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Methods of deep modification of low-bearing soil for the foundation of new and spare air runways

Abstract: After analyzing the impact of aircraft on the airport pavement (parking spaces, runways, startways), it was considered advisable to consider the problem of deep improvement or strengthening of its subsoil. This is especially true for low-bearing soil. The paper presents a quick and effective method of strengthening the subsoil intended for the construction of engineering structures used for civil or military air operations. It allows the use of wastelands, wetlands, swamps, etc. for the above-mentioned purposes, thus creating a dispersed network of landing sites increasing the security of the country and increasing the availability of air transport for large society groups.

Keywords: Runways; Runways load; Ground reinforcement; Blasting agents

Introduction

Civil and military airports (small and large) are connected with their specific infrastructure. This means that the subsoil must be prepared for the new geotechnical requirements. This applies in particular to the location of structures (runways, hangars, access roads) in places that are "difficult" in terms of geology and engineering. This forces the search for new technologies and methods [17], as well as changes in the way of thinking among engineers, investors, and commanders. They all have to face an interdisciplinary challenge, which in this case is the strengthening of a weak subsoil. An additional difficulty in solving this problem is often the need to shorten the implementation time (e.g. especially in combat conditions), investment implementation costs, etc.

The analyzes presented in the article focus mainly on the so-called small airports, their runways founded on the properly prepared (possibly improved or reinforced) low-bearing ground. Properly prepared ground determines the reliability of the entire structure, and further determines the safety of aircraft take-offs and landings.

However, all the considerations carried out here apply perfectly well to the runways of large civil or military airports, as well as their infrastructure.

The terms used here: small airports, runways, etc. are intended to emphasize that they do not have to fully meet all the conditions for large transport airports. This applies, for example, to runways whose parameters, such as length, width, degree of lighting, markings, etc., differ from airport standards. This is particularly important in combat conditions when it is difficult to meet all these conditions.

Improperly designed, prepared, and constructed subsoil for the runway is the cause of undesirable behavior of the runway surface during operation. In extreme cases, it may lead to damage to the runway surface, including loss of ground stability. It can lead to damage to the aircraft and possibly a plane crash in which passengers or crew members are injured.

The basis is the subsoil and its drainage because they determine the reliability and durability (in the probabilistic sense) of the entire structure.

For various reasons, it is worth deliberately locating small airports (runways) on low-bearing grounds (wetlands, peat) - difficult to access for heavy military equipment (tanks, armored vehicles) or due to other requirements (e.g. terrain, location restrictions, local needs). For example, in the event of a fire in April 2020 in the Biebrza National Park, over five thousand three hundred hectares of the park burned down. During the firefighting with the use of aviation equipment, there were big problems with the lack of airstrips in this difficult area. This significantly reduced the effectiveness of aerial firefighting.

In a crisis or combat conditions, the main factor determining success is the time and location of the project. The location should not be limited by ground conditions. The time-consuming process of subsoil strengthening is very important.

It should also be remembered that parts (fragments) of the airport are elements that can be destroyed as a result of unexpected random situations (breakdown, catastrophe, natural disaster), as well as intentionally as a result of military actions. They are the main and convenient target due to their large size and limited possibilities of effective masking and high operational importance. Their reconstruction in these various crises should make it possible to restore operational readiness of the damaged functional elements of the airport **in the shortest possible time**. This is where the method of blasting agents, also known as the method of microbursts, comes in handy - fast, effective, innovative, and cheap.

This method also allows you to quickly create and recreate secondary and alternate airports. Creating them can be quick. For example, sapper troops familiar with explosives in cooperation with engineer troops with knowledge in the field of civil engineering can effectively perform these tasks using the blasting method.

Any airport surface can be laid on a well-prepared, improved, or reinforced subgrade (traditional - asphalt, concrete - e.g. concrete slabs, grass reinforced - e.g. with the use of special mats [2]).

The aforementioned civil or military facilities may also be located on land considered difficult from the point of view of their suitability for broadly understood transport and communication activities. These include wetlands, organic soils, embankment soils, industrial waste, and landfills. The choice of location locations may also be indicated as advantageous for tactical reasons. For example, the location of landing sites on the seaside can be successfully used to improve the safety of navigation at sea.

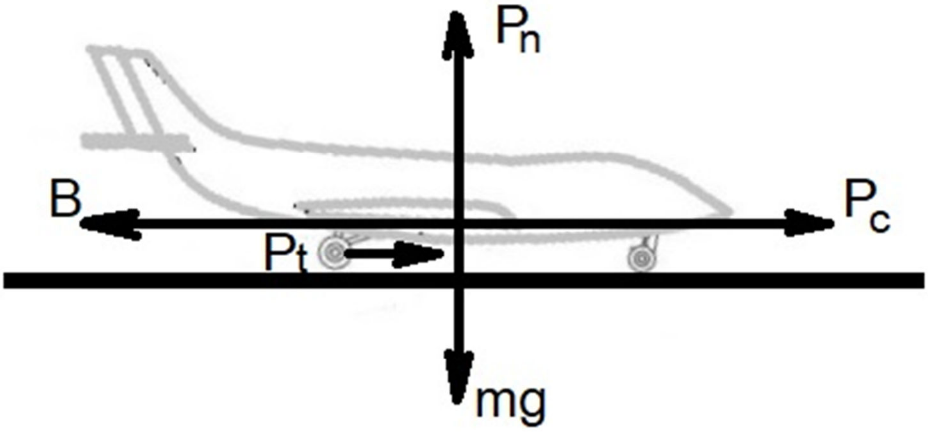
From a tactical point of view, a good solution is also to create a dispersed network of airports in hard-to-reach areas. In such a situation, in the fight against time, methods of soil reinforcement are helpful. However, from the point of view of the limited time needed to prepare the subsoil for the designed airport facilities, an important and effective method from this point of view using explosives to strengthen the subsoil for the aforementioned airport facilities and access roads, including railway roads or railway sidings, should be taken into account.

Forces acting on an aircraft during take-off, flight and landing

Aircraft impacts, e.g. on runways, are complex due to high loads and dynamic effects.

The take-off of the aircraft consists of the take-off phase, which ends when it reaches the speed that allows it to take off from the surface [5]. The take-off procedure is complete when you reach a height of 10.7 m or 15 m.

The maximum static load acting on the airfield pavement and subsoil occurs at the beginning of the take-off phase, i.e. at the beginning of the take-off. During take-off, the aircraft's lifting force P_n increases with the increase in speed, which reduces the load on the pavement and subsoil. The system of forces acting on the aircraft during take-off is shown in Figure **1**.



1. Diagram of the system of forces acting on an aircraft during take-off

In Fig. **1**, the following designations have been adopted:

- $P_c -$ aircraft thrust,
- $P_n -$ aircraft lift force,
- $B -$ inertial force,
- $P_t -$ wheel rolling resistance,
- $m -$ aircraft take-off weight.

After the take-off, there is a stage of the main flight, the course of which, especially in the final phase, affects the landing.

We treat the aircraft as a rigid body, symmetrical in relation to the vertical plane (perpendicular to the landing gear). Its movement is related to the displacement of its center of gravity in the above-mentioned plane and rotation around the horizontal axis, perpendicular to the plane of symmetry. With these assumptions, the vector equation of motion has the form:

$$S\vec{x} = \vec{u} \tag{1}$$

where:

$$\vec{x} = \begin{bmatrix} v \\ \theta \\ S\varphi \end{bmatrix} \tag{2}$$

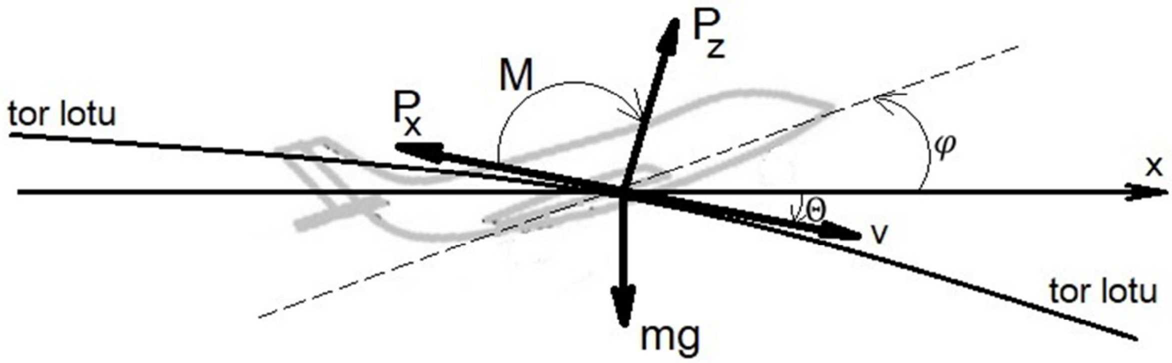
$$\vec{u} = \begin{bmatrix} -\frac{P_x}{m} + g sin\theta \\ -\frac{P_z}{mv} + \frac{g}{v} cos\theta \\ -\frac{I}{M} \end{bmatrix} \quad (3)$$

$$S \stackrel{\text{def}}{=} \frac{d}{dt} \quad (4)$$

In the formulas (2), (3), (4) the following symbols have been adopted:

- $t -$ time,
  - $g -$ gravitational acceleration,
  - $(-P_x)$ −scomponent of the resultant aerodynamic force in the direction of motion,
  - $P_z -$ normal component to the direction of motion of the resultant aerodynamic force,
  - $M -$ moment of the components of the resultant aerodynamic force about the center of gravity,
  - $m -$ aircraft weight,
  - $I -$ moment of inertia of the aircraft about an axis through the center of gravity and perpendicular to the plane of symmetry,
  - $v -$ gravity speed center,
  - $\theta -$ angle of inclination to the x-axis of the path of the center of gravity, considered positive when pointing downwards,
  - $\varphi -$ the angle between the axis x and the axis of the aircraft, considered positive when pointing upwards.

The adopted selected designations are also shown in Figure **2**.



2. Diagram of the forces acting on an aircraft during flight

Note. Equation (1) is a special case of a generalized dynamical system [7].

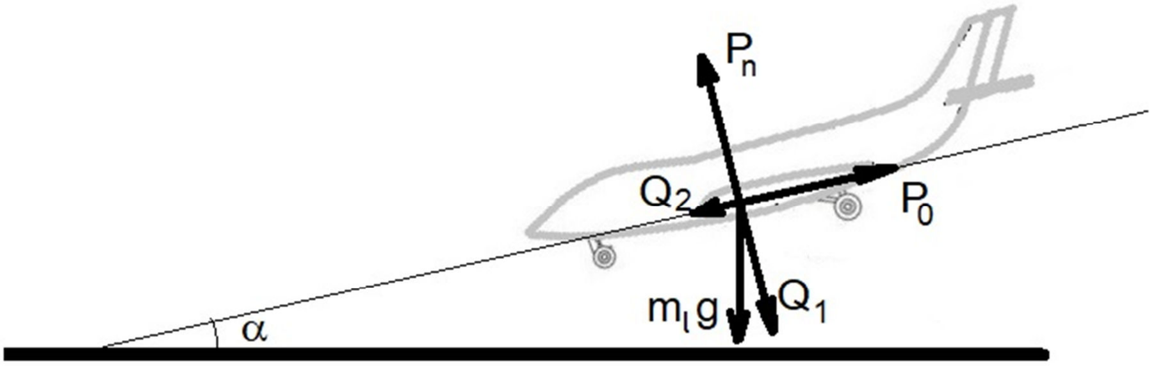
$$S\vec{x} = \vec{\boldsymbol{f}}(\vec{\boldsymbol{x}}, \vec{\boldsymbol{u}}). \quad (5)$$

Therefore, the dynamical system (1) can be analyzed by the methods presented in [7].

Note. *In formula (5), the operation S need not be defined by formula (4). It can be any operation that meets the conditions specified in* [7].

After the main flight, and more precisely after its final part, the aircraft lands.

This landing consists of two phases: the final descent and landing roll [5]. The system of forces occurring during the landing is shown in the figure **3** [1].



3. Diagram of force distribution during descent to landing

In Fig. **3**, the designations as in Fig. **1** have been adopted and additionally marked:

- P_0 – aerodynamic drag force,
- Q_1 – vertical component,
- Q_2 – horizontal component, (force acting directly on the pavement and subsoil),
- m_l – weight of the aircraft at landing,
- α – approach angle for landing.

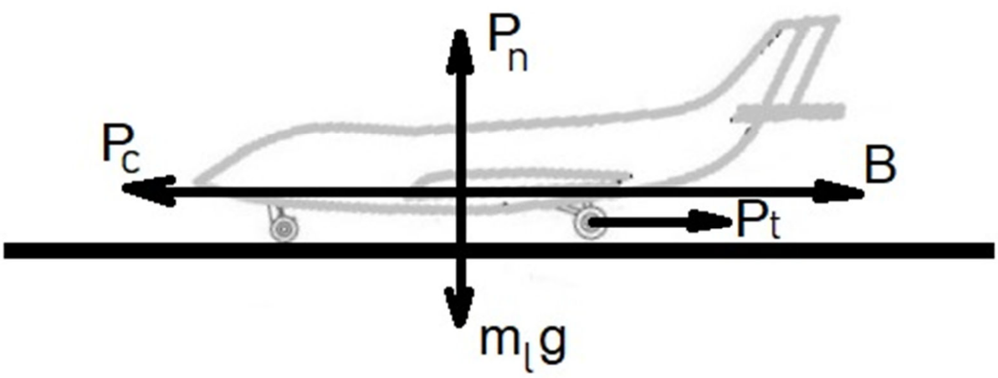
The final descent begins at 15 m or 10.7 m and consists of the aircraft's wheels approaching the surface.

From figure **3** it can be seen that:

$$Q_2 = m_l g sin\alpha \tag{6}$$

The final descent phase ends with leveling out and touching the wheels to the ground. This is the so-called touchdown. This is followed by the run-down phase. During this phase, the aircraft decreases its speed from touchdown speed to zero speed, i.e. until it stops. Deceleration is uniform.

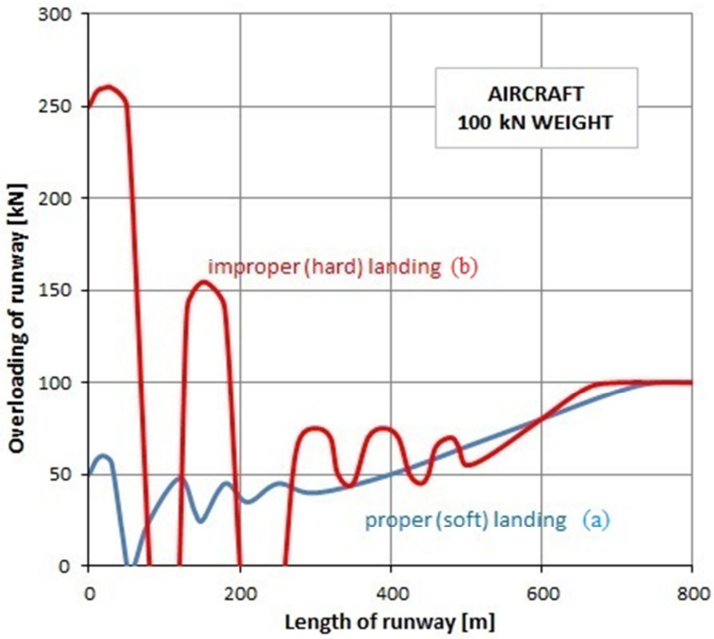
With the markings as in Figure **1**, the forces acting on the aircraft during the landing run are shown in the figure **4**.



4. Diagram of the distribution of forces during the run-up

In addition to typical (standard) landings, there are also unusual (non-standard) landings. During these last landings, the vertical accelerations are significant and can reach the value of even several g. This also results from the analysis of the dynamic system (1). It turns out that at certain angles α the descent is oscillating around a straight line with a slope tgα.

Figure **5** shows examples of runway loads during the landing [10], [13].



5. Runway loading during landing: a) typical landing, b) unusual landing [10]

The analyzes show that the subsoil must be designed for the previously presented loads, taking into account the dynamic effects. These are also dynamic effects generated by surface irregularities. The reason for the formation of such unevenness during the current operation may be the pavement itself or an improperly prepared subsoil, which, especially when it is weak or diversified in terms of geotechnical parameters, should be improved or strengthened.

Reinforcement of the subsoil

Organic soils (e.g. peat), subjected to load, are characterized by high compressibility. During consolidation, internal parameters change [6], [14]. Soils of organic origin are characterized by low initial strength, high deformability, and a large variety of properties depending on the type and content of components in the mineral and organic part. It follows that this type of soil cannot be directly used as a base for the foundation of engineering structures necessary for civil or military aviation operations. In general, it can be stated that weak soils without their modification cannot be used for the implementation of the aforementioned projects.

Subsoil modification in order to improve its geotechnical properties can be implemented in many ways. The geotechnical parameters of the subsoil can be changed or its consolidation accelerated by strengthening or improving the soil with various methods to such an extent that they meet the requirements for the foundation of engineering structures intended for civil and military aviation operations, including runways, runways, accompanying engineering structures and various types of access roads.

From the point of view of the problems presented in the article, two directions of action can be distinguished to improve the quality of the subsoil: methods of soil improvement and methods of soil reinforcement for engineering structures related to the implementation of air operations.

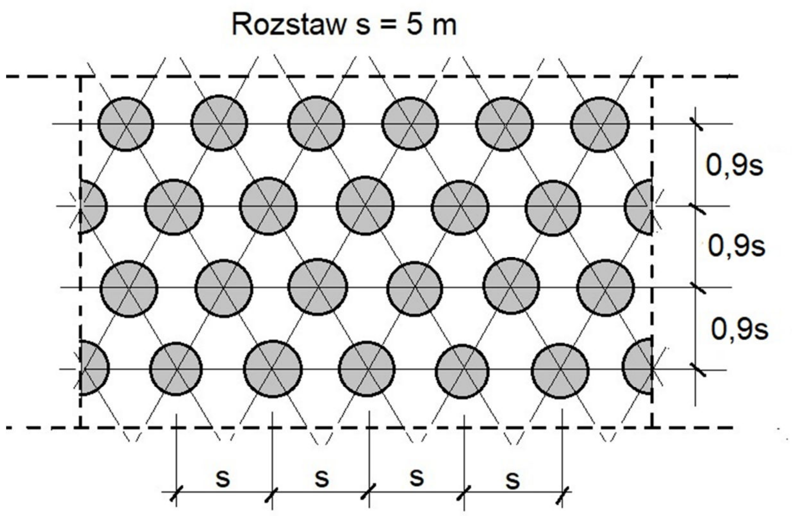
The first of them are methods in which the soil is modified through the use of various types of injections or admixtures to obtain a more compact or compact substrate. This modification consists in strengthening the contacts between the soil grains, which at the same time reduces its porosity, creating a soil useful for taking over high dynamic loads from landing aircraft.

The second of them are methods involving the introduction of a structural element into the soil to increase its mechanical strength or mechanical violation of the soil's internal structure and improve the strength parameters of the soil.

The methods of strengthening or improving the subsoil include: cement injections, vibroflotation, chemical injections, dynamic exchanges, dynamic consolidations, deep dynamic compaction, vibrating exchange methods, vertical drains, stone columns, mixing soils with additives, deep soil mixing, soil reinforcement, overloading static, etc.

To this must be added a method using explosives-blasting agents. A method that is important from the point of view of the subject matter considered here, which has some common features in principle/idea, such as dynamic exchange or dynamic consolidation.

The dynamic exchange method is a combination of methods used for soil compaction, in particular impact methods, with the soil exchange method, the concept of which is to increase the soil's bearing capacity by making stone, gravel, or sand columns in it. The best results are obtained when strengthening organic soils, irrigated cohesive soils, and anthropogenic soils. This technology consists in the dynamic formation of load-bearing gravel columns or columns made of aggregate (e.g. crushed structural concrete, blast furnace slag, crushed stone) using rammers (usually with a weight of 8 to 15 Mg) dropped by gravity, most often from a height of 15 to 30 m. Tamping causes overpressure of water in the pores of the soil, which disperses, causing the filtering water to flow into the drainage column. Detailed selection of the appropriate type of method is possible after a thorough assessment of the parameters of the improved soil, as well as the depth of deposition and stratification of the low-bearing subsoil. In the soil consolidation process, the distribution of impact points (Figure **6**) and the selection of other technological parameters, including the frequency of discharges, are of great importance. After such an operation, the subsoil is prepared for the implementation of e.g. runways on it.

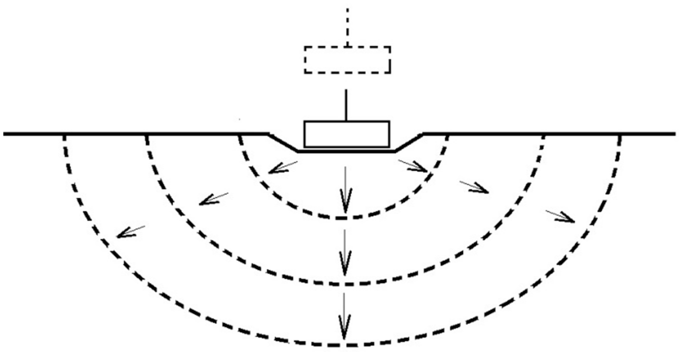


6. An example of the distribution of impact points during the implementation of a construction project

Similar construction equipment is used for dynamic soil consolidation as for a dynamic replacement. This technology consists in repeatedly dropping (usually from a height of 10 to 40 m) a heavy rammer (generally weighing from 10 to 50 Mg) at a frequency of about 1 to 3 beats per minute - photo **7**.

7. Dynamic soil compaction, A2 motorway section Koło-Dąbie (own photo)

As a result of this operation, a lump of reinforced soil is formed in the subsoil. The rammer falling by gravity (Figure **8**) causes overpressure of water in the pores of the soil and the formation of volume waves: transverse and longitudinal as well as surface waves.



8. Dynamic compaction. Propagation of vibrations (waves) in the ground

The propagation of elastic waves consists of the excitation of particles of the medium that are increasingly distant from the source of the waves. However, the most important feature that distinguishes elastic waves [8] from any other ordered motion of medium particles is that in the case of small disturbances, the propagation of elastic waves is not related to the transfer of a substance. For very short durations and large amplitudes, shock waves are formed [11].

After a series of impacts generating the aforementioned waves, the water pressure in the soil pores increases to the level corresponding to the state of soil liquefaction. The next phase causes the dissipation of water overpressure and compaction of the soil - a tighter contact between the grains is created.

After the compaction process - dynamic consolidation is completed, the surface is leveled and compaction is started at subsequent possible locations. After the process is completed, a runway can be placed on the leveled surface of the ground, a mobile airport covering used for the construction of basic elements of airports or landing fields can be laid out.

The method of strengthening the subsoil with the use of blasting agents

In this technology, the aim is to improve the physical and mechanical parameters of the subsoil by compacting granular soils or by creating vertical drainage sand piles (improvement) in cohesive soils as a result of the use of explosives placed in/or on natural soil or embankment to be compacted, or consolidated.

The process of explosion and detonation [15] is spread by the strong shock wave mentioned earlier.

The advantages of this method when strengthening the subsoil intended for aviation purposes include:

- short time of compaction or improvement, particularly important in cases of extreme necessity,
- obtaining compaction of subsoil layers to a great depth, e.g. up to 40 m,
- effectiveness when there are large single boulders or stones in the ground,
- high efficiency in the case of areas exposed to dynamic loads, e.g. when landing airplanes.

The basic feature of this method is the use of high energy generated at the time of the explosion of the explosive. Detonation of an explosive is possible only with the use of a high-voltage electric impulse, for safety reasons, materials sensitive to detonation under the influence of fire are not used [12]. This requirement does not have to apply in the case of mining works performed by the military.

In the process of compaction of granular soil during an explosion, the main phases can be distinguished. In the beginning, the zone of post-explosion gases expands and the shock waves propagate in the soil and water medium at a speed of approx. 3000 m/s. The pressure of the detonation wave is about 1400 MPa. This process causes a change in the structure of the soil skeleton, the grains or particles of which undergo slow or fast rearrangement due to large shear deformations in the soil, then the soil liquefies and water pressure dissipates in the pores. The detonation of the charge causes a sudden increase in water pressure in the pores of the ground, which destroys the existing unstable structure, turning it into a useful one for placing objects or airport elements on it.

The caused rearrangement in the soil environment entails an increase in soil compaction. It depends on the type of soil and its permeability, the location (placement) of the explosive, and the volume of soil to be compacted..

To carry out soil strengthening operations, explosives may be placed on the surface of the soil to be strengthened or at a predetermined depth. In the last case, concentrated or elongated loads are used.

In previous implementations, when concentrated charges were used, their weight did not exceed 10,000 g, while elongated charges usually had a unit weight of about 2,000 g/m.

Polish experience allowed developing the above empirical recommendations for the method of soil strengthening with the use of blasting agents. Other design parameters can also be found in the literature [4].

The theoretical range of the effective impact of an explosion in the case of a concentrated charge or a sequence of concentrated charges is:

$$R1 = k \cdot \sqrt[3]{Q_1} \quad (7)$$

where Q_1 it is the empirically determined mass of the explosive charge (kg) assumed at h depth:

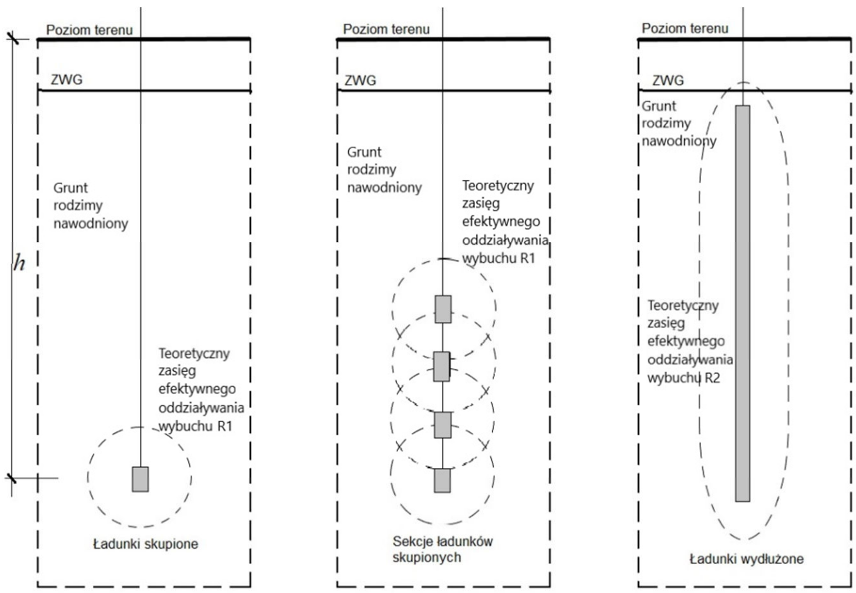
$$Q_1 = 0{,}055 \cdot h^3 \quad (8)$$

The k parameter is an experimental coefficient: k = 2,5 ÷ 3,0. Theoretical range of the effective impact of the explosion in the case of an elongated charge :

$$R2 = 0{,}71 \cdot k \cdot \sqrt[3]{Q_2} \quad (9)$$

where Q_2 it is the assumed mass of the explosive charge (kg/m).

The quantities given earlier are shown in the figure **9**.



9. Hidden explosions with an exemplary arrangement of charges

A single use of explosives does not always give the expected results regarding the strengthening of the soil intended for the construction of runways, runways, access roads to them, etc. Then, a series of explosions [3] must be used, including the sequential firing of charges at various points on the reinforced surface (figure **6**).

Runways/runways are linear engineering structures, similar to roads of various types or railway lines, etc. They can therefore be implemented using experience in strengthening soils for the construction of roads, railways, etc. - Photo **7** and Photo **10**.

10. The method of subsoil improvement using blasting agents, A2 motorway, Koło-Dąbie section [9]

Application for the construction of a distributed network of "small" airports and runways

In Poland, apart from airports in the vicinity of large cities, the so-called regional airports, it is advisable to create small airports with public access (including limited certification) or based on the existing 28 airports entered in the Register of Civil Airports for 2018. Such airports can serve aircraft with a take-off weight of up to 10 Mg.

All these airports could perform a complementary function and serve passengers planning to get to a large transport airport from places at least 3 hours away by other means of transport. In Poland, it is also worth considering the planned construction of the CTH.

These airports could be used, for example, by the Territorial Defense Forces as runways for tactical drones. However, such airports or helipads should be located independently on weak soils intended exclusively for military purposes or with the possibility of quick adaptation for such purposes.

When modernizing existing runways, runways or building new ones, innovative methods based on green geotechnics should be used - giving up concrete and asphalt. Using difficult land for construction, often unsuitable for other purposes and unused - swamps, peat bogs, etc. In these cases, explosives can be used to strengthen them with good effect. They can be located in the coastal zone and therefore additionally be used to increase the safety of navigation at sea. It is worth adding here that many lands located in the coastal belt are weakly bearing, so they can be adapted to the above-mentioned purpose using methods using explosives.

To implement the above concept, the already mentioned aircraft with a maximum take-off weight of 10 Mg can be used. These are generally nineteen-seat aircraft plus two crew members. Their maximum speed is about 500 km/h, and the maximum range is about 1,300 km.

It is a competitive solution in relation to other means of transport, including even high-speed rail, which introduces the possibility of creating a dispersed network of "small" airports, without restrictions in relation to their specific location, including locations on low-bearing land. This is where the soil strengthening method with the use of explosives comes in handy. Such airports can be created and liquidated depending on the needs. The cost of such an operation is low and, due to the technology used, it is neutral for the environment.

It should be added that such airports or runways can also be created in combat conditions, for example for unmanned aerial vehicles. For example, the payload of the RQ-4 Global Hawk unmanned aerial vehicle is approximately 10 Mg.

Due to the lack of location constraints, a distributed system can also be well-designed, taking into account the architecture and topology adapted to all conditions, including crisis conditions.

"Small" airports and small planes are a more flexible form of air transport than air transport using traditional airports. Such a transport network can be a communication supplement for civil airports and military airports. In this way, passengers can be offered convenient and quick access to selected destinations, including hubs, and international airports. This is support for activities related to the leisure industry. These solutions can also be used to transport goods and be used for broadly understood medical transport (transport of patients, transport of organs, transport of medical materials, etc.).

These are systems used in many countries. A similar one works well in the USA and Europe, known as the European Personal Air Transportation System (EPATS). It is a public air transport system intended to be used by the general public.

When planning such a network of airports or airstrips, you should remember what has been written in [16]: "The number of passenger and cargo aircraft is growing rapidly. In 2018, around 26,000 were exploited in the world. planes, in 2038 about 51,000 are to fly. planes. It should be taken into account that a passenger plane on a flight from Europe to North America burns as much fuel as a passenger car over several decades. Before the pandemic, fuel combustion in aircraft engines had a 5% share of the total CO2 emissions in the world. On average, there were 9,000 in the air at the same time per day. planes. In 2018, 11% of the Earth's inhabitants traveled by plane, of which 4% traveled abroad."

Summary

The method of take-off and landing of an aircraft has a significant impact on its impact on the pavement and ground.

The method of strengthening the subsoil using explosives for the construction of engineering structures intended for civil or military air operations is innovative and effective.

It is an easy method to implement, especially with the use of sappers and engineers. It is characterized by a short time of soil consolidation. The possibility of locating on the low-bearing ground and in hard-to-reach areas is also an advantage of this method of soil reinforcement. The given location can be used to create anti-access systems. The described method of soil compaction is economically attractive.

Difficult areas, such as swamps, wastelands, etc., can be used by civil and military aviation. In the latter case, their location may be an additional advantage, also beneficial from a military point of view.

"Small airports" are a way to solve many communication and transport problems in all conditions.

A positive feature is the possibility of their dispersion, and this allows for an increase in the accessibility of large groups of society to air transport and increases the safety and reliability of the entire system in all conditions. It is flexible, reliable as a whole, and scalable (a feature that allows the system to maintain similar performance when increasing the scale of the system - e.g. the increased number of small airports connected does not disturb the quality of the system's operation). Travel time is shortened.

This unconventional and innovative approach to the implementation of civil and military aviation operations should be a desirable and possible direction of development of the civil and military aviation system in Poland, in which the described method of ground improvement should also be used to build infrastructure in difficult areas to supplement the system by building access roads, railway sidings (MPS), warehouses, hangars, technical facilities.

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