Construction of underground structures is generally expensive; their cost has not decreased despite recent technological advancements. Since the price is usually high, underground structures are used when other options are not available.

The development of a new concept for underground constructions is needed. A new concept, its associated technologies, and the consequences of this concept are analysed in this paper.

An overview of current issues and technologies provides an idea of current limitations. A new concept for deep underground construction with some methods and approaches is proposed. A new way of constructing large underground structures and solutions for underground transport and living are also proposed. A few examples of the use of this concept are described.

Author: J. Čadež,
Date: 27.01.2019

1. Why are Underground Structures so Expensive?

Some underground structures, which were constructed centuries or even millennia ago, remain. These structures were constructed in favourable geological conditions, where the initial material has a "self-supporting capacity" of the rock mass. The initial material can support itself without any additional support measures and does not lose its structure with time. In some circumstances, underground constructions are very durable and require minimal maintenance. The material must be homogenous, dry, without larger cracks, fault zones or other irregularities, and relatively unaffected by air and water. Natural materials with properties of hard rock fulfil these requirements.

The first reason that underground structures are expensive is that most of these structures require support measures to maintain their temporary and long-term stability, e.g., the initial material quality is not sufficient for insuring the self-supporting capacity, which requires installation of expensive construction material.

The second reason is that underground structure shapes are usually adapted to the needs of vehicles, for example, road or railway tunnels, which requires a relatively large cross-section profile. We know that the need for support rapidly increases with the excavation profile.

Underground construction requires heavy machinery for excavation and transport that is operated by workers who must be well protected due to challenging conditions underground, which increases the cost of construction.

A relatively inexpensive underground structure to construct should

1) be constructed in homogenous rock with excellent mechanical properties,
2) have a small excavation profile,
3) be constructed without heavy machinery and manpower.

Where we should use such underground structure?

2. Deep Underground Challenge

Heat is available everywhere below the surface of Earth, including areas with favourable geotechnical conditions. The geothermal gradient for most of Earth is approximately 25 °C per km of depth. Therefore, temperatures at depths from -500-700 m range from 20-25°C degrees, at a depth of -3000 m from 50-70 °C, and above 100 ^{0}C at a depth of -5000 m.

Geothermal energy is known as a potentially powerful source of clean energy with practically no impact on the environment. Enhanced Geothermal Systems (EGS) can provide an inexpensive and powerful source of energy to replace coal and nuclear power plants; however, this option is rarely mentioned.

Let us see, where are the limitations, which prevent to use the geothermal energy in the big scale.

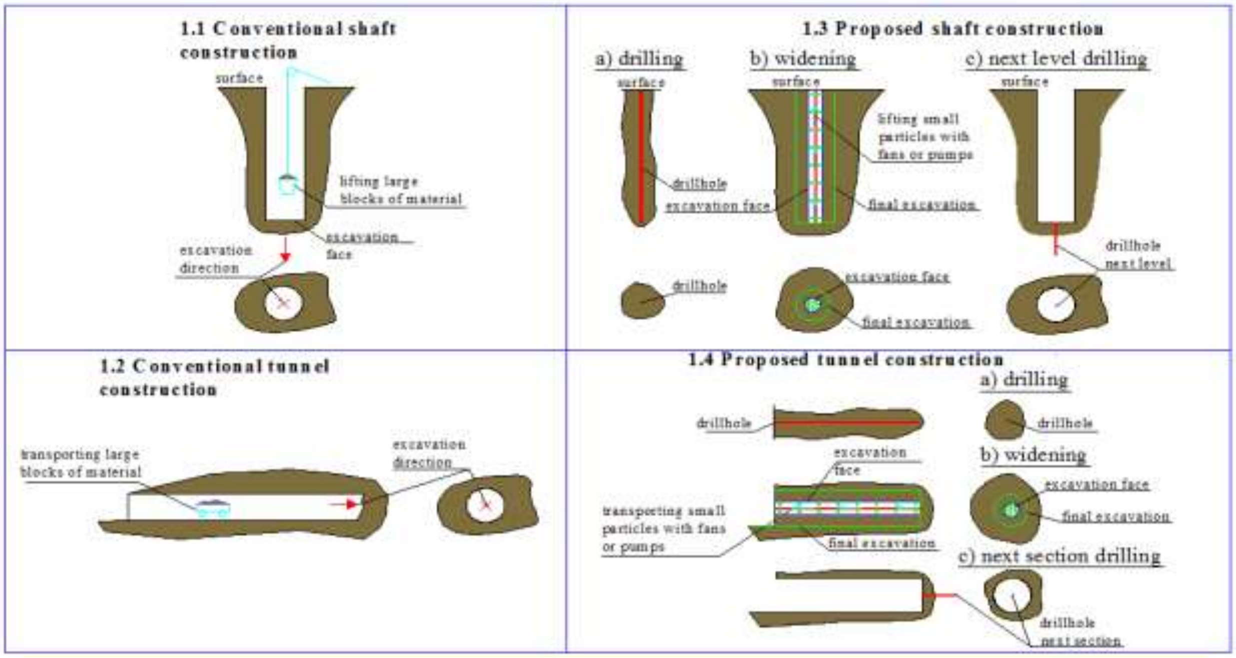


***Fig. 1** Conventional and proposed tunnel and shaft construction*

At depths of several km, the area of interest had been reached in only two ways. The first method is deep mines excavation, which requires a substantial amount of time; and the second method is the use of long bore holes, which are drilled from the surface and typically cost several million EUR for a kaleidoscope-shaped drill hole with a small diameter. The high costs and uncertainty of deep drilling deep and the limited capacity of a single drill hole are the largest limitations for exploitation of this source.

3. Current Underground Construction Philosophy

Underground construction consumes a considerable amount of time due to the availability of only one or two working sites, for instance, tunnel faces on each side of a hill or an end of a shaft, as shown in Fig. 1.1 and 1.2. Time is important, and therefore, underground construction technology is rapidly developing to improve the progress of excavations. The advances primarily improve the progress with the use of “brute force” at the excavation face; however, the number of working sites remains constant. This approach is successful in the excavation of tunnels, where an advance of several 10 m a day can be achieved.

However, this case is not valid for vertical structures such as shafts, which require a substantially greater amount of time (daily progress of shaft excavations is measured in meters) due to the limited working space at the bottom of the shaft, time necessary for lifting the material and safety measures for the protection of workers and machinery at the bottom of the shaft.

4. Going Wide Rather than Going Ahead

Fig. 1.3 and 1.4 show the procedure for the proposed method of excavation for shafts and tunnels, respectively. The concept involves a cylinder with a length and diameter of 100 m and 3 m, respectively. In the middle of this cylinder is a smaller cylinder with a length and diameter of approximately 10 mm and 100 m. Both cylinders are placed in a block of hard rock: the small cylinder represents the drill hole, and the large cylinder represents a shaft or a tunnel.

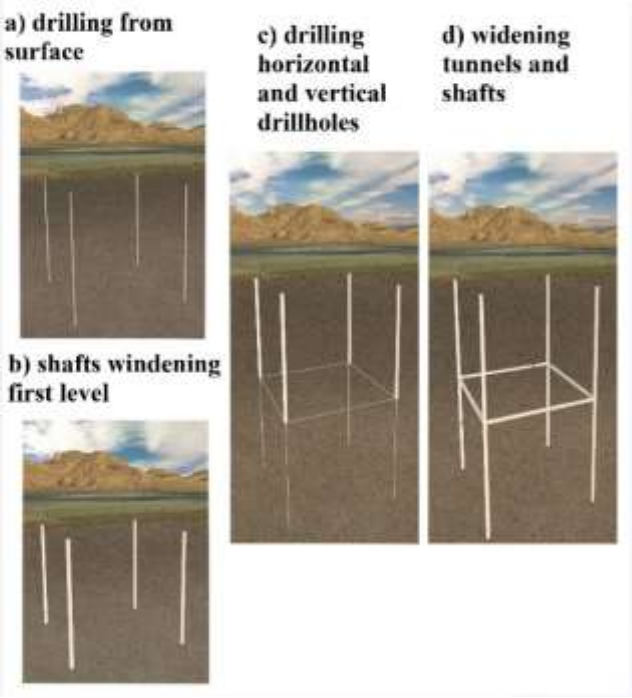


Fig. 2 *Proposed concept of underground construction*

Excavating a drill hole with a length of 100 m is a common task that can be performed within a week. This task is not extremely expensive and can be performed without significant deviation from the horizontal line. After the drill hole is finished, we attempt to widen the drill hole for 1.5 cm a day, for example.

The working area for widening a drill hole with a diameter and length of 10 cm and 100 m, respectively, is 31,41 m^2 at the mouth of the hole. In the process of widening, the working profile rapidly increases to almost 1000 m^2 when the structure nears an outlined shaft with a diameter of 3 m.

At the beginning, we can obtain an excavation surface of 31.41 m^2 in 24 hours or 1.3 m^2 in 1 hour. Within 24 hours, we need to remove 0.54 m^3 of material. To remove the final 1.5 cm from a 3 m diameter shaft, we can obtain a 932.58 m^2 surface in 24 hours or a 38.86 m^2 in 1 hour. Therefore, within 24 hours, we need to remove 14.06 m^3 of excavated material or 0.59 m^3 in 1 hour. Since the excavated material consists of small particles and the amount is small, it can be transported to the surface with a small pump or even a ventilator at the bottom. Thus, we need a smooth technique to simultaneously obtain as large a drill hole surface as possible and excavate the material in the preferred way.

Thus, we need a smooth drilling technique to simultaneously obtain as large a drill hole surface as possible and excavate the material in the preferred way.

4.1. Little Rodents

Several methods are have potential for excavating and removing rock, which is suitable for the new concept. The techniques based on past studies include techniques that do not require mechanically caused forces to excavate rock material. These techniques can be separately applied or combined to remove material in the desired manner.

Let's mention some of obvious candidates.

Cavitation is a destructive process that causes a substantial amount of damage to the turbines. Within the water bubbles are created, implode close to the wall and create significant local pressure. A lesser known fact is that the power of cavitation is also used to improve the drilling efficiency, which helps to crack rock in the drilling direction.

Some techniques have been applied for decades; for example, with jet cutters, a strong water jet cracks rock. Ultrasonic drilling had been developed by NASA to drill on Moon or Mars since it can make small drill holes with low energy consumption.

Other technologies that use electric power, electromagnetic fields or microwaves have been tested and proven to have a destructive impact on rock. Some chemical substances weaken rock, which can be affected by extreme heat or cold.

4.2. Overcoming the Going Deep Challenge

The shaft's length of 100 m was not arbitrarily chosen. The drilling of a shaft of this length is not time-consuming and is relatively inexpensive. After the shaft is finished, its bottom at level -100 m is employed as a working platform for the next stage and is constructed similarly to the bottom in the first stage.

Fig. 2 shows some phases of this construction. Several groups of drill holes are drilled close to each other, and the widening of each hole is performed according to our proposal. A new set of drill holes of 100 m are excavated, and the procedure is repeated. Each level serves as a platform for excavation of the next level and transport of material, which enables modular construction. Groups of shafts can be connected by horizontal tunnels.

Modular construction that consists of relatively short drill holes in which a device is installed is proposed. A combination of previously mentioned techniques are applied to the boundaries of the drill hole, and the excavated material is elevated to the surface. When a section is finished, the bottom of the shaft serves as a platform for the next phase of drilling and construction.

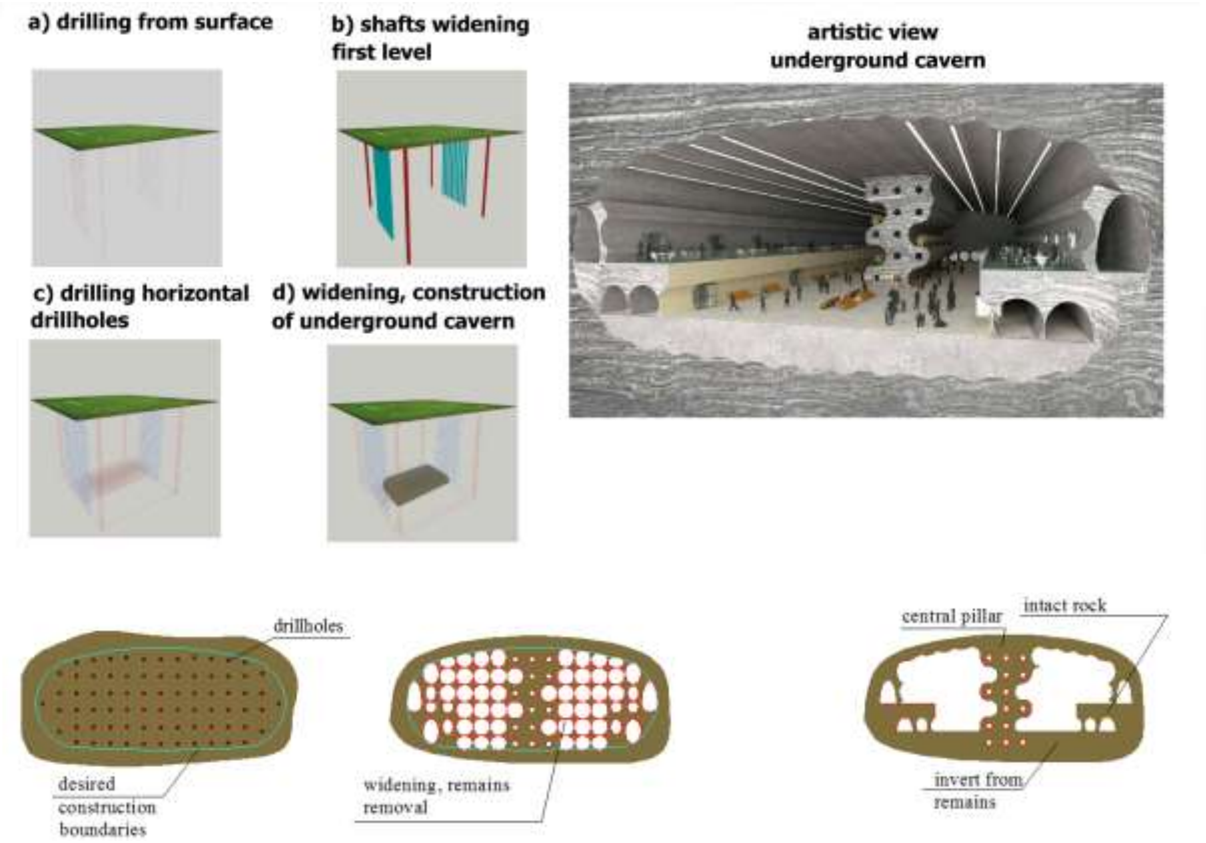


Fig. 3 *Construction of large underground cavern*

As previously mentioned, shaft excavation is slower than tunnel excavation; a 1 m/day advance is a reasonable approximation. According to our proposal, 100 days is required for a shaft with a depth of 100 m, which is equivalent to 1.5 cm daily advance of drillhole widening.

A drill hole drilled in homogenous rock material offers a controlled environment, where more violent and more effective techniques may be applied in the early phases of widening, and smooth techniques may be applied in subsequent phases to maintain the outer boundary of the shaft stable.

The result of this construction is a system of vertical shafts and horizontal tunnels, which does not substantially differ from deep mine systems. This kind of system only enables deep underground access. We need additional facilities.

4.3. Large Underground Structures

Large and stable underground structures can be constructed in favourable geological conditions in tho ways. In the first method, an underground structure of a circular or elliptic shape is constructed. In the second method, several underground objects are constructed in close proximity and connected, with support pillars between two objects. Both methods assure long-term stability.

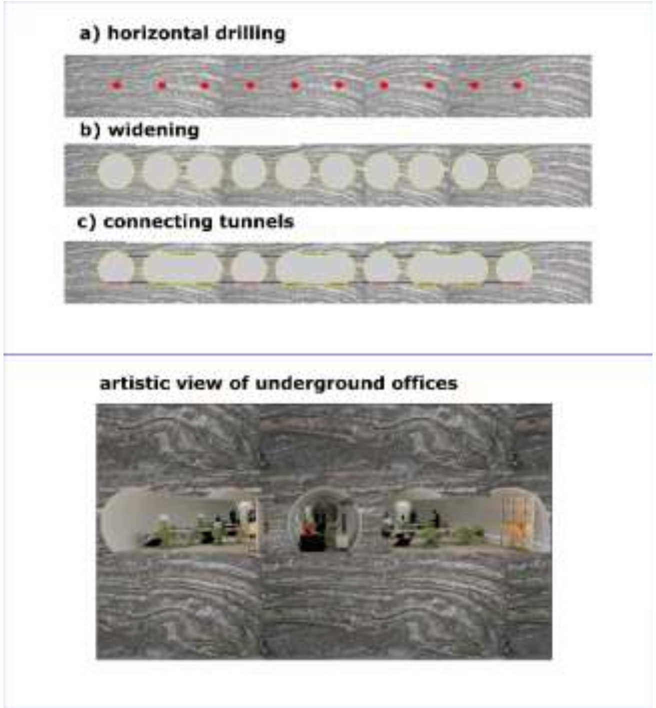


Fig. 4 *Underground construction with pillars*

Fig. 3 shows the phases of the construction of an elliptical cavern. The first step is vertical drilling, and the second step involves widening of the drill holes into shafts. In the third step, a number of horizontal drill holes are created at different levels between the shafts. Half of the holes are drilled from one side, and half of the holes are drilled from the other side. In the next step, widening to the desired diameter is conducted.

The result is a honeycomb-like structure. If we remove the remains of the overlay section with conventional techniques (using explosives), the result is a well-shaped underground structure. As the remains of the rock are used to straighten the floor, heavy rock blocks do not have to be transported to the surface.

Fig. 4 shows the steps for the construction of a stable underground structure with support pillars. We need to drill several boreholes from the surface side by side and widen them into the shafts. In this case, the widening should be finished by leaving intact material between neighbouring tunnels. The walls should be removed at certain places. The result is a relatively wide open space.

4.4. Underground Power Plant

Fig. 5 shows a system of underground shafts, tunnels and caverns, which can serve as an underground power plant based on EGS. The system consists of numerous vertical shafts at the bottom level for conveying heat, connection tunnels, shafts, caverns for turbines and generators, and a power station cavern. Shaft construction and all other work (tunnels and caverns) can be simultaneously conducted. If we extrapolate the time for the construction of a shaft with a length and diameter of 100 m and 3 m, respectively (100 days for a daily 1.5 cm average widening progress), a depth of several kilometres (the area of interest) can be achieved within 10 years. The construction time and amount of excavation are within the range of the largest construction projects. Ten years is a long time, and the starting investment is high; however, once the desired depth is achieved, adding capacity is considerably faster and less expensive.

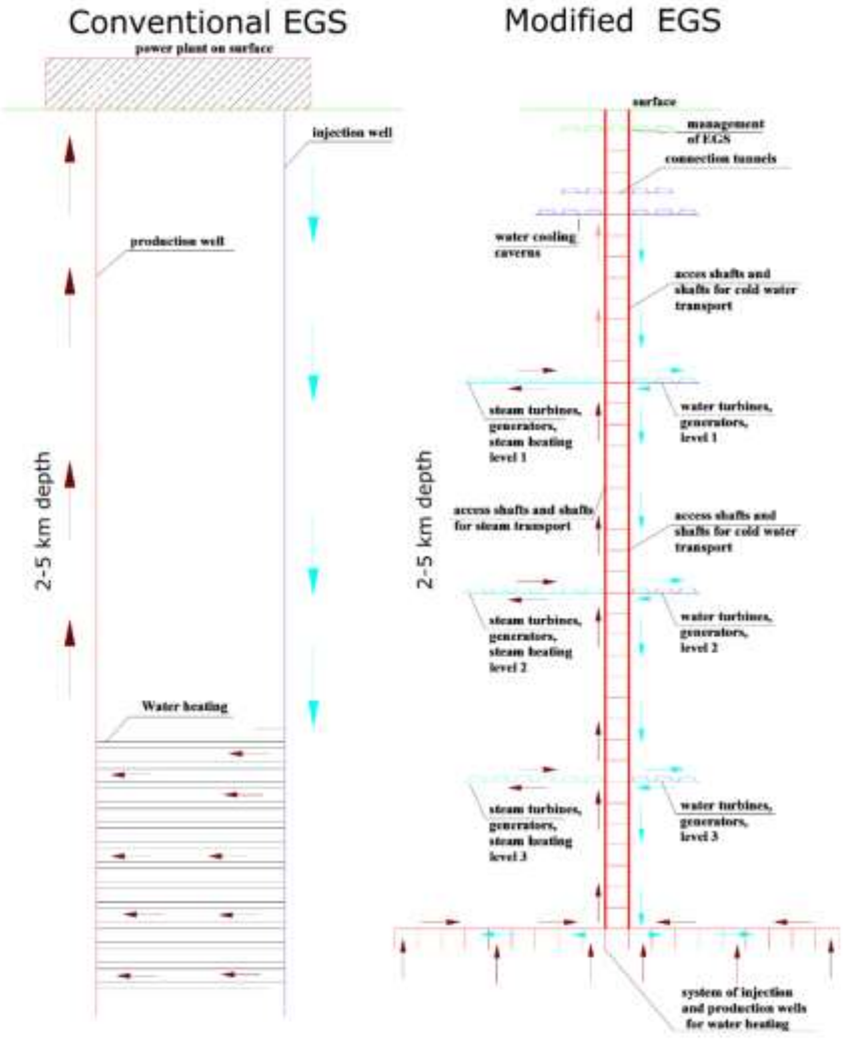


Fig. 5 *Conventional and modified EGS*

5. Art of cob

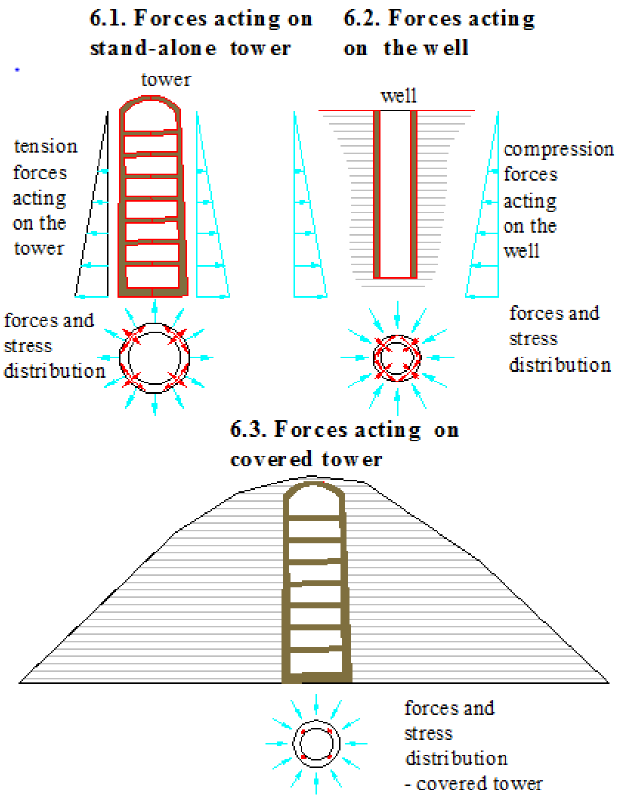


Fig. 6 Forces acting on tower, well and covered tower.

Cob is an ancient technique in which sand, clay, water and straw are used to create construction material. Clays are very common and are abundant in many places. The portions of each ingredient in the substance are not strictly defined. Numerous combinations give the construction material solid properties, which creates an opportunity for mixing the excavated dense material with clay and obtaining a construction material with solid properties.

Cob has numerous advantages, such as durability, excellent insulation properties, relatively satisfactory compression stress resistance, and low cost. Cob also has disadvantages, such as relatively poor resistance to shear and tensile stresses.

5.1. Forest of Towers

Classical stone towers are often circular constructions that are not particularly high, as the weight of the tower causes shear and tensile overload on the tower construction near the surface, as shown in Fig. 6.1. Wells—another circular construction—can be deep and sustain their shape for a long time, as the surrounding rock or soil supports the well structure by applying compression force to the well boundaries, as shown in Fig. 6.2. This kind of structure is substantially more robust than a standalone tower.

Tower walls and wells can be reinforced by adding material, as shown in Fig. 6.3. This material creates a horizontal force on the tower walls, which improves the tower stability and enables construction of higher towers made of cob.
Fig. 7 shows several towers: "the forest of towers" of circular shape, which are constructed close to each other and are covered by the excavated material. The shape of each tower is circular; the inner diameter of a tower is 6 m; and the clearance profile of each tower is slightly more than 28 m. Towers with small diameters are provided

between the large towers. We can separate towers and create rooms that are connected by horse-shoe profile tunnels with a narrow tower in the middle. The result is an array of four-room apartments with a service shaft and an exit to the hallway.

The diameter of the arched connecting tunnels and hallways can be relatively small, and they are distributed around the construction. Thus, the total stability is not compromised.

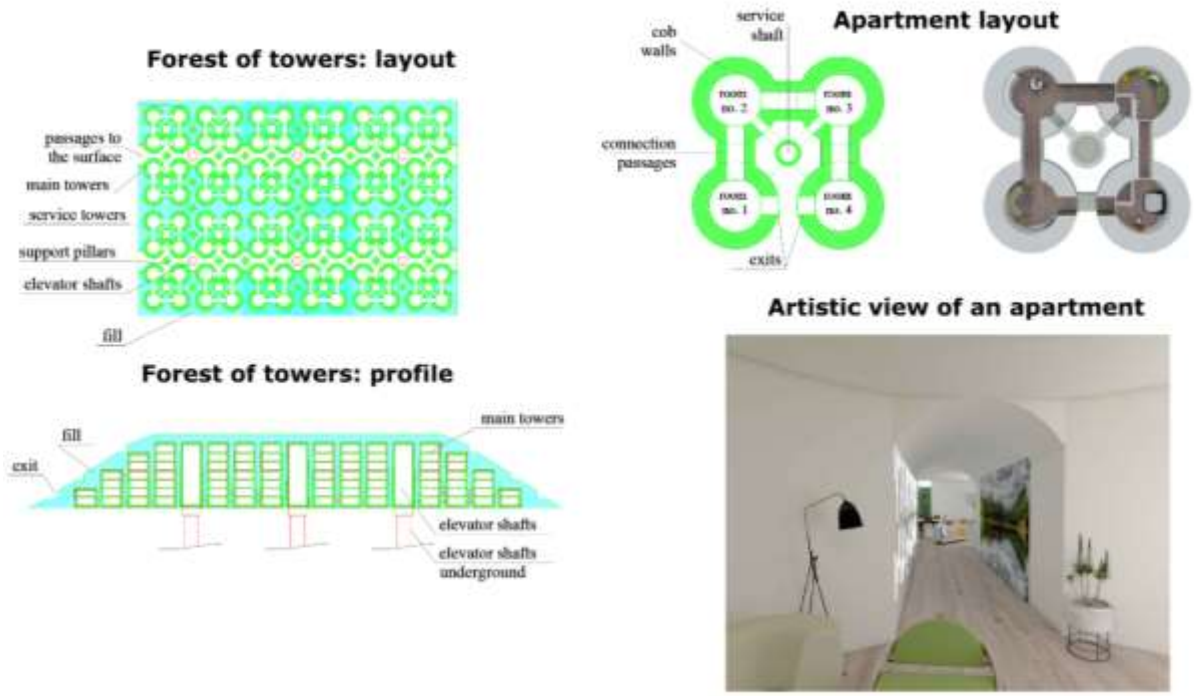


Fig. 7 *Forest of towers*

A structure that consists is deep underground constructions and the covered "forest of towers" resembles a molehill, as shown in Fig. 8. In terms of infrastructure, the proposed construction does not substantially differ from ordinary multi-level constructions or even skyscrapers, where transport is driven by elevators and supply is driven by service shafts. With one exception: ordinary constructions have windows.

Daylight has a considerable impact on people and cannot be completely replaced by artificial light. Therefore, a minimum amount of daylight must be insured in some way for every resident of an underground settlement, which can be achieved in two ways.

The first option consists of technical solutions (transferring daylight through cables from the surface collectors), and the second option involves establishing "house" rules, which obligate residents to obtain a sufficient amount of daylight every day. We are not designed to live underground, as we are not designed to live in extreme heat and cold conditions, or in space, for example. However, technology offers numerous tools that enable us to live as we are used to in towns and houses, even underground.

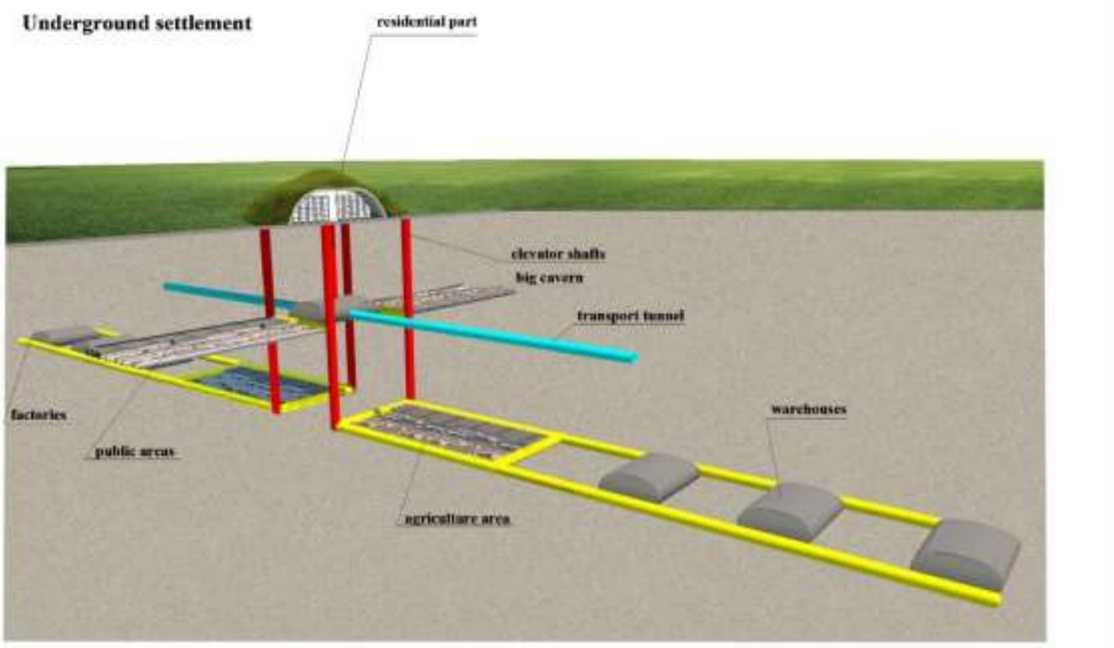


Fig. 8 *A molehill*

6. "Hard Rock Transport"

Transport is an important part of life that does not always satisfy the needs of people. The construction of transport lines is expensive and time-consuming due to poor geological conditions at construction sites; rock exists below the weak layers of soil.

The proposed concept matches the conventional shaft excavation speed, which does not affect tunnels, where conventional techniques are considerably faster. Matching the speed is not important for deep excavation as tunnel construction does not occur along a critical path but is important when we consider other applications of this concept.

Fig. 9 shows a section with a relatively flat area with two main points of interest: for example two large cities on each end, and three cities between the large cities, which can be, for example, smaller cities. Less important points of interest may include smaller settlements that are randomly distributed around the area. The best way to cover an entire area involves connecting the main points of interest by constructing a direct line

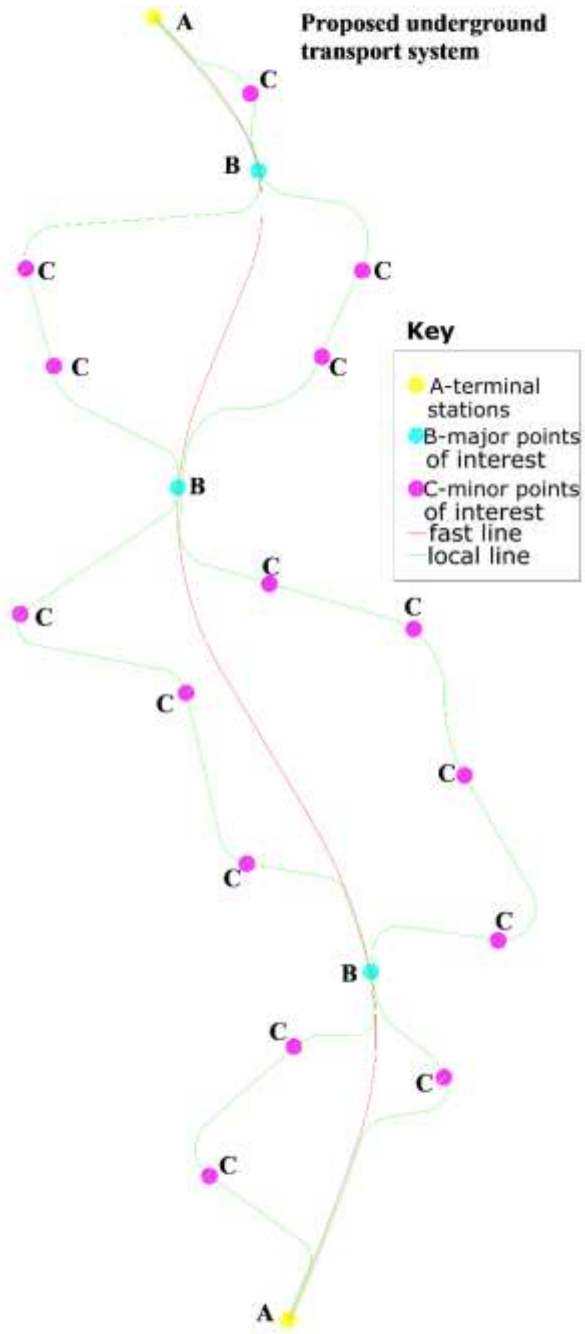


Fig. 9 *Layout of an underground transport system*

from start to end, which is relatively smooth, and connecting minor points of interest with the main points by two curved lines.

Fig. 10 shows the construction phases of two underground structures, which are positioned relatively close together. In the first stage, four vertical drill holes are excavated for each structure and are widened into shafts. In the second stage, horizontal drill holes are excavated to connect all shafts at their bottoms. In the third stage, horizontal drillholes are widened, and drilling towards the neighbouring structures and between tunnels is performed.

With shafts, the depth with favourable geological conditions can be accessed, and the tunnel construction speed may match the conventional speed by increasing the number of attack points.

7. Examples of New Concept Application

7.1. Public Transport in Ljubljana

Ljubljana is a typical Central European city; it is located along a river with a castle hill in the old centre of the city. Ljubljana is partly divided by shallow hills that divide the town area. A larger number of hills exist at the city boundaries.

Geologically, Ljubljana is partially positioned on weak clay and alluvial levels at a maximum depth of 100 m. Under the soft layers exist low- or medium-quality rock that penetrates the surface in the form of shallow hills in some locations.

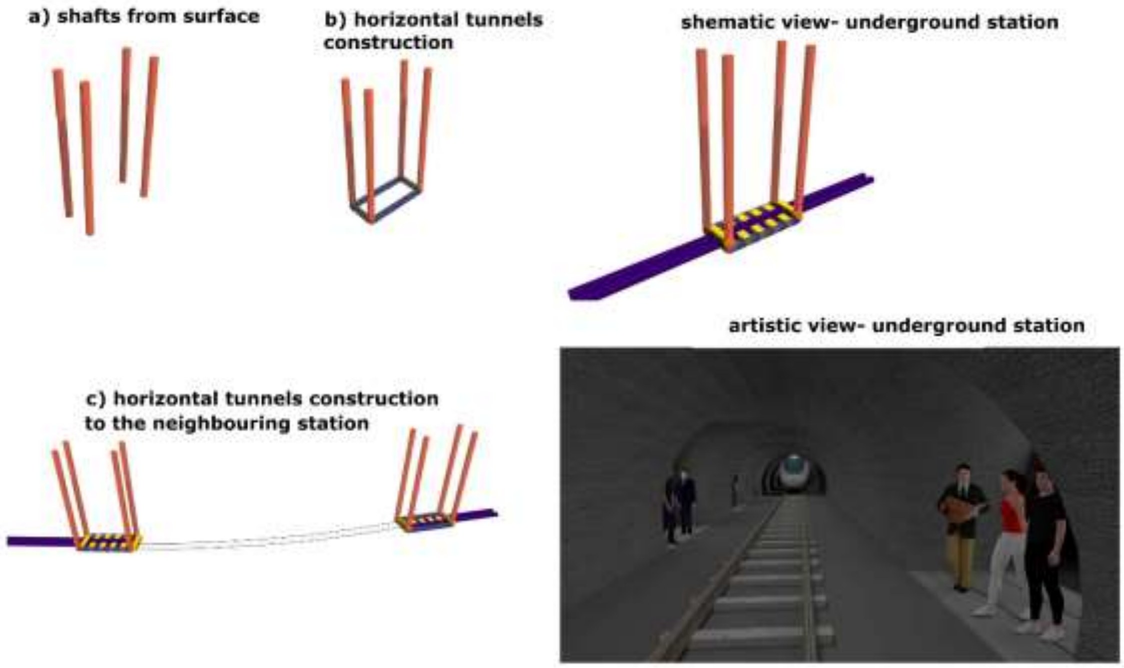


Fig. 10 *Underground station*

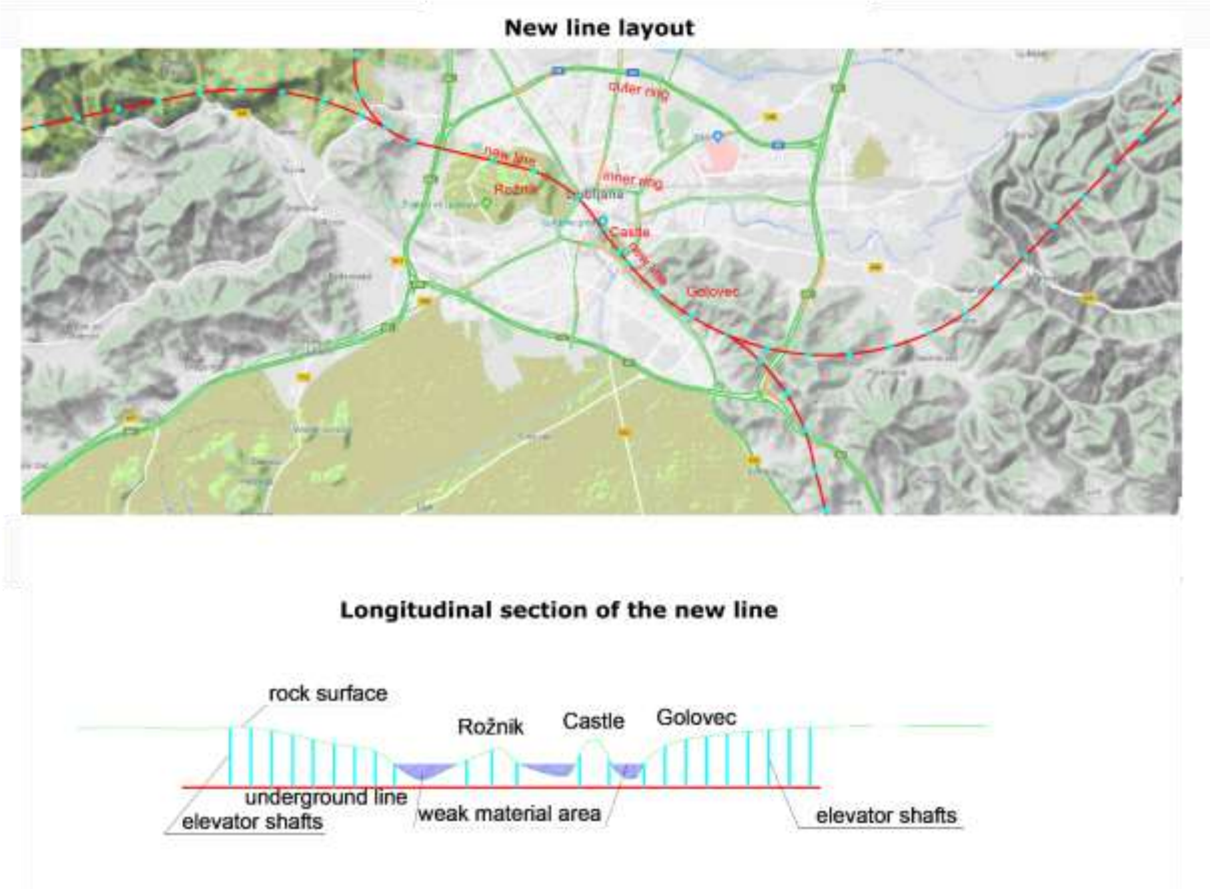
Fig. 11 shows a city map of Ljubljana, where the current traffic lines are shown in green. The main elements of the traffic system are the outer ring roads, the inner ring roads and seven main connection roads between the ring roads. All roads and highways are placed on flat land and avoid the hills.

The red lines represent the transport system, as presented in the previous chapter. Cyan dots represent the location of construction shafts and stations, which are generally installed at 1 km distance.

The general route of the existing traffic system follows open spaces and flat areas. The new line needs areas with better geological conditions, which generally exist in elevated areas. The general route should follow the elevated areas, which existing traffic systems avoid.

This example shows the advantages of the proposed concept. First, since the construction of shafts can simultaneously begin, the time of construction should be shorter and may encompass a large area. Second, the construction should be less expensive as due to solid geological formations way below the earth's surface. Last, the proposed construction avoids established transport lanes, which can be very important in populated areas.

But of course, it required a combined vertical/horizontal transport system.



New line layout

Longitudinal section of the new line

Fig. 11 *Underground transport system in Ljubljana*

7.2. Fjord Problem

Norwegians have an interesting traffic problem. The depths of Fjords can exceed 2 km and generally cut the land perpendicularly to the coast. Thus, any local transport between two coastal cities in addition ferries and coastal roads is difficult and expensive. Certain ideas have been proposed to overcome such an unfavourable configuration but they are expensive and challenging. Therefore, we examine an alternative.

The general idea is to build a system of shafts and tunnels under fjords according to the proposed concept. A combined vertical/horizontal transport through such a construction can be achieved by directional elevators, which are not driven by ropes but are operated by the principle of magnetic levitation, which enables both vertical transport and horizontal transport. Since ropes are not employed, a larger number of elevators can use the same tunnel or shaft and move similar to subway trains in a row, which can provide sufficient capacity and speed of transport.

8. Going Up?

The proposed concept of construction has advantages in larger and specific projects. A relatively old concept of travel to orbit, which is referred to as a star tram, where the idea is to send a projectile into orbit at a certain initial speed of several km/s, might be a good candidate.

This concept requires a ramp with a minimum of length of 100 km in tunnels at high elevation, preferable at 5000 or 6000 m, a magnetic levitation (maglev) drive in vacuum tunnels, and a powerful source of electric supply.

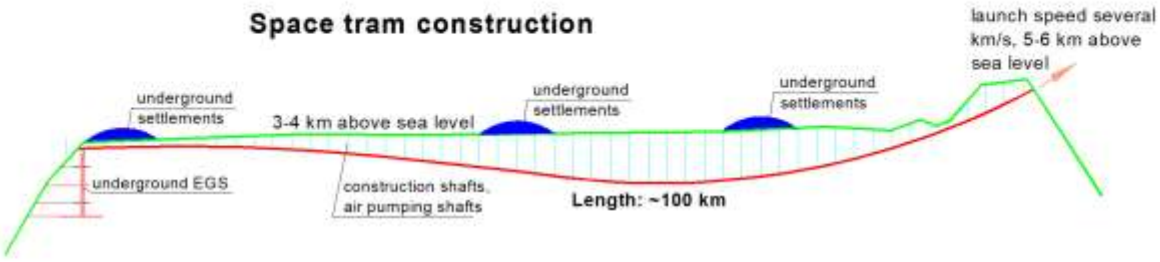


Fig. 12 *Space tram construction*

Fig. 12 shows a modified “space tram” concept in accordance with the proposals in this article. Shafts are constructed at certain distances, which reduces the construction time. The power supply is provided by a modified EGS, as previously proposed, and shelters are provided by the "forest of towers".

The proposed concept offers several solutions for difficult engineering problems that arise with such construction. Shorter construction times, for example, and automatized shafts and tunnels excavation at high elevations would be beneficial. Shafts can be used to maintain a sufficient level of vacuum, and enclosed underground residential structures can insure decent living conditions at these altitudes, including a comfortable level of oxygen and low altitude pressure in living areas.

9. Conclusions

We have constructed numerous underground structures but we only scratched the Earth's surface. Technology is available but the economic interest in or reward for deep underground exploration does not exist.
The proposed concept can be used to economically and wisely exploit underground resources and may help us to solve existing problems, such as pollution, lack of energy and transport issues.

Safety should be considered when expanding this concept. This concept can insure shelter on a large scale when needed but I would like to stay optimistic and predict that shelter will not be necessary in the future.

Deep underground project
January 2021

https://deeepunderground.com/
https://join.deeepunderground.com/