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Wanda KOKOSZKA[1]

RISK ANALYSIS WITH AN APPLICATION TO LOCAL ROAD INFRASTRUCTURE

The paper presents the concept of the risk evaluation for road infrastructure exposed to natural hazards – floods and landslides. Floods and surface mass movements impose a serious threat to the contemporary activities and people's lives in modern economy. The natural meteorological and hydrological phenomena are main causes of a landslide activation. Typically, heavy or prolonged rain is combined with the progressive flooding. In river valleys, an increased lateral erosion of rivers and rapid snow melting in early spring would also lead to flood events. In Poland, the Carpathian regions are mostly predisposed to the formation of landslides. This may be favoured by the nature of shapes associated with high and steeply sloping slopes of the valleys and flysch geological structure. The paper presents the general characteristics of precipitation in Poland and the concept of a risk assessment with risk matrix. The issue is illustrated by an exemplary detailed risk matrix for a selected section of the road infrastructure in Subcarpathian province.

Keywords: natural hazard, road, flood, landslide, risk matrix

1. Introduction

Over the last decades, extreme natural phenomena, such as heavy or prolonged precipitation and the associated increase in landslide risk, cause significant economic and financial losses in the areas affected by these phenomena**.** The current situation should force to constant improvement of the principles and research methods used in hydrology, including monitoring of precipitation, both design and dimensioning of construction and communication infrastructure, drainage and sewage systems, and drainage of endangered areas. The issues of modeling and forecasting climatic impacts caused by atmospheric precipitation on building constructions are the matter of great importance, especially in the case of strongly urbanized areas, where the financial, economic and social consequences can be serious. In the literature and such standards as EN 1990-1999 [1] and ISO 2394 [2], the strategies and rules for ensuring an adequate level of safety of buildings and other structures for exceptional

[1] Wanda Kokoszka, Rzeszów University of Technology, Department of Geodesy and Geotechnics, ul. Poznańska 2, 35-959 Rzeszów, Poland, tel. 178651013, wandak@prz.edu.pl. http://orcid.org/0000-0003-0486-9881

loading, including climatic influences, have been defined. The hitherto models of climatic impacts are adapted to semi-probabilistic methods of structural design, i.e. they allow to estimate characteristic values (quantiles of the order 0.05–0.02 interactions treated as random variables) multiplied by partial safety coefficients γ_F, in order to get their design values [1]. Semi-probabilistic methods of calculations of engineering structures are based on values of actions similar to mean values. However, in the probabilistic methods of 2nd and 3rd order the design values should be estimated directly [3]. With this approach, the extreme values of actions and effects of actions are decisive for the safe and reliable structural work, in comparison to those for which there is a high probability of occurrence. The extreme values of the interactions with a very low probability of occurrence decide about exceeding the ultimate limit states and destruction of the structure. The doubts about classical principles and research methods regarding climatic actions, including recommended standard methods, are caused by the disproportion of the time scale (the length of the time interval) from which the measured data originates (most often several dozen years), which indicates the contractual character of the recommended exceptional actions [4,5]. The repeatability obtained for values assessed as extreme may reach even several thousand years. Therefore, determining the values of exceptional loading, their forecast and risk assessment in relation to the planned and existing buildings and communication infrastructure is a very important task due to the potential social, economic and financial consequences.

2. Spatial development and climate monitoring

The area of Poland is located in the moderate climate zone [6,7] and is exposed to the occurrence of various extreme phenomena of natural threats directly affecting building structures. These include landslides. In the Carpathians, which occupy about 6% of Poland, the number of 23000 landslides have been identified and documented, which is about 95% of all landslides registered in Poland. In the most susceptible regions of these mountains, about 40% of the area is covered by landslides or other forms of mass movements. The area of Polish Carpathians is about 19500 km^2, therefore, it can be estimated that in this region of Poland for every square kilometer of area and for each 5 km of road infrastructure network, there is one landslide on average [8].

2.1. Ground based weather stations in Poland

In Poland, the tasks in the field of hydrological and meteorological protection of people and the economy are performed by the State Hydrological and Meteorological Service (PSHM), and their fulfillment under the Act of 18 July 2001 Water Law [9] was entrusted to the Institute of Meteorology and Water Management – National Research Institute (IMGW). The main tasks of PSHM are as follows: measurement and observation works, data transmission, processing and distribution. In the case of climatic actions on historical constructions, historical data is the matter of highest importance.

Both short-term intense rainstorms with a local territorial range, as well as long rainfall of lower intensity, but with a broad range of terrain, may cause damage to the environment and urban and industrial risk. Such phenomena occur now and will happen in the nearest future. Therefore, it is necessary to aim at limiting the detrimental effects of such random events by determining both the probability and performing risk quantification.

The PN-EN 752: 2008 [10] standard limits the frequency of flooding from sewage systems or the lack of possibility to a rainwater collecting, to the rare socially acceptable repetition of their occurrence once every 10 years for rural areas and 20, 30, or 50 years, respectively, for urban areas – according to their spatial zoning. That is the reason why a systematic research on precipitation and determination of the statistical frequency of their maximum amount, intensity and unit exertion are so important, even for rare rainfall repetitions. As far as statistical analysis is concerned, sufficiently long and continuously updated archival material from rainfall observations is necessary. A verification of statistical material regarding precipitation is a task justified not only economically, but also technologically. The data acquires particular significance in relation to quantitative differences, such as calculated yield rainfall for reliable channel dimensioning [11,12,13], or retention reservoirs [7,14], as for models and standards used in Poland [7,8]. Precipitation in moderate climate zone occurs both in liquid drops (rain, drizzle) and in solid state (snow, hail).

Neither the rain intensity is constant in time nor in the area covered by precipitation. Momentary unit intensity of precipitation may be several times higher than the average. High intensity may occur once or more times during the rainfall, appearing in random sequence. These phenomena, variable in nature, are difficult to describe in individual terms in time and space, e.g. in the urban catchment scale, but necessary for generalizations or simplifications for design purposes. At present, it is recommended to take into account various scenarios of atmospheric precipitation (variable in time and space) taking into consideration either actual series of local rainfalls measured for at least 30 years, or a model rainfall, based on e.g. Euler 2nd order or Weibull distributions created from IDF or DDF curves the so-called synthetic hietograms [4].

As for a design of safe building facilities and infrastructure, both short-term (fleeting) rainfall with high unit intensity (q) and long-term rainfall (widespread) with significant territorial range (A) and high efficiency are decisive ($Q=q(A)$).

Heavy or volatile rains come from stormy clouds (cumulonimbus), usually lasting several dozen minutes (sometimes few hours) and are characterized by high intensity and varied local range, covering the area from several to even several hundred square kilometers. They occur in Poland in the summer time, from May to September, and usually in July. Rain phenomena lasting longer (up to several days) usually consist of several precipitation, occurring immediately after each other, separated by periods without precipitation. As for the design of slopes and the occurrence of landslide phenomena, long-term (widespread) rainfall affecting the state of the soil is the matter of the greatest importance. They cause the largest water infiltration of the subsoil [7].

In order to increase the reliability of the road infrastructure and construction objects designed on the slopes (in accordance with EN 1990 [1] and ISO 2394 [2]), the need of refining the principles of dimensioning based on continuous precipitation measurements over several decades becomes crucial. This is a need to capture the possible trend of climate change, especially in recent decades and to develop methods for estimating both the threat and risk taking into account economic consequences. The efficiency and credibility of each calculation method, as evidenced by the principles of reliability, determines the fulfillment of the requirements for safe and durable use in the designed lifespan.

2.2. General characteristics of precipitation in Poland

Precipitation being a discontinuous meteorological phenomenon is characterized by high temporal and spatial variability of occurrence, as well as a significant variation in the sum of heights. A number of environmental determinants determine the precipitation phenomenon of a specific area. Among them, the most important are the geographical location, the distance to water reservoirs (including seas and oceans), the shape of the surface and the elevation of the area above sea level, vegetation cover and specifics of terrain, and others. The rainfall measurement takes place pointwise, in a given network of measuring stations, what in relation to larger areas requires the use of appropriate interpretations of the measurement results obtained. The relationships of the intensity (or height) of the rainfall with the duration and frequency of occurrence, developed for many geographical regions of the world (America, Asia or Europe) are qualitatively similar to each other. [7,15,16]. However, it does not mean that they are quantitatively identical, especially at the microscale of local precipitation.

Referring to the extreme rainfall of long duration occurring in Poland, it should be pointed out that the greatest value of precipitation for a 24-hour period is the rainfall recorded on June 30, 1973, the sum of which was equal to 300 mm (Hala Gąsienicowa). The sum of precipitation for the 48-hour period (29 to 30 June 1973) was equal to 372.8 mm, and for the interval of 72 hours (June 29 - July 1, 1973) was measured at 384.5mm. The amount of rainfall over 24 hours indicates that the area of Poland is characterized by the highest values among neighboring countries in region. In Poland, the highest sums of precipitation lasting 48- and 72-hours occurred in the area of the Śnieżnik Kłodzki massif on July 5-7, 1997. The highest 48- and 72-hour precipitation in total was then equal to 422.0 and 557.0 mm, respectively [17]. During the flooding period of July 1997 on the IMGW network, the highest daily sum was measured at the station in Międzygórze and amounted to 200.1 mm (July 6, 1997), the 48-hour total was equal to 364.6 mm (July 4, 07), and the 72-hour in total reached 431.2 mm (July 05-07). The monthly rainfall amounting to 702.0 mm was also record-breaking (measured at Kamienica) [7,17,18].

On the basis of the analysis of maximum precipitation levels with duration of 5 minutes up-to 72 hours (Table 1) for the climatic conditions of Poland and selected European countries, a comparable amount of precipitation may be observed. For most European countries, 24-hour volumes have a rainfall level close to Poland - 300 mm. Also extreme amounts of short-term precipitation, most often convective rains, in Polish climatic conditions are comparable with the recorded rainfall levels in neighboring countries. The reader may find many details of torrential and heavy rainfall patterns occurring in Poland [17,18].

Table 1. The maximum precipitation for selected European countries [mm] according to [7]

Country	**Duration of precipitation**					
	Min.			Hours		
	5	10	15	24	48	72
Poland	25.3	80.0	79.8	300.0	428.0	557.0
Germany		126		312.0	379.9	458
Czech Rep	29.8	39.8	50.2	345.1	380.0	536.7
Hungary		64.2		260	288	
Norway	17.9	31.5		229.6	378.9	402.4

3. Natural hazards and spatial management in Poland

In the case of Poland, the landslide threat applies to all counties and communities located within the Carpathians, in the following provinces: Silesia, Małopolska and Subcarpathian, where after rainfall the state of the ground changes. Landslide processes generally trigger with a certain delay in relation to rainfall, that is the reason why their intensity may take place in the following weeks after the occurrence of heavy and continuous precipitation. Usually in the Carpathians, after the rainfall, the sum of which exceeds the range of 70-100 mm, generally shallow landslides become active whereas, after over 400 mm rainfall - large and deep landslides may be formed.

The main reason for the high financial losses occurring in landslide areas in Poland is not well thought-out activity of investors, manifested in the location of the construction and communication infrastructure on the threatened or active slopes. Financial expenditures for reconstruction and/or repair of damaged facilities and roads are significant. The losses caused by landslides are counted in millions. In the Małopolska province alone, they amounted to approximately PLN 170 million in just two years (2000-2001). It should be emphasized that often, however, the effects are removed, not the cause of such mass movements. Often, incorrect stabilization of landslides is the result of insufficient geological recognition, based only on theoretical premises, not confirmed by appropriate geological-engineering studies. [19]. Financial and economic losses caused by landslides may be estimated, while social and moral losses are almost impossible to be valued. The only effective solution to the landslide problem is the exclusion from the new development of the areas of currently and periodically active landslides and the limitation of buildings predisposed to their occurrence, and, above all, appropriate monitoring and development of landslide hazard maps. The System Guards Against Landslides (SOPO) project, implemented in recent years in Poland, offers the chance to avoid major problems related to mass movements in the future by introducing landslide cards, that is, indication, description and regular observation and monitoring in the most-threatened areas, to limit private, public construction works in areas at risk. The SOPO project is an opportunity to limit the negative effects of mass movements throughout Poland.

The difficulty in forecasting landslides is closely related to rainfall and results from irregularities in the occurrence of various weather phenomena. Catastrophic rains may occur once every several, a dozen or even several hundred years. Their occurrence is in practice unpredictable, only the statistical probability of their occurrence may be determined.

The end of the last decade of the 20th century and the beginning of the 21st century were marked by the exceptional severity of catastrophic events in the Polish Carpathians. After a long break between 1980-1990, when there was no high precipitation in this area, since July 1997 there has been a radical change in the amount of precipitation and spatial distribution. After the rainfall in July 1997, the great amount of water contributed to the launch of the Carpathian slopes. New landslides were created and old renewed in the western and central part of the mountains, in areas with new housing and communication infrastructure, which often led to its deterioration. The winter weather conditions of 1999/2000 contributed to the renewal of great many landslides mainly in the area of the Carpathian Foothills (over 2500 reported cases).

L. Starkel [20] writes about a specific "cluster of extreme phenomena", which began with catastrophic precipitation in the summer of 1996, marking the activation of an enormous number of landslide processes in the Carpathians. The cluster lasted for several years until 2010. A strict determination of the end of the landslide process is very difficult, because once the stability of the slope is disturbed, even with less efficient driving force, it is in a state of unstable equilibrium.

Landslides alongside with floods contribute more to the development of landforms. In contrast, however, from the flooding, which is a catastrophic but episodic phenomenon, landslides are a continuous phenomenon, when the mass movements occur on the slopes constantly, even without the action of a stronger triggering force. And often landslide suddenly becomes a catastrophic phenomenon of unpredictable strength and intensity.

Landslides formed as a result of recent catastrophic precipitation and floods associated with them together with losses counted every year in hundreds of millions caused that the mass movements entered the catalog of natural disasters and were included into the Polish law.

4. Risk analysis and expected losses for the selected section of road infrastructure

4.1. Methodology

In the risk assessment is to determine the risk acceptance criterion. There are numerous proposals for quality criteria and the criteria mixed, usually not very precise and led to substantially different results [21,22,23]. Most often these are different variants of the principle of ALARP, i.e. the risk as low as reasonably practicable. The PN-EN 1991-1-7 [24] presented a mixed criterion in tabular form as the mathematical expectation of the consequences of an undesired event (Table 2).

Table 2. Matrix of acceptable quantitative risk levels according to [24]

Probability of Failure / Consequences	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
Very large	X				
Large	X				
Medium		X			
Low			X		
Very Low				X	
X – represents the largest acceptable level of risk					

The social acceptability of risk is determined by comparison with other types of individual risk and lack of social acceptance for disasters, in which great many people may lost their lives. In EU countries acceptable level of probability of loss of life or *health of a person* p_{fd} *is estimated depending on the natur*e of the risk [12,25] as:

* The voluntary risk (e.g. professional work, sport) $p_{fd} = 10^{-3}$/year;
* Natural risk (e.g. floods, hurricanes, landslides) $p_{fd} = 10^{-4}$/year;
* The imposed risk (such as construction failure, acts of terrorism) $p_{fd} = 10^{-5}$/year.

The criteria proposed in the form of matrices of mixed quality and acceptable levels of risk are presented in many publications, including [26,27,28]. Depending on the consequences and costs of damage, the level of risk associated with damage of the road infrastructure located in the area of floods may be considered as acceptable, when the risks of loss of life of people as a result of the damage of the road is small, and its economic, environmental and social consequences are small, or inadmissible (Table 2).

The common form of presentation of risk dependent on the probability of occurrence of hazards and their consequences is a risk matrix. If the available knowledge on the consequences of hazard is imprecise, incomplete, subjective and/or is qualitative, the risk R may be considered as a fuzzy parameter and estimated with linguistic variable or fuzzy sets using the following formula (1):

$$R = H\,x\,C \tag{1}$$

where: H - is imprecise occurrence associated with the occurrence of hazards, and
C - is imprecisely, fuzzy defined loss caused by a hazard, consequence.

The qualitative form of both the hazard and the financial loss caused by damage of transport infrastructure, may be expressed in the form of linguistic variables, which are described by fuzzy sets, or fuzzy numbers.

In a situation, where the risk and financial consequences of damage of the road infrastructure may be estimated as linguistic variables, subjectively, and/or imprecisely, a relevant assessment is presented in the form of fuzzy matrix or as linguistic variable (Fig. 1) [29].

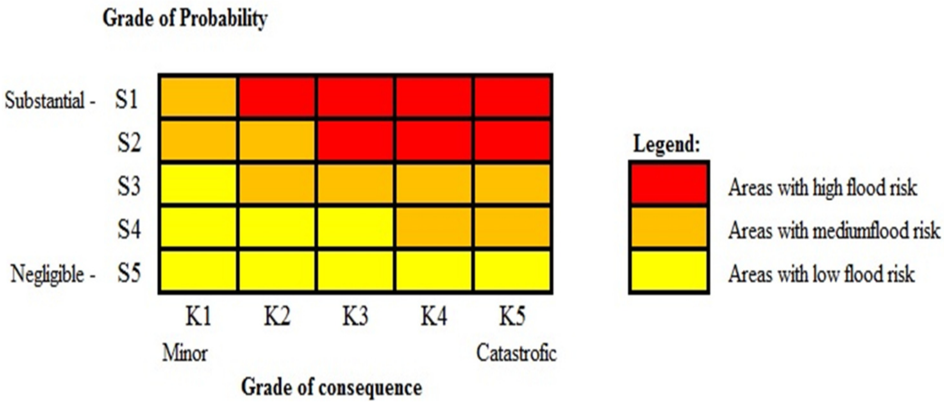

Fig. 1. Example of risk matrix based on flood probability and consequence according to [29]

4.2. Case study

This study therefore sought to develop a landslide risk map showing the risk of floods and landslide occurrences in selected area of Niebylec community. The identification of areas prone to landslide is a fundamental component of disaster management and an important basis for promoting safe human occupation and infrastructure development in areas of Subcarpathian region, considering the devastating impacts of land movements. The study were assisted with investigating the characteristics and factors which determine the value of a risk map for road infrastructure. There were several reasons responsible for a the formation of landslides in the considered area. Undoubtedly, the direct cause is a torrential rainfall. The association of the formation or activation of landslides in the Outer Carpathians (named Flysch Carpathians) with the height and intensity of precipitation is indisputable and has already been described many times [30,31,32]. In addition, the flysch geological structure, which is characterized by alternating layers of water-permeable sandstones and poorly permeable shales, clays and marls becomes another serious reason. Also, the presence of quaternary weathered cover more susceptible to landslide processes and tectonic structure, i.e. arrangement of rocks, cracks, faults become a source of threat. The landslide in analyzed does not significantly differ, when considering its parameters and local precipitation (Fig. 2).

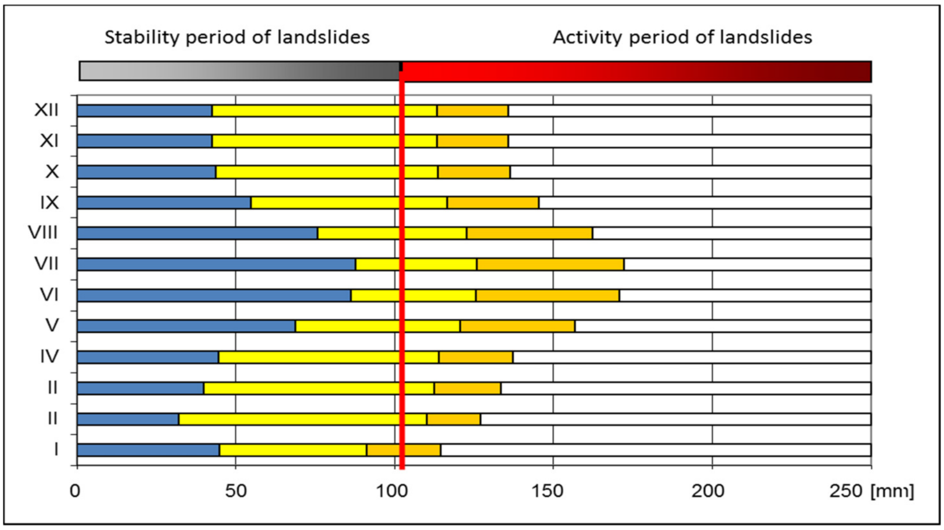

Fig. 2. Potential stability and activity period of analysed landslides in relation to the year's average of maximum rainfall amount of rainfall for Niebylec community

Risk assessment of flood for the sketch of road infrastructure was performed according with the algorithm for the selected area (Table 3):
1) the class of hazard of flooding of the land surface was determined,
2) the clas of consequences of the road section was determined.
3) risk matrix for sketch of the road infrastructure was determined (Table 4):

Table 3. Grade of hazard and consequence

Hazard /Consequences	Grade of hazard/ consequences
Very small	1
Small	2
Medium	3
High	4
Very High	5

Table 4. Risk matrix

Hazard xConsequences	Very small	Small	Medium	High	Very High
Very small	1	2	3	4	5
Small	2	4	6	8	10
Medium	3	6	9	12	15
High	4	8	12	16	20
Very High	5	10	15	20	25

Risk	Grade of risk
Very small	1,2,3,4
Small	5,6,8,9
Medium	10,12
High	15,16
Very High	20,25

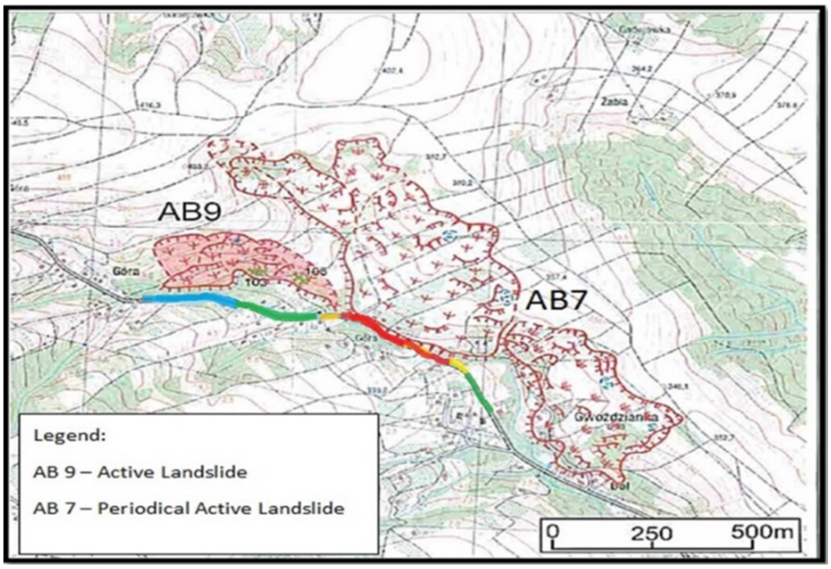

Fig. 3. Final risk map of the road section for Niebylec community [own elaboration based on 33,34]

The last stage of analyzes was the elaboration of the final risk map of the road infrastructure (fig. 3).

Analyzed local road has pavement of flexible structure. The construction cost of 1 km road distance is 720 950 PLN for this type of structure and road category. The financial consequences associated with the destruction of the road are high. The risk of road damage is very high for 0,3 km section, because the road is located near a watercourse and landslide, so the hazard risk of landslides and flooding for this road is significant.

5. Conclusions

Floods and landslides belong to natural threats and cause losses both in the natural environment, as well as in infrastructure and construction. In the communes of south-eastern Poland, there is both a flood risk and a landslide risk. These two threats very often go hand in hand as long-term precipitation causes flooding of buildings located near watercourses and, at the same time, starts landslide processes on slopes above river valleys. The knowledge of hydrogeological conditions and monitoring of geotechnical and hydrological parameters of a given terrain is the basis for forecasting the occurrence of these threats and the development of a landslide risk map. Therefore, the article underlines the issue of monitoring of these two threats in parallel.

The implementation of an investment on a landslide or in the vicinity of landslide area or flood risk area is possible, if it is combined with technical activities enabling both hazard identification and estimation of the risk of both threats. After recognizing and assessing the risk, the economic calculation of the investment will indicate whether it is economically justified to invest in such areas. On the other hand, due to the cost of the necessary safeguards it may suggest the withdrawal of investment in such risky area. This problem concerns not only private, but also public investments. It also involves the design and construction of linear infrastructure facilities used for roads and railways, which should be carried out taking into account the risk assessment. Furthermore, it is also important to ensure the safety of people and the existing building infrastructure. Increasing the level of security each time increases the economic costs of projects, especially in relation to the societies of developing countries. However, such investments in the nearest future may provide better development conditions and oppose migrations of people from the endangered areas.

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