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Influence of rainfalls of varying intensity on slope stability

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The paper presents results of calculating the infiltration process and slope stability of one of the shallow landslides that were activated in Targanice near Andrychów (Beskid Mały Mts.) as a result of a disastrous rainfall lasting about 2.5 hours. The study aimed at the analysis of slope stability conditions in terms of the formation of a wetting front related to a single rainfall of constant and varying intensity.

Infiltration calculations made using the one- and two-dimensional (hydrological) Green–Ampt model revealed significant differences in the precipitation–infiltration–surface-runoff relationship, showing that calculations using the one-dimensional model give higher values of infiltration and thus rate this method as a more conservative (safe) one from the point of view of slope stability assessment. It is shown that rainfalls of a high intensity at the initial phase decreasing with time and rainfalls of constant intensity contribute to the highest values of infiltration accumulation and thus to the penetration depth to the soil. The depth of the wetting front changing during the rainfall influences the slope stability conditions.

Key words: shallow landslides, infiltration, Green–Ampt model, slope stability, Carpathian flysch

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INTRODUCTION

One of the basic factors contributing to mass movements is water which, in the form of rain, infiltrates deep into slopes. On the one hand, this phenomenon causes changes in the moisture content of soils within the slope, leading to the diminishing of their shear strength; on the other hand, infiltrating water constitutes the source of groundwater supply, raising its level in rainy periods and leading to a reduction of the effective stress in the slope.

In research works concerning surface mass movements, the relation between the level of precipitation and the intensity of landslide activation is very often analysed. On the global scale covering large geographical areas, values of the threshold rainfall are often quoted. This parameter is often defined as the cumulated rainfall in the period preceding the activation of mass movements. In our country, in the case of deep landslides built of soils with the prevailing content of shales, the cumulated (within 30 days of the preceding period) threshold rainfall exceeds 250–300 mm, and if sandstone is the prevailing formation, the rainfall triggering landslides of Beskidy slopes were estimated as 500 mm (Gil, Długosz, 2006), whereas shallow landslides are initiated at smaller rainfall amounts (200–250 mm) (Rączkowski, Mrozek, 2002; Gorczyca, 2004; Gil, Długosz, 2006); however, their intensity is higher than that in case of structural landslides. It should be stressed that apart from the quantity of rainfall, its character and time distribution are also important.

Rączkowski and Mrozek (2002) have reported that short torrential rains with the intensity of 1–3 mm/min trigger mudflow and debris flow first of all. It should be noted that the above-mentioned values of threshold rainfall do not take into consideration the local conditions of slope stability depending on inclination and the geotechnical characteristics of soils in the slopes. The stability of surface layers of slopes is strictly related to rainfall water infiltration process (Pradel, Raad, 1993; Cho, Lee, 2002, etc.), the intensity of which depends both on the parameters of soil and the external factors, mainly the duration and intensity of the rainfall. As can be seen in the results obtained by various calculation methods (including Tsai, 2008; Tsai et al., 2008; Xue, Gavin, 2008; Jia et al., 2009), rainfall characteristics have a considerable influence on the velocity of water infiltration into the surface layers of the slopes and thus also on their stability.

The study was aimed at the analysis of slope stability conditions in terms of the formation of a wetting front induced by a single rainfall of constant and varying intensity. Results of the research conducted at several dozens of landslides in Targanice near Andrychów (Beskid Mały) were used in the analysis, and one of them was analysed in detail.

STUDY AREA

Targanice is situated in the Outer West Carpathians; its soil, called flysch, is composed of alternating sandstones, shales, and mudstones. In terms of tectonic setting, the Targanice area is located in the marginal part of the Silesian Unit comprising Godula and Istebna flysch sandstones, intercalating with shales in the upper part of the section. At the top, flysch sediments are weathered to the depth of 3 m. This upper layer is formed by the loam containing abundant rock fragments.

In the night of 24 August 2005, a disastrous rainfall hit the area for 2.5 hours. The rainfall was of local extent, covering mainly the drainage basin of the Targaniczanka stream. As a result of the rainfall, several shallow landslides less than 3–4 km^2 were set in motion (Fig. 1). The slopes close to the stream are inclined at 15 to 35°. Mass movements took place on slopes inclined more than 20° and covered mainly with grass. In some places, landslides formed on partially (Wrzosowa) or totally (Złota Górka) forested surfaces. The main geotechnical characteristics of slope soils where three studied landslides were formed (Brzezińska streem vicinity) are presented in Table. For the further detailed analysis, soil data on Landslide 1 were used.

METHODS

The study includes the slope stability calculations using the limit equilibrium approach of the infinite slope model to determine the critical conditions of the slope at the moment of the loss of its stability and the activation of landslide 1, the Brzezińska stream, which was previously subject to analyses (Zydroń, Niebylski, 2008). The limit values of the strength parameters of the soil of the site under analysis

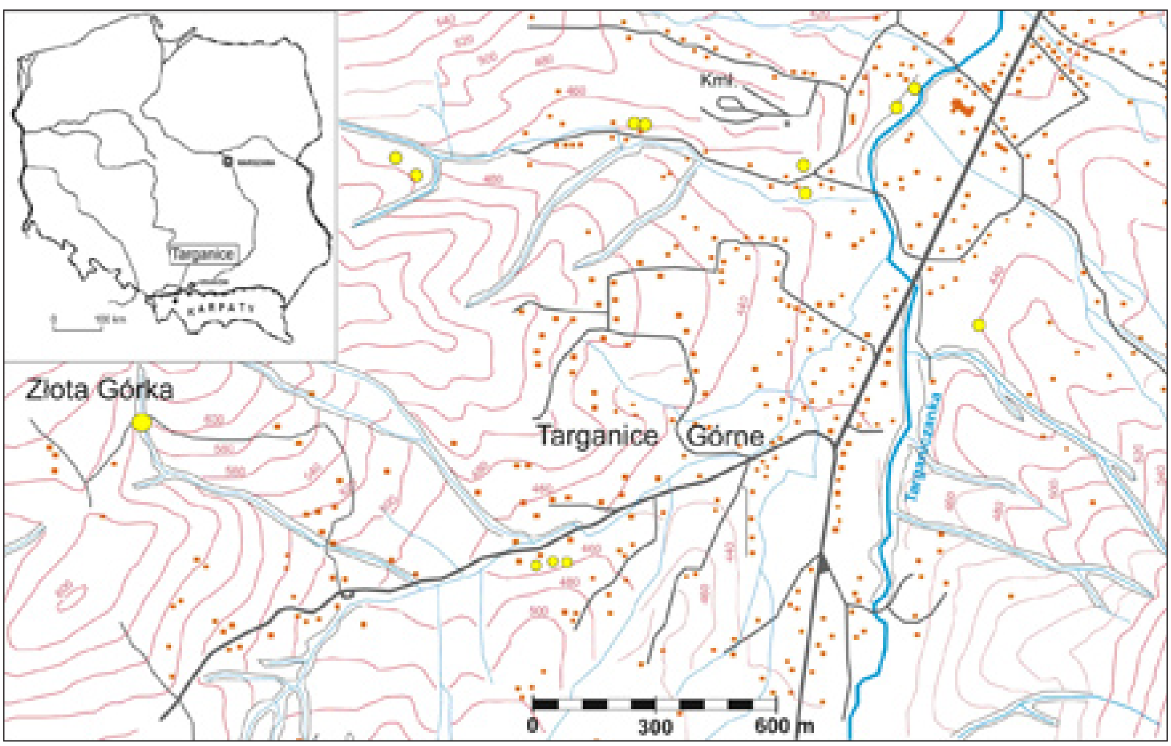

Fig. 1. Distribution of landslides in Targanice, activated in August 2005

1 pav. Targanicos nuošliaužų, išjudintų 2005 m. rugpjūtį, schema

Table. **Geotechnical properties of slope soils of Targanice area (Zydroń and Niebylski 2008, Zydroń et al., 2010; Zydroń, 2010)**
Lentelė. **Šlaitų dirvožemių geotechniniai parametrai (Zydroń and Niebylski, 2008; Zydroń et al., 2010; Zydroń, 2010)**

Parameter	Landslide 1*	Landslide 2	Landslide 3
Fraction content, %:			
– cobbles (>63 mm)	0.0	3.0	2.3
– gravel (63–2 mm)	24.0	36.0	44.2
– sand (2–0.063 mm)	12.9	13.4	10.4
– silt (0.063–0.002 mm)	48.0	35.9	31.9
– clay (<0.002 mm)	15.1	11.7	11.4
Natural moisture content, %	19.4	18.7	19.8
Total moisture content, %	25.2–29.4	29.0	27.1
Bulk density, g/cm^3	1.79–1.91	1.80	1.88
Dry density, g/cm^3	1.50–1.60	1.52	1.57
Density of solid particles, g/cm^3	2.68	2.71	–
Consistency limits, %:			
– plastic	20.7–21.5	17.6	22.3
– liquid	32.6–36.2	26.6	29.6
Plasticity index, %	11.9–14.7	9.0	7.3
Permeability coefficient, m/s	$1.0 \cdot 10^{-5} – 4.4 \cdot 10^{-6}$		
Effective angle of internal friction, °	38.6; 37.4		
Effective cohesion, kPa	0; 3.9		

* Soil parameters in the lower part of the landslide.

were calculated using the backward analysis method and then applied for further calculations.

Subsequently, the infiltration was calculated using the one-dimensional Green–Ampt infiltration model (Green, Ampt, 1911). Knowing the critical depth of the sliding surface, which is confined to the depth of the wetting front, the time of rainfall water infiltration to that particular depth was determined. Three values of the initial soil moisture (0.6–0.8) were assumed in the calculations to obtain the values of the threshold rainfall (magnitude and duration). The further infiltration calculations were performed using the one- and two-dimensional Green–Ampt models, assuming various schemes of rainfall time distribution for the same rainfall depth. Two-dimensional Green–Ampt models were calculated applying HEC_HMS program which is used basically for the assessment of surface runoff (effective rainfall). In the final part of the study, the stability of a particular slope depending on the assumed rainfall scenario was determined.

Concept of slope stability conditions and selection of soil parameters in stability calculations

In slope stability analysis, it is often assumed that the loss of stability occurs along the plane parallel to the surface of the slope (translational landslide). Often (see Skempton, DeLory, 1957 in Pradel, Raad, 1993), the following equation is used to determine the factor of safety (FS):

$$FS = \frac{c' + (\gamma_{sr} - \gamma_w) \cdot z_w \cdot \cos^2\alpha \cdot \mathrm{tg}\varphi g}{\gamma_{sr} \cdot z_w \cdot \sin\alpha \cdot \cos\alpha}, \quad (1)$$

here:

c' = effective cohesion,

φ' = effective angle of internal friction,

α = angle of slope inclination,

γ_{sr} = unit weight of fully saturated soil,

γ_w = unit weight of water,

z_w = depth of wetting front location.

Equation (1) assumes that a flow of water parallels the ground surface in the wetting zone, and the location of the sliding surface corresponds to the wetting front. The equation assumes also that the water flow is interfered by a layer of a lower permeability as it infiltrates down, creates a suspended groundwater table, and water is set in motion.

The critical slope stability depth of the wetting front (and the sliding surface, $z_w = d_{cr}$) can be determined transforming formula (1) and assuming $FS = 1.00$. In this way, we obtain:

$$d_{cr} = \frac{c'}{\cos\alpha \cdot (\gamma_{sr} \cdot \sin\alpha - \gamma' \cdot \cos\alpha \cdot \mathrm{tg}\varphi g)}. \quad (2)$$

As the rainfall water flows through unsaturated soil (infiltrates), the suction pressure is an important parameter that should be taken into consideration in calculations. It is a force keeping water in soil and is negative in relation to the atmospheric pressure, thus it is the factor increasing the shear strength of the soil. Considering the soil as a three-phase system, the factor of safety *FS* can be described (Tsai et al., 2008):

$$FS = \frac{\mathrm{tg}\varphi g}{\mathrm{tg}\alpha} + \frac{c' - \gamma_w \cdot \psi_c \cdot \mathrm{tg}\varphi^b - \gamma_w \cdot \psi_p \cdot \mathrm{tg}\varphi g}{\gamma \cdot z \cdot \sin\alpha \cdot \cos\alpha}, \quad (3)$$

here:

ψ_p = pore pressure,

ψ_c = suction pressure, in the formula assumed as negative in relation to the pore pressure,

z = depth of the sliding surface location.

When the surface layer stability above the groundwater level is considered, the adequate values of the suction pressure are substituted into the equation, and the influence of the pore pressure is omitted (the last part in the numerator). When the stability below the groundwater table is analysed, the adequate value of the pore pressure is substituted in the equation, whereas the suction pressure equals zero. Then, when the sliding surface is situated at the level of the groundwater table, the values of the suction pressure and pore pressure are equal to one another and to zero. Assuming that the depth z in formula (3) corresponds to the location of the sliding surface d_{cr} and upon transforming the above equation, we obtain the formula describing the depth of the sliding surface:

$$d_{cr} = \frac{c' - \gamma_w \cdot \psi_c \cdot \mathrm{tg}\varphi^b - \gamma_w \cdot \psi_p \cdot \mathrm{tg}\varphi g}{\gamma \cdot \cos^2\alpha \cdot (\mathrm{tg}\alpha - \mathrm{tg}\varphi g)} . \tag{4}$$

The derivation of the above equation is described in detail in the paper of Collins and Znidarcic (2004). The authors stress that this formula makes the location of the sliding surface dependent on slope inclination, the geotechnical characteristics of the soil and the value of the pore or suction pressures, and therefore can be used for both fully saturated and non-saturated soils. In order to determine the depth of the sliding surface, the values of pore or suction pressures are incorporated in calculations. As a result, we obtain the distribution of critical values of the pore (suction) pressure in the soil profile, on exceeding which the slope stability is disturbed. The one-dimensional model of slope stability is often considered oversimplified. However, as calculation results show (Collins, Znidarcic, 2004), this model is more conservative as compared with the calculation based on the two-dimensional slope model. Moreover, the one-dimensional model of a slope can be easily integrated into the model of water flow in soils and then, applying GIS tools, used for the spatial analysis of slope stability (Montgomery, Dietrich, 1994; Xie et al., 2004).

Infiltration under conditions of uniform rainfall intensity

Calculations of the water infiltration were performed using the Green–Ampt model which, in its basic form, takes into consideration water infiltration in vertical direction. This model involves a number of simplifying assumptions: a) initial moisture content of the soil profile is fixed; b) infiltrating water causes full saturation of soil pores; c) water moves deep into the profile, forming a distinct boundary (wetting front) between the zones of saturated and non-saturated soils; d) the permeability coefficient and suction pressure have constant values at the base of the front. The infiltration capacity and accumulation are calculated. Infiltration capacity is defined as the maximum quantity of water, which can be accommodated by the soil at a given location and time. The infiltration accumulation describes the quantity of rainfall water, which is stored in a soil profile. Infiltration capacity and accumulation are described, respectively, by the following equations:

$$f = k_s \cdot i = k_s \frac{z_f + \psi_f + H_p}{z_f} = \frac{dF}{dt} , \tag{5}$$

$$F = z_f \cdot (\theta_s - \theta_1) = k_s \cdot t + (\theta_s - \theta_1) \cdot \psi_f \cdot \ln\left|\frac{(\theta_s - \theta_1) \cdot \psi_f + F}{(\theta_s - \theta_1) \cdot \psi_f}\right| , \tag{6}$$

here:

k_s = permeability coefficient of the soil (cm/s),
i = hydraulic gradient (–),
H_p = height of the ground surface flooding (cm),
z_f = depth of the wetting front (cm),
Ψ_f = height of the soil suction at the wetting front (cm),
θ_1 = initial volumetric soil moisture content (–),
θ_s = volumetric saturation moisture content (–).

When rainfall intensity (i) exceeds soil permeability, after some time the ground surface is flooded; this sets in motion the surface runoff and marks the saturation of the soil down the entire profile of the wetting front. The depth of the wetting front (z_p), the values of accumulation at the moment of flooding (F_p) and the time of flooding (t_p), measured at the beginning of the rainfall, can be determined using the following equations:

$$z_p = \frac{k_s \cdot \psi_f}{J - k_s} , \tag{7}$$

$$F_p = \frac{k_s \cdot \psi_f \cdot (\theta_s - \theta_1)}{i - k_s} , \tag{8}$$

$$t_p = \frac{(\theta_s - \theta_1) \cdot \psi_f \cdot k_s}{i \cdot (i - k_s)} . \tag{9}$$

Then, infiltration capacity, accumulation and the depth of the wetting front at a period after flooding of the surface can be calculated using the following formulae:

$$F_p = \frac{k_s \cdot \psi_f \cdot (\theta_s - \theta_1)}{i - k_s} , \tag{10}$$

$$F_p = \frac{k_s \cdot \psi_f \cdot (\theta_s - \theta_1)}{i - k_s} , \tag{11}$$

$$z_p = \frac{k_s \cdot \psi_f}{J - k_s} . \tag{12}$$

When the intensity of rainfall is lower than the infiltration capacity, which is often the case at the initial phase of the rainfall, the quantity of infiltrating water is proportional to rainfall intensity.

Infiltration under conditions of varying rainfall intensity

The method of calculating infiltration under conditions of rainfall of variable intensity is similar to that of infiltration under conditions of constant rainfall. The basic difference concerns the fact that the rainfall intensity is changing in time in case of varying rainfall; therefore, calculations are conducted for time intervals of averaged constant rainfall intensity. In case of rainfall of constant intensity, the flooding of the ground surface is possible only in case when the intensity of the rainfall equals the infiltration capacity of the soil. In turn, in case of rainfall of varying intensity, there are two possibilities of ground surface flooding:

– the rainfall intensity is higher than the infiltration capacity during the whole rainfall time interval,

– the infiltration capacity is higher than the rainfall intensity at the initial phase of the time interval, but it decreases with time and becomes lower than the rainfall intensity.

Moreover, one more scenario of calculations is still applicable when rainfall intensity is lower than the infiltration capacity and the whole bulk of the rainfall infiltrates the ground, resulting the in undersaturation of the ground surface.

A detailed description of calculations is presented by Chow et al. (1988). The depths of the wetting front obtained with formula (12) were integrated with the depth of the sliding surface (formulas (1) and (3)) and used for stability calculations.

RESULTS AND DISCUSSION

Figure 2 shows the envelope of the calculated values of the pore pressure, determined on the basis of strength parameters of soils given in Table 1 for three different slope inclinations. The presented relationships explain to a large extent the mechanism of landslide initiation in the vicinity of Targanice. Regardless of the assumed geotechnical parameters, the loss of slope stability could occur only at the positive values of pore pressure, i. e. when the sliding surface was below the groundwater table. In the study area, the groundwater table is commonly situated a couple of meters below the ground surface, and the rainfall in the course of 2.5 hours is not able to force sudden changes in the groundwater depths and does not cause a complete saturation of the slope soil. Therefore, the only explanation of positive pore pressures in the considered case can be the infiltration of rainfall water, which causes formation of a saturated zone of soil in the surface layer of the slopes and setting in motion of surface runoff along the plane parallel to the surface of the slope. Figure 2 depicts an example of a pore pressure line, which illustrates the value of this parameter at the flow of water parallel to the slope inclined at 26°. The crossing of this line with the line of the critical pore pressure determined for the slope of the same inclination – the landslide 1 neighborhood (Fig. 2a) – shows the critical depth when the limit equilibrium occurs, i. e. the factor of safety is equal to 1.0. A comparison of the position of the plotted pore pressure line with the critical pore pressure lines shows that the critical depth is dependent on slope inclination. The smaller it is, the larger is the critical depth. In turn, in the case depicted in Fig. 2b for the soil with the cohesion equal to 0, the slope is unstable for the whole range of positive values of the pore pressure, regardless of the inclination of the slope.

The depth of the sliding surface for the landslide 1 presented in Fig. 2a does not fully reflect the results of observations

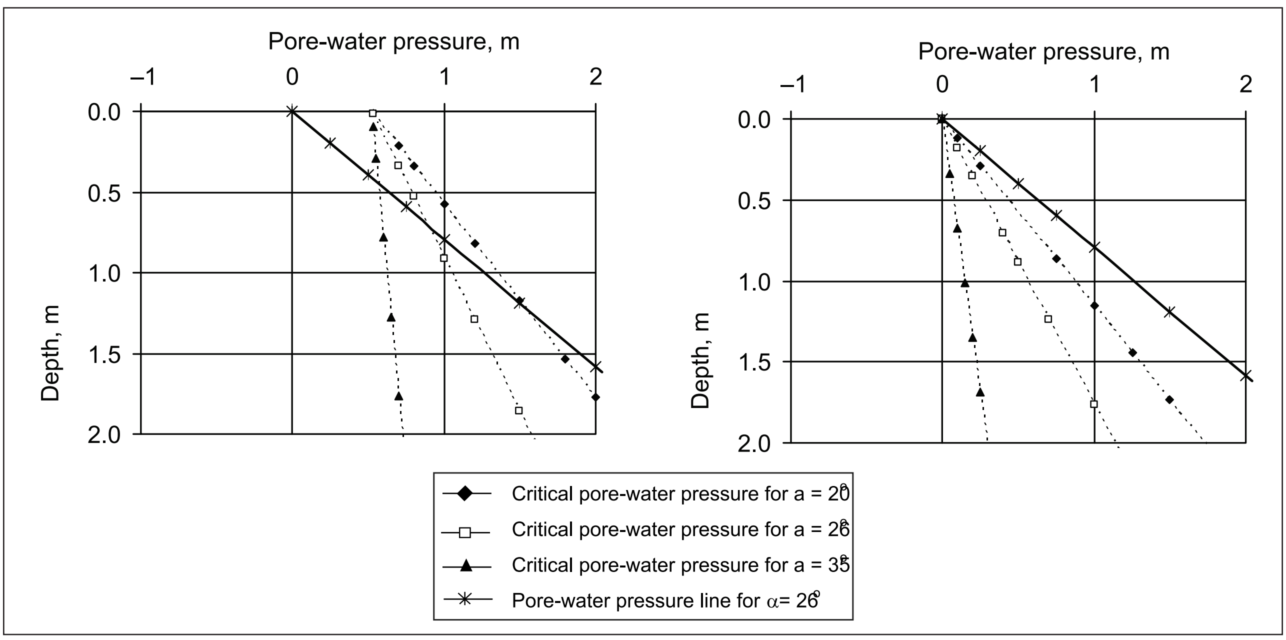

Fig. 2. Critical values of pore pressure versus the surface slope and soil strength parameters: $a - \varphi' = 37.4°$, $c' = 3.9$ kPa, $b - \varphi' = 38.6°$, $c' = 0$ kPa

2 pav. Porinio slėgio ir paviršiaus nuolydžio kampo kritinės reikšmės ir dirvožemio stiprumo rodikliai: $a - \varphi' = 37.4°$, $c' = 3.9$ kPa, $b - \varphi' = 38.6°$, $c' = 0$ kPa and field measurements, probably because of an imprecise assessment of the cohesion value. Therefore, the strength parameters of the soil of the analysed landslide were evaluated by the method of backward analysis. Formula (2) was used in calculations assuming the sliding surface depth to be 0.6 m. Consequently, the effective values of the angle of internal friction and cohesion were, respectively, 37.4° and 1.0 kPa. These results provide the base for calculating the safety factor.

Infiltration under conditions of constant rainfall intensity was calculated using the one-dimensional Green–Ampt model assuming, in accordance with the prior assessment, that the infiltration depth (and the depth of the sliding surface) was 0.6 m and the value of the soil surface layer permeability coefficient was equal to 4.4.10–6 m/s. Three scenarios, differing in the initial moisture content of the soil and related suction pressure, were considered in the calculations. The values of these parameters were assumed on the basis of the results presented by Zydroń (2010) and equal $Sr = 0.6$, $\Psi_f = 21.5$ cm for scenario 1 and $Sr = 0.6$, $\Psi_\phi = 3.6$ cm for scenario 3. In scenario 2, the parameter Sr is 0.7, and the average value of the suction pressure at the base of wetting front is assumed $\Psi_f = 17.6$ cm.

Figure 3 presents the relationship between the intensity and duration of precipitation, required to saturate the slope soil down to the depth of 0.6 m. The initial soil moisture was taken into consideration. Calculations showed that the smaller the initial moisture content of the soil, the longer the time of infiltration to a particular depth. Moreover, for the soil of assumed geotechnical parameters, at the increase in the precipitation intensity exceeding 0.6 mm/min, the influence of this parameter on the infiltration time was practically the same. These results show that the further increase in its intensity causes first and foremost the generation of surface runoff after exceeding the above value of rainfall intensity.

Considering that the duration of the rainfall was about 2.5 hours near Targanice, one can infer that the infiltration of the rainfall water down to the depth of 0.6 m could occur only when the degree of moisture content in the weathered zone of the slopes was about 0.8. At such moisture of the soil, the rainfall intensity sufficient for the saturation of the soil layer 0.6 m thick amounts to 0.37 mm/min. Taking into consideration the duration of the rainfall, its total value equals 55.5 mm, and this value was taken for the further analysis.

Calculations of the infiltration that takes into consideration variations in rainfall intensity were carried out using 10-minute time intervals of constant intensity of the rainfall. Six precipitation scenarios (hyetograms) were analysed:

(1) the most intensive rainfall occurs at its initial phase and decreases with time,

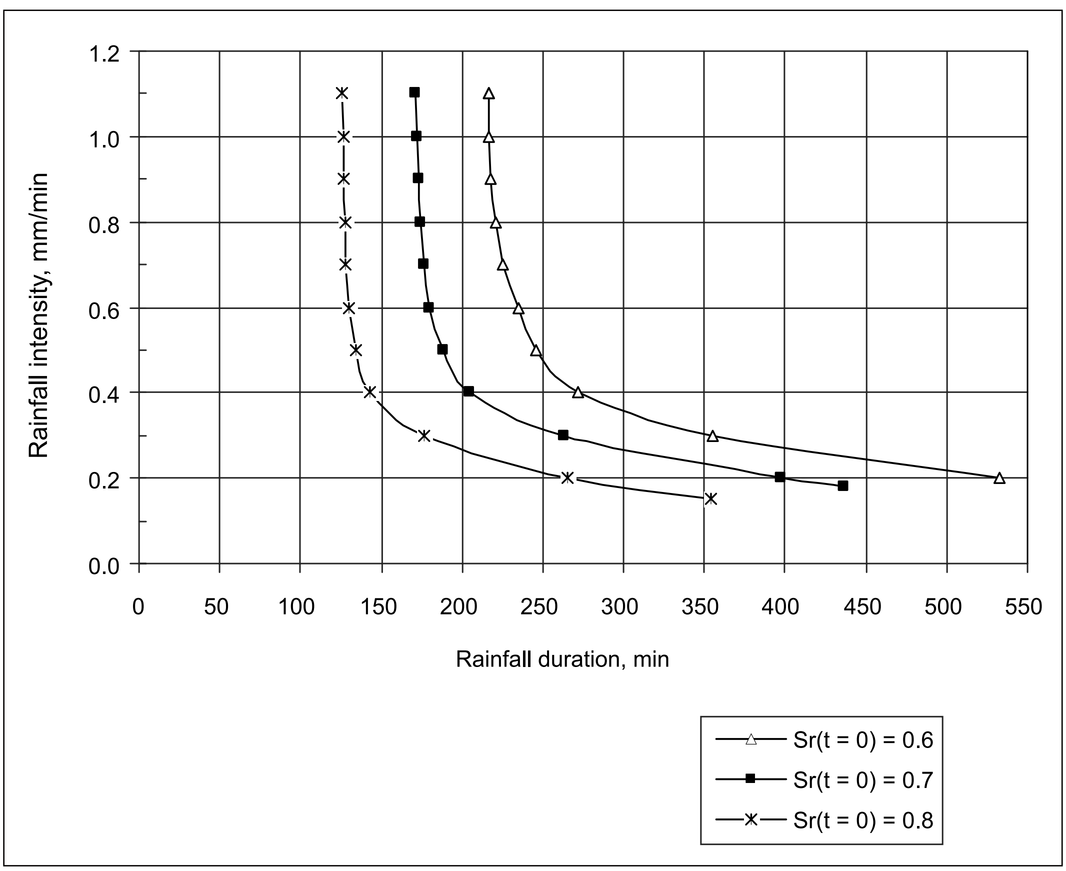

Fig. 3. Intensity versus duration of the threshold rainfall
3 pav. Ribinės liūties intensyvumo ir trukmės grafikas

(2) increasing intensity of the rainfall with time,

(3) the rainfall is most intensive in the middle phase and is of the same intensity at the initial and final phases.

In turn, the precipitation scenario 4 was assumed according to data given by Kupczyk, Suligowski (1997) who use the dimensionless total rainfall amount curves versus its duration. This approach is applicable (alongside the others) to mountain areas. Scenario 5 assumes the German guidelines taking into consideration characteristics of rainfalls of short duration (DVWK, 1985). Additionally, for the sake of comparison, the impact of a constant intensity rainfall (scenario 6) was calculated. All the assumed scenarios are illustrated in Fig. 4.

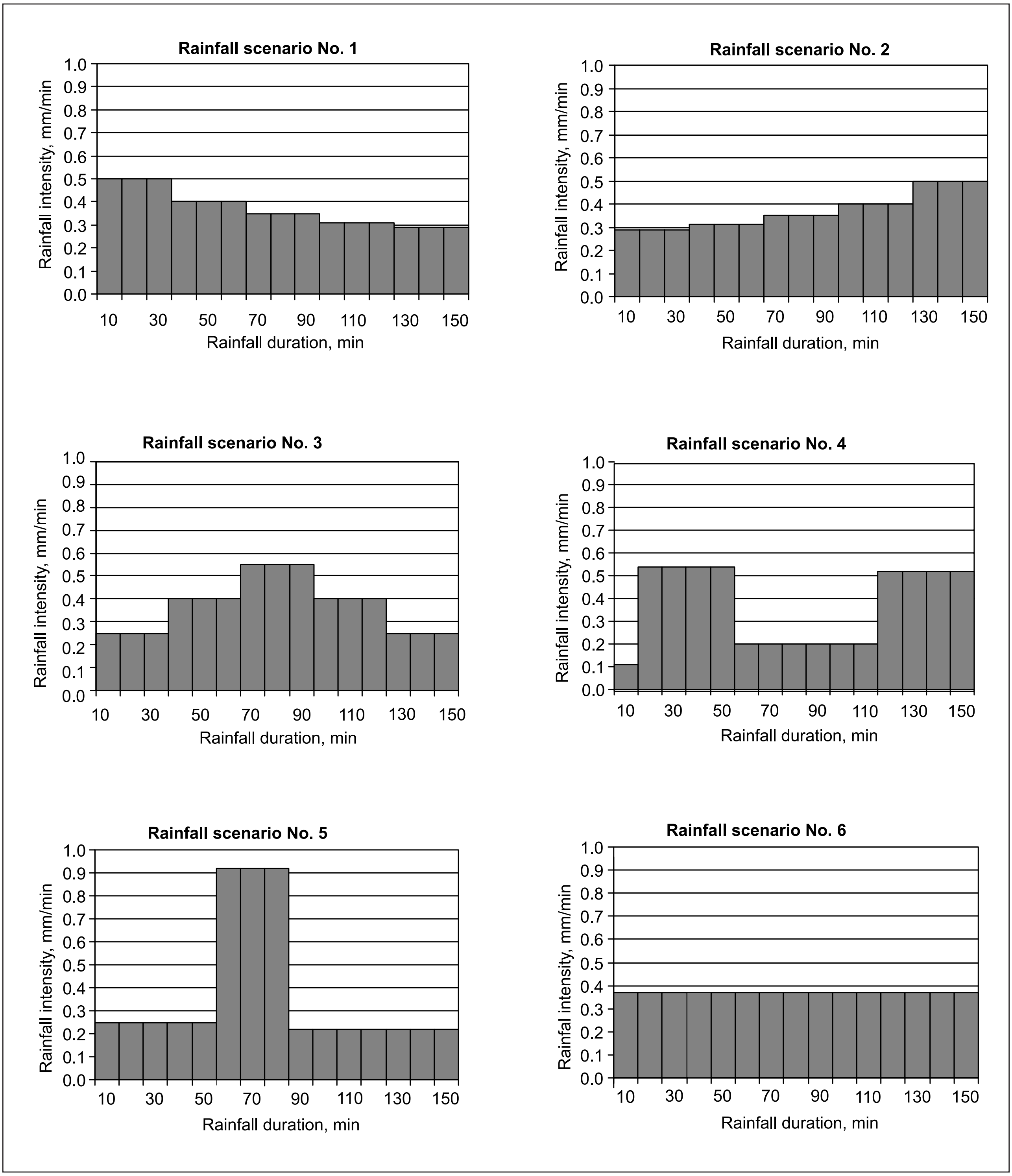

Fig. 4. Rainfall hyetographs used for the analysis

4 pav. Analizuoti liūties hietografai

Figure 5 shows a comparison of the results of calculating the magnitude of rainfall water infiltration into slope soil using one- and two-dimensional Green–Ampt models. The larger amounts of infiltrating water were obtained by the one-dimensional model for all scenarios, except scenario 5 which showed nearly the same water volumes in both models.

It is worth noting that the values of the infiltration accumulation determined using the two-dimensional model fall into a relatively narrow range of 36–43 mm, while they range within 41–55 mm in case of the one-dimensional model. As regards the stability of slopes, the one-dimensional model gives more conservative results, that's why it was used for the further analysis.

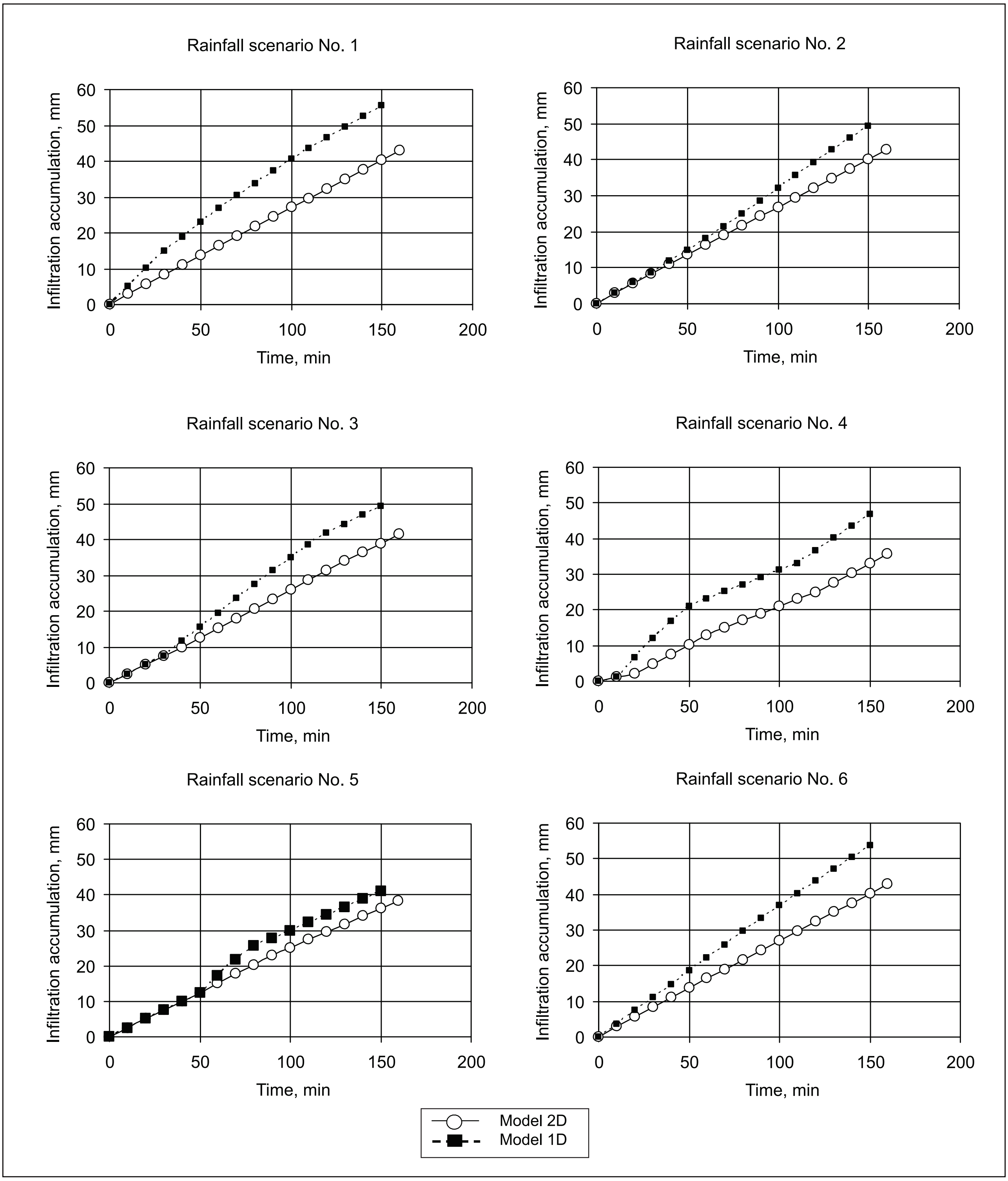

Fig. 5. Comparative plots of the quantity of water infiltrating into the soil depending on rainfall characteristics and the computational model
5 pav. Vandens infiltracijos į dirvožemį palyginimas esant skirtingoms lietaus charakteristikoms ir skaičiavimo modeliui

The results of calculations using the one-dimensional Green–Ampt model revealed significant differences in the depth of the wetting front during and after the rainfall (Fig. 6). For precipitation scenario 1, the infiltration front was situated at a depth of 0.62 m after 150 minutes of the rainfall and was most conducive for water infiltration into the soil. The slowest infiltration process was observed in scenario 5 where the final depth of the wetting front was 0.46 m. Interestingly, in the case of constant rainfall intensity, the depth of the wetting front was somewhat smaller than that in scenario 1 and reached 0.6 m. The relationship between the rainfall intensity and the infiltration capacity has an essential influence on the course of the rainfall water infiltration process. Figure 7 presents the extreme cases

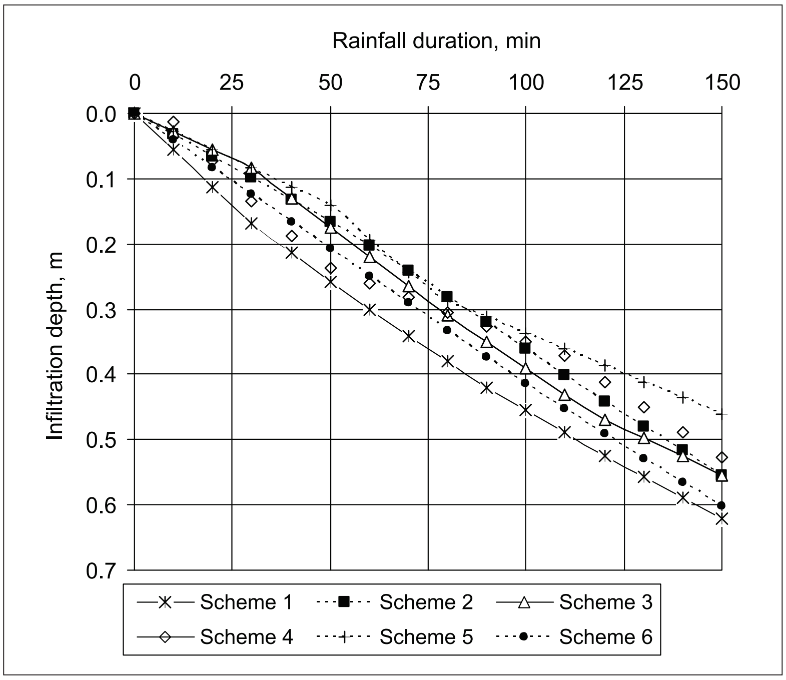

Fig. 6. Depth of the wetting front versus rainfall intensity time distribution
6 pav. Drėkinimo gylio priklausomybė nuo liūties intensyvumo pokyčių

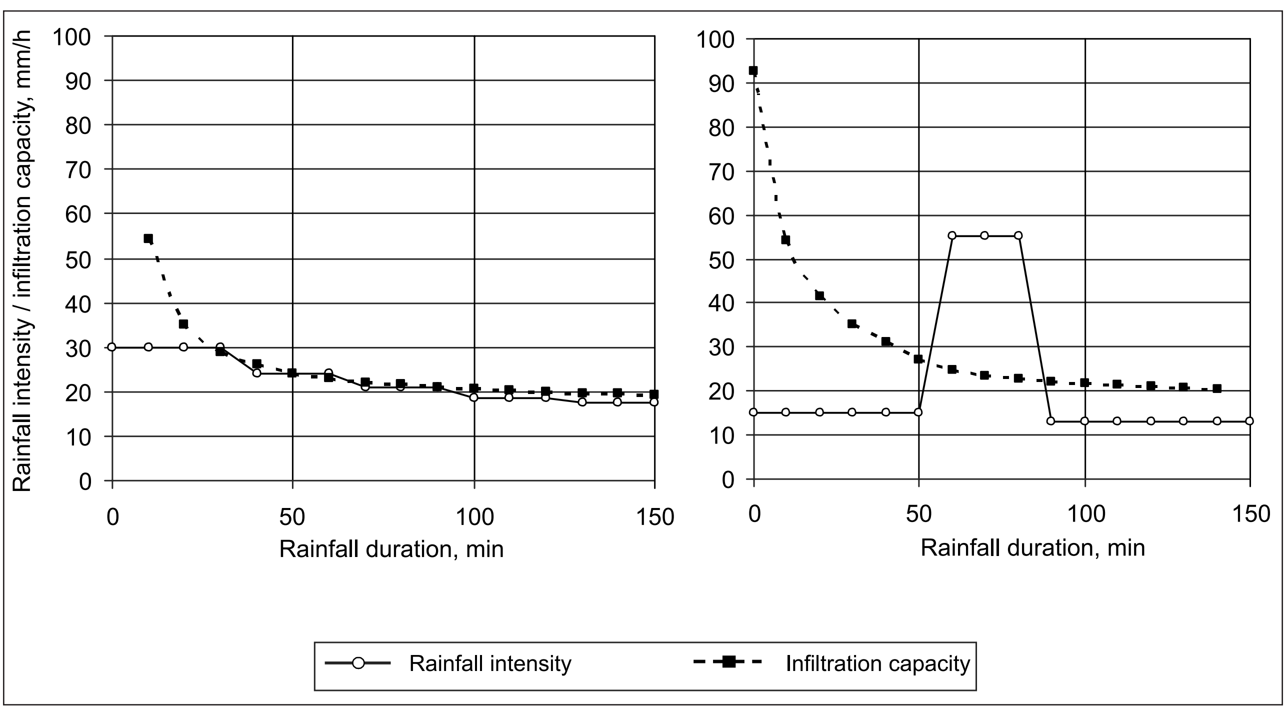

Fig. 7. Changes of the infiltration capacity of the soil and rainfall intensity
7 pav. Dirvožemio infiltracijos rodiklio kaita ir liūties intensyvumas

taken to the calculations. In case of the rainfall scenario 1, for almost the whole rainfall period, its intensity was close (mostly slightly larger) to the infiltration capacity, which signifies that practically the whole amount of the rainfall infiltrated into the soil. A somewhat different rainfall–infiltration capacity relationship occurred in case of the precipitation scenario 5, showing that its intensity was significantly higher than infiltration capacity in the middle phase of the rainfall, which means that a great part of the rainfall was transformed into the surface runoff. The results of calculations of accumulated rainfall and infiltration amounts, set together in Fig. 8, confirm the above statements. One can see that in cases of the rainfall

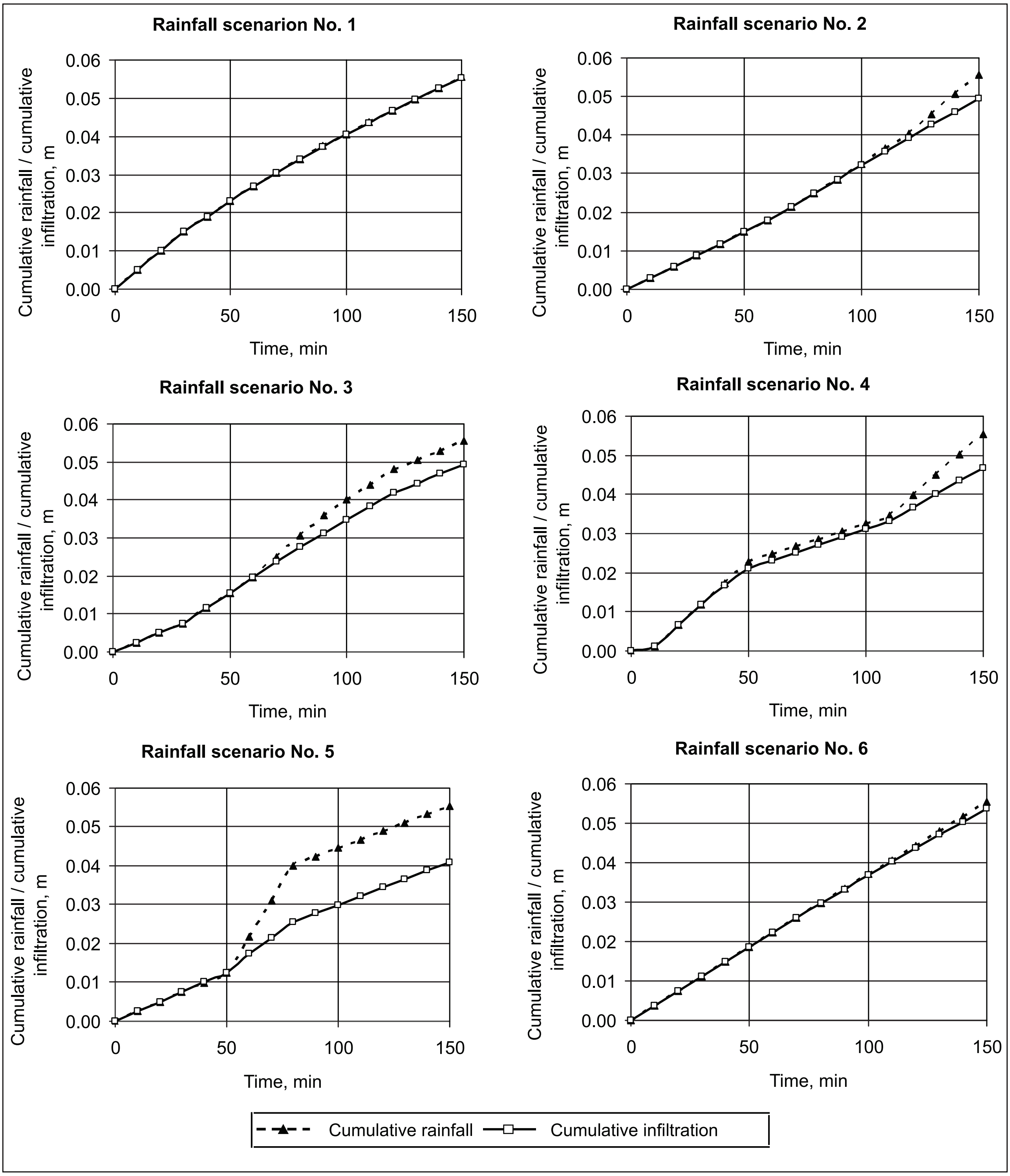

Fig. 8. Accumulation of infiltration and rainfall depending on the time distribution of its intensity
8 pav. Infiltracijos ir vandens akumuliacijos priklausomybė nuo liūties intensyvumo

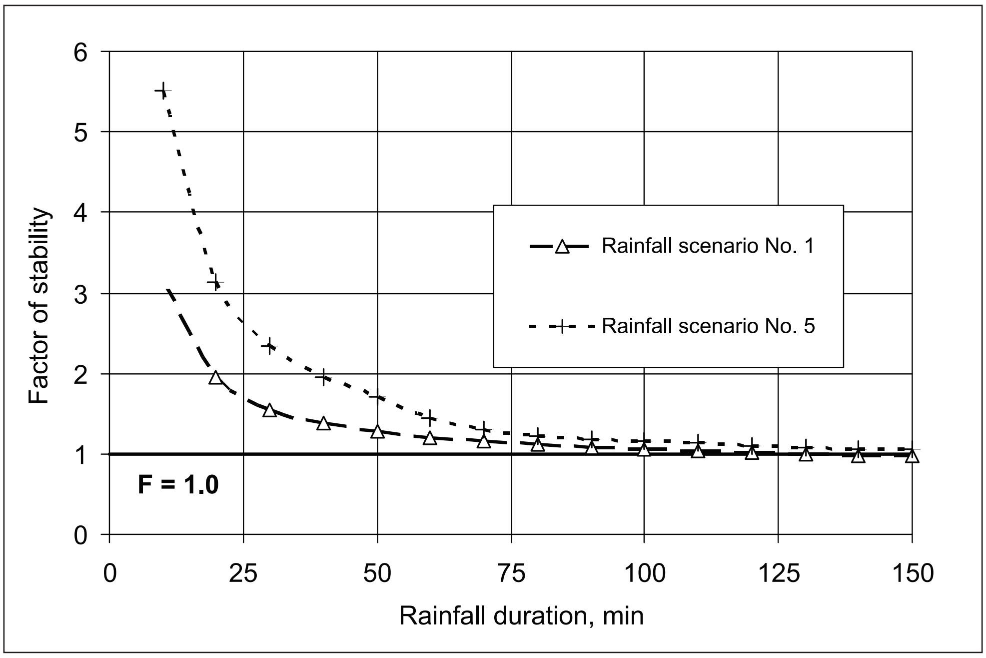

Fig. 9. Changes of the stability factor in relation to the depth of the wetting front and its type
9 pav. Stabilumo veiksnio kaita, susijusi su drėkinimo gyliu ir jo tipu

scenarios 1 and 6 the values of both parameters are equal to one another, which means that practically the whole amount of the rainfall infiltrated into the slope; the values of the surface runoffs were, respectively, 0.2 and 3.5% of the total amount of the rainfall. In turn, the largest difference of the accumulated and infiltrated rainfall was obtained for scenario 5 in which the value of the surface runoff was 26.1%.

The obtained relationships between the infiltration and rainfall are similar to those provided by Tsai (2008); Xue, Gavin (2008), Jia et al. (2009). These authors have unanimously stated that rainfalls of the highest intensity at the initial phase and the intensity decreasing with time are conducive to the largest infiltrate accumulation. The least effective, from the point of view of the infiltration amount, are rainfalls of increasing intensity. Somewhat different relationships were stated in case of a constant rainfall intensity. According to the aforementioned authors, rainfalls of this trend have moderate values of infiltration accumulation, while in the present study the constant rainfall is highly effective as regards the amount of infiltration, similarly to a rainfall of decreasing intensity. The obtained relationship may result from the accidental similarity of infiltration capacity and rainfall intensity in the time span under analysis.

The magnitude of infiltration influences the depth of the wetting front and thus the stability of slopes in the case of cohesive soils. Figure 9 presents a comparison of the safety factor values calculated by formula (2) for the extreme rainfall scenarios 1 and 5. In case of scenario 1, the value of the safety factor is 0.99 at the end of the rainfall, whereas the value of the safety factor amounts to 1.05 in case of scenario 5, which means that rainfall water infiltration does not disturb the slope limit equilibrium conditions. In the remaining cases, the values of the safety factor are 0.97–1.01, reaching the lowest value in scenario 6. Assuming the stability conception by Collins, Znidarcic (2004), using formula (3) for calculations and taking into consideration the most unfavourable conditions of the groundwater flow (horizontal flow in the direction of sloping), the calculated values of the safety factor are within 0.78–0.86. Notably, this type of the loss of the stability mechanism may be related basically to the rising groundwater level and cannot be triggered by the infiltration process. Formula (3) for determination of the safety factor, suggested by Collins, Znidarcic (2004), is more universal as compared with the one proposed by Skemton, DeLory (1957, formula 1); however, the results by both formulas are convergent as the stability of the saturated soils is considered, and the value of the pore pressure in formula (3) is expressed as follows:

$$\Psi p = z_w \cdot \cos^2\alpha. \quad (13)$$

It should be stressed that the evaluation of slope stability expressed by formula (4) based on the critical values of pore pressure provides a practical tool for monitoring the state of slope stability, since the value of this parameter is relatively easy to obtain.

CONCLUSIONS

The stability of slope surface layers was calculated taking into consideration the influence of rainfall of varying intensity on the value of water infiltration into the soil profile. Calculations of infiltration, made using the one- and two-dimensional (hydrological) Green–Ampt model, revealed significant differences in assessing the precipitation–infiltration–surface runoff relationship. It is shown that the calculations by the one-dimensional model lead to higher values of infiltration and thus rate this method as more conservative, i. e. more safe, from the point of view of slope stability assessment.

The results obtained from infiltration calculations using the one-dimensional Green–Ampt infiltration model have revealed a significant influence of rainfall intensity variations on the depth of rainfall water infiltration; the differences in the depth of wetting front for the considered time of the rainfall amounted up to 35% and were to a large extent related to the calculated surface runoff. It has been shown that rainfalls of the highest intensity at the initial phase, of a decreasing intensity with time, and rainfalls of constant intensity contribute to the largest values of infiltration accumulation and thus to the depth of infiltration into the soil. The depth of the wetting front, changing in the course of rainfall, influences the slope stability. The concept of the stability assessment, suggested by Collins and Znidarcic (2004), provides a universal approach to slope stability assessment for both saturated and non-saturated soils. Assuming the pore pressure of the soil as the main criterion in slope stability assessment makes this method easily applicable for engineering practice purposes.

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KINTANČIO INTENSYVUMO LIŪČIŲ POVEIKIS ŠLAITŲ STABILUMUI

Santrauka

Straipsnyje aptariami skirtingi liūčių scenarijai, kai liūties intensyvumas kinta, ir jų poveikis šlaitų stabilumui. Taikant Green-Ampt šlaitų stabilumo skaičiavimo modelį buvo atskleisti ryškūs skirtumai tarp skirtingų scenarijų ir prielaidų. 1D ir 2D modelių rezultatai labai skiriasi. Konservatyvesni1D modelio rezultatai, autorių nuomone, geriau atspindi šlaitų stabilumo rizikos grėsmes, todėl šis modelis naudotinas atliekant praktinės rizikos įvertinimą.

Nevienodo intensyvumo liūtys turi didelį poveikį šlaitų stabilumui, susijusiam su vandens infiltracijos gyliu. Nustatyta, kad labiausiai šlaitus destabilizuoja liūtys, intensyviausios pradinėje fazėje, ir liūtys, kurių intensyvumas išlieka panašus per visą liūties laikotarpį. Pasiūlyta skaičiavimo metodika (Collins, Znidarcic, 2004) yra labai efektyvi ir paprasta sudarant nuošliaužų grėsmės žemėlapius. Šio metodo pagrindas – porinio slėgio koncepcija.

Raktažodžiai: paviršiaus nuolydis, šlaitų stabilumas, infiltracija, Freen-Ampt modelis