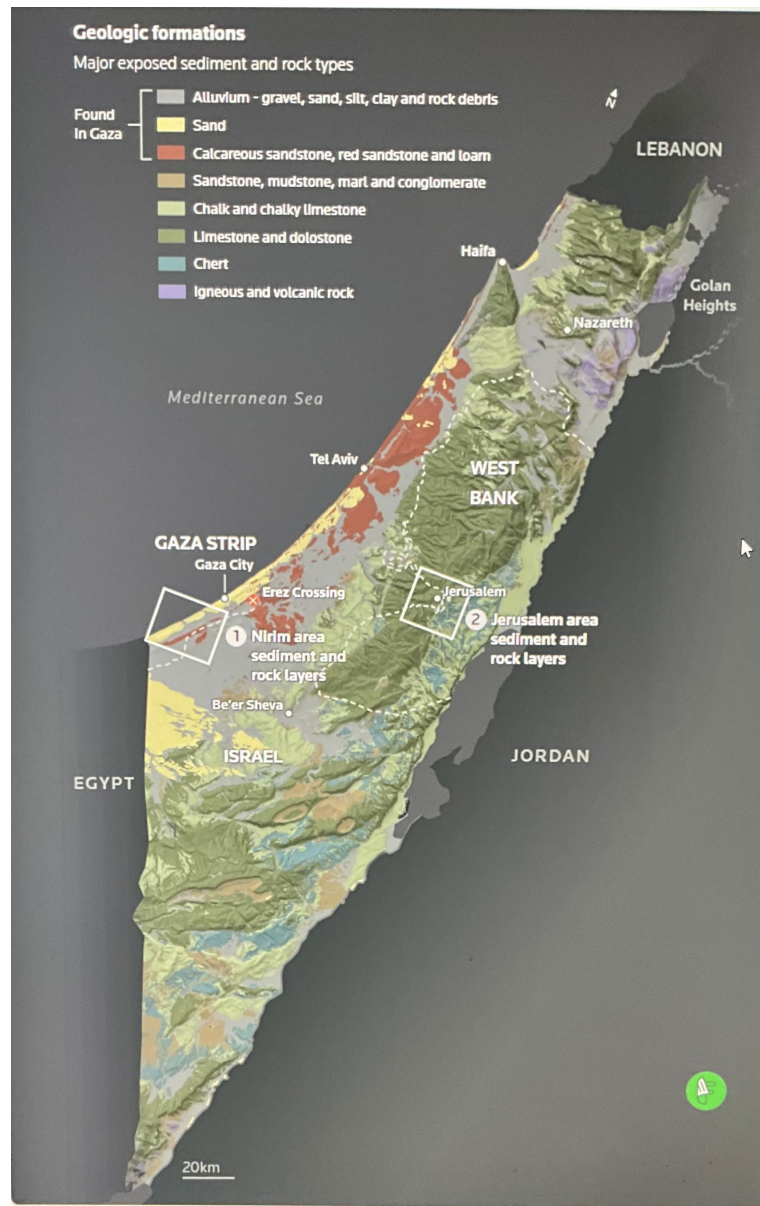


Figure 12. Geologic formations in Israel. Photo Credit: Reuters.

security fences, etc.), and the Green Line between Israel and West Bank (Figure 12), including both settlements and Palestinian villages. If estimates include east Jerusalem, this amounts to about 8.5% of the West Bank. In recent weeks, similar complaints have been forwarded to Israeli security forces by Seam Zone residents.

“In the two years before the discovery of the tunnels in the north, there were many residents who complained, but at first they were not believed,” recalled Dr. Richemond-Barak, a senior lecturer at the Lauder School of Government, Diplomacy and Strategy at Reichman University, who recognizes a great similarity between the various arenas [16]. Having gained substantial experience in researching Israel’s underground threats, she is convinced that the publications in the media concerning the region of Emek Hefer and the Sharon point to a failure of the

security forces.

The Israel Defense Forces said Friday it had located a short underground tunnel near a hospital in the West Bank city of Tulkarem (**Figure 13**) amid an ongoing counter-terrorism operation [17]. The tunnel had an entrance but no exit, the military said, indicating that it was still under construction. The IDF said troops would investigate the tunnel (**Figure 14**) and then destroy it (**Figure 15**).



Figure 13. The search for tunnel shafts in West Bank. Photo Credit: Via Maariv.



Figure 14. An Israeli armored vehicle drives on torn up street during a raid in Tulkarem on September 3, 2024. Photo Credit: JAAFAR ASHTYEH/AFP.



Figure 15. Israel-Gaza border soil tunnels being blown up. Photo Credit: YouTube.

While Hamas built a vast tunnel network under the Gaza Strip, the dismantlement of which has been a key challenge of the ongoing war there, tunnels are rare in the West Bank, where the IDF regularly operates to demolish terror infrastructure. The military resumed its major operation in the northern West Bank on Tuesday after a lull of a few days. The operation, dubbed “Summer Camps,” was launched on August 28 (2024). Since the operation resumed, the IDF says it has killed 10 gunmen in clashes and drone strikes.

Also Friday, police released footage showing members of the elite Yamam unit detaining a wanted Palestinian in a hospital in the West Bank city of Halhul. The Palestinian suspect had been wounded in an attempted car bombing attack in Halhul a month ago, police and the Shin Bet said.

Since October 7, troops have arrested some 5000 wanted Palestinians across the West Bank, including more than 2000 affiliated with Hamas. According to the PA health ministry, more than 670 West Bank Palestinians have been killed in that time. The IDF says many of them were gunmen killed in exchanges of fire, rioters who clashed with troops or terrorists carrying out attacks. During the same period, 33 people, including Israeli security personnel, have been killed in terror attacks in Israel and the West Bank. Another six members of the security forces were killed in clashes with terror operatives in the West Bank.

4. Summary

The primary objectives were: 1) assess the soil and geological materials, climate, bedrock, permanent water table and flooding conditions that exist on the Israel border to determine where earthen soil tunnels could be successfully created, 2) assess the use by Hamas of soil tunnels during the October 7, 2023 invasion of Israel, 3) document the new Israel Defense Force (IDF) understandings, culture, and approach to categorizing, blocking, and destroying the Gaza tunnels, 4) apply IDF lessons learned on the Israel-Gaza border to southern Lebanon-Israel border where Hezbollah has built a vast tunnel network, 5) utilize pioneering and advanced underground warfare skills learned by IDF in Gaza to conduct raids into the Hezbollah tunnels along the Israel’s northern border with Lebanon and 6) apply lessons learned by IDF on how to liberate areas in Lebanon underlain by soil tunnels. The environmental impact of the creation and destruction of soil tunnels is never included in the initial military analysis. The military strategy and need to win the war are always the priority and collateral damage to the environment can take decades to document, if ever. Soil tunnel construction and destruction often has adverse environmental and human health impacts on the Israeli border landscape.

Earthen tunnels have been utilized in modern warfare and smuggling. In military conflicts the inferior side utilizes earthen tunnels to hide troops, supplies and equipment from the other side. The use of tunnels in most cases was in arid areas with a relatively low permanent water table. The soils and unconsolidated parent materials were often deep. However, in modern warfare shallow to bedrock sites

were used when mechanical power drills were available, and the noise and vibrations could not be detected by the country or opposing force on the other side of the border or by the opposing military forces. In all cases the goal was to hide and avoid detection. In some cases, the tunnels needed to be resilient when subjected to bombing or electronic detection and need to have entrances and exits that are covered. In deeper tunnels ventilation systems were needed. One way to eliminate soil tunnels was to flood them with water or sewage. This was routinely done on the border between Gaza and Egypt. A source of water from a river, lake, sea or ocean was needed to flood the tunnels. At the Gaza strip, Mediterranean Sea water was used. The most restrictive site conditions, when creating an earthen tunnel, were flooding and a highwater table. Only flooding cannot be mitigated.

Soil tunnels, on the Israeli borders with Gaza, Egypt, West Bank, Syria, and Lebanon have a long history of use for warfare, as invasion pathways, smuggling, and storage of rockets, missiles and ordnance and are causes of serious political tension between the countries. Invisible roads are used by migrants seeking asylum for safety and economic opportunity and for illegal smuggling of drugs and human trafficking. Soil tunnel construction and destruction often has adverse environmental and human health impacts in the Israeli landscape. These underground networks shelter soldiers, store weapons and supplies, are transport corridors, and serve as communication and intelligence conduits. Although peace may be elusive, the history of soil tunnels suggests several defensive approaches that can reduce Israeli vulnerability to illegal infiltration and increase homeland security.

Spencer [8] noted *“It is unlikely that any military will face a tunnel system like that in Gaza, where an enemy’s political-military strategy rests on the tunnels and they are deliberately placed under civilian areas. But militaries will continue to encounter subterranean environments in warfare. Some countries continue to invest in thousands of kilometers of military tunnels and bunkers to protect everything from nuclear sites, radar installations, and runways to full military bases. It is also hard to separate urban warfare from underground warfare in major cities that have existing civil infrastructure underground for transportation, water, and other essential services”*.

“The lessons from the IDF’s adaptations and, ultimately, transformation of culture toward underground warfare are deeply important for other militaries—especially those whose own cultures are characterized by the notion that tunnels are obstacles that should be avoided or only dealt with when required. The lessons learned by the IDF will save the lives of other soldiers in other battlefields. The IDF have also shown others that subterranean environments can be used for more than only defensive tactics. With the right culture, understanding, intelligence, technologies, and tactics, they can be used for simultaneous maneuvers on the surface and subsurface. That changes everything” [8].

There is one subterranean challenge that even General Goldfus and his division could not overcome: destroying tunnels. Israel’s strategic goal in Gaza includes

destroying Hamas's major military capabilities. This logically requires destroying a certain percentage of the vast underground network the group has so heavily relied on.

Contrary to some reporting, removing Hamas's ability to plan and conduct military operations does not require destroying all of Hamas's tunnels. Not every tunnel is as important as others. The cross-border tunnels between Gaza and Egypt that served as Hamas's strategic lines of communication—enabling vital weapons supplies—large tunnels linking northern and southern Gaza or connecting different cities or brigade areas of operations and allowing freedom of movement, and command-and-control tunnels like the data center found under a United Nations building in Gaza City do require destruction. The destruction of hundreds if not thousands of tactical tunnels that connect different buildings across the Gaza strip is not critical to achieving Israel's military objective and may exceed any reasonable ability Israel has to remove those tunnels.

But there is a gap in military methods for destroying tunnels. Military history has generated far more knowledge about creating tunnels than destroying them. Modern bunker-busting bombs can penetrate the earth in a small area to strike at a target in a tunnel or bunker but cannot effectively destroy the full length of a tunnel. The environmental and human health impact of bunker-busting bombs, blowing up tunnels with explosives, and the flooding of tunnels with sea water and sewage pose serious threats to environment and groundwater.

5. Conclusions

Soil tunnels have a long history as defensive and offensive war strategies, invisible roads for illegal smuggling of drugs and human trafficking, and migrants seeking asylum for safety and economic opportunity. Some of the earliest tunnels were under the walls of otherwise well-fortified cities thus it is not surprising that new tunnel crossings have emerged along Gaza, Egypt, West Bank, Lebanon, Syria and Israel borders. These underground networks store weapons and supplies, shelter soldiers, are transport corridors and serve as intelligence and communication conduits. Although peace may be elusive, the history of soil tunnels suggests several defensive approaches that can reduce vulnerability to illegal infiltration and increase homeland security. First, the characteristics of certain types of soil and geographies make them uniquely suited for tunnel building sites: arid climates, unconsolidated soil materials, and a deep-water table. Countries with warfare or smuggling issues along their borders, such as Israel need detailed soil and hydrology maps of their borders to identify soil types, topographies, and areas where potential soil tunnels could be constructed. In the case of Israel most of their borders are susceptible due to favorable arid climate, soils, and geology. An exception is the international border with Jordan where soil tunnels would be vulnerable to Jordan River flooding. Israel Defense Forces (IDF) and border patrol will need to continue to monitor the noise and vibrations, to identify future soil tunnel locations. In the case of Israel their entire border is susceptible because of the arid

climate, soils and geology.

The environmental impact of the creation and destruction of soil tunnels is never included in the initial military analysis. The military strategy and need to win the war are always the priority and collateral damage to the environment can take decades to document, if ever. Soil tunnel construction and destruction often have adverse environmental and human health impacts on the Israeli border landscape. Once the IDF finds cross-border soil tunnels they blow them up using TNT which puts a significant amount of dust and toxic materials into the air exposing animals and humans. The explosions create trenches without any topsoil remaining to be cultivated lowering long-term soil productivity. In late 2009, Egypt started construction of a subterranean barrier to curb the use of smuggling tunnels in Philadelphi Corridor under the control of the Palestinian Authority. In 2010, Mubarak regime sprayed toxic gas into the Corridor tunnels, killing four Palestinians. In 2011, Egypt sealed a series of smugglers' tunnels between its border and the Gaza Strip. In 2013, the Egyptian military shut down the smuggling tunnels connecting Sinai and Gaza by flooding them with sewage. In September 2015, the Egyptian Army pumped seawater from the Mediterranean Sea into the tunnels. The blowing up of soil tunnels, spraying of toxic gas, filling soil tunnels with sewage (coli), and seawater (salt) posed serious threats to the health of people living near the Israeli border, environment, soils, and groundwater.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Olson, K.R. (2024) The Need for International Cooperation between Israel and Other Middle East Nations to Protect the Jordan River Landscape. *Open Journal of Soil Science*, **14**, 283-307. <https://doi.org/10.4236/ojss.2024.145016>
- [2] Sneh, A., Bartov, Y. and Rosensaft, M. (1998) Geological Map of Israel (Map). Ministry of National Infrastructures-Geological Survey of Israel.
- [3] Lucke, B., Ziadat, F. and Taimeh, A. (2013) Soils of Jordan. In: Ababsa, M., Ed., *Atlas of Jordan, History, Territories and Society*, Institut Francais de Proche-Orient. 72-76. https://www.researchgate.net/publication/279848566_The_Soils_of_Jordan/
- [4] Olson, K.R. and Speidel, D.R. (2020) Review and Analysis: Successful Use of Soil Tunnels in Medieval and Modern Warfare and Smuggling. *Open Journal of Soil Science*, **10**, 194-215. <https://doi.org/10.4236/ojss.2020.105010>
- [5] Lappin, Y. (2021) New Report Exposes 'Land of Tunnels' in Lebanon, Pioneered by Hezbollah. <https://www.jewishpress.com/news/middle-east/lebanon/new-report-exposes-land-of-tunnels-in-lebanon-pioneered-by-hezbollah/2021/08/13/>
- [6] Beeri, T. (2021) Hezbollah's 'Land of Tunnels' the North Korean-Iranian Connection. Alma Research and Education Center. <https://docslib.org/doc/1898204/hezbollahs-land-of-tunnels-the-north-korean-iranian-connection/>
- [7] Miller, E. (2014) Hamas, Hezbollah, and the Tunnels: Who's Inspiring Whom?

- <https://www.timesofisrael.com/hamas-hezbollah-and-the-tunnels-whos-inspiring-whom/>
- [8] Spencer, J. (2024) Israel's New Approach to Tunnels: A Paradigm Shift in Underground Warfare. Modern War Institute at West Point.
<https://mwi.westpoint.edu/israels-new-approach-to-tunnels-a-paradigm-shift-in-underground-warfare/>
- [9] Richemond-Barak, D. (2018) Underground Warfare. Oxford University Press, 296.
<https://doi.org/10.1093/oso/9780190457242.003.0002>
- [10] Rudoren, J. (2014) Tunnels Lead Right to the Heart of Israeli Fear. The New York Times.
- [11] Lichtenwald, T.G. and Perri, F.S. (2013) Terrorist Use of Smuggling Tunnels. *International Journal of Criminology and Sociology*, **2**, 210-226.
<https://doi.org/10.6000/1929-4409.2013.02.21>
- [12] Khoury, J.A. (2014) Egypt Right to Create Buffer Zone on Gaza Border. Haaretz.
- [13] Pelham, N. (2012) Gaza's Tunnel Phenomenon: The Unintended Dynamics of Israel's Siege. *Journal of Palestine Studies*, **41**, 6-31.
<https://doi.org/10.1525/jps.2012.XLI.4.6>
- [14] Erlanger, S. (2007) Isolation of Gaza Chokes Off Trade. Herald Tribune.
- [15] Matza, M. (2004) In Gaza, Sewage Stains Beaches and Piles of Garbage Mount on Streets. Reuters, Philly.com.
- [16] Kapushchevsky, O. (2024) Israel Cannot rule Out Terror Tunnels under West Bank Settlements, Expert Says. <https://www.jpost.com/arab-israeli-conflict/article-781223/>
- [17] Fabian, E. (2024) IDF Finds Under-Construction Tunnel in West Bank's Tulkarem. Times of Israel Community.
<https://www.timesofisrael.com/idf-finds-under-construction-tunnel-in-west-banks-tulkarem/>