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The mechanism and stages of development of a field road gully in relation to changes in the surrounding land relief

Mechanizm i stadia rozwoju śródpolnego wąwozu drogowego na tle zmian ukształtowania powierzchni w jego otoczeniu

Keywords: road gully, loess areas, soil erosion, Lublin Upland
Słowa kluczowe: wąwóz drogowy, obszary lessowe, erozja gleb, Wyżyna Lubelska

INTRODUCTION

Ground roads located on slopes under agricultural use determine the direction of surface runoff, particularly during intensive rainfall. This results in their erosion and rapid downwearing. Its rate depends on the slope inclination, intensity of use of the road, and type of the eroded substrate. In a uniform slope system, such a process results in the development of two subsystems: one of the fields and the other of the ground road, separated with a low turfed ridge resembling a balk. In the loess areas of the Lublin Upland, the rate of notching of roads on slopes is considerable, reaching up to several centimetres annually (Miszczak 1960; Nowocień 1996; Janicki et al. 2002). Due to the physical properties of loess, and particularly its ability to retain vertical walls in the dry state, the lateral development of the slopes of the road landform is usually substantially delayed in relation to the rate of its notching. This results in the development of road gullies with a box-shaped profile (Gardziel, Rodzik 2000; Rodzik et al. 2008).

On relatively gentle slopes with an inclination of up to several degrees, with cross-slope field orientation perpendicular to the road, the adjacent road constitutes the turning zone for cultivation. This results in transport of material from the field to the road, and then along the road down the slope. In such conditions, a road trough can develop, with simultaneous downwearing of the surface of the road and the adjacent fields. This particularly occurs in Roztocze, where informal roads run across long and narrow fields (Rodzik, Zgłobicki 2010). The proceeding erosion can eventually lead to a dissection of the trough with a gully. The identification of the mechanism of development of such road erosional landforms is facilitated by the analysis of the structure of soil profiles on gully scarps.

The objective of the paper is to determine the mechanism and stages of development of a small road gully on the Nałęczów Plateau as an example of the development of field road gullies in loess areas. The location of the landform among arable fields and its small size permitted conducting detailed field research meeting the aforementioned objective. The field research was carried out in autumn 2005. Preliminary study results have been published (Rodzik et al. 2010).

STUDY AREA

The study object is a small field road gully dissecting the slope of a small valley, constituting the upper section of an erosional-denudational valley (Fig. 1A). The small valley slope, with a denivelation of approximately 10 m and mean inclination of approximately 5º, is exposed to the south. The study object is located in a loess catchment of a gully system in Kolonia Celejów, located in the western part of the Nałęczów Plateau (Fig. 1B). Its geographical coordinates are as follows: 51º20'41'' N and 22º6'19'' E. The gully is adjacent to arable fields with a width of 15–20 m, with a cross-slope orientation, perpendicular to the edge of the gully (Fig. 1C). The crops include cereals, root vegetables, and berries. The fields are separated with balks on which agricultural scarps developed, with varied heights not exceeding 1 m.

The loess cover with a thickness of 10–20 m is composed of younger Vistulian loesses with high contents of $CaCO_3$ even exceeding 10%. They are mainly deposited on glacigenic formations of the Odranian (Saalian) Glaciation, and particularly on fluvioglacial sands and glacial tills. Saprolite of Palaeocene origin is locally deposited directly under the loess (Harasimiuk, Henkiel 1976). The surface of the loess cover in the part of the catchment not dissected with gullies includes small erosional-denudational valleys, ablation troughs, closed troughs, as well as plateau and slope hummocks (Rodzik et al. 2009). The landforms developed in the Pleistocene, synchronically with the accumulation of the loess cover or after its termination (Maruszczak 1958).

In the Holocene, after the stabilisation of the surface by forest vegetation, Luvisols developed, with the profile Ah-Eet-Bt1-Bt2-BC-C-C_{Ca} or similar (Turski, Słowińska-Jurkiewicz 1994). Already in the Neolithic, the area was under agricultural use by inhabitants of a settlement of the Funnel Beaker Culture, located in the nearby Karmanowice (Nogaj-Chachaj 2004). The Neolithic surface soil erosion is evidenced by soil profiles in the troughs and closed depressions, subject

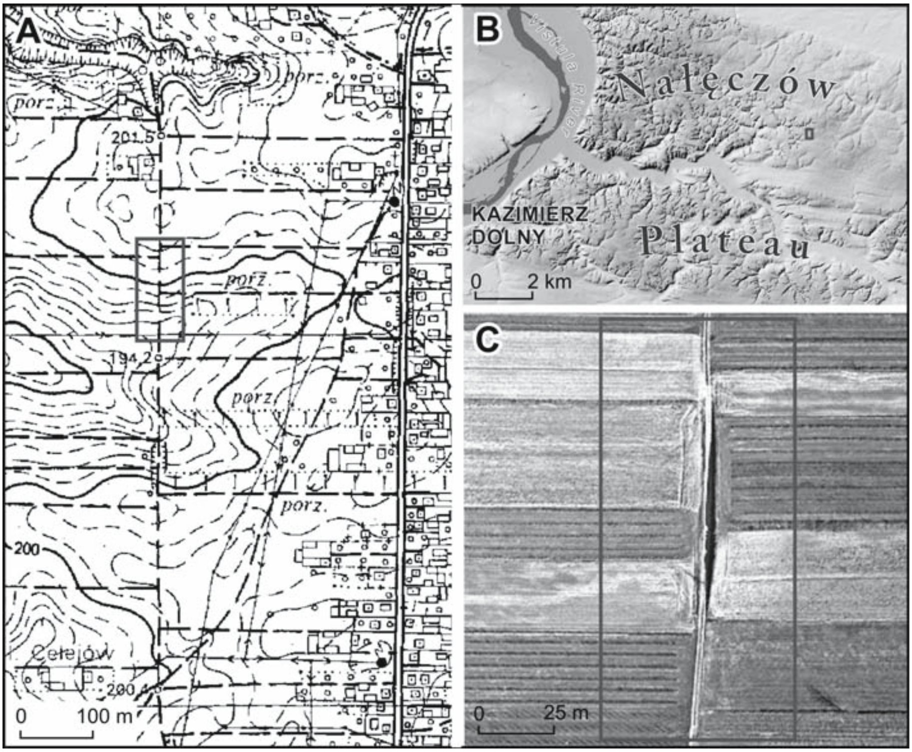

Fig. 1. Location of the study polygon (following Rodzik et al. 2010, modified): A – on the topographic map 1:10 000, sheet Klementowice (1984), B – on the raised-relief map (DEM) of the western part of the Nałęczów Plateau "Land of Gullies" developed by B. Hołub et al. (2006), C – in an aerial photograph (2004)

to aggradation with delluvia in the Neolithic (Rodzik 2010). The soils changed to a little degree, and regenerated under dry ground forests over the next millennia, because the Nałęczów Plateau was hardly penetrated by later prehistoric cultures (Nogaj-Chachaj 2004). Only the modern agricultural use resulted in a substantial transformation of the soil cover through erosion processes (Klimowicz, Uziak 1994). Historical data suggest that the catchment in Kolonia Celejów has been under continuous agricultural use for the last approximately 600 years. This resulted in considerable eroding of soils on slopes, and accumulation of material in valley bottoms (Rodzik 2010).

METHODS

The determination of changes in the topographic surface involved the comparison of the structure of profiles of non-eroded and eroded soils. Methodological guidelines for the determination of the degree of erosion of Luvisols in comparison to sequences of non-eroded soils are provided by Marcinek (1994). Well developed loess Luvisols with varied colours of particular genetic horizons are particularly useful for this purpose. The thickness of the horizons can be identified with relatively high accuracy (1–2 cm) (Rejman et al. 2009; Rodzik et al. 2014). In the vicinity of the studied gully, in a polygon with dimensions 130 x 60 m, a total of 70 soil and sediment-soil profiles distributed in an irregular grid every 10–20 m, were described. The distribution of the analysed profiles resulted from their exposure in scarps of the gully and high balks with varied width (Fig. 2A). The majority of the profiles were sampled with undisturbed soil and sediment structure by means of a *Eijkelkamp* sampler.

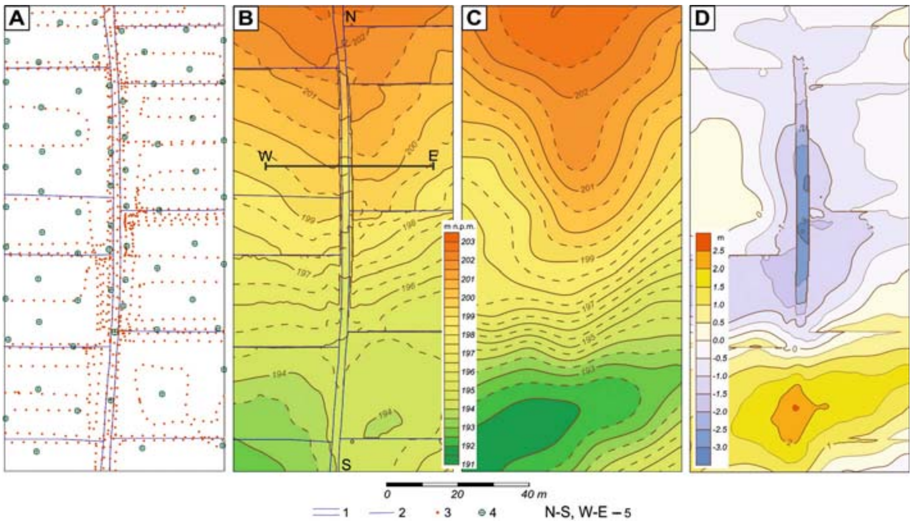

Fig. 2. Study polygon (following Rodzik et al. 2010, supplemented): A – distribution of measurement points, B – modern topographic surface, C – former (approx. 1400 AD) topographic surface, D – denudational balance; 1 – road, 2 – balks, 3 – GPS measurement points, 4 – soil profiles, 5 – cross-sections

The total determined thickness (including horizon BC) of Luvisols in the non-eroded profiles on the plateau in the catchment amounted to approximately 155 cm. Because it is usually 10% lower on the warm slope (Rejman et al. 2009), a thickness of 140 cm was adopted as the basis for calculations. A difference to 140 cm was added to the determined depth of occurrence of the soil bottom, and in the case of entirely eroded soils, a difference to the mean depth of decalcination, amounting to 155 cm on the warm slope. In the case of aggradation of a profile, the difference constituted the thickness of the aggradated sediments.

The development of the map of the modern land relief involved field measurements in the GPS system, performed by means of a Leica System 500 receiver. They were performed in the same polygon 130 x 60 m, located on the slope and bottom of the valley. The GPS measurements were conducted by the Stop-Go method with consideration of the faults of balks and edges of the road gully (Fig. 2A). More than 2,000 measurements were performed, providing a basis for the determination of the modern topographic surface. Based on GPS points, a grid of points evenly distributed every 25 cm was interpolated in the Surfer software. The minimum curvature algorithm was applied, permitting using the faults. They constitute a barrier for information flow. Points located on one side of a fault are not considered in the calculation of values of points on the other side.

A similar procedure was applied in the development of the map of the original surface (Fig. 2C), where data from 70 soil profiles were used. The development of the map did not consider faults, assuming their lack on the surface before agricultural use. The comparison of the two surfaces permitted the determination of the denudational balance of the study polygon (Fig. 2D), as well as modelling the development of the gully in nivelation-soil sections.

Changes in the land management and distribution of fields and ground roads were identified based on maps presenting the state of spatial management from the early 19th century. Information on changes which occurred since the 2nd World War was additionally obtained from the inhabitants of Kolonia Celejów: Stefan Furdal and Piotr Rogoza.

RESULTS

The map of modern land relief suggests that the studied gully, with a shape of a bow with eastern orientation, dissects a slope hummock along its top (Fig. 2B). The gully is "inserted" in a shallow (approx. 0.5 m) trough-like landform with a width of 10–15 m. The modern gully has a length of 80 m and depth of up to 1.8 m, whereas its left, east slope is higher than the right one by 10–35 cm (Fig. 3). The width of the bottom amounts to 2.5 m, and the aperture of the edges reached up to 3.5 m. The inclination of the gully bottom equals 5º, and 3º at its mouth. In 2005, the volume of the gully amounted to approx. 250 m^3.

Sediment-soil profiles on the gully slopes mostly represent entirely eroded soils. The former horizon Ap with a thickness of 30–50 cm, i.e. twice as high as the depth of ploughing, is deposited on the decalcinated horizon C or on horizon Cca. The agricultural diamicton constituting horizon Ap is also carbonate, particularly at the bottom. The gully on most of its length dissects the carbonate loess up to a depth of 1–1.3 m. Fragments of lower horizons of Luvisol: Bt2 and BC, were only preserved on the walls of the upper section of the gully (Fig. 4).

Fig. 3. View of the gully from above and from below in April 2004 (Photo W. Zgłobicki)

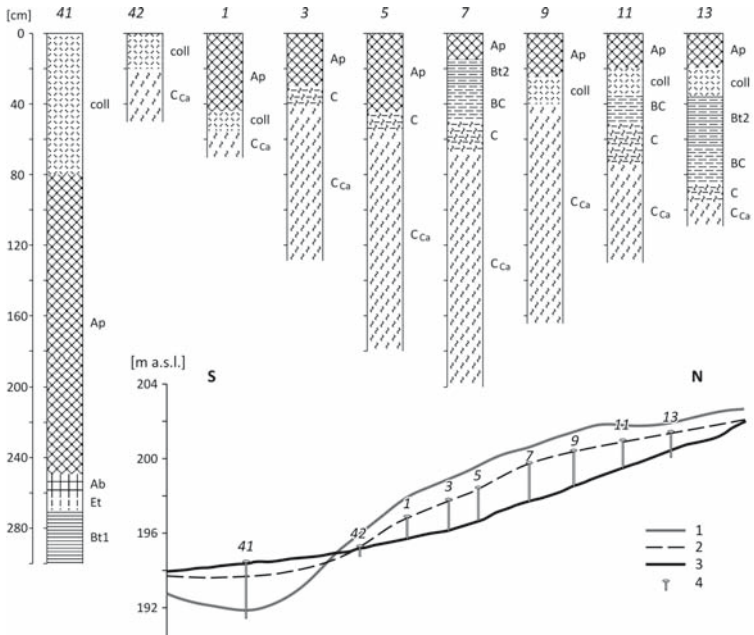

Fig. 4. Long profile through the polygon along the road: 1 – topographic surface approx. 1400 AD, 2 – modern upper edge of the gully, and the bottom of gully sediments, 3 – modern gully bottom and fan surface, 4 – location of sediment-soil profiles

Along with the growing distance from the gully, soil profiles within the study polygon become more and more complete. Soil on the concave convergent slope was found not to be eroded or to show slight aggradation (Fig. 5). In the bottom of the small valley, soil profiles are considerably aggradated with agricultural diamicton. Below the road, the Luvisol horizon Ab occurs at a depth exceeding 1 m, and above the road – even 1.5 m.

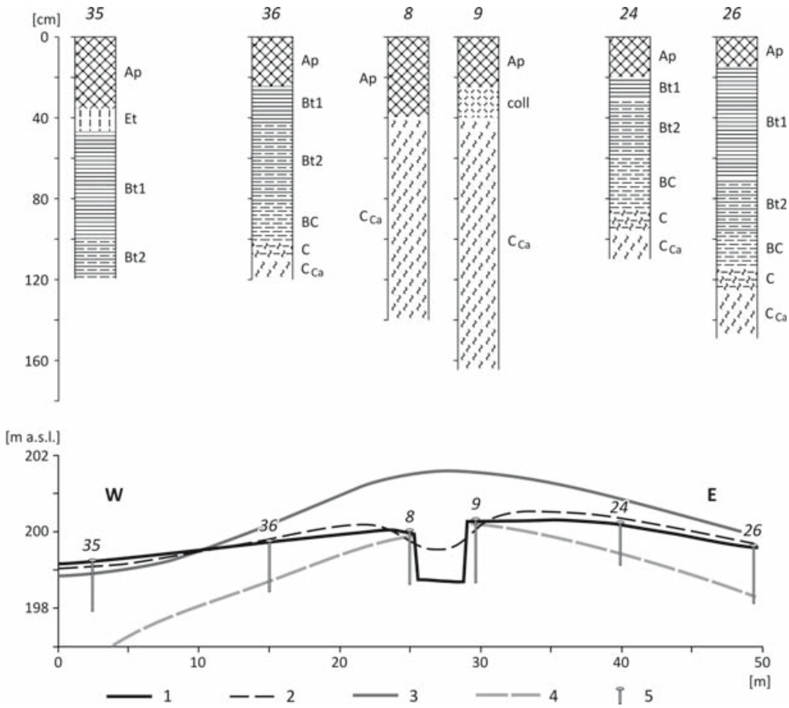

Fig. 5. Cross-section through the polygon: 1 – original (approx. 1400 AD) topographic surface, 2 – topographic surface in the 1970's, 3 – modern topographic surface, 4 – boundary of loess decalcification, 5 – location of soil profiles

At the mouth of the gully, an elongated fan developed, forming a bank-dyke along the ground road, crossing the small valley's bottom. The maximum thickness of the bipartite complex of sediments of the fan amounts to 2.5 m on the valley's axis. The upper series with a thickness of 0.8 m is distinguished by fine lamination with load deformations suggesting traces of wheels and animal hooves. In the uppermost layer, up to a depth of 0.3 m, a substantial amount of $CaCO_3$ was recorded in the sediments. In the bottom layer, the content of carbonates was scarce. The bottom series of sediments of the fan has a thickness of up to 1.7 m and is a typical non-carbonate agricultural diamicton with a massive structure. It is deposited on subfossil Luvisol the humic horizon (Ab) of which in the investigated profile begins at a depth of 2.5 m (Fig. 4).

The result of the comparison of the original (from before 600 years) and modern surface is the denudational balance of the study polygon (Fig. 2D). The total volume of material eroded from the slope amounted to more than 3,800 m^3, and the volume of accumulated material – to less than 3,000 m^3. More than 20% of eroded soil material was therefore removed outside the polygon which does not constitute a closed geosystem.

DISCUSSION OF RESULTS

Stage 1 – surface soil erosion

This stage includes the period of management of fields belonging to the Celejów estate. It can be assumed that the beginning of the agricultural use of the land was synchronic with the establishment of adjacent villages in the premises of the Celejów estate: Karmanowice and Stok, at the turn of the 14th century. The founding of a parish in the neighbouring village of Klementowice is related to the existence of the settlement (Sakławski 1974). Three-field crop rotation was applied in the cultivation of cereals for export, particularly in the 16th and 17th century (Maruszczak 1988). In the study area, three-field crop rotation was performed within leas with a width of approximately 100 m and approximate orientation of SE-NW. This suggests the distribution in the catchment of relatively young branches of the gully system, probably developed within leas (Rodzik 2010).

It is difficult to determine the degree of changes in the soil cover during the time. The applied farming system based on three-field crop rotation ensured relatively good protection of the soil. In the majority of slopes of the dry valley, the degree of soil erosion was probably weak or moderate, and horizon Bt1 could be within the range of ploughing. The slope hummock in the study polygon was distinguished by exceptional predisposition for downwearing. It had a convex and divergent slope with an inclination exceeding 5º (Fig. 2C). In such places, soil erosion proceeds exceptionally fast (Janicki et al. 2002; Rodzik et al. 2014). Therefore, exposure of even the bottom soil horizons was possible, particularly after the introduction of cultivation of root vegetables and crop rotation in the early 19th century. The considerably increased rate of soil erosion is suggested by intensive accumulation of soil colluvia in the valley bottom (Fig. 2D, 4). The area was probably predisposed for accumulation due to the boundaries of leas slanting towards the axis of the valley.

During the partial subdivision of the estate in the second half of the 19th century, resulting from the conducted mass land consolidation (Kowalik-Bodzak 1964), the orientation of fields changed to W-E. A ground road was established separating fields of the new part of the Karmanowice village located on the eastern side of the road from the fields of the Celejów estate, located on its western side. The road ended just above the modern gully. It was only sporadically used as an access road to the fields. Therefore, it must have been turfed, and it probably was not eroded on the slope. It can be assumed that the stage of surface soil erosion lasted for approximately 550 years. The mean rate of sediment accumulation in the valley bottom at the place of their maximum thickness of 1.7 m amounted to 3.1 mm annually. The value is somewhat higher than the rate of modern accumulation in troughs, and slightly lower than the rate of accumulation in bottoms of dry valleys, determined by the ^{137}Cs method by Zgłobicki (2002). A rate of agricultural diamictin accumulation in bottoms of field depressions of up to 0.7 mm annually was obtained for a test areas in the Perznica river catchment in the Drawskie Lakeland, under agricultural use since the 1970's, studied by similar methods (Szpikowski 2010).

Stage 2 – development of the road trough

The fields of the Celejów estate adjacent to the road were subdivided in 1938. Several farms were established in the area over the following years. This resulted in an increase in the importance of the investigated road, now used as an access road to the new farms and their fields, as well as a path for cattle led to pastures. Due to high traffic increased by the contribution of livestock, the road was devoid of vegetation cover. This enabled its erosion on the valley slope (S. Furdal and P. Rogoza 2005 – oral information).

The process of erosional surface downwearing affected not only the road, but also fragments of the adjacent fields, developing a road trough. Due to the field distribution perpendicular to the road, it was commonly used as a turning zone during cultivation. Until now, the surface of fields in the belt with a width of several meters adjacent to the gully is inclined towards it (Fig. 2B). Slopes of the former road trough constituting the predecessor of the gully were therefore retained (Fig. 5). The beginning of development of the trough was synchronic with the commencement of intensive use of the road in the late 1930's. The termination of its development was determined by separating the road from the fields at the end of the 1970's. This was related to the mechanisation of agriculture. It was difficult to drive a tractor out of the field into the increasingly deep road (S. Furdal and P. Rogoza 2005 – oral information). Such a system functioned for approximately 40 years.

The comparison of the soil profiles outside and inside the trough suggests that it reached a depth of 1 m and width of 10–15 m. The maximum downwearing of the topographic surface (in relation to the original surface) on the slopes of the trough reached 1.5 m, and certainly exceeded the value on the road in the axis of the trough (Fig. 5). The mean rate of downwearing of the road surface in the axis of the trough along its middle section was determined as 2.5 cm annually. Entirely eroded soil profiles on the edges of the middle and lower section of the modern gully suggest that the trough sank in carbonate loess, which certainly intensified the erosion of its bottom.

Soil material from fragments of fields located on the trough slopes, as well as carbonate loess eroded in its bottom, were transported on the surface of the road. Erosion at this stage corresponds to the weakly carbonate accumulative series on the road fan, located at a depth of 0.3–0.8 m. The rate of accumulation within its boundaries was calculated as 12.5 mm annually.

Sub-stage 3a – transitional

The change of traction from horse-powered to tractors by particular field owners was not synchronic. Mechanisation concerned the Karmanowice village earlier than the poorer farms in Kolonia Celejów located over the gully (S. Furdal and P. Rogoza 2005 – oral information). On the western side, an erosional-accumulative scarp started developing, separating fields from the road. It developed through downwearing of the road surface, but also through the aggradation of the edges with agricultural colluvia accumulated on the slope of the former trough. In 1984, the scarp still did not reach a height of 1 m. It is not marked in the topographic map from that year (Fig. 1A).

Over the period of at least several years, an asymmetric road landform developed, with a low scarp on one side (E), and a relatively gentle trough slope on the other (W), on which transport of material from the field to the road occurred. The road surface was therefore inclined towards the scarp. This resulted in its undercutting and retreat, leading to the migration of the road by 2–3 m to the east (Fig. 2A, B), and the asymmetry of the modern gully (Fig. 3, 5).

Sub-stage 3b – development of the road gully

The road was separated from the fields on its western side in the mid 1980's (S. Furdal and P. Rogoza 2005 – oral information). A scarp began developing on its western side, and the cross profile of the road landform became box-shaped. Until 2005, the gully dissected carbonate loess up to a depth of 1.5 m. The maximum thickness of the removed material – from the original surface (from before 600 years) to the gully bottom – exceeds 3 m (Fig. 2D, 5). The rate of downwearing of the road surface throughout stage 3 was estimated as approximately 4 cm annually. Erosion at this stage corresponds to the accumulation of the uppermost carbonate accumulative series on the road fan with a thickness of 0.3 m. The rate of accumulation within its boundaries was similar to that at stage 2, amounting to 12 mm annually.

The rate of development of the gully in Kolonia Celejów is high in comparison to other, relatively shallow road gullies with similar bottom inclination (Miszczak 1960; Nowocień 1996). This can be explained by higher susceptibility of material. Gullies of this type usually initially cut into relatively consolidated soil horizons, whereas the gully in Kolonia Celejów has been cutting into susceptible to erosion carbonate loess from the beginning. Widening of the catchment of the investigated gully by the trough slopes are also of importance.

FINAL REMARKS

The development of road gullies in areas under agricultural use can include multiple stages. This can be determined by the orientation of fields towards the ground road located on the slope. In the case of the direction of ploughing perpendicular to the road, it is used as the turning zone. This results in transport of material from the fields to the road, and the development of a road trough. In such conditions, the road on the slope constitutes a part of a uniform slope system with the adjacent fields. This expands the catchment of the road and increases the rate of erosion, which leads to the development of a gully. A road gully develops after separating the road and the fields into independently functioning slope subsystems.

The complex application of interdisciplinary methods: geodesic-satellite, sedimentological-pedological, cartographic-geostatistical, and geographic-historical, permits the reconstruction of the state of the original relief, even in the case of its multi-directional, anthropogenic development. It is important to determine turning points in the manner of land use, resulting in the change of the type, direction, and intensity of geomorphological processes.

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STRESZCZENIE

W pracy przedstawiono rozwój niewielkiego, śródpolnego wąwozu drogowego na Płaskowyżu Nałęczowskim, formującego się w ciągu kilkudziesięciu lat. Rozcinająca zbocze lessowej dolinki forma ma 80 m długości i do 2 m głębokości. Rozwój wąwozu ukazano na tle zmian ukształtowania powierzchni sąsiednich pól, spowodowanych erozją gleb uprawnych. Współczesne ukształtowanie powierzchni określono za pomocą pomiarów GPS, zaś dawną powierzchnię odtworzono na podstawie polowej analizy profili glebowych i osadowo-glebowych. Pozwoliło to na określenie pierwotnego położenia powierzchni topograficznej przed około 600 laty oraz jej późniejszych zmian.

Stwierdzono, że rozcinany przez wąwóz garb stokowy był pierwotnie znacznie wyższy, gdyż jego powierzchnia obniżyła się o ok. 1 m w kilkusetletnim stadium erozji gleb. Rozwój wąwozu przebiegał kilkuetapowo. Najpierw formowała się niecka drogowa, co związane było z wykorzystywaniem drogi jako strefy nawrotu podczas uprawy sąsiednich pól. Po jej pogłębieniu zawracanie na drodze było utrudnione, więc nastąpiło jej oddzielenie od przyległych pól skarpami, zaś na drodze zaczęła rozwijać się forma podobna do wąwozu. Wcinanie dna niecki określono na 2,5 cm rocznie, zaś wąwozu – na 4 cm rocznie.

Określono bilans denudacyjny poligonu badawczego o powierzchni 0,78 ha. Stwierdzono, że ze zbocza dolinki ubyło ponad 3800 m^3 materiału, z czego prawie 80% zostało zdeponowane w dnie dolinki u wylotu wąwozu. W miejscu maksymalnej miąższości osadów natężenie akumulacji w stadium powierzchniowej erozji gleb określono na 3,1 mm rocznie. W stadiach rozwoju niecki i wąwozu natężenie akumulacji wzrosło do 12 mm–12,5 mm rocznie.