A MODEL OF THE CONDITIONS FOR SPONTANEOUS RELEASE OF BIOGAS FROM A SANITARY LANDFILL IN SOUTHERN BULGARIA

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ABSTRACT. The conditions that lead to a spontaneous release of biogas are studied, as well as the reasons for the following self-ignition of the sanitary landfill situated near the town of Haskovo, Southern Bulgaria. A geophysical survey was performed according to the method of electrical resistivity tomography (ERT) and a two-dimensional geoelectrical model of the sanitary landfill was constructed in the area of the studied site. The geoelectrical model has been transformed into an anthropogenic section of the work areas affected by the fire. The constructed section is in accordance with the applied technology for deposition of waste materials and the geodetic measurements of their volume. A model for the conditions for accumulation, circulation, critical mass formation and biogas explosion has been developed, presenting in detail the possible scenario for the occurrence and the progress of such incidents. Measures and principle schemes are proposed for limiting the dangerous accumulation of biogas in the sanitary landfill.

Keywords: sanitary landfill, electrical resistivity tomography, biogas, self-ignition, ecology

МОДЕЛ НА УСЛОВИЯТА ЗА СПОНТАННО ИЗТИЧАНЕ НА БИОГАЗ ОТ ДЕПО ЗА НЕОПАСНИ (БИТОВИ) ОТПАДЪЦИ В ЮЖНА БЪЛГАРИЯ

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РЕЗЮМЕ. Проучени са условията за спонтанно изтичане на биогаз и причините за последвалото самозапалване на регионалното депо за неопасни (битови) отпадъци край град Хасково, Южна България. Проведено е геофизично изследване по метод ERT (Electrical Resistivity Tomography) и е съставен двумерен геоелектричен модел на сметищното тяло в района на проучвания обект. Геоелектричният модел е трансформиран в антропогенен разрез на засегнатите от пожара работни участъци, който е валидиран с прилаганата технология за депониране на отпадъци и геодезичните измервания на техния обем. Разработен е модел на условията за натрупване, циркулация, формиране на критични количества и взривяване на биогаза, представящ в детайли възможния сценарий за възникване и протичане на подобни инциденти. Предложени са мерки и принципни схеми за ограничаване на взривоопасното натрупване на биогаз в сметищното тяло.

Ключови думи: депа за битови отпадъци, електротомография, биогаз, самозапалване, екология

Introduction

The subject of the presented study is the north-western part of the Regional Sanitary Landfill of the municipalities of Haskovo, Dimitrovgrad and Mineralni Bani, located near the village of Garvanovo, where an incident related to spontaneous leakage and self-ignition of biogas occurred (see Fig. 1).

The studied region is about 10000 m^2. The terrain is flat with a slight slope to the south-southeast. The geological base is made up of volcanic rocks, which in their upper parts are cracked and weathered to a different degree and in separate places are decomposed to clay. The rock massif is partially overlaid by diluvial clays with small thickness (less than 1 m). According to the accepted technology, a shielding layer of compacted clay with a thickness of 0.5 m is applied to the bottom of the landfill. The waste depositions are spread over certain work areas. The studied region includes two work areas – northern (a new one) and southern (an old one). The waste is defragmented and compressed in 20–30 cm thick seams that are accumulated in layers with a working height of about 1.8–2.0 m. These layers are covered (sealed) with separating coats of clay. In the upper part of the landfill body the waste depositions are slightly water-saturated. Zones completely saturated by landfill waters (leachate) are present at the landfill bottom. Part of the leachate may penetrate through the clay screen and infiltrate into the geological base.

Geoelectrical model

Electrical resistivity methods have wide application in the detailed mapping of the near-surface section. Their efficiency is connected to the differentiation according to electrical resistivity and is tied to the existing preconditions for presence of ionic conductivity (Keller, Frischknecht, 1981; Grigorova, Koprev, 2019). Electrical resistivity tomography was selected for the performed surveys as it can be effectively applied for obtaining a detailed picture of the geoelectrical differentiation in the near-surface section of landfill sites (Gyurov, Stoyanov, 2004; Dimovski, Stoyanov, 2011). This method is based on the use of modern equipment, optimal measuring techniques, and computer processing of acquired data (Griffiths, Barker, 1993; Dimovski et al. 2007; Grigorova, Koprev, 2018).

The objectives of the performed ERT survey are development of a geoelectrical model of the near-surface section, determination of the thickness and degree of watersaturation of the landfilled waste, achievement of a qualitative assessment regarding the conditions for the accumulation and circulation of biogas in the work areas where the incident occurred. The field measurements were accomplished a few days after the incident.

The geoelectrical model is based on the determined by the computer programme RES2DINV (Loke, 1999; 2001) electrical resistivity distribution, as well as on the available information for the geological section, the waste disposal technology and the results of the performed systematic monitoring. The composed scheme of the geoelectrical section in the studied area is illustrated in Figure 2.

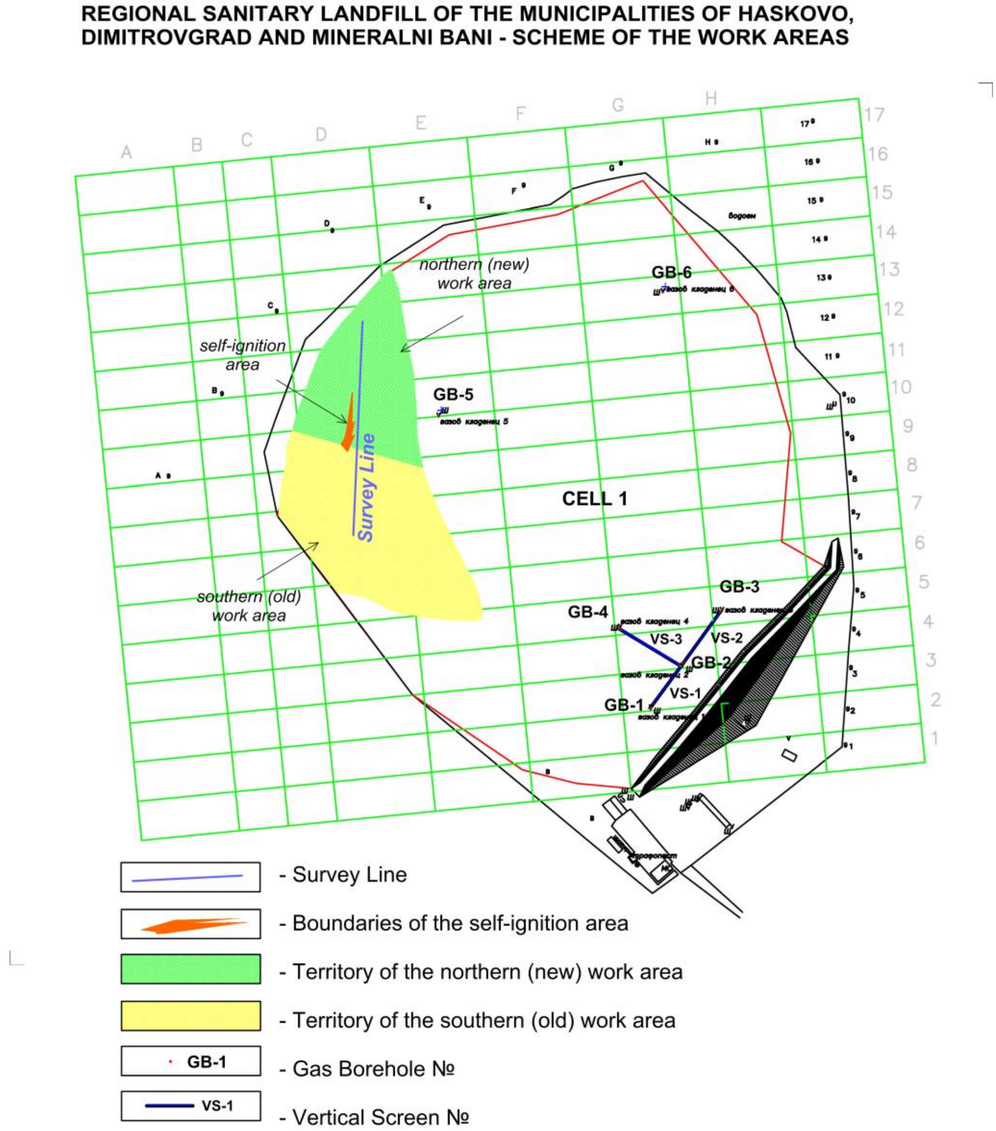

Fig. 1. Scheme of the studied region, illustrating the location of the survey line and the scope of the self-ignition incident

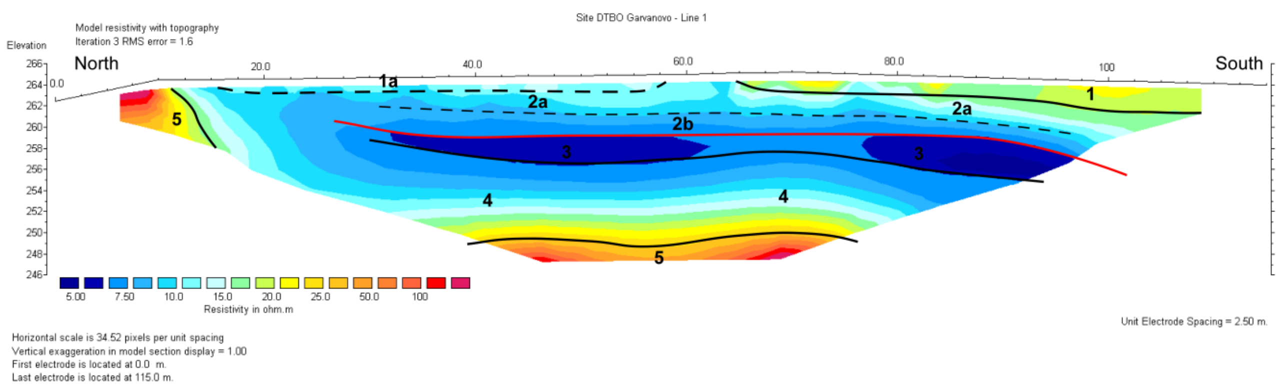

Fig. 2. Electrical resistivity distribution along the survey line

Taking into account the specifics of the ionic conductivity (Daniels, Alberty, 1966), the cross-section is differentiated in seven electrical resistivity media, marking layers of different origin and characteristics:

- The first electrical resistivity medium (Layer 1) is characterised by relatively high values of the resistivity of the studied section – in the range from 17.5 Ωm to 22.5 Ωm. It covers the near-surface part of the section in the southern half of the studied area. The thickness of this medium is about 1–3 m, with high values referring to the most southern end of the profile. It most probably maps the upper sealing layer of sandy clays and the very poorly water-saturated to dry part of the underlying last (topmost) layer of deposited waste.
- The second electrical resistivity medium (Layer 1a) has lower values of the electrical resistivity than the first one – from 12.5 Ωm to 17.5 Ωm. It covers the near-surface part of the section in the northern half of the studied area. Its thickness does not exceed 0.8–0.9 m. The second electrical resistivity medium is likely to represent the top sealing layer of clay over the last layer of deposited waste in the northern part of the sanitary landfill.
- The third electrical resistivity medium (Layer 2a) is typified by average resistivity values of 10 Ωm to 15 Ωm and has a thickness of about 2.0 m. It is likely to map the last (topmost) layer of deposited waste, the underlying clay layer and the uppermost parts of the waste deposited underneath. These parts of the section are poorly saturated and with relatively low density.
- The fourth electrical resistivity medium (Layer 2b) has lower resistivity values – in the range of 7.5 Ωm to 10 Ωm. It is spread ubiquitously underneath the third electrical resistivity medium and has a thickness of 1.7 m to 2.2 m. It is most likely to outline the boundaries of the first layer of waste deposited at the base of the sanitary landfill. This part of the section is saturated with landfill waters (leachate) typified by excessive total mineralisation and high electrical conductivity.
- The fifth electrical resistivity medium (Layer 3) is characterised by the lowest resistivity values for the studied section – from 5 Ωm to 7.5 Ωm. It denotes a layer-like body with a thickness of about 1.5–2.0 m and more. Layer 3 maps the clay barrier layer placed in the bottom of the landfill and the upper part of the underlying geological section, represented by highly weathered volcanic rocks, decomposed to clay. This part of the studied section is water saturated with the landfill leachate.
- The sixth electrical resistivity medium (Layer 4) locates parts of the subsurface section with a wide range of electrical resistivity – from 7.5 Ωm to 25 Ωm and has a thickness of about 7–8 m. It outlines the upper part of the geological base of the landfill, represented by marginally cracked and weathered to a different degree volcanoes. The established differentiation in the values of the electrical resistivity implies that Layer 4 is partially contaminated by leachate emissions penetrating beneath landfill bottom and infiltrating in depth.
- The seventh electrical resistivity medium (Layer 5) is characterised by the highest resistivity values – from 25 Ωm to over 150 Ωm. It most likely maps the relatively solid and unaltered by secondary changes segments of the rock massif. In the central part of the research area Layer 5 is almost horizontal (with a barely visible slope to the south) and is situated at a depth of about 15–16 m. At the start of the survey line, on the northern border of the landfill and beyond it to the north, it is located in the surface part of the section, where there are also visible surface outcrops.

Model of the anthropogenic section

The model of the anthropogenic section is composed along a line passing through the work areas affected by the fire. It is based on the results of the geophysical survey and is illustrated in Figure 3. Basically, it follows the geoelectrical section and is validated with the applied waste disposal technology and the performed regular geodetic measurements.

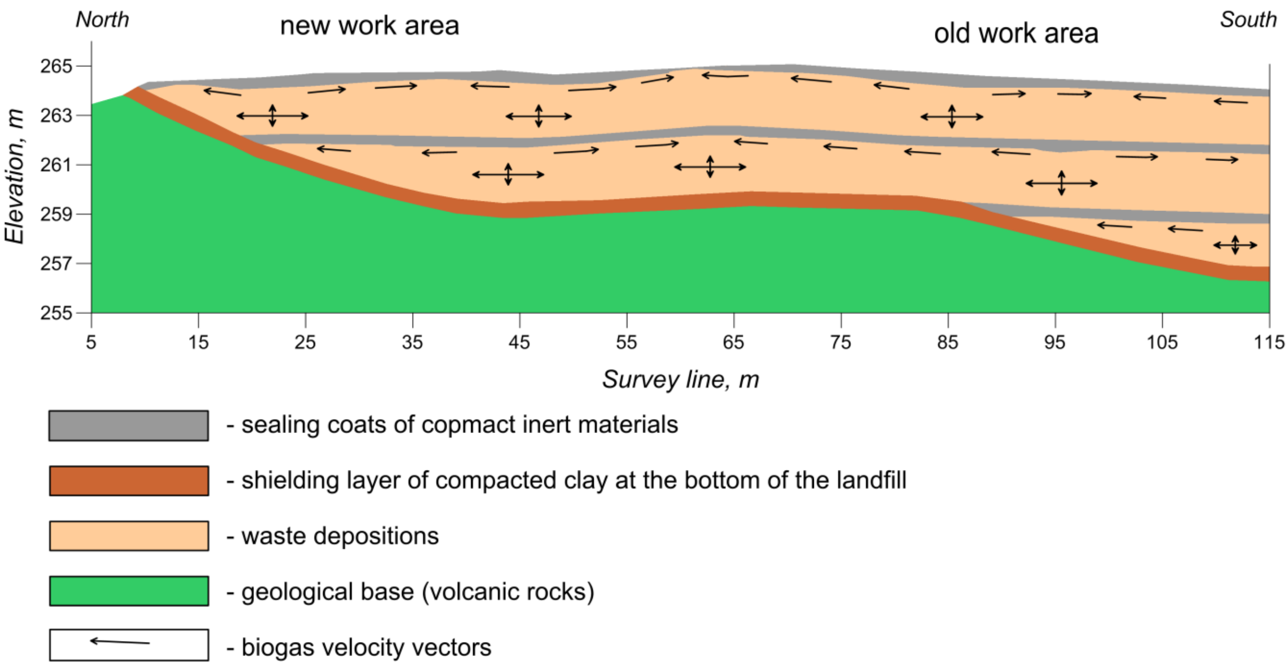

Fig. 3. Anthropogenic section of the sanitary landfill site along the survey line

The composed model gives an idea of the environment in which the critical accumulation of biogas has occurred, clarifies the conditions for the emergence and development of gas-transport processes and reveals the reasons of spontaneous explosions and fires. It illustrates the spatial boundaries and geometric characteristics of the differentiated layers and coats in the northwestern part of the sanitary landfill in the so-denoted northern (new) and southern (old) work areas.

Based on the presented in Figure 3 anthropogenic section, the following summaries and conclusions can be made:

- The geological base is covered by a compacted clay layer about 50–60 cm thick.
- The average thickness of the landfill body along the studied line is about 5–6 m.
- In the new work area the section includes two layers of waste with a total thickness of 4–5 m. Only in its most northern part, where the geological base is elevated, only one layer of waste is present with a thickness of 1–2 m.
- The old work area in its northern half is composed of two layers of waste and in the southern one - of three layers. The total thickness of the landfill body increases from north to south from 4–5 m up to more than 6–7 m.
- In both areas the waste layers are covered by a compact coat of inert materials 20–30 cm thick. In some places, the last sealing layer is unconsolidated, thinner (5–10 cm) or missing. This feature is quite distinct at the boundary between the old and the new work area as well as along the northern periphery of the landfill.
- The waste layers are practically encapsulated between the coats of compacted inert materials. This presupposes that the gas-transport in the landfill is predominantly in horizontal direction and the vertical one is of subordinate importance. In Figure 3 this aspect is illustrated schematically with the velocity vectors of the landfill biogas migration.
- Large amounts of biogas accumulate under high pressure in the encapsulated wastes. This process is accelerating in periods characterised by more rainfalls and higher temperatures when the degradation processes are more intense and the quantity of biogas formed is bigger.
- Interlayer gas exchange and/or spontaneous leakage of gas emissions into the atmosphere occur in areas with unconsolidated, very thin or disintegrated coating layer (the so-called "windows"). Through these "windows" it is possible that atmospheric O_2 can enter into the landfill, which in turn leads to the formation of an explosive mixture with the landfill biogas.

Conditions for biogas accumulation, circulation, spontaneous leakage, formation of critical quantities and self-ignition

Biogas gas is produced by the degradation of organic waste (manure, sewage sludge, municipal solid waste) under anaerobic conditions in a landfill. The various groups of anaerobic microorganisms are involved in the whole biogas-production process. The main steps are three: hydrolysis, acetogenesis and methanogenesis (Wellinger et al., 2013).

The hydrolysis is a process of breakdown of organic polymers (cellulose, hemicellulose, starch, proteins) into smaller compounds through the activity of bacterial produced extracellular enzymes.

In the second step (acidogenesis), the resulting intermediates with a low molecular weight (sugars, amino acids) initially ferment to organic acids and alcohols. After secondary fermentation the key products acetic acid (CH_3COOH), hydrogen (H_2) and carbon dioxide (CO_2), sources of carbon and energy for methanogenic bacteria, are produced.

In the methanogenesis (the third step) methanogenic bacteria convert the resulting products from the second phase to biogas (methane and CO_2). Methanogenic bacteria and acid-producing bacteria act in a symbiotical way.

The scheme of accumulation, circulation, formation of critical quantities and self-ignition of the biogas according to which the incident occurred is illustrated in Figure 4. Following the general scheme presented, the processes passed under the subsequent scenario:

1. The landfill biogas gradually accumulated in larger amounts in the upper part of the landfill body in the areas encapsulated by well-persistent layers of compacted inert materials (Fig. 4-A).
2. In the old work area, the amount of biogas and the space it occupies are much larger than these in the new work area. The reasons for this are the bigger volume of disposed waste, the better "encapsulation" and the possibility for inflow of additional quantities of biogas from the southern parts of the landfill.
3. At the same time, small amounts of biogas continuously flow into the atmosphere through the so-called "windows" in the near-surface "sealing" layer (Fig. 4-A). This process does not pose a serious risk of self-ignition or explosion if there is no accumulation of a critical amount of explosive mixture of CH_4, H_2 and O_2.
4. The degradation processes that have been going on for many years cause the accumulation of larger and larger quantities of landfill biogas in the encapsulated spaces, which is accompanied by a significant increase in pressure (Fig. 4-B).
5. An important fact is that, at the time of the incident, the weather conditions were favorable for the formation of much larger quantities of biogas. The amount of rainfall is one of the highest in the last 5 years (50% higher than the average for this period). The temperature is also among the maximum recorded in the same period. The bigger amounts of biogas and the high temperature released under these conditions are responsible for a more rapid increase in the concentration of flammable components (CH_4 and H_2) and for raised pressure in the landfill.
6. The increased pressure forms more intense flows to the surface and respectively amplifies the rate of gas emissions. As a consequence, in the spontaneously leaking areas the permeability increases, channels and larger gaps are formed in depth. The opportunities for entry of atmospheric O_2 into the landfill body also greatly escalate.
7. The intermixing of biogas, characterised by high CH_4 and H_2 content, and atmospheric O_2 resulted in the accumulation of a critical quantity of explosive mixture in the surface area of the sanitary landfill at the boundary between the old and the new work area (Fig. 4-C). Most likely, when the process reached its critical point self-ignition occurred.

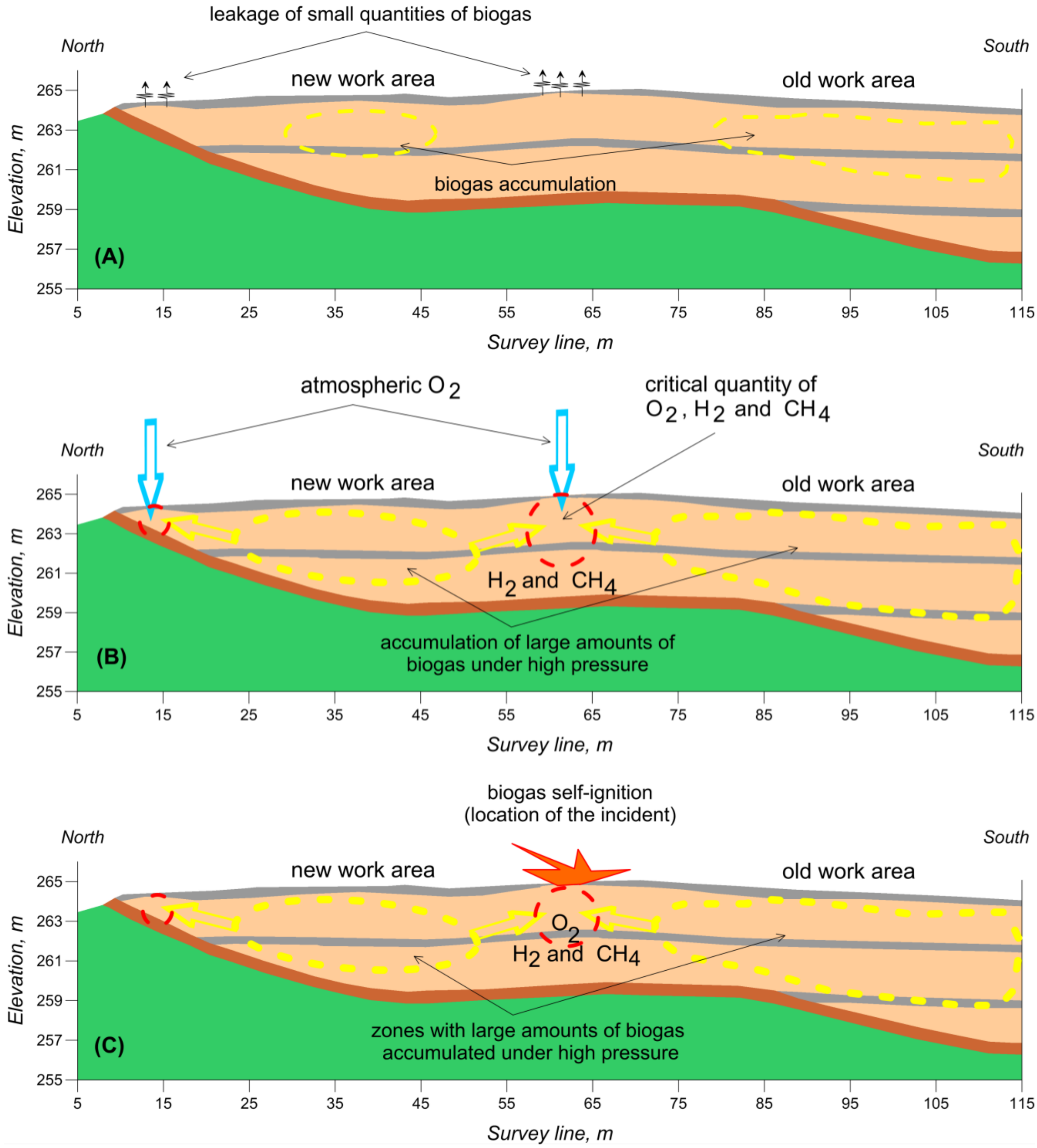

Fig. 4. Scheme of accumulation, circulation, formation of critical quantities and self-ignition of the biogas

Conclusions

The performed retrospective analysis of the conditions and the reasons for the incident occurrence shows that the main problem is connected to the accumulation of large quantities of high-pressure biogas in the new part of the landfill.

The problem can be solved by building a sufficiently well-developed system of facilities (gas boreholes and vertical screens) for collecting and removing biogas outside the landfill body. For illustration, in Figure 5 a schematic solution for the affected by the accident northwestern part of the sanitary landfill is presented.

The solution includes the construction of two new gas boreholes that have to be located in the central parts of the work areas at a distance of 50–60 m apart. The newly built boreholes will drain the biogas formed in the two work areas, thus eliminating the possibility of its accumulation under high pressure, the formation of critical quantities and subsequent self-ignition. Vertical screens (four-beam pattern) can be constructed around the boreholes in order to increase the efficiency of the system.

The proposed approach toward resolving the problem is a more moderate option, which makes a reasonable compromise between the effectiveness of the measures and the financial costs incurred for their completion.

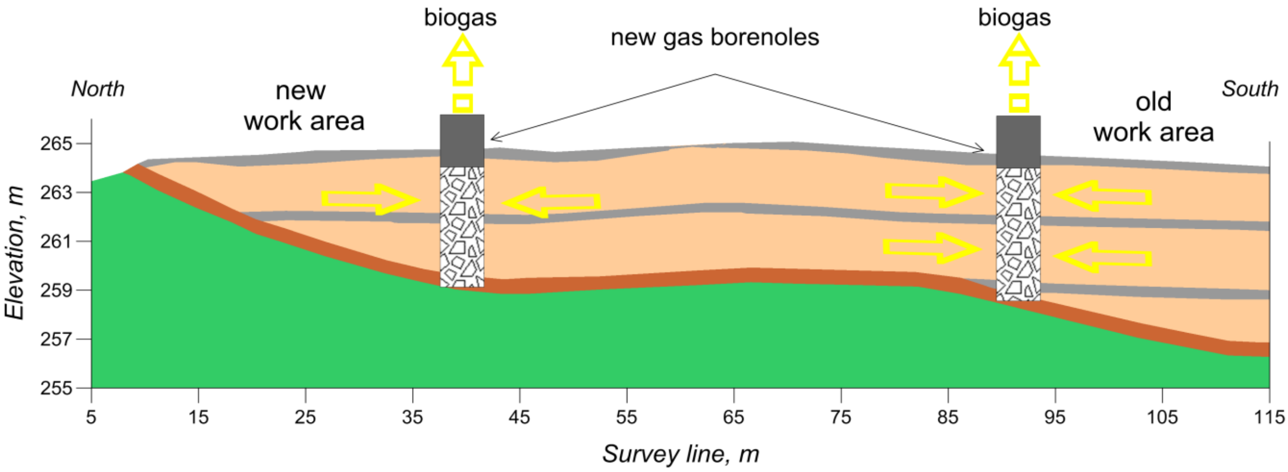

Fig. 5. Scheme of the proposed solution for the affected by the accident northwestern part of the sanitary landfill. Location of the new boreholes

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