PROTECTIVE SCREENS AND THEIR INNOVATIVE DEVELOPMENT CONTRIBUTING TO THE PERCEPTION AND PREVENTION OF EMERGENCIES IN GEOTECHNICS

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Abstract

In the fields of geotechnics, hydraulic engineering and engineering geoecology, one of the most effective engineering measures for protecting various civil and industrial structures from external dynamic and filtration impacts is the use of screen structures. The authors have developed innovative protective screens designed to mitigate the effects of shock waves during mine and tunnel construction. These screens are made from recycled metal cans and used vehicle tyres, offering simplicity and cost-effectiveness. The authors have also developed a method for creating a borehole-based dynamic screen to protect structures from catastrophic seismic waves. This approach involves detecting approaching seismic waves from major earthquakes using specialised electronic sensors installed in zones of anticipated seismic activity. These sensors then initiate short-delay explosions of borehole charges to form the dynamic protective screen. During detonation, an explosion-induced pseudo-fluidised zone is created in the rock or soil, absorbing the destructive energy component of the seismic wave. Methods have also been developed for engineering loess collapsible loams using rigid protective-reflective screens. This is achieved by reinforcing the perimeter of the compacted area through the base of contour trenches down to the bottom of the collapsible layer using binder injection, thermal treatment or freezing. Studies of the borehole explosion-protective screen were conducted in Zaporizhzhia, Ukraine. A reduction in vertical ground vibration intensity behind the seismic protective screen was recorded during explosions of nearby charges in the range of 1.2–2.2 times the intensity (attenuation factor). Additionally, the authors have developed a new anti-filtration screen design where brine waste is used as the anti-filtration medium and where the drainage pipes are made from recycled vehicle tyres bonded together.

Keywords: protective screen, seismic waves, borehole, innovative designs, waste materials, explosion, protected structure, drainage pipes

I. Introduction

In geotechnics, hydraulic engineering, and engineering geoecology, one of the most effective engineering measures for protecting various civil and industrial structures from external adverse dynamic and filtration effects is the use of different types of protective screens.

It is well known that during the excavation of underground tunnels and mines, various protective screen designs are used to mitigate the negative impact of underground explosions.

An analysis of engineering methods for seismic protection of structures against the effects of seismic waves generated by catastrophic earthquakes shows that underground screens represent one of the most promising yet understudied solutions.

The theoretical foundation for the creation of underground barriers (screens) to impede the propagation of wave disturbances in soil—whether of seismic, explosive, impact, or vibrational origin—was established in the mid-20th century through the efforts of researchers such as G.I. Pokrovsky [1], G.M. Lyakhov [2], A.A. Vovk [3], N.U. Turuta, I.A. Luchko, and V.A. Poplavsky [4], L.M. Geiman [5], I.I. Glass [6], A.I. Ivolgin [7], A.A. Gurin, P.S. Maly, and S.K. Savenko [8], V.S. Polyakov, L.Sh. Kilimnik, and A.V. Cherkashin [9], U.T. Begaliyev [10] and others.

Research into the construction of anti-filtration screens made from various materials has been extensively covered in the monographs by S.N. Popchenko, Yu.N. Kasatkin, and G.V. Borisov [11], V.V. Sokolskaya [12], V.N. Zhilenkov [13], V.M. Goldberg and N.P. Skvortsov [14], V.S. Altunin, V.A. Borodin, V.G. Ganchikov, and Yu.M. Kosichenko [15], L.I. Kulchitsky and F.G. Gabibov [16] and others.

The attenuation of shock air waves is achieved by constructing massive screens (barriers) near the explosion site from various materials, such as concrete, rock, metal, water, and others.

Seismic protection screens function by reflecting and damping the destructive component of seismic energy, allowing only a residual portion of the seismic energy - safe for the protected structures - to reach them.

Anti-filtration screens are intended to prevent the ingress of water or contaminating (toxic) fluids into protected areas.

The development of cost-effective and efficient protective screen designs, along with the corresponding construction technologies, is a pressing issue in the fields of geotechnics, hydraulic engineering, and engineering geoecology.

II. Development of innovative screens for attenuating shock air waves using recycled waste

Conventional and widely used designs for mitigating shock air waves typically involve the construction of thick concrete structures, which require significant material and labor resources [17]. Moreover, the dismantling of such screens is often technically complex and costly.

The authors developed two original designs of protective screens utilizing recycled household waste materials.

The first screen design (see Fig. 1) includes a supporting shield (1) made of wooden planks or metal sheets, anchored to the walls of the excavation using anchor bolts (4). On the surface of the shield facing the direction of the shock air wave, preassembled honeycomb blocks (2) are attached. These blocks are constructed from recycled, uniformly shaped metal cans. To absorb the impact of the shock wave, the honeycomb blocks are covered with a membrane (3) made from either a wooden or plastic sheet.

The honeycomb blocks represent a spatial structure composed of identical recycled metal cans, which are tin cylindrical hollow elements. These elements are connected either by adhesive bonding or by simple stacking.

To enable the honeycomb structure to absorb the pressure of the shock wave, its surface on the side facing the wave is covered by a membrane (3) made of a lightweight sheet material (e.g., fiberglass, plywood, etc.). The membrane (3) is attached to the honeycomb blocks, for example, using adhesive bonding. The membrane is not connected to the excavation walls and can move relative to the support shield along the axis of the excavation, functioning like a piston. The support shield (1) is fixed to the excavation walls using anchor bolts (4).

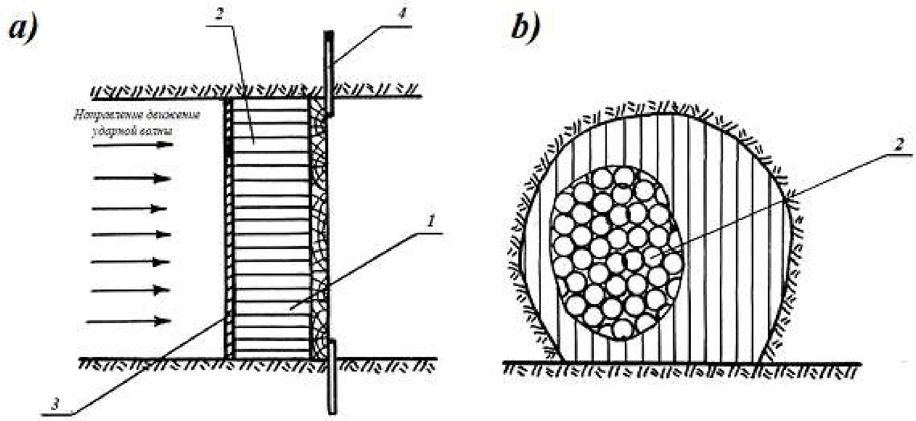

Figure 1: *Screen for attenuating shock air waves: a) longitudinal section; b) front view*

The system operates as follows.

When the shock wave strikes the membrane (3), it causes the membrane to move like a piston along the axis of the excavation. This movement relative to the support shield results in deformation of the honeycomb structure, which is composed of cylindrical metal cans. As the honeycomb blocks (2) deform, they absorb the energy of the shock wave.

The energy absorbed by the honeycomb structure is determined by the following expression:

$$A = F \cdot L, \tag{1}$$

where F is the resistance force of the honeycomb blocks to deformation, and L is the length of the honeycomb blocks.

The deformation force of the honeycomb blocks is determined by the following expression:

$$F = \sigma \cdot S, \tag{2}$$

where σ - the failure stress and S is the cross-sectional area of the honeycomb structures. The failure stress of honeycomb structures made from recycled tin cans is determined by the following formula:

$$\sigma = 28.63\sigma_T \frac{t^2}{d^2} + 1{,}16\sigma_{\text{shear}} \frac{t}{d}, \tag{3}$$

where σ_t is the tensile yield strength of the material of the recycled tin cans, σ_{shear} is the shear yield strength of the can material, *t* is the wall thickness of the recycled can, and *d* is the diameter of the can.

In the proposed design, the damping effect is determined by the geometric parameters of the honeycomb structure formed from recycled cylindrical metal cans and the length of the honeycomb blocks. If necessary, the honeycomb blocks can be assembled from multiple rows. When selecting the above-mentioned honeycomb parameters, it is important to ensure that the failure stress of the honeycomb structure is lower than the failure stress of the support shield (1) and membrane (3).

The efficiency of the proposed design lies in its significantly reduced cost, as the honeycomb blocks are made from recycled materials with a specific geometric shape that allows for the formation of a honeycomb structure by simply laying the cylindrical elements horizontally against each other. This considerably simplifies the assembly of the screen structure without compromising its functionality. Additionally, the use of perfectly cylindrical elements improves the accuracy of structural calculations. The dismantling process of the screen is also extremely simple.

The second protective screen design (see Fig. 2) consists of a support shield (1) fixed to the excavation walls using anchor brackets (2). Toroidal elements (3) are mounted on the surface of the shield using hooks (4) attached to the shield (1). To absorb shock waves, the toroidal elements are covered with a membrane (5), which is connected to the toroidal elements (3) using rotating latches (6) that pivot around their axes.

The protective screen is assembled as follows: The support shield (1) is made from wooden planks or metal sheets, which are secured to the excavation walls using anchor bolts or anchor brackets (2).

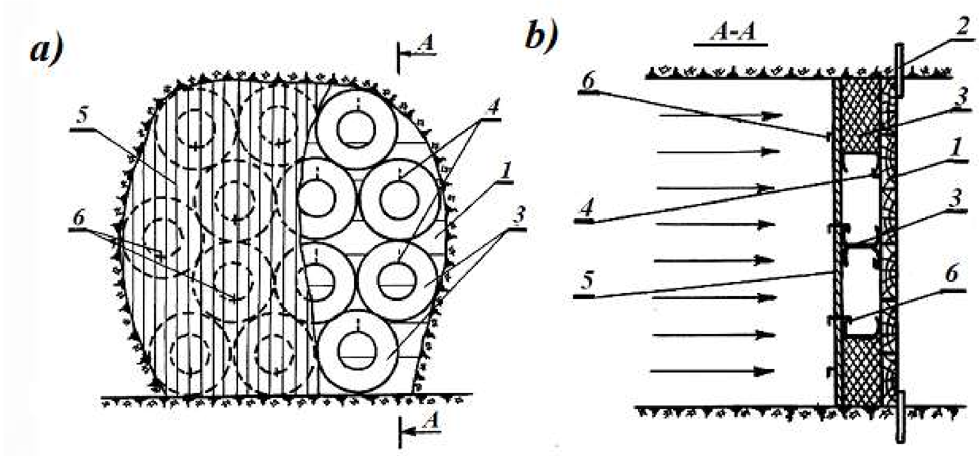

Figure 2: *Screen for attenuating shock air waves using recycled tires: a) front view; b) longitudinal section A–A*

Uniform toroidal elements (3) are selected, which are made from recycled steel-belted vehicle tires. The tires (3) are sequentially positioned against the support shield (1) for marking, and at the point where the central vertical axis of each tire intersects the circumference of its inner hole, hooks (4) are installed and fixed to the shield (1), with the hooked ends oriented upward.

After installing the hooks (4), which contact the shield using one of the tire's side flanges, the membrane (5) - a lightweight sheet material such as fiberglass - is marked to match the geometry of the tires (3) mounted on the shield (1). At the intersection points of each tire's vertical axis with the circumference of its inner hole (in the lower part), U-shaped rotating latches (6) are installed. These latches (6) are initially oriented with their bends facing upward. During the attachment of the membrane (5) to the tires, the latches (6) are rotated 180° around their axes so that the inner hook of each latch enters the hollow toroidal space of the tire and locks onto the opposite side flange of the tire.

This protective screen operates as follows.

When a shock wave impacts the membrane (5), it causes the membrane to move like a piston along the axis of the excavation. This movement relative to the support shield results in elastic, damping compression of the spatial structure formed by the rubber-reinforced toroidal tires. Due to the unique mechanical properties of recycled steel-belted tires, the energy of the shock air wave is effectively dissipated.

When selecting the tires, it is essential to ensure that the compressive yield stress of the recycled tires is lower than the failure stress of the support shield and membrane.

The effectiveness of this second protective screen design lies in its high damping capacity, structural simplicity, and ease of assembly and disassembly.

III. Development of a borehole-based dynamic screen for protection against seismic waves

The analysis of known borehole screens for protection against hazardous seismic waves, presented in [18], has shown that such systems generally involve the creation of cylindrical cavities (either vertical or inclined), which are most often filled with materials capable of absorbing the destructive component of seismic vibrations. These types of screens typically function as passive systems, waiting in place to respond to seismic impact.

The authors have developed a method for creating a borehole-based dynamic screen intended to protect structures from the effects of catastrophic seismic waves.

Figure 3 shows a schematic arrangement of boreholes (1) placed on the side facing the protected structure (2), designed to reduce seismic impact. Special explosive charges (3) are placed within the boreholes (1). In plan view, the boreholes (1) with charges (3) are positioned along an arc, with the convex side facing the predicted epicenter (4) of the earthquake. If the epicenter is difficult to predict accurately, the boreholes (1) with explosive charges (3) are arranged in a circle around the protected structure (2) at equal intervals.

With such an arrangement, the detonation of each borehole charge (3) produces a stress wave, according to Huygens' principle, which propagates toward the incoming seismic waves. This interaction is intended to occur in the zone in front of the dynamic protective screen.

The goal is to ensure that interference or amplification between the explosive and seismic waves does not occur. This is feasible because the seismic wave generated by the earthquake and the dynamic wave produced by the borehole charges (3) differ significantly in shape and timing of their compression phases. Furthermore, as the distance from the earthquake epicenter increases, the seismic shock wave stretches in duration.

The most reliable reduction in seismic intensity is achieved when the seismic wave from the catastrophic earthquake reaches the location of the explosive charges (3) at the moment of gas bubble pulsation and formation of the compression zone. The delay interval between the onset of the earthquake and the detonation of the charges (3) in the dynamic screen, taking this phenomenon into account, can be calculated using the following formula:

$$\tau = \frac{r}{C_y^m} - \frac{r_s}{v_y}, \quad (4)$$

where ρ is the distance from the earthquake epicenter to the explosive charges of the screen; C_y^m is the propagation velocity of longitudinal stress waves in the rock mass, m/s; r is the radius of the compression zone formed by the detonation of the screen explosive charges, which can be determined using the formula provided in [19]; v_y - the velocity of rock mass displacement during the detonation of the dynamic screen BB explosive charges, approximately equal to 100 m/s.

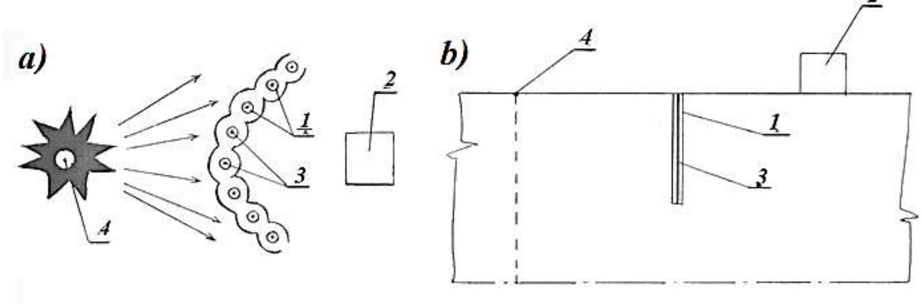

Figure 3: *Schematic of object protection using a dynamic screen: a) plan view; b) longitudinal section*

The radius of the compression zone generated by the detonation of the screen explosive charges is determined by the formula given in [19].

$$r_s = k_x R_0 = 10 R_0 \left(\frac{25 \cdot 10^4 g}{\sigma_s C_y{}^m \rho} \right)^{1/8} \times \sqrt[3]{\frac{\rho_x G_x}{\rho_A G_A}} \quad , \tag{5}$$

P_0 – radius of the explosive charge in the dynamic screen; g – acceleration due to gravity; σ_s- – compressive strength of the rock; ρ– density of the rock (soil); ρ_A – density of ammonite; ρ_x – density of the explosive charges; E_A– explosion heat (energy) of ammonite; E_x – explosion heat (energy) of the explosive used.

$$k_x = k \sqrt[3]{\frac{\rho_x G_x}{\rho_A G_A}} \; ; \tag{6}$$

$$k = 6 \div 7.$$

By substituting equation (5) into equation (4) and performing mathematical transformations, we obtain the final formula for determining the delay interval between the onset of the earthquake and the detonation of the explosive charges in the protective screen.

$$\tau = \frac{r}{C_y{}^m} - 0.1 R_0 \left(\frac{25 \cdot 10^4 g}{\sigma_s C_y{}^m \rho} \right)^{1/8} . \tag{7}$$

In practice, the reduction of seismic wave intensity during a catastrophic earthquake using the proposed method can be achieved through short-delay blasting, by selecting the charge mass at each stage such that the amount of explosive material decreases toward the protected object. In this case, the seismic waves generated by the larger explosive charges at the initial delay stage are mitigated by the successive delayed detonations of the following stages.

The approach of a seismic wave from a catastrophic earthquake is detected by special electronic sensors installed in regions of predicted seismic activity. These sensors initiate the short-delay detonations of borehole explosive charges in the dynamic protective screen.

During the detonation of the borehole charges (3) in the dynamic protective screen, a blast-induced pseudo-liquefied zone of rock or soil is formed. This zone absorbs the destructive component of the energy carried by the catastrophic seismic wave.

Following the activation of the short-delay borehole charges, the dynamic screen transitions into a static screen phase, as the mechanical properties of the rock or soil within the screen zone differ significantly from those of the surrounding medium - particularly when the surrounding material is solid (rocky) ground. When camouflet cavities are formed in soft soils after borehole detonations, and compacted zones are formed along borehole walls, additional seismic wave attenuation also occurs.

The seismic waves that reach the protected object after passing through the protective screen will have lost their destructive energy component, and the remaining seismic energy is absorbed by the structure without causing visible damage.

The distance between the dynamic protective screen and the protected structure must be selected such that the seismic waves generated by the short-delay explosions produce a permissible and safe background level with respect to the protected object, as well as for humans, animals, and the surrounding environment.

IV. Development and study of protective screens in deep compaction of collapsible soils using hydro-blasting

F.G. Gabibov developed engineering methods for the compaction of loess-like collapsible clay loams using rigid protective-reflective screens [20]. The formation of screens along the perimeter of the compacted area significantly reduces the intensity of seismic vibrations beyond the treated zone. This occurs due to both the reflection of waves from the inner surface of the screen and the attenuation of wave energy within the screen material itself. The wave reflected from the screen stretches the seismically active period caused by internal blasting within the compacted zone, thereby improving the quality of compaction of the collapsible clay mass.

One of the simplest problems concerning the interaction of a plane wave in a linearly elastic medium with a flat barrier was examined by G.M. Lyakhov [21]. According to [22], the system of equations governing the adiabatic motion of an ideal fluid, in cases of planar, cylindrical, and spherical symmetry, can be expressed in the following form:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} = 0; \frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x} + \rho\frac{\partial u}{\partial x} + \nu\frac{\partial u}{x} = 0;$$

$$\frac{\partial s}{\partial t} + u\frac{\partial s}{\partial x} = 0; p = p(\rho S), \tag{8}$$

where u – particle velocity; ρ – density; p – pressure; S – entropy; t – time; ν – equal to 0, 1, or 2, respectively.

The motion of a continuous medium can be described using two approaches: the Eulerian and the Lagrangian methods.

In the developed methods for compacting collapsible clay loam masses in built-up areas, protective screens are formed prior to the wetting of the soil mass. This is achieved by reinforcing the perimeter of the compacted area - through the base of the perimeter trenches down to the bottom of the collapsible layer - using grouting with binding solutions, thermal treatment (firing), or freezing.

The creation of screens around the perimeter of the compacted mass or zone not only allows for more efficient use of the energy from deep explosions and prevents damage to nearby structures, but also reduces water loss away from the compacted zone.

Field investigations of a borehole blast-protection screen were conducted in the 17th microdistrict of the Khortytsia residential area in Zaporizhzhia (Ukraine). The construction site is composed—down to a depth of 32.0 meters - of a stratum of loess-type collapsible soils, underlain by Neogene deposits up to 10 meters thick. The collapsible soil layer is characterized by frequent interbedding and pinching out of layers with varying properties. The upper layers, down to a depth of 18 meters, exhibit a relative collapsibility ranging from 0.04 to 0.73; the lower layers, from 18 to 32 meters deep, show a relative collapsibility of 0.01 to 0.03. The total potential deformation magnitude is 2.56 meters.

The preparation of the foundation for a residential building using the hydro-blasting method was carried out in a partially developed microdistrict. The minimum distance from the blast boreholes to the foundation of an existing residential building was 10.5 meters. A nine-story residential building was constructed on the hydro-blasted foundation.

Due to the fact that the distance between the compacted sites and the existing ten-story residential building was only 11 meters, it was necessary to implement a seismic protection screen along the path of propagation of blast waves from the deep charges toward the structure being protected. Experimental and theoretical studies of such screens (artificial barriers) demonstrated that their use can reduce ground vibration intensity by a factor of 1.2 to 2.

Prior to the blasting operations, as part of the engineering design of the building's foundation preparation, the effectiveness of vibration attenuation by the seismic protection screen was determined through numerical analysis. The screen consisted of two rows of fully drilled boreholes, each with a diameter of 350 mm, depth of 15 meters, and spacing of 1 meter.

For the purpose of verifying the calculated data and to determine the permissible explosive charge mass, experimental studies of ground and structural vibrations under blast loading were carried out. Ground and building vibrations were measured using standard seismometric equipment, and the oscillograms were recorded on roll photographic paper.

Vertical vibration displacement sensors were installed on the ground to determine the screening coefficient of the seismic protection barrier. Measurements of horizontal vibration displacements of the residential building were taken on the first floor and on the roof.

Since horizontal vibrations dominate during deep blasting impacts, vertical vibrations of the building were not recorded.

The obtained maximum vibration parameters correspond to the impacts of individual deep explosions (with an explosive charge mass of 5 kg) in the rows closest to the existing residential building. Analysis of the experimental data on ground and building vibrations allows for the following key conclusions:

The amplitudes of horizontal vibration displacements of the residential building at the first and tenth floors were 0.26–0.68 mm and 0.37–1.78 mm, respectively. The vibration intensity at the building foundation was estimated at 3–3.5 points on the seismic intensity scale, which does not exceed the permissible limit of 4 points. The horizontal displacement amplitudes at the tenth floor generally did not exceed 1.1 mm, which is considered acceptable.

A reduction in the intensity of vertical ground vibrations behind the seismic protection screen was observed during explosions of the nearest explosive charges to the protected building, with a reduction factor ranging from 1.2 to 2.2.

The periods of forced ground oscillations (under deep explosion loads) were determined to be: in the horizontal direction T_H= 0.2–0.5 s and in the vertical direction T_V =0.19-0.4 s.

V. Development of an anti-filtration barrier for groundwater remediation from petroleum products

Fig.4 shows a drainage system with an anti-filtration barrier used for the remediation of groundwater contaminated with petroleum products.

Perpendicular to the flow of groundwater (1) and petroleum products (2) floating on its surface, an anti-filtration curtain (3) is constructed from compacted gumbrin, without extending it down to the aquiclude. A perforated drainage pipe (5) is installed in the trench, placed above the base of the petroleum product layer (4), with openings (6) located in the upper third of its circumference. A filter layer (7) - for example, made from gravel-crushed stone - is placed above the drainage pipe (5). The upper boundary of the filter (8) is positioned above the maximum petroleum product level (9).

The drainage system with the anti-filtration curtain used for groundwater purification from petroleum products operates as follows:

The petroleum products (2), migrating with the groundwater, reach the anti-filtration curtain (3) and are retained by it. The curtain is constructed in the following manner: a trench is excavated (not reaching the aquiclude), and gumbrin is filled into the trench. Gumbrin is a waste product from the purification of industrial oils, specifically a bentonite clay used to filter technical oil. The resulting gumbrin retains hydrophobic and anti-filtration properties typical of clays. However, unlike traditional clays, gumbrin has low cohesion.

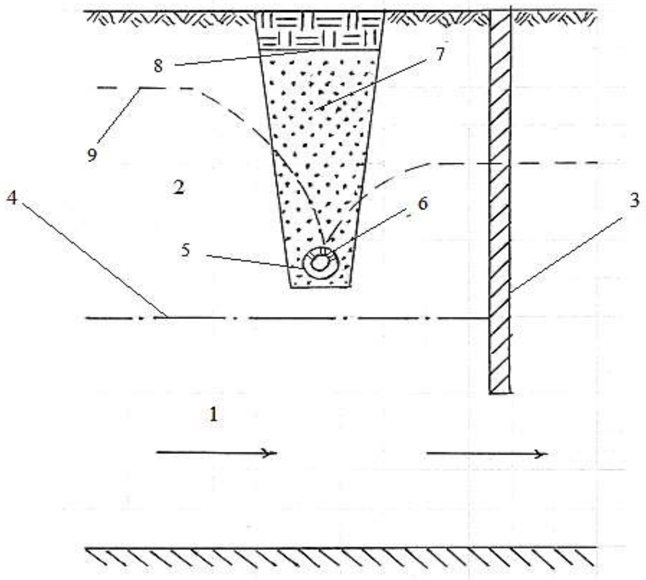

Figure 4: *Anti-filtration barrier used for groundwater remediation from petroleum products*

When compacted layer by layer, gumbrin forms a stable and effective anti-filtration barrier (3) within the trench.

As groundwater continues to flow beneath the anti-filtration curtain (3), it proceeds toward natural discharge zones, while petroleum products (2) are directed into the drainage pipe (5) through the filter material (7) and the perforations (6).

The technical and economic efficiency of this newly proposed design lies in its cost-effectiveness, achieved by utilizing waste products from the oil refining and transportation industries to construct the anti-filtration barrier.

IV. Conclusion

1. The authors developed innovative protective screens for attenuating blast air waves during the construction of mines and tunnels, utilizing recycled metal cans and automobile tires. These designs are characterized by simplicity and cost-effectiveness.
2. A method was developed for creating a borehole-based dynamic protective screen to safeguard structures from the impact of catastrophic seismic waves. In such a dynamic protective screen, short-delay detonations of borehole charges form a blast-induced pseudo-fluidized zone in the rock (or soil), which absorbs the damaging portion of the seismic wave energy.
3. Engineering methods were developed for the densification of collapsible loess-like silty clays using rigid protective-reflective screens. This is achieved by reinforcing the perimeter of the treated area through the bottom of contour trenches and to the base of the collapsible layer using grout injection, thermal firing, or freezing.
4. Field investigations of borehole-type seismic protective screens were conducted in the city of Zaporizhzhia, Ukraine. A reduction in the intensity of vertical ground vibrations behind the seismic screen was recorded during detonations of nearby explosive charges in the range of 1.2 to 2.2 times.
5. The authors developed a novel anti-filtration barrier design, in which gumbrin, a byproduct of industrial oil filtration, is used as the anti-filtration medium. The drainage pipes in the system are constructed from recycled automobile tires fastened together.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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