

Inspection of Deep-Seated Fire Within Waste Disposal Site by Infrared Thermography

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Abstract

This paper presents a case study conducted to determine the areal extent of the subsurface fire at municipal solid waste disposal site in Croatia. Field measurements consisted of surface temperature assessment using infrared thermography from different positions on the ground and above the ground. In addition, boreholes were drilled to a depth of 9 m at four locations where the temperature profile was recorded by thermocouples and composition of extracted waste was inspected. The results showed that infrared thermography was a useful method of identifying hot spots at the landfill in question.

1. Introduction

Problem of fires at landfills but also other solid waste treatment facilities are known to occur frequently all over the world [1, 2, 3, 4, 5]. At municipal solid waste (MSW) landfills wide variety of different waste products are intermixed and compacted at a daily basis. Many of these waste materials can serve as a combustion fuel. These fires can originate from within the waste mass and are not visible on the surface, so the term “deep-seated fire” is sometimes used [6, 7, 8]. Sources of ignition can include local chemical processes or the burial of hot material within the waste [9, 10]. Once a fire is started, the oxidation of, e.g. organic material can provide enough oxygen for the fire to become self-sustaining. Since heat is generated during this process, the temperature of the waste increases forming so-called hot spots. Elevated temperatures can lead to smouldering combustion, but this does not necessarily produce smoke and flames. However, if enough oxygen is delivered into the waste flaming combustion can occur. Besides, existence of hot spots is likely to have different environmental impacts such as an increase in the range of trace gasses emitted, an increase in odour nuisance, an increase in emissions to the atmosphere due to increased permeability of the cover, failure of the sides or base of the landfill allowing leachate into the ground, etc [7, 11].

The detection of hot spots can be made through periodical surveys, mainly based on visual inspections or, less frequently, on monitoring systems. As oxygen is available in limited quantities, complete combustion cannot be achieved, resulting in the formation of carbon monoxide and other products of incomplete oxidation. Therefore, monitoring the carbon monoxide content in gasses from the waste is a method of detecting smouldering fire [6, 7, 8, 10]. The extent of a smouldering fire is usually determined by temperature measurements. Monitoring the surface temperature by thermal imaging can provide an indication of the area and location of increased temperatures. The depth and temperatures in the core of the fire are usually determined using thermocouples [3, 10, 12].

Although infrared thermography (IRT) is mentioned as a method that could be used to evaluate extent of a fire at landfills published data are very scarce. IRT is mostly used to monitor temperature differences at the top of gas extraction wells or for detection of gas leakages [13, 14, 15, 16]. Also, possibilities of using satellite thermal images for monitoring of thermal field over landfills has been investigated [17]. This paper presents a case study performed at operating landfill of MSW in Croatia where indications of subsurface fire were reported by the landfill owner. Investigation included visual inspection, infrared thermography imaging and temperature measurements to verify the existence of the subsurface fire and to evaluate its extent.

2. Landfill location and description of the problem

Landfill is located in Croatia in Šibenik-Knin County approximately 8 km of air distance southeast from the centre of the city of Šibenik. Landfill is operational for disposal of household waste since 1971. In the period 2008.-2011. remediation of the landfill was conducted which included installation the system of gas wells for passive degassing and waste shaping and covering with the water impermeable top layer the so-called landfill cap. Landfill cap (Fig. (1)) is a composite system consisting of gas drainage layer, the geosynthetic clay liner (GCL), geo-drainage and 80 cm thick re-cultivating cover layer of humus. Gas drainage layer consists of gravel with particle sizes 16-32 mm approximately 30 cm thick covered with geo-composite liner which should enable easier flow of gasses over the capped area and to protect GCL. GCL is composed of layer of bentonite clay sandwiched between two sheets of nonwoven geotextiles. It prevents infiltration of precipitation into the landfill but also the penetration of gasses from the landfill to the atmosphere [18]. Geo-drainage acts as a geomembrane for water penetration from environment into the waste. It consisted of geomembrane



liner 2,5 mm thick made of HDPE (high density polyethylene) with textured surface protected by a layer of nonwoven geotextile.

Today this landfill is a part of the regional waste management facility which covers an area of about 25 ha (Fig. (2)). Three additional waste disposal cells (cell 1, cell 2 and cell 3) were constructed with bottom impermeable layer and drainage system to prevent leaching of liquids from the waste to the soil while leachate is collected and further treated. These newly formed disposal cells have approximate surface area of 8.8 ha. On the northern part of the landfill, landfill cap was finished including layer of hummus and vegetative layer while on the southern part of existing waste geosynthetics placed during remediation process will serve as an intermediary capping layer on which further placement of waste is planned (Fig. (2)).

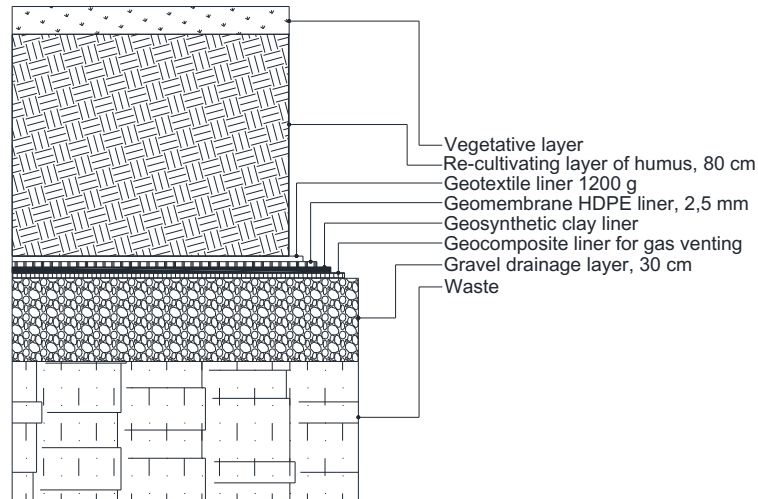


Fig. 1. Landfill cap layers

After remediation works have been conducted, Gradska čistoća d.o.o. Šibenik as the investor determined, through a visual inspection of the terrain, that there have been changes that indicate the possibility of underground fire. The most pronounced changes were the subsidence of the terrain, the thermal degradation and colour change of the layers of the sealing cover and the occasional appearance of smoke and steam. The area of potential subsurface fire is shown in Fig. (3) with visible settling area and additionally placed gravel cover in order to prevent air intrusion below geomembrane.

Investigation with an aim to verify the existence of subsurface fire was initiated in January 2013. During this assessment visual inspection and IRT imaging was performed. In May 2013 second field assessment was performed and included visual inspection and thermal imaging from the same locations as in January. IRT imaging was made from 4 positions (positions 1, 2, 3 and 4 in Fig. (2)). Positions 1, 2 and 3 were on the ground and position 4 was at approximately 20 m above the ground from working platform of the fire truck. Thermal imaging was performed using handheld long wavelength (LW) infrared (IR) camera Flir ThermaCam P640 with image resolution 640×480 pixels, camera lens 24°, temperature sensitivity 60 mK and temperature operating range from -40°C to 1500°C.

To have a more accurate location of the underground fire along the vertical axis, as well as temperature distribution inside the body of the waste in February 2014 temperature measurements were made. Four boreholes were drilled up to 9 m in depth by geotechnical drilling equipment and were approximately 131 mm in diameter (B1 – B4 in Figs. (2) and (3)). Material from each borehole was sampled and its composition was evaluated (Fig. (4)). After each removal of the drilling rig, thermocouples were lowered to the bottom of the hole. Temperature in the hole was measured using type K thermocouples connected to a data logger Ahlborn Almemo 2890-9. Temperature reading was recorded when it was determined that stable temperature is achieved. To ensure that thermocouples will reach the bottom they were attached to a weight (Fig. (5)). During the measurement thermocouples were 5 - 10 cm above the bottom, so the measured temperature represents the gas temperature. Surface temperature was measured directly below GCL membrane using Rotronic Hygropalm with Pt100 insertion probe AC1902 (Fig. (5)). The originally intended measurements of temperatures at equidistant depths (every 1 m) were not possible due to the inhomogeneity of the waste and the resulting different drilling speeds, as well as technical limitations regarding the heating of the drilling rig. Namely, the drilling process was performed without cooling with water, so that the measured temperatures would not be affected by evaporation effects.

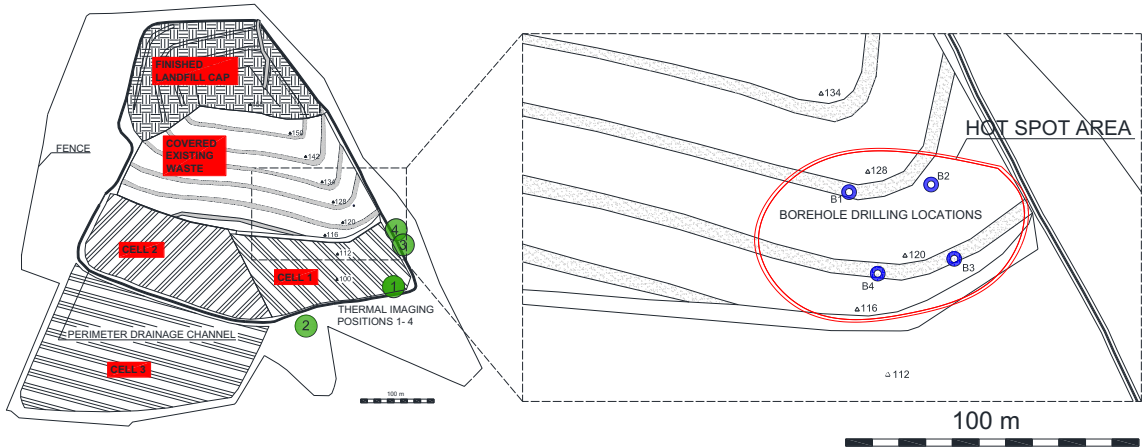


Fig. 2. Ground plan of inspected landfill with locations of thermal imaging positions (green circles, positions 1-4) and borehole locations B1 – B4 within the area of possible underground fire

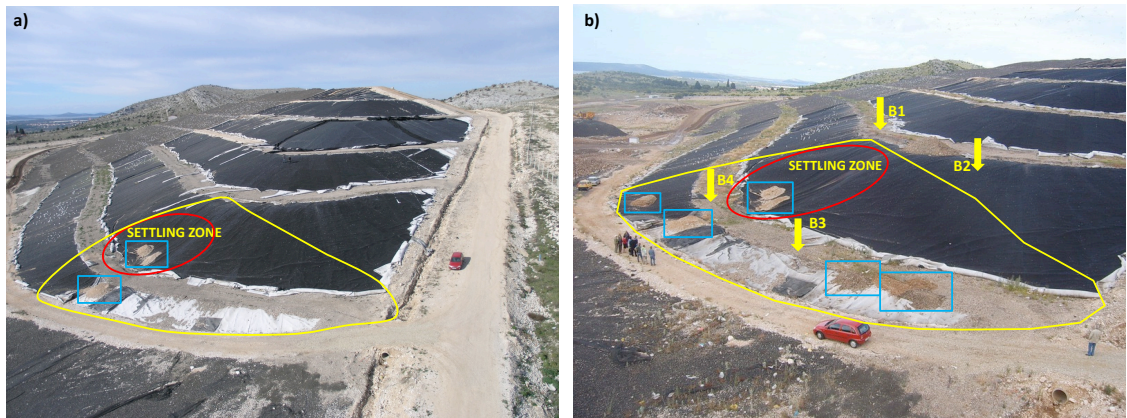


Fig. 3. Photo of the landfill with estimated area of subsurface fire based on IRT (yellow line), settling area (red line) gravel cover (blue rectangles) and positions of boreholes a) photo taken from position 4 from fire truck working platform in January 2013; b) photo taken from position 4 from fire truck working platform in May 2013)



Fig. 4. Borehole B1: a) drilling of borehole; b) extracted material up to a depth of 6 m

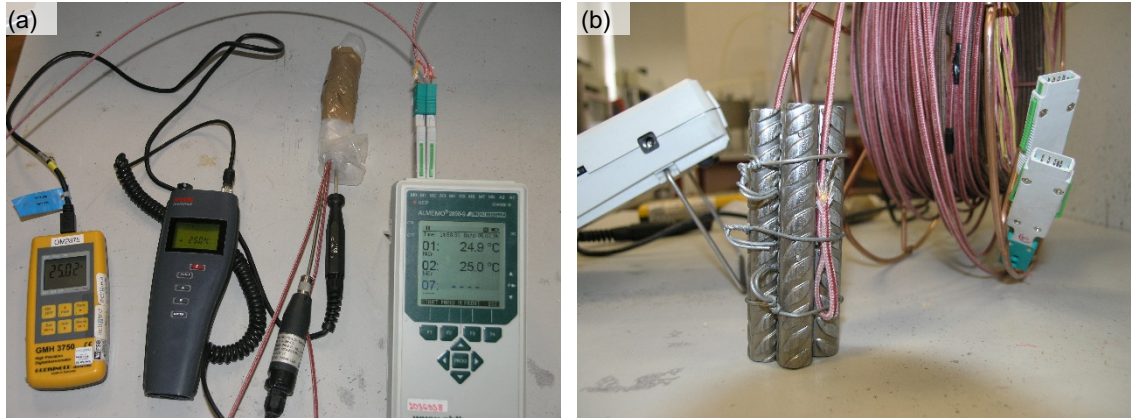


Fig. 5. Temperature measuring instruments: a) checking measurement accuracy Albhorn Almemo and Rotronic measuring systems; b) close-up of type K thermocouples attached to a weight mad of reinforcement bars

3. Results and discussion

3.1. Thermal imaging

First survey which included IRT imaging was conducted on January 29th between noon and 2 PM on a sunny day with partly cloudy sky and almost no wind. Air temperature and wind speed data were not measured on site. As reported by Croatian Metrological and Hydrological Service (CMHS) on the day of survey at the area of the city of Šibenik air temperature was 12-13°C, relative humidity of air 34-43% and wind speed 1-3 m/s.

Qualitative interpretation of temperatures represented by thermal images is made and this served to quantify the landfill surface area of increased temperature. Although quantitative interpretation of temperatures is not of primary interest for the presented case study, some consideration of important effects that impact temperature distribution on thermographic images is necessary. Radiant power or radiant flux Φ_{det} in W/m² captured by camera within its operating range of wavelengths can be written [19]:

$$\Phi_{det} = \tau_{atm} \varepsilon \sigma T_{ob}^4 + \tau_{atm} (1 - \varepsilon) \sigma T_{refl}^4 + (1 - \tau_{atm}) \sigma T_{atm}^4 \quad (1)$$

where T_{ob} , T_{refl} and T_{atm} are temperatures in Kelvin of the surface of an object, reflected temperature and atmosphere temperature respectively, τ_{atm} is atmospheric transmittance, ε is surface emissivity and σ is Stefan-Boltzman constant ($\sim 5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$). From Eq. (1) T_{ob} is calculated and represented on IR thermal image. All IR images presented in this paper throughout a survey have the same values set for τ_{atm} , ε , T_{refl} and T_{atm} .

Inspected area of the landfill had its slopes covered by black surface textured HDPE geomembrane which act as virtually almost perfect absorber of radiation ($\varepsilon \approx 1$) [20]. During visual assessment it was noticed that geomembrane was contaminated by fine soil particles that could have been carried by wind and by landfill operational activities. Soil contamination could affect emissivity of the area covered with HDPE geomembrane. Access plateaus separating slopes consist mostly of compacted crushed aggregate with wide range of particle sizes mixed with soil (Fig. (3)). These plateaus are partially covered with low vegetation which is mostly grass. In the region where the landfill is located mostly limestone aggregate is available. For limestone aggregate emissivity between 0.95-0.98 was measured [21]. For light dry soils and for dark wet soils emissivity of 0.90 and 0.98 was reported respectively [22] while emissivity of green grass was found to be in the range 0.96-0.98 [23]. Part of the surface is overlaid with white coloured nonwoven geotextile liner (Figs. (3) and (4)). Nonwoven geotextiles are made with polypropylene or polyester fabric which have surface emissivity in the range 0.78-0.88 [24, 25]. The higher the surface emissivity in the 8-14 μm band of wavelengths reduces the amount of reflected radiation which is represented by the second term on the right side of Eq. (1) and consequently reduces error in surface temperature evaluation due incorrect estimation of T_{refl} . In all IR images presented ε was set to 0.95 so it is expected that largest error in estimated surface temperature due to different emissivity will be in the area of geotextile liner.

In Fig. (6) visual images and IR images taken from positions 1 - 4 are presented. From all four positions area of maximum temperatures correspond well with the area of largest settlement within the landfill. By moving away from the settled area temperature gradually decreases which would indicate that the centre of a fire is below the settled area and generated heat is transferred to the surrounding waste by heat conduction. One should not exclude the impact of the distance of the landfill surface from the IR camera. Since landfill is inclined these distances differ throughout the IR Image. The longer distance decreases τ_{atm} leading to the lower temperature at IR image, however, it is not expected that this contribution would be more than 2-3°C throughout the image which can be estimated by using Eq. (1). This effect can explain why in Fig. (6d) dispersion of temperatures outside the hot spot is lowest. In Fig. (6d) distances from the IR camera to the landfill are within a smaller range compared to other imaging positions. Temperatures evaluated at several points along a horizontal line of the same slope outside the hot spot vary only by 1.3°C. Therefore, this image is most representative to evaluate temperature difference between the hot-spot area and surrounding landfill.

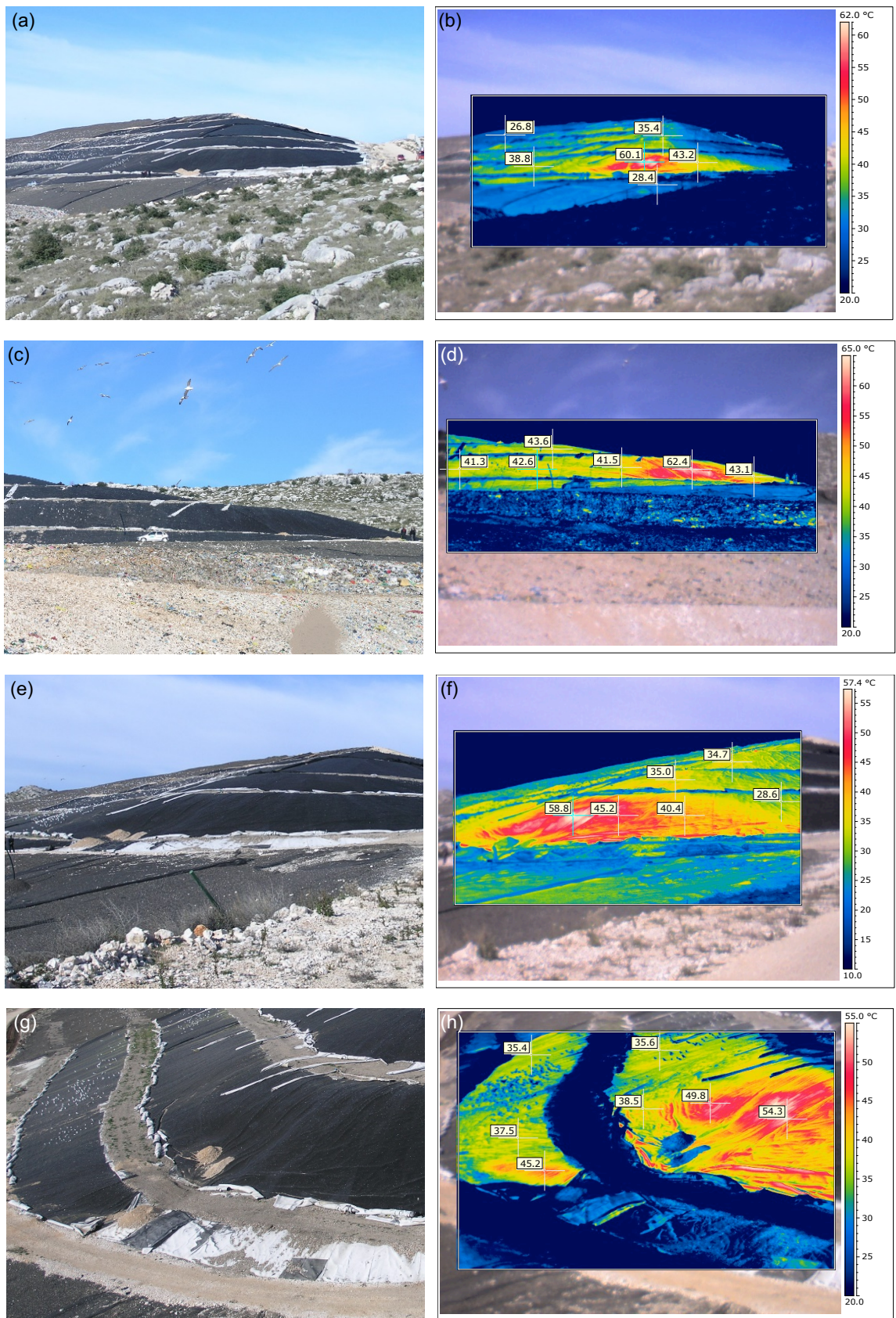


Fig. 6. Visual images and IR images taken during the first survey in January from position 1 (a, b), position 2 (c, d), position 3 (e, f) and position 4 (g, h)

HDPE geomembrane shows higher temperature than other surface materials. After placement in landfill MSW is self-heated due to biological decomposition first aerobically and when the oxygen is consumed anaerobically [3, 10]. Aerobic decomposition has approximately 20 times higher quantity of heat release compared to anaerobic decomposition [26]. This can result in temperature increase up to 60 - 70°C depending on the rate of decomposition and heat retention properties of the compacted waste [10, 27, 28]. Maximum waste temperatures reported in literature vary from approximately 40 – 65°C for total waste heights of 20 – 60 m [12] while in loosely compacted and dry landfills temperatures return to the 21 – 43°C range [10]. These processes of heat release and temperature increase can go on for more than a decade [12].

As shown in Fig. (1) HDPE geomembrane is placed on GCL liner serving as gas barrier and gas drainage layer consisting of coarse crushed aggregates. This enables easier flow of gases generated by decomposition of waste close to the landfill surfaces and consequently increases the influence of the heat transfer by convection on the overall near surface temperature distribution. Simultaneously, HDPE can absorb more of solar radiation than other surface materials present on the landfill. Pelte et al. tested absorption of HDPE in the range of wavelengths corresponding to solar radiation and determined that almost all of the radiation is absorbed [20]. Therefore, during the sunny day, as was at the day of first survey, HDPE is heated from above and from below more than other parts of the landfill.

The layer of compacted crushed aggregate on access plateaus is 15 - 40 cm thick which was determined by drilling and it is placed on top of HDPE geomembrane and geotextile liner. This layer acts as thermal insulation so the temperature on its upper surface are lower compared to HDPE geomembrane. Besides, the insulating properties of the aggregates even out the temperatures on the surface, so the differences due to the higher locally generated heat from the waste are less noticeable.

In Fig. (6g) there is a bottom slope covered with geotextile liner placed above HDPE geomembrane. Thermal image (Fig. (6h)) shows that this area also has significantly lower temperature than slopes covered with HDPE. Geotextile acts as a thermal insulation so its surface temperature is lower than that of HDPE. Another effect leading to different temperatures of geotextile and geomembrane could be related to the higher albedo of geotextile and consequently less absorbed solar radiation. Senese et al. determined that nonwoven geotextile can reflect up to the 60% of solar radiation [29]. The IR images also contains a contribution to the temperature distribution caused by the assumption that the emissivity of geotextiles and geomembranes are equal. Since geotextile has lower emissivity than 0.95 in IR image its temperature will appear as apparently lower than its actual surface temperature. This can be easily verified using Eq. (1).

The distribution of the surface temperatures of the soil and the associated sealing cover in the IR images indicated with great certainty the existence of an underground fire. Increased temperatures up to 20°C in the area of large settlement point to the local heat generation source. However, it was not possible to determine the depth of the fire or assess its intensity using the thermographic method. Based on the temperature distributions presented on IR images and considering uncertainties related to the different type of sealing cover, area potentially affected by subsurface fire was estimated and it is shown in Fig. (3a)

During the second survey IR imaging was conducted shortly after the rain and with a moderate wind. Measured air temperature was 16°C. Both air temperature and wind speed were measured close to the surface. Comparison of landfill temperature distribution on IR images shows that temperatures during the second survey were much lower than during the first survey which was attributed to the evaporative cooling accelerated by the wind.

In relation to the first IR survey of the terrain carried out in January 2013, in the period until the repeated survey in May 2013, there was additional filling of aggregate material by the Investor (Gradska čistoća d.o.o., Šibenik), with the aim of closing the damage to the geotextiles due to an underground fire (Fig. (3b)). However, this did not significantly change the thermographic picture of the soil, as well as the coverage and zone of the underground fire.

3.2. Temperature measurements

Measured temperatures within boreholes B1-B4 are presented in Fig. (7). Temperature measurements in boreholes B1 and B2 were carried out to a depth of 8.5 m and in boreholes B3 and B4 to a depth of 6,0 and 6,2 m respectively. In boreholes B3 and B4 drilling was stopped at these depths because compact rock base was reached. The highest temperature of approximately 100°C was measured in borehole B1 and was measured at depths of 4 m and 6 m. From these depths, mostly stone material was extracted by drilling, with no visible municipal waste. Given that the waste in the observed period had a high moisture content, most of the released power of the fire was used to evaporate water. As long as water (moisture) was present in the waste, there could be no increase in the temperature of the waste above the boiling point of water (100°C). However, the very process of water evaporation indicates a constant source of heat with an elevated temperature, which is characteristic of an underground fire.

The highest temperature in borehole B2 was measured at a depth of 7.3 m and is 76°C. At that depth, municipal waste mixed with soil and smaller stone fractions was extracted by drilling. In borehole B3, the highest measured temperature is 45°C, and the extracted material shows that it is mainly stone material with very little municipal waste. The highest temperature in well B4 was measured at a depth of 4.2 m and is 76°C. On the basis of the material extracted by drilling, it is evident that municipal waste with increased depth turns into predominantly stone material.

The analysis of the results of in-depth temperature measurements shows that boreholes B2 and B4 are most likely located in the peripheral area of the underground fire. Dominant direction of the underground fire passes through wells B1 and B3, with the centre of the fire located closer to the axis of borehole B1.

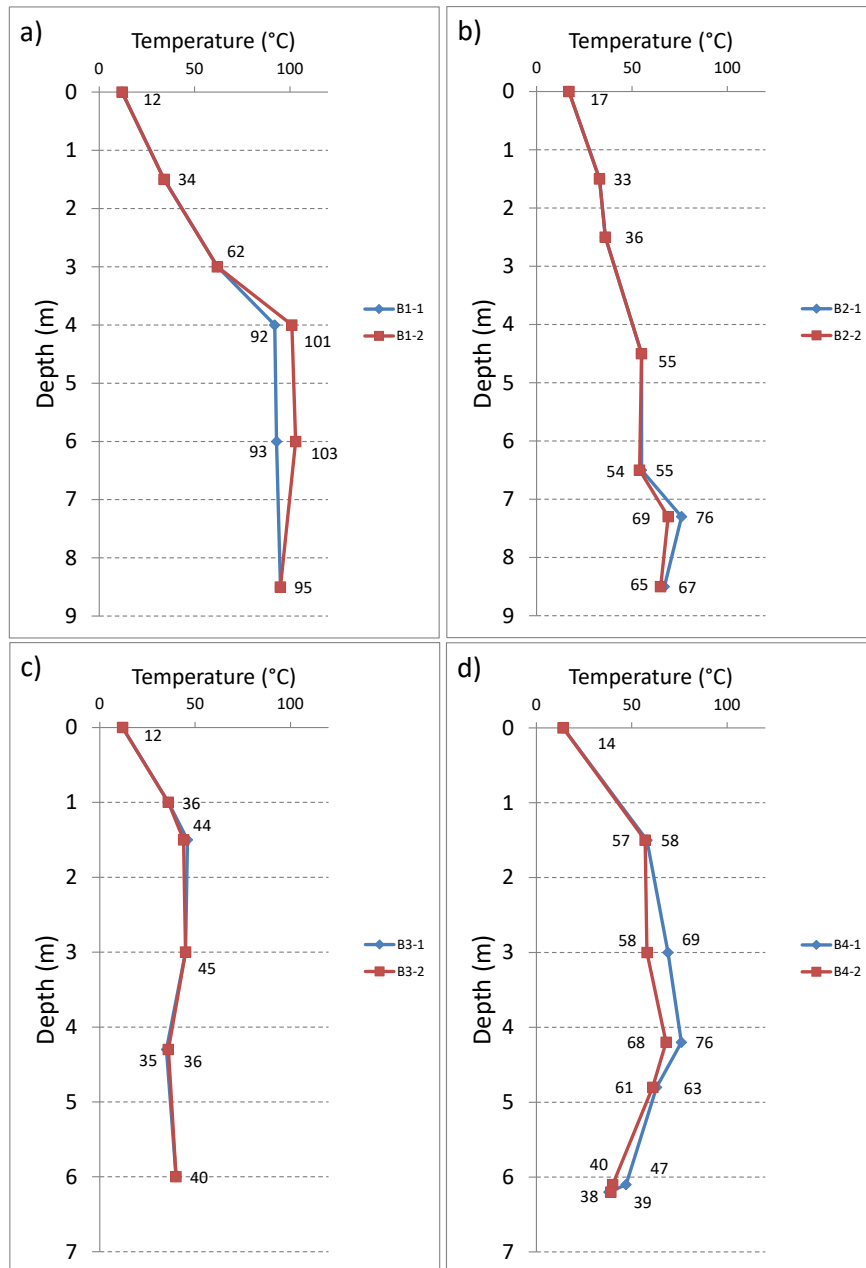


Fig. 7. Temperature profiles at location of boreholes: a) B1; b) B2; c) B3 and d) B4

4. Conclusion

Based on several assessments of the landfill which included visual inspection, IRT imaging and measurement of vertical temperature distribution in the body of waste it is confirmed that there is a deep-seated fire at the south-eastern part of the landfill. It can be classified as a deep smouldering fire, which exists for a long time with a centre estimated at a depth of 4 to 6 m. According to the analysis of IR images it is estimated that the orthogonally projected surface area caught by fire is around 4000 m².

Inspection of landfills for determination of hot spots by IRT requires analysis of information about landfill design and waste composition and careful consideration of different parameters that affect thermal image temperature distribution to avoid misleading conclusions. In the presented case different cover layers placed at the top of the landfill surface made estimation of the area of increased temperatures more challenging.

However, it has been shown that IRT can be effective in detecting variations in the subsurface temperatures within a MSW landfill and the resulting thermograms can then be used as a tool to designate regions of interest for additional ground-based investigation or remedial action.

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