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HERITAGE OF WAR: ANALYSIS OF BOMB CRATERS USING LIDAR (KĘDZIERZYN-KOŹLE, POLAND)

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Abstract

One of the biggest areas in Europe with relief transformed as a result of area bombardment carried out in the 1940s is located near Kędzierzyn-Koźle. Most craters can be observed on orthophotomaps and shaded relief rasters. In land subject to intense economic activity, the bomb craters were backfilled as early as in the 1940s and 50s, however, they have been preserved in forest and swampy areas. Owing to the analysis of digital elevation models and shaded relief rasters, it was found that a 5.9-hectare detailed research site included 282 bomb craters of various types, giving an average of 48 craters per ha. However, there are crater concentrations containing almost 75 items/ha. The article presents the morphometric parameters of craters and the reconstruction of their emergence and transformation processes, which are stored in landform morphology. The usefulness and accuracy of digital elevation models and shaded relief rasters was tested for different resolutions in the analyses of craters occurring in a variety of environmental conditions. It was also suggested that this area should be protected as a terrain for interdisciplinary research into the effects of intensive WWII activities. It is significant owing to its historical value, as well as the contemporary spatial economy.

***Keywords**: Bomb craters; Bomb crater ponds; LiDAR/ALS; WWII heritage*

Introduction

Warfare has long-established surface impacts, and the geomorphological legacies of the Second World War are still present in many European landscapes [1, 2]. Huge numbers of bomb craters were created by large-scale aerial bombardment. Studies of landscapes remodelled by explosions of ground-launched or aerial bombs have largely focused on the battlefields of Europe [3-5]. There are a few papers that present studies of the geomorphological traces of past conflicts [6-9]. In Poland, there are few publications that deal with the issue of war relics recorded in the relief [10, 11], but air raid craters in the Koźle Basin have been discussed by J.M. Waga and M. Fajer [12] and by Waga et al. [13].

In the last twenty years, much attention has been paid to the analysis of LiDAR scanning images and the application of other detection methods when studying the archaeology and geomorphology of battlefields [14], in particular, those covered by medium and high vegetation. These methods provide great research potential [15-18].

In the area of Kędzierzyn-Koźle specific transformations of relief are connected with military activities. Both for historical and contemporary land use reasons, special attention should be paid to the numerous remains surviving from bomb explosions from WWII.

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In 1944, during area bombing of that location, the United States Army Air Force (USAAF) dropped the following:

– demolition bombs – (RDX) 500-pound (227kg) and 250-pound (113kg),
– general-purpose bombs (GP) – 500-pound and 250-pound and
– incendiary bombs – 250-pound and 70-pound.

The aim of the research presented in this article was to determine the quality characteristics (number and morphometry), spatial distribution and layout of bomb craters located near the former IG Farbenindustrie AG Heydebreck plant (at present ZAK Kędzierzyn), which lies within a former military area, and to attempt to recognise the geomorphic processes that modified the craters. The results will later permit an analysis of the geotechnical changes in the soil caused by explosions in the zones where there are concentrations of craters and to analyse the degree of threat to the area arising from the presence of unexploded bombs (UXBs). A methodological goal, which is often present when working with modern research tools, was to test the usefulness of digital elevation models (DEMs) with 1 x 1m, 0.1 x 0.1m and 0.05 x 0.05m resolution and the relevant shaded relief rasters for detailed research into the morphology and morphogenesis of these forms.

Today it should be emphasised that the survival of numerous WWII bomb craters in the Kędzierzyn-Koźle area is an unusual phenomenon in Europe. Their remains, located in forests as well as open and semi-open wetlands, document the extreme war effort of the sides in the conflict and give an idea of the immense cost of conducting wars. The application of laser scanning (ALS) in the study of similar war remains facilitates the management of war heritage, including the landscape of the conflict as a whole and as a witness to war [18] and its elements, for example bomb craters, as part of this heritage [19].

In the economic context, bomb craters are an undesirable spatial element which complicates urban planning and management. They, also a create difficult areas for investment owing to the presence of unexploded bombs. According to post-war estimates, 10–15% of bombs that were dropped did not detonate as planned [20, 21]. However, for historical and environmental reasons the areas occupied by craters are an excellent field for scientific research. For that reason, the complex of forms in the area around Kędzierzyn-Koźle Azoty certainly provide one of the most valuable such areas in Europe as far as their research potential is concerned. The results of such research make it possible to develop strategies for, inter alia, their remediation, use or protection as natural or educational sites [2, 22, 23]. A selection of war relics from the past should be protected in Poland, like in other Western European countries. This need not necessarily require considerable outlay, like on the battlefields of Verdun, in Normandy or in the Ardennes, but it should at least take the form of passive protection of the heritage. In the authors' opinion, considering the exceptional assemblage of remains of the impact of bombing on former infrastructure and the functioning of the contemporary natural environment, the study area is eligible for protection as a form of nature and landscape complex as provided for under Polish law.

Location and characteristics of the study area

The study area is located in southern Poland, within Racibórz Basin, also known as Koźle Basin [24, 25]. Detailed research was conducted on 5.9ha located at the western boundary of the former IG Farbenindustrie, Kędzierzyn – Racibórz railway route and Bierawa cargo-passenger station (Fig. 1). At present, it is covered by broad-leaved tree species. The area lies in the Odra valley, near to the mouth of the River Kłodnica, within an extensive alluvial fan adjacent to the Vistulian terrace [26]. Both forms are composed of sandy sediments containing fine gravels of up to 15mm in diameter and, in some layers, a dust fraction. The surface is covered by aeolian sands whose thickness in the study area does not exceed 1m. In land depressions in the form of trough-shaped valleys transformed by water erosion and deflation from shallow braided riverbeds, there are organic sediments of up to 1.0m in thickness [12].

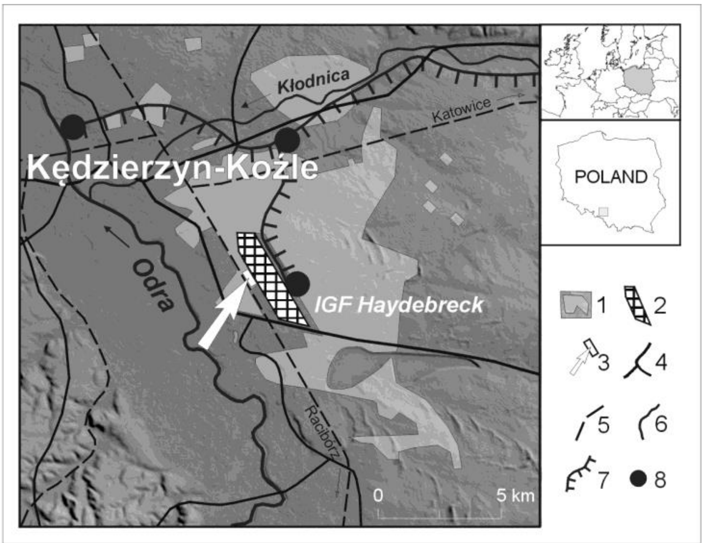

Fig. 1. Location of study area: 1 – zones with bomb craters surviving from World War II, 2 – former IG Farbenindustrie Haydebreck site, 3 – area of detailed research, 4 – roads, 5 – railway track, 6 – river, 7 – canal, 8 – port

The presence of a sandy bed, organic sediments and water conditions resulted in the development of podzols in the study area, and in lower locations also peat and muddy peat soils [27]. The soils have a low agricultural and production value, which is why the area ends up being used as forest [28]. The northern and western part of the land is very waterlogged. The groundwater level in that area is located at a depth ranging from 0 to 2.5m and its excess is transported through field drains into the Odra River.

With its poor atmospheric circulation, the Koźle Basin is often affected by thermal inversions and stagnation of air masses. However, owing to its north-west facing aspect, it is relatively quickly ventilated in windy weather due to the prevailing westerly winds. During WWII these features were used to the advantage of the German army which laid anti-aircraft smoke screens.

Circumstances of the emergence of bomb craters around Kędzierzyn-Koźle

During WWII Germany faced a scarcity of oil resources and was forced to establish the production of substitute synthetic liquid fuels, oils and lubricants. The biggest fuel production complex in Nazi Germany was established near Kędzierzyn [29]. The Germans developed existing systems for hydrocarbon synthesis based on coal via the Fischer-Tropsch method in Odertal (Zdzieszowice) and constructed large plants in Blechhammer (Blachownia Śląska) and Heydebreck (Kędzierzyn) which used the Bergius process (production of liquid hydrocarbons for use as synthetic fuel by hydrogenation of bituminous coal at high temperature and pressure). They intended to produce 730 000 tons of fuels a year. Owing to technical problems and the consequences of bombing conducted by the USAAF, this level was never attained [29, 30].

Intense bombing of plants located in the Koźle Basin was conducted by American B17 and B24 bombers which dropped nearly 40 thousand individual bombs [12, 30]. Due to a very active anti-aircraft artillery defence, bombs were dropped from high altitudes between 6 700 and 8 900m. In addition, the targets were covered with extensive smoke screens which had a very great impact on the accuracy of hits and dispersion of bomb drop points. Heavy bombing of fuel plants in the area of Kędzierzyn started on 7 July 1944 and finished on 26 December 1944. It included 16 raids, 13 of which involved the chemical plant in Kędzierzyn itself [30]. A description of the bomb drops on the IG Farbenindustrie Heydebreck plant is presented in Table 1.

Materials and methods

In the first stage of research an online shaded relief map was examined (based on Lidar data from 2012) [31]. Then high-resolution *.las data were examined. These derived from airborne laser scanning (ALS) at a density of 12 pt/m^2 and mean vertical accuracy of 0.1m obtained from a survey dated 9 April 2019 using a Leica ALS70 scanner [32]. All data were created in the EPSG:2180 coordinate system. Class 2 points (ground) from the first and second return were selected from the *.las files and used to develop digital elevation models of 0.1 x 0.1m and 0.05 x 0.05m resolution. Global Mapper [33] software with default settings was used to create the digital elevation models. One applied the 'binning' method, which is a data processing technique that takes point data and creates a grid of polygons, while an inverse weighted distance algorithm is used to fill in the gaps. These models were then employed to create shaded relief rasters of the same resolution with standard lighting configuration (azimuth 315°, altitude 45°). Materials prepared in the above manner constituted the basis to perform detailed analyses of the crater distribution and morphology. The surface relief was analysed in detail and on this basis the location and condition of bomb craters was determined and the crater density, diameter and depth were calculated. In Poland, specialist bathymetric scanners are not applied in small water bodies of a non-economic character. Due to the lack of access to such specialised data, we did not use LiDAR for bathymetric applications in our research. Therefore, there was an attempt to employ Class 2 points (ground) and Class 9 points (water), that is points representing areas beneath the water, in the analyses of ponds located in the craters. A more efficient application, namely 'creating a longitudinal profile on the basis of DEM' in the geoportal [30], based on a 1 x 1m resolution model, was used to determine the depth of craters. It is a fast and effective tool for preliminary analysis of the depth and shape of the bomb craters. In the next step, all of the bomb craters distinguished were manually digitised. The Kernel Density tool with standard settings and ArcGIS [34] software was applied to calculate the density of craters in the research area. Remote research methods were used in most situations. The reference forms were located in the area with a GPS Map 62ST and they were subsequently measured with a Nikon Forestry Pro II laser rangefinder, and the depth of ponds in bomb craters with a surveying rod. The diameter of the craters and their present apparent depth were measured (morphometric parameters after P.W. Cooper [35].

Geological conditions were identified in excavations and shallow sampling performed with a hand-auger. Surface ground and soil conditions were examined with a 1-metre sampling stick. Moreover, to correctly recognise the environmental conditions (mainly the geological structure, soil and water conditions), the content of specialised 1:50,000 maps on geological, sozological (environmental conditions) and hydrographical conditions, as well as a soil map from the Opole Spatial Information System [27] and information from the geological database [36] were also reviewed.

To determine the dates of air raids, the type and tonnage of bombs and the type of fuses used, drop heights, bombing directions and the effects of the bombing, the following resources were analysed: archival mission reports, operations reports, unpublished documents for the period 4th July to the 26th December 1944 and publications found on the Air Force Historical Research Agency website (https://www.afhra.af.mil), National Archives (https://www.archives.gov) and those of The Fifteenth Air Force (https://15thaf.org), as well as scientific literature on the allied air offensive against the Third Reich and the websites of associations documenting warfare in Silesia and its material remnants, including, most of all, those of the 'BLECHHAMMER – 1944' association.

Effects of bombing recorded in land morphology – the study material and its analysis

In the Kędzierzyn-Koźle area, thick forest cover and open wetlands ensured the survival of a complex of craters created by aerial bombing (the largest in Poland and one of the largest in Europe). In total 17 688 bombs with a total weight of 3 995.25t were dropped on the IG

Farbenindustrie plant and its neighbourhood. Apart from incendiary bombs, 17 369 cratering bombs, i.e., demolition and general-purpose bombs, were used there (Table 1).

Table 1. Intensity of 15th USAF air raids on fuel plants IG Farbenindustrie AG Heydebreck. (Source: Waga and Fajer [12], compiled on the basis of data from the work by Konieczny [30]).

Air raid date	Number of aircraft	Bomb tonnage	Number of bombs
7.07.1944	162	479.75	1 600 (B500)
			319 (Z500)
7.08.1944	266	622.75	1 173 (O500)
			2 344 (O250)
			146 (B500)
			404 (Z500)***
22.08.1944	100	237.25	949 (B500)
27.08.1944	119	297.0*	1 310 (B500)*
		(200-250)**	(800-1 000)**
13.10.1944	271	670	2 980 (B500)*
17.10.1944	117	289.75	1 079 (B500)
17.11.1944	115	199	796 (B500)
20.11.1944	171	314	1 019 (B500)
			476 (O250)
2.12.1944	154	279.75	1 119 (B500)
12.12.1944	51	98.5	394 (B500)
17.12.1944	87	172.25	689 (B500)
19.12.1944	42	61.5	200 (B500)
26.12.1944	121	273.75	1 095 (B500)
Total	1 776	3 995.25	13 376 (B500)
			1 173 (O500)
			2 820 (O250)
			319 (Z500)
			17 688

Note. * Estimated number and tonnage of bombs per aircraft during raids in the period described
** Number and tonnage of bombs as estimated by the German Armaments Inspectorate
*** Estimated number of bombs after deducting the tonnage of demolition and general-purpose bombs
(B) = demolition bombs (RDX) – B500-500lbs
(Z) = incendiary bombs – Z500-500lbs
(O) = general-purpose bombs (GP) – O500-500lbs, O250-250lbs

As a result of efficient smoke screens laid over the plant in Kędzierzyn, heavy shelling by anti-aircraft batteries, and the high altitudes of the drops, many bombs missed their targets: chemical installations, an on-site power plant, roads, bridges, rail infrastructure, and military facilities. Some bombs exploded in neighbouring forests, fields, and villages. Moreover, the wartime German administration recorded those cases where bombs fell but did not explode [30]. In the 1940s and 1950s, remnants of the bombing were removed in industrial and settlement areas, as well as on communication routes, while craters in fields and grasslands were backfilled. Only craters in forests and waste land remained.

The study area is the area most densely pitted by airborne ammunition in all the Koźle Basin. There are large explosion craters created by 500-pound bombs, ranging from 8 to 14m in current diameter and up to 3.0m deep, and smaller ones – mainly produced by 250-pound bombs, with diameters amounting to 5–9m and depths of up to 1.5m. There are also small hollows, which imply the existence of undetonated bombs.

Craters in orthophotomaps and shaded relief rasters from ALS are perceived as pockmarked structures. A total of 282 craters were identified in the area using shaded relief rasters with a resolution of 1 x 1m, 0.1 x 0.1m, and 0.05 x 0.05m. The number, however, does not fully reflect the actual number of bombs that detonated. There must have been more, but not all craters survived. This results from the high density of payload drop sites, explosion sites that overlap, and subsequent remediation and natural activity. Some crater relics are barely noticeable in the field. They are partly or entirely filled with mineral or organic content, construction debris, and other waste. We find out about their existence from minor forms appearing at ground level or the vegetation change that covers them. According to the analyses conducted, the average density of craters in the study area is 47.8/ha, but it reaches the rate of 75/ha in clusters (Fig. 2). The IG Farbenindustrie Heydebreck plant was bombed repeatedly, so the fall fields from different missions overlap.

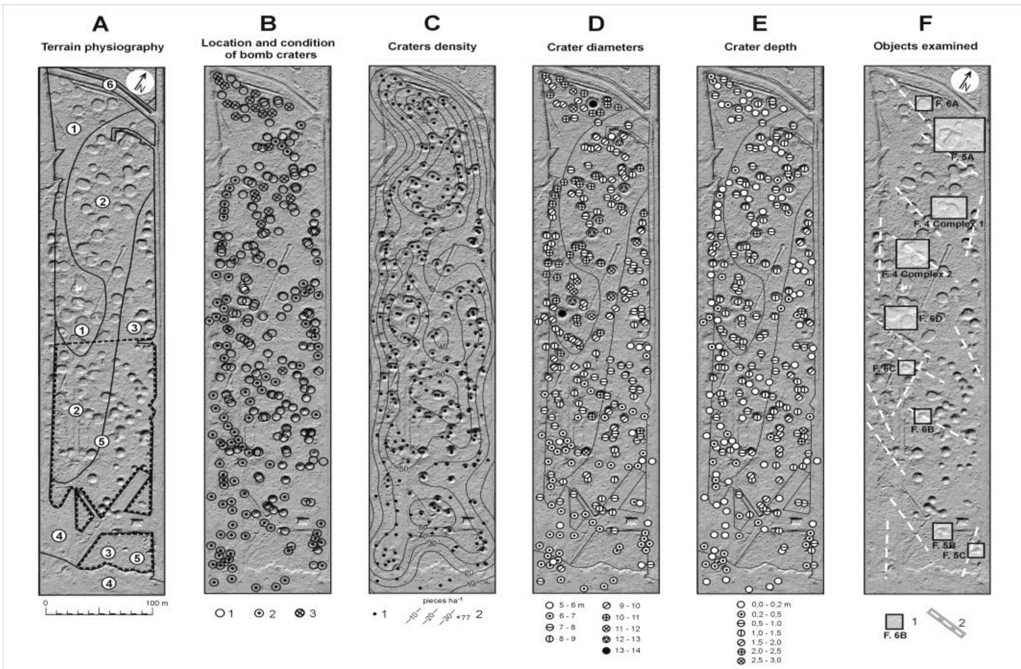

Fig. 2. Area of detailed research

A – terrain physiography: 1 – marshy area at the bottom of the trough-like valley, 2 – area where shallow groundwater occurs in the lower parts of the trough-like valley, 3 – area with deeper occurrence of groundwater in higher parts of the valley slope, 4 – embankments, dykes, flat areas, 5 – areas intended for use, 6 – drainage ditches, B – location and condition of bomb craters: 1 – craters with a clear morphology, 2 – craters buried by human activity, 3 – craters filled with material from an adjacent explosion and as a result of natural processes, C – crater density: 1 – bomb hits, 2 – hit density scale (x77 the point with the highest density index), D – crater diameters, E – crater depth, F – objects examined in detail (1), raid axes (2)

There are also cases when bombs hit the contour of former craters or even their very centre. Both situations make it difficult to identify the impact of particular raids. However, an attempt to determine the relative age of certain craters can be made. For example, it may be observed that some small-diameter craters in the study area are to a large extent filled with soil content ejected from craters during later raids. (Fig. 3). Moreover, one may attempt to recreate more complex sequences of explosions that took place in adjacent craters. However, it is only effective in water-filled landforms, as water played a significant role in their development. The course of events was recorded in the layout of sedimentary structures located within the bottoms of ponds (Fig. 4). This, apart from the accounts of bombing raids on the IG Farbenindustrie AG Werk Heydebreck given by eyewitnesses [29], provided general information about the course of bomb explosions and the subsequent processes within the near-surface soil layers. Furthermore, the analysis of the distribution of craters made it possible to determine estimates of the axes of raids on the IG Farbenindustrie Heydebreck plant (Fig. 2F). These were axes of azimuths close to 5°, 15°, 30°, 55°, 60°, 70°, 80°, and 90°.

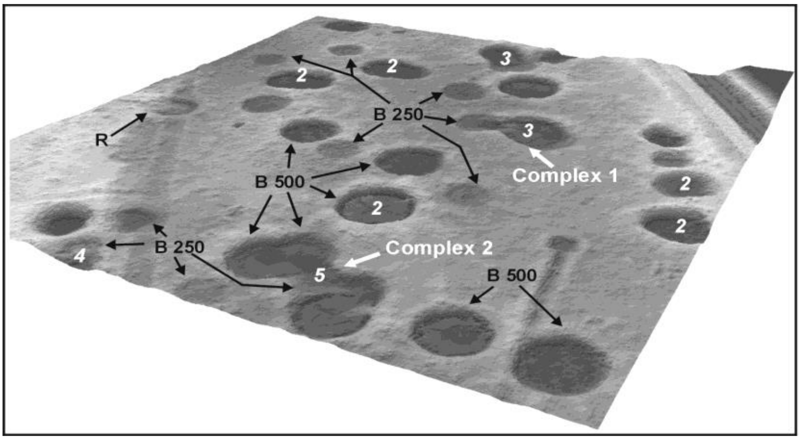

Fig. 3. Coloured shaded relief raster of a fragment of the research area: Complex 1, Complex 2 – features examined in detail, ~~red~~ numbers – number of bomb hits in crater sets, black arrows indicate older craters after 250-pound bomb explosions, the remaining craters are after 500-pound bombs, R – crater subject to partial reclamation.

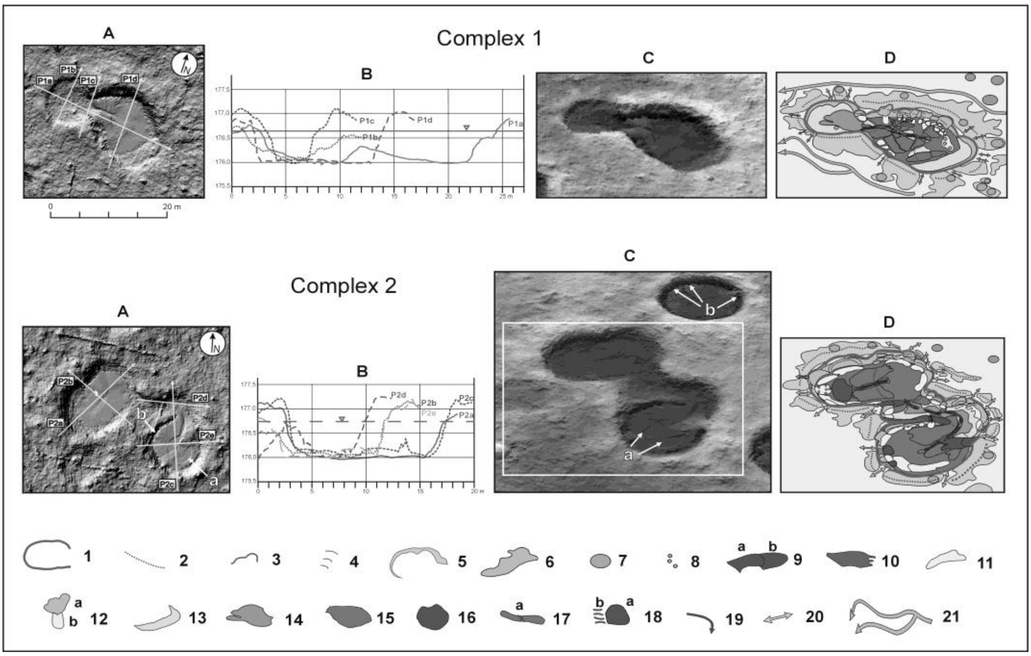

Fig. 4. Objects of detailed research – Complex 1 and Complex 2. A – orthogonal models with profile lines, a) "shadow" of a floating island made of leaves, b) "phantom depressions" at the edges of craters; B – profiles; C – oblique models; in complex 2, a and b as in orthogonal models A; D – geomorphological sketches: 1 – outlines of the edges of the craters, 2 – ridge line, 3 – edges of landslide niches, 4 – thresholds within the landslides and edges of bank cuts, 5 – crater slopes, 6 – fragment of rim surrounding the crater, 7 – packets of thrown material from the crater, 8 – packets of residuum at the bottom of the crater, 9 – embankment separating crater: (a) bar periodically protruding above the water, (b) underwater bar, 10 – accumulation platform on the outer side of the underwater embankment, 11 – underwater cone – delta, 12 – landslides: a – landslide niches, b – landslide tongues (colluviums), 13 – bottom terrace (step) – bottom of an older crater, 14 – a niche in the removed material or a cavity washed out in the bottom of an older crater, 15 – bottom of a younger crater, 16 – the deepest part of the youngest crater, 17 – inlet channel with a transverse sill within it (a), 18 – zooturbations: trough trodden in the bottom (a) and gutters – "slides" on the edge of the pond (b) made by deer at the wading site – bathing, 19 – route of intensive water and suspension flow within the cut bed of the form, 20 – erosion of the embankments on the periphery of the crater caused by the ejection of water and liquefied soil by an explosion and the return of part of the fluid medium, 21 – the course of the external water drainage channels

Four zones of different physiography were established in the study area: 1 – a strongly saturated area at the bottom of a trough-shaped valley, 2 – an area with shallow groundwater, covering a gently inclined bottom part of the valley, 3 – an area with a lower groundwater table on higher parts of the slope and the inter-valley divide, 4 – an area covered by banks of various thicknesses, made up of debris and exhausted ballast from subgrades or soil.

The first three zones had been relatively lightly transformed by human activity, while the fourth one is mainly embankments. Under the supervision of the German war administration, the railway embankment running along the southwestern edge of the study area and the southern section of the subject area were reclaimed several times. Some craters adjacent to the tracks near IG Farbenindustrie Heydebreck were converted into shelters and trenches serving inter alia as, (according to the oral testimony of witnesses), transit storage dugouts where unexploded ordnance was first brought to be later taken away as recycling materials. The Russian troops also used them after pushing back the frontline. Over a certain period, such functions may have been performed by a bomb shelter located in the northern part of the area (Fig. 5).

In the first zone covered by the study, organic silt soils at the bottom of a trough-shaped valley reach a thickness of 0.3–0.7m. Craters in that area are currently filled with water; they are 6–12m in diameter and mostly 0.4–1.1m deep. The diameter of one of the craters is 14m, but research into the morphology of its bottom revealed the existence of a ring structure, implying a centric, subsequent hit with a bomb in an older form. There are also numerous connected craters. Some of them are currently almost filled with sediment. In the second zone of the study, craters are filled with mineral sediment and organic matter to a lesser degree than in the first one. Crater diameters in that area are up to 13m in the case of forms originating from overlap hits and up to 11m for craters made by single explosions. The craters at the bottom of the valley are deeper, often reaching 1.0–1.5m.

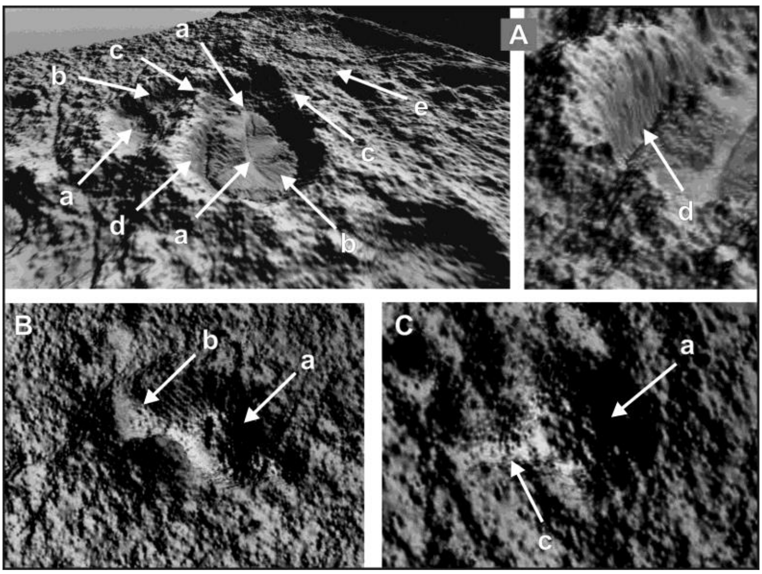

Fig. 5. The use of craters as elements of warehouses and fortifications:
a – place where the bomb fell, b – warehouse or shelter, c – entrance,
d – fragment of a wall, e – rebuilt driveway, A – adaptation of 2 adjacent craters as a warehouse for unexploded ordnance, B – ground bunker located next to crater,
C – crater used as a bunker

One of them, most likely formed by an overlap hit, is as deep as 2.1m. Its pond depth was also noted and appeared to be the greatest in the study area (1.35m). The rims surrounding the craters are also higher there. In this zone, there are also conjoined craters. In some of the ponds, laser scanning revealed well-preserved forms within the bottom, which developed when the craters were created or during their initial transformation – shortly after the bomb explosions. Probing the bottoms of surrounding crater complexes revealed that they were covered with a relatively thin, 7–12 centimetre organic layer (peat). In the deepest parts, there was a very thin band of suspended organic matter over the peat layer.

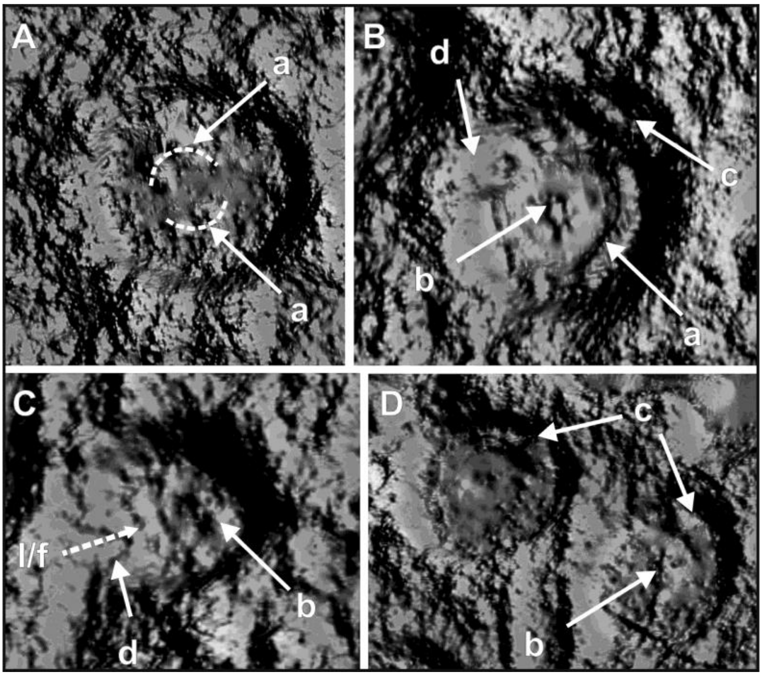

Fig. 6. Selected examples of crater morphology:
a – ring structure at the bottom of a double-hit crater, b – central hummock,
c – edge break up, d – landslide/flow (l/f arrow indicates the direction
of slope movement and the displacement of the central hummock).

The first complex of craters examined in this zone comprises three forms of various diameters and ages (two smaller forms are older) (Fig. 4). Within the bottom, one can observe: a ridge separating two craters, which inclines towards the centre of the big crater; an inlet channel which cuts through it; a niche left after material was carried away from part of the bed of the small crater; hanging terraces originating from the bottoms of the two older forms; slumped terraces in the areas of crater edges; fragments of a split underwater accumulation platform with a cut-through cone embedded in it; another bank made up of slope material at the bottom of the large crater formed by a returning wave bouncing off the eastern bank; a cut-through inlet dividing the second bank; landslide niches within the forms noted above and landslide tongues related to the destruction of the steep sides of the craters; as well as minor outliers or collections of residue made up of material more resistant to wash erosion. On the edge of the form, above the water surface, there is a rim made up of the material crushed and ejected from the craters by the explosions. The rim is cleaved by inlets, which carried water away from a hollow or transported water towards it. Moreover, there are also small hummocks, which may be associated with lumps of material blown out of the craters. The picture of the second complex of five conjoined craters located to the south is much more elaborate (Fig. 4).

The course of its modelling was also more complicated. However, most attention is caught by a rim section which originally surrounded the south-eastern crater and which has been ruptured due to the great impact, angled and wash-eroded. The rim is cut by an inlet channel running across the bottoms of the two oldest forms and the cone within the south-eastern crater. The two youngest post-explosion forms are located in the north-west. Between them, one can see a bank which is heavily wash-eroded all over its surface and, additionally, split transversally by an inlet channel. The deepest part of the complex lies to the west, where the youngest post-explosion form is probably located.

LiDAR data reveal pocket-like hollows in the bottom of the banks of the complex described above, as well as in other craters. However, field study did not confirm their existence. In some craters located in the first and second zone, laser scanning indicated small central hummocks (Fig. 6B, C and D). Similar forms in crater bottoms had earlier been identified in the adjacent area, on the west side of the Kędzierzyn – Racibórz railway track [12].

In the third zone, where the groundwater lies at a lower level, the craters are the deepest, while the secondary natural transformations in their morphology are the smallest. It concerns both the changes occurring immediately after the blast and later, throughout the following years. The depth of numerous craters in the area reaches 1.75m, while the deepest one measures 3.0m. This originated from two explosions which took place in the very same location. Compared to the other zones, the craters here are of smaller diameter – about 6–10m. Nevertheless, forms reaching 5–6 metres in diameter and current depth of up to 1 m may also be observed in zone 3. Craters 6–7m in diameter and 1.0–1.5m deep are the most abundant forms in the fourth zone. Single bigger forms, with a diameter larger than 10 m and a depth exceeding 1.5m, also appear at the edge of the railway bank. Their origin, however, is connected with overlapping hits.

Discussion

Morphometry and the distribution of craters

A clear relationship between the diameters of craters and the geotechnical properties of the ground can be noted in the study area, and, above all, with its lithology and water conditions. D.G. Passmore *et al*. [19] presented a diagram of the correlation between the size of post-explosion craters and the weight of bombs, the kind of fuse, and the type of soil. The sizes of bomb craters located in the study area match the given parameters (Fig. 7), although bombs were dropped from higher altitudes. They are more consistent, however, with the values provided by the National Defence Research Committee [37] and AAF Evaluation Board [38]. Large craters are the dominant form among those preserved in the western and central parts of the area. In the eastern section, all craters are smaller in size. In particular zones, marked by relatively consistent physiographical conditions, size differences are visible between single craters created by the 250 and the 500-pound bombs (if fuses with similar parameters – nose: 0.1s and tail: 0.01/0.025s were applied).

There is always the question of the correlation between the size of a crater and the drop height, that is, the power of the impact. Based on morphometric analyses of the forms located in individual physiographical zones (mainly the size and depth of the forms) and the number of craters in hit sequences, it can be assumed that the majority of bombs dropped on the study area were 500-pound payloads. This is very clear in high-resolution shaded-relief rasters and it is also confirmed in the data from Table 1. In very wet and swampy areas, one may observe a shift in average crater diameters towards larger values. The reason for such a development of craters lies in the uncohesive, waterlogged ground, even bearing the characteristics of quicksand, on which the bombs were dropped. For the areas located higher up in zones 3 and 4, the ranges of diameters are shifted towards smaller values. Nevertheless, this does not imply that only small-calibre bombs were dropped in that area. In the case of zone 4, smaller diameters of craters may result not only from the non-waterlogged ground but also the thickness, compactness, and criss-crossing of the area, as well as being locally covered with a special surface, for example, a road. This decreased the effectiveness of ground penetration by bombs. Some shift in the size of crater diameters towards smaller values is also visible in the other zones, but only in places where the area was developed for use – levelled, embanked, grassed over and, most of all, drained.

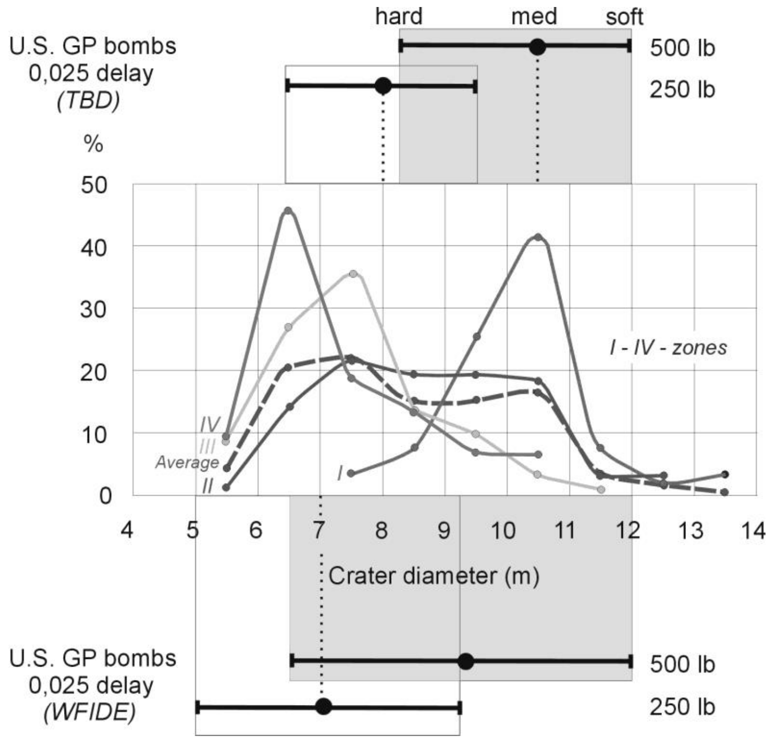

Fig. 7. The diameters of the test craters (middle part of the figure) in relation to crater diameters for a range of bomb types used in WW2 [2]. The labelled whiskers show variation in crater diameter due to ground conditions. Data for US GP bombs is for drop heights of 3,048 m, level flight and airspeed of 402 km/h. Key to source data: TBD – Terminal Ballistic Data [39]; WFIDE – Weapon Data – Fire, Impact, Explosion [37].

Bomb crater morphology – opportunities and limitations in DEM application

The remote-sensing research that was carried out indicated the usefulness of high-resolution DEMs in resolving the problem of the distribution of aerial bomb hits. Moreover, in the study area, high-resolution air scanning revealed the plasticity of the bottoms of several ponds with clearer water. Despite the application of the wave-length of 1064 nm, not commonly used in bathymetric scanning, some of the impulses reached the bottoms of some ponds or craters and returned to the receiver. A shaded relief raster, which is the most useful interpretation in analyses of bed morphology, was obtained from 0.1 x 0.1m resolution data. For certain, these images should not be considered reliable geodetic materials. The depth of the pond basins examined is small (usually up to 0.7 m, while the maximum does not exceed 1m). The image from LiDAR data is blurred in ponds by increased organic detritus content and where the activity of animals has led to water cloudiness. Another factor preventing laser beams from bouncing properly off the bed of the water body were the collections of sticks and leaves, which formed pulpy ‘floating islands’ on the water. These reflect light similarly to a floating mat and this proved the case in two craters in the study complexes, where double reflections are visible on shaded relief rasters derived from models of pond bottoms (Fig. 4).

Another problem is the apparent existence of hollows – ‘pockets’ on the bottom of ponds within the vicinity of their edges. It should be assumed that the phenomenon was caused by very steep or even vertical sides of the craters [40, 41], and also the accumulation of floating leaves near the shore during the spring survey (9 April 2019). The identification of factors responsible for the appearance of shadow zones and the blocking of some of the return signals after the beams have bounced off the pond bottom require further research. Similar irregularities in the modelling of steep slopes and river channels, as well as snow covered sites located in that area, were found by G. Mandlburger *et al.* [42] and D. Backes *et al.* [43], among others, who used topobathymetric and bathymetric scanners. The existence of steep banks, carpets of leaves floating next to them or the presence of nearshore ice and snow can block the return of part of the signal which has bounced off the bottom and reflected back to the LiDAR receiver and lead to the emergence of images of phantom hollows. This phenomenon is also affected by the considerable diffuse bottom reflection in water bodies (which was noted by P.E. La Roque and G.R. West [44], among others), delayed return and the gradual fading of a scattered signal [45].

Interestingly, in the Kędzierzyn-Koźle area, central hummocks (a "central cone", after F. Trusheim [46]) frequently appear in bomb craters. In the first and second zone of the study area several such forms were found (Fig. 6). They developed in places where bombs penetrated waterlogged layers of sandy formations, as well as sandy and gravel formations, similar to quicksand. In these places, waterlogged formations flew at great speed out of the crater sides and even their bottoms in the response phase of the blast-compressed ground. In addition, the force of gravity and cohesion worked simultaneously in the process of filling the craters. Such forms were described by F. Trusheim [46] based on observations made in Greater Poland at the beginning of WWII. The problem was discussed in the article of J.M. Waga and M. Fajer [12] regarding craters located in the adjacent area, on the other side of the Kędzierzyn - Racibórz railway track. Shaded relief rasters of 1 x 1m resolution obtained from LiDAR scanning are very useful in determining the location of craters over large areas and in the general analysis of their sizes. They frequently provide an inaccurate picture of their particular elements. In the third study zone there was an image of a central hummock in one of the deep craters seen on a shaded relief raster dating from 2012. Its presence was not identified on the image from new scanning and a new model of 0.1 resolution. In the field, it turned out that it was a ‘virtual phantom’. The image of the hummock was probably created by a reflection of the pulpy ‘floating island’ made up of leaves. Therefore, for similar analyses, it is advisable to apply higher resolution models and conduct verification field work.

Record of the geomorphological processes

During a bomb explosion, a lower content of water in the ground reduces the efficiency of its penetration and destruction by the shockwave. For that reason, craters located in dry areas are of smaller diameters. They are also backfilled with sediment to a lesser degree. In the case of an area which was poorly covered by vegetation and whose ground was not bound by root systems, shortly after the dynamic of the explosions secondary processes took place in craters located in the shore zones of the ponds: mudflows, landslides, shore erosion (abrasion) and finally also zooturbation. Also, larger volumes of material slide down the edges of craters and created slumped terraces. For that reason, one may sometimes observe arched embankments or steps (Figs. 4 and 6) on the bottoms of the ponds that were studied. These can sometimes be interpreted as ring structures connected with double explosions, or maybe the fall of unexploded bombs.

A field study confirmed a major role of vegetation, especially vegetation root systems, in currently binding the sides of the water-filled craters. Roots create a type of natural nonwoven bio-mat. In some zones it was probably already compact enough in the initial phase of a crater’s existence to considerably reduce the wash erosion of shore zones [47].

In adjacent craters, or those partly overlapping and filled with water, one can observe traces of the turbulent transfer of water and the fluidised element of ground material. At the time of the explosion this mixture was first pushed into an older form to immediately return and flow into a newly formed crater. The course of the mixture transfer was complicated if there were several hits close together. Water and the fluidised content that filled older systems of craters were violently moved to a new crater. Consequently, it involved a whole sequence of transferring liquid and semi-liquid material into new areas. It has left sediment traces behind from which the process may be recreated.

Following the last explosion, the morphological development of conjoined craters proceeded more slowly. It involved the processes of creeping or falling from the edges and sides to the bottoms of the craters. The freshness of the relief of the older bottom forms identified in binary and multi-centric craters indicates that subsequent morphodynamic processes had a moderate impact on their development.

Other natural factors that may result in major morphological changes in low-lying and water-filled craters include high-water stage transfers in adjacent watercourses and the activity of ungulates beating their paths to watering holes or creating wallows in shore zones. Contrary to vicinal areas, no water erosion was identified in the study area. There are also a few traces of the activity of wild boar and cervids, which used some ponds for bathing.

Conclusions

The study conducted over the remains of bombing missions attacking Kędzierzyn-Koźle Azoty in 1944 leads to the following remarks and conclusions:

A great density of craters, which have a conspicuous relief, was identified in the study area – on average 47.8 items/ha, and more than 75/ha in places where they are concentrated. The number may have been larger as parts of the oldest craters were damaged during subsequent raids.

In the four zones established in that area (each with internally uniform soil and water conditions) there are craters of three sizes. Bigger craters were created by the dropping of 500 lb bombs, smaller ones by 250 lb bombs and the smallest ones may be connected with UXB. The largest craters originate from overlap hits (explosions overlapping in the same place). Craters made by 2 or 3 hits were identified.

The diameters of craters created by explosions of the same type of bombs (500 lb) are larger in waterlogged areas and smaller in drier, higher located areas, although they contain the same mineral content.

The deeper that groundwater is found, the more craters of smaller diameter and larger depth can be identified. Moreover, in such location’s craters underwent the smallest secondary transformation caused by natural elements.

Natural conditions, and also former human-induced land development, particularly the existence of hardened, compact, embanked areas artificially covered with turf and with a drained surface, influenced the size of craters.

Complexes of water-filled joined craters were preserved in the area. In some of them, owing to better water transparency, shaded relief rasters from LiDAR data include a legible record of the geomorphological processes, including those occurring within the basins of ponds created by bombs that detonated.

The analysis of fragments of DEMs, which were generated from high-resolution LiDAR data in 1 x 1m, 0.1 x 0.1m and 0.05 x 0.05m resolution, indicated an adverse impact of ‘floating islands’ composed of leaves on the quality (accuracy) of modelling including, in particular, a change in the image of the bottom relief of craters. Similarly, correct modelling of water body bottoms is impeded by steep and vertical banks and the accumulation of leaves next to them.

The study area has unique relief but is also unpredictable due to unexploded bombs. Therefore, it should remain free from investment. It is recommended that this area be preserved for historical and ecological reasons by transforming it into a nature and landscape complex, using it as a study area for historical and landscape study as well as for research into recognition of the threats posed by unexploded bombs.

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