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QUANTITATIVE ASSESSMENT OF THE INFLUENCE OF WATER PRESSURE ON THE RELIABILITY OF WATER-PIPE NETWORKS IN SERVICE

Making use of the results of many year observations and in-service studies, analyses were performed and generalizations were made regarding the reliability of the water-pipe networks of Brzeg, Kłodzko, Oleśnica, Opole and two regions of the city of Wrocław. The contribution of reduced pressure head and reduced daily variations in the forcing pressure at the pumping stations to the rate of pipe failure was quantified. Taking into account the results of water loss analysis for the water-pipe networks under study, the effects of pipe failure were assessed. A correlation was found to occur between water loss, water pipe loading, failure rate and maximal head of the forcing pressure at the pumping station.

1. INTRODUCTION

Since they are the most costly elements of water supply systems, water-pipe networks should be characterized by a high reliability level and low running costs. In Poland, most of the water-pipe networks that are in service have been made from grey cast iron with no protective coatings. In consequence, the frequency of of failure is very high, which has to be attributed not only to the long service history of the pipes but also to the pipe laying technology used, which was obsolete even at the time when the water-pipe networks were constructed. A previous study into water-pipe-related issues [1] has substantiated the strong influence of two other contributory factors on the rate of pipe failure: that of the pressure head and that of water pressure variations. Pressure exerts an influence on the rate of water flow through the damaged elements of the network, regardless of the underlying cause of the damage produced. It is therefore necessary to adopt appropriate measures for controlling the pressure in the network, since any reduction in excess pressure or water pressure variations substantially decreases the number of failure events, the

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repair costs involved, and the water loss in the pipeline. The aim of this study was to analyze the issues mentioned above.

2. SCOPE OF THE STUDY AND THE METHODOLOGY USED

The information required for this study was derived from the history of the water-pipe networks of Brzeg, Kłodzko, Oleśnica, Opole and two regions in Wrocław. These documents provide data (collected over the periods of several or many years) on the forcing pressure head at the pumping stations, the number and type of failure events in mains and distributing pipelines, as well as episodes of discontinuity in water supply to the users (cause, duration, effect). Waterworks continue to upgrade the level of reliability on the pathway of the water supplied to the users, e.g. by reducing excess pressure head in the network and daily pressure variations. Taking these into account and making use of pertinent data, two periods were distinguished in the operation of the water-pipe networks under study, with modernization as the dividing line.

The values of reliability levels were assessed before modernization (Period I: with excess pressure in the network) and after modernization (Period II: with reduced pressure head and pressure head variations) of the water distribution systems. The data obtained from the waterworks regarding the average values of maximal manometric forcing pressure head at the pumping stations are compiled in the table.

To our knowledge, the effect of forcing pressure head and forcing pressure variations on the rate of pipe failure has not been subject to scientific investigations in Poland.

Table

Forcing pressure at pumping stations before and after modernization of the water distribution system

Town	Period of excess pressure		Period of reduced pressure		$(H_{maxI}-H_{maxII})/H_{maxI}$ (%)
	Period I of research	H_{maxI} (MPa)	Period II of research	H_{maxII} (MPa)	
Brzeg	1991–08.1996	0.50 (0.46–0,54)	09.1996–2000	0.45	10
Kłodzko	1992–08.1997	~ 0.70	09.1997–1999	≤ 0.60	~ 15
Oleśnica	1981–1992	~ 0.50	1993–2000	~ 0.40	~ 20
Wrocław, Region 1	1990–1994	0.40–0.45	1995 -06.1997	0.22–0,28	~ 40
Wrocław, Region 2	1990–1994	0.40–0.45	1995–1998	0.22–0,28	~ 40
Opole	1996–2001	no data	–	–	–

The total length of the pipelines being analyzed approached 560 km. Among the materials used for pipe manufacture, grey cast iron (accounting for approx. 60% (Kłodzko, Opole) to 100% (Wrocław, Region 1) of the total pipeline length) and plastics

(PVC and PE HD, which accounted for 35% (Brzeg, Opole) of the total pipeline length) were prevalent. In the course of the study, however, the material structure of the pipes had changed substantially. In each of the areas being analyzed, the proportion of cast-iron pipes decreased, whereas that of plastic pipes increased (by 6 to 11%). This was due to the construction of new pipelines, as well as to the replacement of the obsolete pipes (made of cast iron, steel or asbestos cement) with brand-new plastic pipes (PVC and PE HD). As for the age of the pipelines under study, those constructed before 1940 accounted for 12.9% of the total pipeline length in Brzeg and 57.6% of the total pipeline length in Wrocław (Region 2). The diameters of those pipes ranged from 80 mm to 1000 mm. Within this range, pipes with the smallest diameters (80 to 250 mm) occurred in the highest proportion, which varied between 60.8% of the total pipeline length in Wrocław (Region 2) and 94.2% of the total pipeline length in Kłodzko.

Water pipe loading (daily volume of water, m^3/d, pumped into the network per unit length of the pipeline, 1 km) decreased in each of the investigated areas by 30% to 60% over the period of the study. The underlying cause was the significant drop in water consumption observed since 1990.

3. EFFECT OF PRESSURE ON THE RATE OF PIPE FAILURE

The results of our research onto the water-pipe networks of Brzeg, Kłodzko, Oleśnica and Wrocław have demonstrated that the pressure head (H_{max}), and its daily variations (ΔH) in particular, exerts a major impact on the frequency of pipe failure. This finding has been substantiated, *inter alia*, by the analysis of the average failure rate (λ) values for the water-pipe networks over the two periods of operation determined using the values of water pressure head (figure 1).

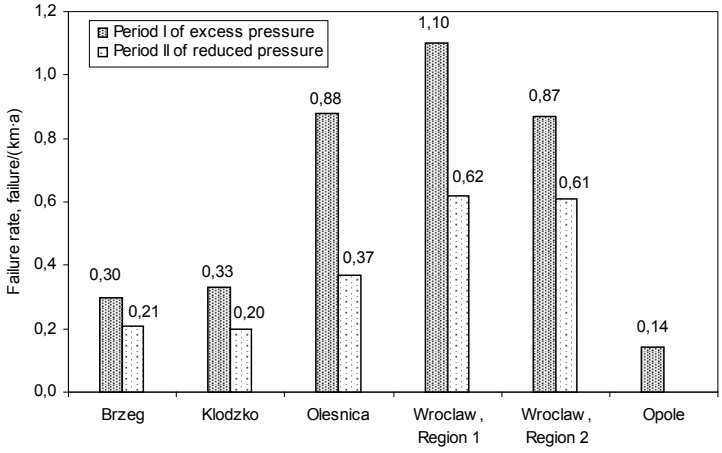

Fig. 1. Overall failure rate (λ) for water-pipe networks over Period I and Period II

Prior to modernization, i.e. over Period I characterized by excess pressure in the water distribution system, the overall failure rate (λ) was high, averaging from 0.30 failure/(km·a) in Brzeg to 1.10 failure/(km·a) in Wrocław (Region 1). After modernization, i.e. over Period II with reduced pressure in the water distribution system, average failure rate (λ) decreased, ranging from 0.20 failure/(km·a) in Kłodzko to approx. 0.60 failure/(km·a) in Wrocław (Regions 1 and 2).

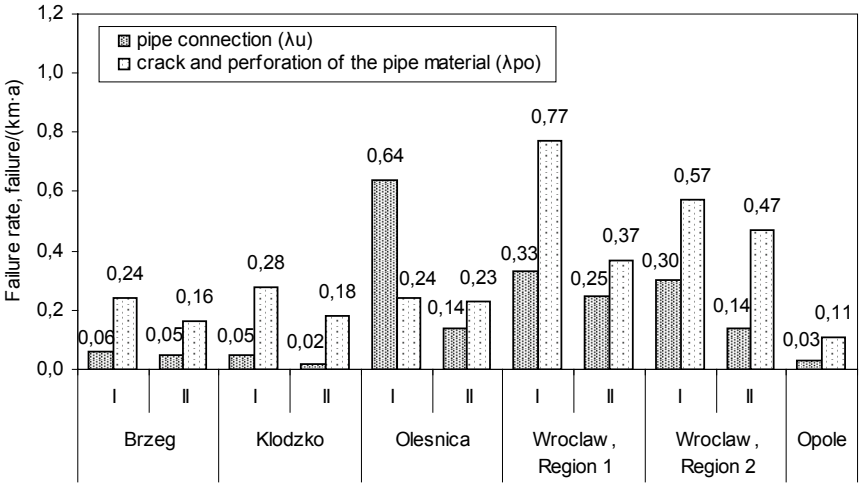

Fig. 2. Failure rates (λ_u, λ_{po}) for the water-pipe network (including type of damage), observed over Period I and Period II

The improvement is attributable to the modernization of the water distribution systems, and the benefits provided can be itemized as follows: maximal forcing pressure (average values from the periods of investigations) was reduced by 10% in Brzeg and by approx. 40% in Wrocław; daily variations in forcing pressure decreased visibly, thus accounting for pressure stabilization in the water-pipe networks of the municipalities being analyzed (the table). Consequently, an approx. 1.5- to 2.3-fold decrease in average failure rate (λ) was observed, which varied from 30% in Brzeg and Wrocław (Region 2) to 58% in Oleśnica. The failure rate for pipe connections (λ_u) ranged between 17 and 78%, and that for cracks and perforation of the pipe material (λ_{po}) – between 4 and 52% (figure 2).

Additionally, our previous studies have demonstrated that the annual costs of pipe repair per one-km length of the pipeline decreased by 30 to 58% [1]–[3].

Although in each of the water distribution systems considered separately, a correlation was established between the forcing pressure head at the pumping station and the frequency of pipe failure (the higher the pressure head, the greater the failure frequency), no such a correlation was found to occur when comparing the water-

distribution systems with one another. Seemingly, this is to be attributed, on the one hand, to the particularity of each system and, on the other hand, to the influence of some contributory factors other than pressure head or failure rate [1], [4], [5].

The correlation between the forcing pressure at the pumping station, pressure variations and pipeline failure rate was analyzed using the water-pipe network in Brzeg as a case in point. The available data sets provide detailed information on the daily variability of the forcing pressure at the pumping station over the time span from January 1991 to December 2000. Figure 3 depicts the variations in the values of the following major operating parameters observed in particular years:

- relative (related to the values measured in 1991) loading (O_s) of the water-pipe network,
- average values of maximal daily forcing pressure head (H_{max}) at the pumping station,
- the highest values of maximal daily forcing pressure head (H_{max}) at the pumping station,
- average values of maximal daily variations in forcing pressure head ($\Delta H = H_{max} - H_{min}$) at the pumping station,
- the highest values of maximal daily variations in forcing pressure head (ΔH) at the pumping station,
- average values of total rate of water-pipe failure (λ).

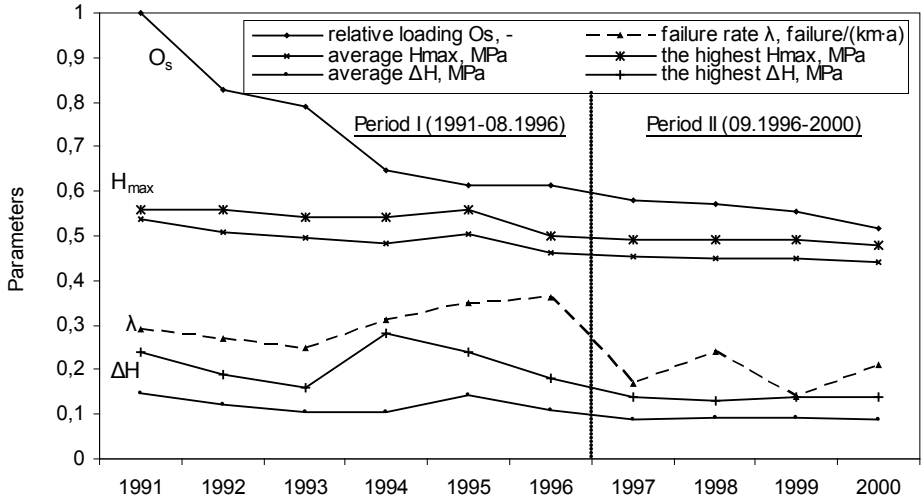

Fig. 3. Operating parameters of the water-pipe network of Brzeg

In particular years of observation, failure rate (λ) decreased significantly with decreasing average daily variations in pressure head (ΔH) according to the following relation (figure 4):

$$\lambda = 2.282\Delta H + 0.009. \quad (1)$$

Statistically less significant was found to be the influence of the decrease in the average value of the maximal forcing pressure at the pumping station on the decrease in the rate of pipe failure (figure 5):

$$\lambda = 1.0622H_{max} - 0.2487. \quad (2)$$

It can be concluded that under the operating conditions in the time span from 1991 to 2000 (H_{max} = 0.54 – 0.44 MPa, ΔH = 0.15 – 0.09 MPa), the variations in the forcing pressure at the pumping station exerted a stronger influence on the overall rate of pipe failure (as well as cast-iron pipe failure [1], [5]) than the variations in the pressure head.

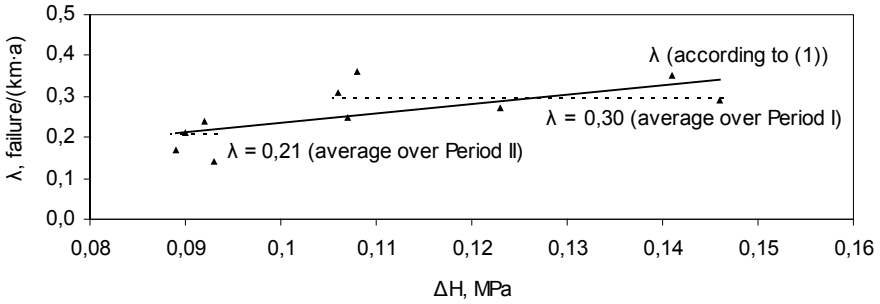

Fig. 4. Failure rate (λ) for the water-pipe network, related to the variations in forcing pressure (ΔH) at the pumping station of Brzeg

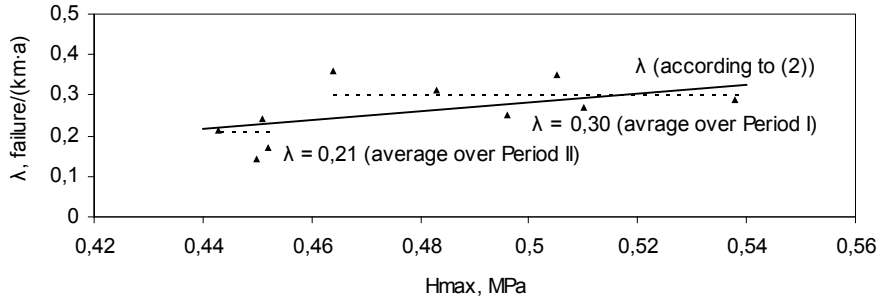

Fig. 5. Failure rate (λ) for the water-pipe network, related to the maximal forcing pressure (H_{max}) at the pumping station of Brzeg

The contribution of the variations in forcing pressure head to the rate of pipe failure becomes particularly distinct when comparing the average values of the parameters ΔH, H_{max} and λ measured before and after modernization of the pumping stations. The results obtained for the water distribution system in Brzeg have revealed that the

decrease in the average values of daily pressure variations by 25% (from 0.12 MPa over Period I to 0.09 MPa over Period II) with a concomitant reduction in the maximal pressure by 10% (from 0.50 MPa to 0.45 MPa) caused the overall rate of pipe failure to fall by 30% (from 0.30 failure/(km·a) to 0.21 failure/(km·a)).

Our analyses were performed with the average values of the maximal pressure head (H_{max}) and and its daily variations (ΔH) at the pumping station. The highest values of the maximal pressure before the modernization of the pumping station (Period I) were variable, and frequently totalled 0.56 MPa; the largest variations amounted to 0.28 MPa (figure 3), and in some instances even 0.40 MPa. After modernization (Period II), pressure stabilized, and pressure head did not exceed 0.49 MPa at maximal variations up to 0.14 MPa (figure 3), which contributed to the decrease in the rate of pipe failure.

4. EFFECT OF PRESSURE ON WATER LOSS IN THE WATER-PIPE NETWORK

The quantitative relation between the head of forcing pressure at the pumping station and the rate of pipe failure with concomitant water loss was analyzed for the water-pipe networks of Oleśnica, Brzeg and Kłodzko, using data sets collected over the time spans of 1993–2000, 1996–2000 and 1995–1999, respectively. The analysis entailed overall failure rates (λ) for main conduits and distributing pipelines, as well as water losses (S), derived from relevant annual water supply and consumption balance [1], [6].

The towns being analyzed do not very much differ in the number of population (30,000 to 40,000) or in the length of the water-pipe network (68 to 75 km), which serves 440 to 560 inhabitants per 1 km. The water distribution systems in Kłodzko and Oleśnica displayed similar values of water pipe loading (O_s), which approached 100 m^3/(km·d) in the last year of observation (1999 and 2000, respectively); the O_s values for the water-pipe network in Brzeg (in 2000) were slightly higher, approaching 130 m^3/(km·d). Over the periods of observations, the values of O_s for the three water distribution systems decreased by 16 to 23%. While the operating conditions were similar, noticeable differences were observed in the maximal forcing pressure at the pumping stations between Oleśnica (0.40 MPa), Brzeg (0.45 MPa) and Kłodzko (0.65 MPa).

The variations in the percentage of water loss with the change in the pipe loading value are described by the following relations:

$$\text{Oleśnica} \quad S = 1.2607 + 0.082767\, O_s \quad \text{for } O_s \text{ from 131.3 to 101.2 m}^3\text{/(km·d)}, \tag{3}$$

$$\text{Brzeg} \quad S = 15.3868 - 0.01784\, O_s \quad \text{for } O_s \text{ from 153.3 to 128.9 m}^3\text{/(km·d)}, \tag{4}$$

$$\text{Kłodzko} \quad S = 13.660 + 0.0604\, O_s \quad \text{for } O_s \text{ from 136.9 to 105.0 m}^3\text{/(km·d)}. \tag{5}$$

The percentage of water loss (i.e. the proportion of the water volume lost to the water volume pumped into the pipeline) decreased slightly with decreasing O_s values. In addition, with the same loading of the water-pipe networks, O_s = 130 m^3/(km·d), the lowest water loss was measured in Oleśnica (12.0%), a slightly higher loss in Brzeg (13.1%), and the highest loss in Kłodzko (21.5%). This is an indication that water losses are influenced primarily by the pressure H_{max}, which was the lowest in Oleśnica, took a higher value in Brzeg, and was the highest in Kłodzko.

To determine the effect of the forcing pressure on the size of water loss due to leakage, analysis was carried out in order to ascertain whether there was a correlation between pipe failure rate and water loss. Consideration was given to the average annual overall pipe failure rate (λ, failure/(km·a)) and size of water loss (S, %), which include the effect of the pipeline load. In this way, the following relations have been obtained:

$$\text{Oleśnica} \quad S = 7.209 + 10.044\,\lambda \quad \text{for } \lambda \text{ from 0.53 to 0.30 failure/(km·a)}, \tag{6}$$

$$\text{Brzeg} \quad S = 10.809 + 9.156\,\lambda \quad \text{for } \lambda \text{ from 0.36 to 0.14 failure/(km·a)}, \tag{7}$$

$$\text{Kłodzko} \quad S = 18.564 + 9.364\,\lambda \quad \text{for } \lambda \text{ from 0.39 to 0.09 failure/(km·a)}. \tag{8}$$

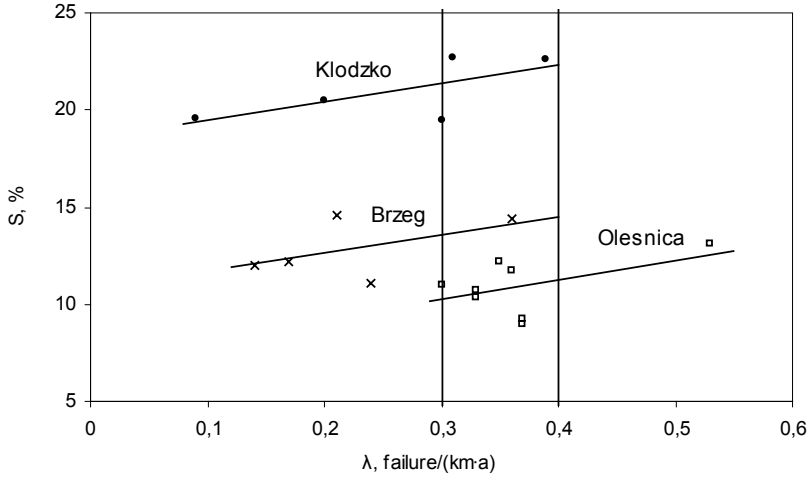

Fig. 6. Variations in the percentage of water loss (S) related to failure rate (λ) for the water-pipe networks of Kłodzko, Oleśnica and Brzeg

The relations in figure 6 make it clear that even though the water distribution systems being analyzed display very similar rates of pipe failure, the water losses observed differ from one municipality to another. In this context, comparisons were made of the values of the water loss calculated in terms of (6), (7) and (8) with relevant values of the failure rates (λ = 0.30 failure/(km·a) and λ = 0.40 failure/(km·a)) in

the systems differing in pressure conditions (average H_{max} values of 0.40 MPa in Oleśnica (1993–2000), 0.45 MPa in Brzeg (1996–2000) and 0.65 MPa in Kłodzko (1995–1999)). The percentage of water loss increased in a linear mode with the increase in the forcing pressure at the pumping stations:

$$\text{for } \lambda = 0.30 \text{ failure/(km·a)} \quad S = -6.609 + 43.286\, H_{max}, \tag{9}$$

$$\text{for } \lambda = 0.40 \text{ failure/(km·a)} \quad S = -5.429 + 42.857\, H_{max}. \tag{10}$$

From the analysis of the relations in figure 7 and the results of previous studies, as well as from the comparison of the operating parameters applied in particular water distribution systems, it is obvious that the pressure head at the pumping station is to be blamed for the water loss. For example, at the same overall pipe failure rate amounting to 0.3 failure/(km·a), in Oleśnica, where the pressure head at the pumping station was the lowest (H_{max} = 0.40 MPa), water loss was 10.2%; in Kłodzko, where the pressure head at the pumping station was the highest (H_{max} = 0.65 MPa), water loss was twice as high, amounting to 21.4%.

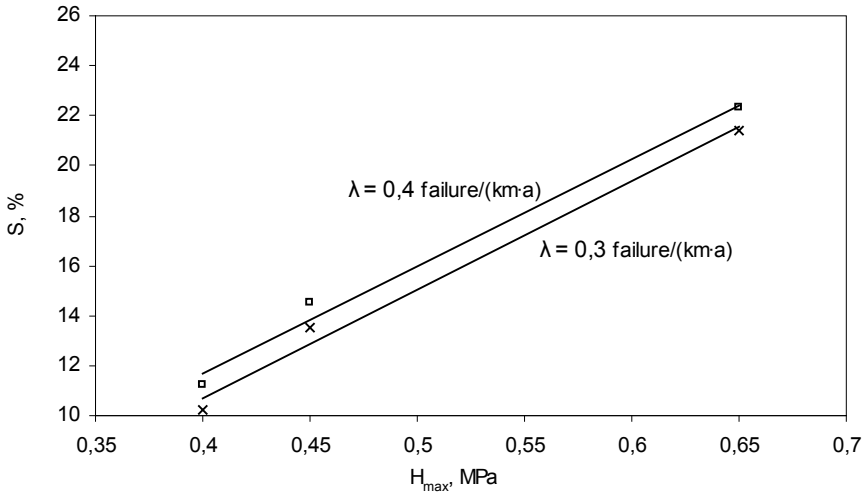

Fig. 7. Variations in the percentage of water loss (S) in the water-pipe networks which show the same rate of pipe failure (λ) but differ in the H_{max} value

The percentage of water losses as well as the differences in the size of water loss between the water-pipe networks under analysis were also influenced by the type and size of pipe damage, and by the duration of water outflow [7]. In each of the water distribution systems, pipe cracks and pipeline perforations prevailed, and their proportion in the total number of failure events was the lowest in Oleśnica (62%) and the highest in Kłodzko (89%).

5. SUMMARY

The results of observations and analyses performed so far substantiate the need not only of modernizing obsolete water-pipe networks, but also minimizing the pressure head and its variations in the 24-hour cycle. The effects of such actions are manifold – upgraded reliability level [8] and operating safety of the water distribution system [9], [10], decrease in the frequency of pipe failure and the volume of water loss, reduction in pipe repair costs and, more importantly, a higher standard of services offered to the users.

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