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RELIABILITY ASSESSMENT OF BUILDING STRUCTURES UNDER TYPHOON CALAMITY*

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Abstract: Typhoon is one of the most destructive natural calamities. Statistical data on 1949 - 1990 typhoons in China were used to analyze the frequency and strength of the typhoons, the relation between them and the average global ground temperature. The probability distribution of wind speed and the load of low buildings were obtained respectively on the basis of statistical data on the No. 9015 and No. 9711 typhoon. The finite element method and experimental comparison were used to obtained the probability distribution of lateral force resistance of a three-story brick-concrete building. Finally, the reliability indexes of this kind of building under No. 9015 and No. 9711 typhoon; and some valuable suggestions are given.

Key words: building structure, typhoon calamity, reliability
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INTRODUCTION

The typhoon is a very destructive storm occurring on the tropical ocean surface and depending on the potential heat released from the micro vapor condensation as the main energy source for its maintenance and development. Typhoon can bring calamities in different degrees to the areas hit by it directly, kill thousands of people, and result in great losses to the national economy. Table 1 gives the number of deaths caused by global tropical cyclones and other natural disasters from 1964 to 1978 (Emanuel 1987).

Table 1 Global natural calamity statistics(1964 - 1978)(Emanuel 1987)

Natural calamity	Total death for 15years	Maximun death number	Natural calamity	Total death for 15 years	Maximun death number
Tropical cyclone	416972	300000(Bangladesh 1970)	Snowslide collapse	5790	1450(Peru 1974)
Erathquake/Tsunami	195328	66794(Peru 1969)	Volcanic eruption	2572	2000(Zaire 1973)
Flood	26724	8000(VictNam 1964)	Temperate zone cyclone	1860	166(England 1966)
Strong windstorm	4062	540(Bargladesh 1969)	Hot wave/Cold wave	505	291(India 1973)

From 1949 to 1980, China was the country where tropical low pressure, typhoon and strong typhoon from the northwest Pacific, including the China Sea, landed most frequently (China, 8 times per year; Philippines, 5.4 times per year; Japan, 4.3 times per year). Strong typhoons also occur most frequently in China (3.4 times per year), and cause enormous economic losses. Table 2 gives the times per year and strength of typhoon landings in provinces (cities and autonomous regions) during 1949 - 1980 (Xu, 1994).

Zhejiang Province is one of the areas where typhoon occurs very frequently, and causes losses(Zhou et al., 1994). Typhoons affected this province 8 times during 42 years (1949 - 1990), i.e. No. 5612, 6126, 6214, 6312, 7413, 7910, 8114 and 8807; No. 5612, 6126, 7413, 7910 and 8807 landed in this province. The effects of typhoon No. 5612 and 8807 on Zhejiang Province should be particularly pointed out. Typhoon No. 5612 landed at Xiangshan at 24 o'clock, August 1st, 1956. Its landing intensity was at > 12 grade and caused about 4000

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deaths. It was the greatest typhoon calamity of the province since the founding of the People's Republic of China. Typhoon No. 8807 landed at Xiangshan at 0 o'clock, August 8th, 1988, at > 12 grade landing intensity and devastated Hangzhou overnight, cutting off electricity, water supply, and telecommunications, stopped the production of more than 1000 factories and enterprises, and caused direct economic loss of one billion yuans Rmb. In 1997, Zhejiang was again battered by the most destructive typhoon (No. 9711) since the founding of the People's Republic of China. It landed near Wanling around 21 o'clock August 18th, bringing with it fierce winds and storm, and high tidal waves. The seawalls along the Zhejiang coast were mostly destroyed and the area was flooded. In situ data recorded by the Ying County Meteorological Observatory showed the instantaneous velocity of the wind in Ying County reached 112 m/s, when typhoon No. 9711 arrived.

Table 2 Occurrence frequency of typhoons and their intensities in 1949 – 1980(autonomous provinces and cites)(Xu, 1994)

Province	Tropical low pressure			Typhoon			Strong typhoon			Total		
	Times	Average	%	Times	Average	%	Times	Average	%	Times	Average	%
Guangxi	1	0	8	11	0.3	92	0	0	0	12	0.4	3
Guangdong	22	0.7	13	88	2.8	54	54	1.7	33	164	5.1	49
Taiwan	3	0.1	5	17	0.5	27	43	1.3	68	63	2.0	19
Fujian	9	0.3	15	28	0.9	48	22	0.7	37	59	1.8	18
Zhejiang	1	0	8	4	0.1	31	8	0.3	61	13	0.4	4
Shanghai	2	0.1	29	4	0.1	57	1	0	14	7	0.2	2
Jiangsu	1	0	33	2	0.1	67	0	0	0	3	0.1	1
Shandong	2	0.1	20	8	0.3	80	0	0	0	10	0.3	3
Liaoning	2	0.1	40	3	0.1	60	0	0	0	5	0.2	1
Total	43	1.3	13	165	5.2	49	127	4.0	38	336	10.5	100

Typhoons caused enormous losses in Zhejiang Province(Zhou et al., 1995). Just during the 6 years from 1987 to 1992, the direct economic losses due to typhoon calamities reached as high as 17 billion Rmb. Many hectares (223 100) of fields were flooded, 280 000 houses collapsed, 5 116 km of seawalls destroyed, 1 177 people died, and production output was reduced by about 3 640 000 tons. Typhoon No. 9 711 brought about the biggest wind-storm-tide calamity in a century. This typhoon resulted in 0.7 million hectares fields damaged, 0.1 million hectares fields made barren, 18 counties flooded, 586 km of seawalls damaged, 550 km of seawalls, and 1163 km of irrigation ditches broke down. In many places, electricity and communication were cut off, and traffic slowed down. The stopping of work in factories and enterprises caused about 18.6 billion yuans in losses. Typhoon calamity has been an important factor holding back the social and economic development of Zhejiang Province.

Table 3 Simulated relation between ocean surface temperature and hurricane parameters

Ocean surface temperature(℃)	The lowest pressure (bPa)	Maximun wind velocity(m/s)	Ocean surface temperature(℃)	Lowest pressure (bPa)	Maximun wind speed(m/s)
27	911	72	31	865	88
28	902	75	32	849	93
29	891	79	33	829	99
30	879	83	34	805	106

THE CHARACTERISTIC AND PROBABILITY DISTRIBUTION OF TYPHOON

One of the essential conditions for typhoon formation is the existence of extensive high temperature ocean surface, and of the high temperature seawater from tens to hundreds of meters deep. Particularly, when the temperature of the seawater from the surface to 60 meters deep is 26℃ ~ 36℃, typhoon is very easily formed. Emanuel's (1987) simulation results indicated that with the rise of the ocean surface temperature, the central atmospheric pressure of the tropical cyclone keeps on decreasing, while the highest wind velocity keeps on increasing (see Table 3).

1. Possible typhoon occurrence frequency changes due to warming global climate

The increase of the density of CO_2 and the other gases in the atmosphere leads to the greenhouse effect causing warming up of global climate and rise of sea surface temperature to higher values conducive to formation of typhoons (Wang et al., 1991). Available research data show clear linear interrelation between the typhoon occurrence frequency and variation of average global ground temperature, as described by the following equations:

$$PHF_t = a_1 \Delta T_{t-t_0} + b_1 \quad (1)$$

$$CHF_t = a_2 \Delta T_{t-t_0} + b_2 \quad (2)$$

where

ΔT—variation of average global ground temperature (℃, 5 years' running average)

PHF—frequency of typhoon occurrence of northwest Pacific (time/year, 5 years running average)

CHF—frequency of typhoon landing in China (time/year, 5 years running average)

t—times/year

t_0—landing times/year

a_1, a_2, b_1, b_2—constant

After using the principle of minimum multiplication to determine $t_0 = 26$ years, the linear regressive equation for Eq. (1) can then be expressed as:

$$PHF_t = 40.14\Delta T_{t-26} + 21.89 \quad (3)$$

Correlation coefficient $\gamma_1 = 0.90$, and variance $\sigma_1 = 3.99$. The linear regressive equation for Eq. (2) is

$$CHF_t = 7.89\Delta T_{t-26} + 6.64 \quad (4)$$

Correlation coefficient $\gamma_2 = 0.78$, and variance $\sigma_2 = 0.966$.

Table 4 Possible variation of typhoon occurrence frequency after the warmer global temperature

Range of global average ground temperature rise (℃)	Typhoon occurence in Northwest Pacific Ocean		Typhoon loanding in China	
	Frequency (times/year)	Rate of increase	Frequency (times/year)	Rate of increase
0	28.2	-	7.0	-
0.25	35.9	27%	9.4	34%
0.5	46.0	63%	11.4	63%
0.75	56.0	99%	13.3	90%
1.0	66.0	134%	153	119%
1.25	76.0	170%	17.3	147%
1.50	86.1	205%	19.3	176%
±2	±5.98	±0.21	±1.93	±0.28

Note: The frequency at 0℃ is the average value from 1951 – 1980

Scientists (Miller, 1967; Wang et al., 1987) commonly agree that if the density of CO_2 along with other kinds of greenhouse-effect-causing gases in the atmosphere keeps on increasing at the present speed, the global average ground temperature will rise 1.5 ℃ to 4.5 ℃ in the middle of the 21st century. The effect of this temperature rise on the typhoon occurrence frequency cannot be neglected. If the global average ground temperature will rise 1.5 ℃ in the middle of the 21st century, the possible variation of the typhoon occurrence frequency in the Northwest Pacific Ocean and the occurrence frequency of typhoon landing in China can be estimated according to Eqs. (3) and (4) (see Table 4). If the temperature rises too much, the above linear relationship may not be maintained any more. However, we may believe that as the range of the temperature rise is small, this relationship will not change greatly.

From the above analysis we can see that when global climate gets warmer, typhoon calamities will be more and more serious, so it is necessary to pay more attention to the analysis of the reliability of building structures resistance against typhoons.

2. Study of distribution regularity of typhoon speed in Ying County, Zhejiang Province

(1) Statistical data on typhoon

Typhoon is a stochastic process varying with time. The distribution of various typhoons is quite different. We tried to conduct a preliminary analysis of the distribution of typhoons, in order to find out its general regularity. For this purpose, we visited the Ningbo Meteorological Bureau and conducted statistical analysis of on-the-spot observation data of the Ying County observatory of Ningbo.

In the history of Zhejiang Province, several extremely strong typhoon calamities (No. 5612, 6126, 7413, 7910, 8807, 9015, 9711, etc.) occurred, so a great deal of on-the-spot measured data was accumulated. However, very few studies have been made on the regularity of typhoon distribution up to now, so no ready case can be used for reference. Here, we just analyze the on-the-spot measured data on typhoons No. 9015 and No. 9711. Typhoon No. 9015 was of medium strength, while Typhoon No. 9711 was a stronger case. The occurrence frequencies of the different wind speeds of the two typhoons are listed in Table 5 and Table 6 (Wind speed value in the table is the average for ten minutes).

The data in Table 5 and Table 6 are plotted in Fig. 1. By optimizing the probability distribution, the wind speed of typhoon accord with the extreme value I type distribution, whose probability distribution function and density functions are:

$$F_X(x) = \exp[-\exp(-\alpha(x-k))] \quad -\infty \le x \le \infty \tag{5}$$

$$f_X(x) = \alpha\exp\{-\alpha(x-k) - \exp[-\alpha(x-k)]\} \quad -\infty \le x \le \infty \tag{6}$$

in which

$$\left.\begin{aligned} \alpha &= 1.2825/\sigma_x \\ k &= m_x - 0.5772/\alpha \end{aligned}\right\} \tag{7}$$

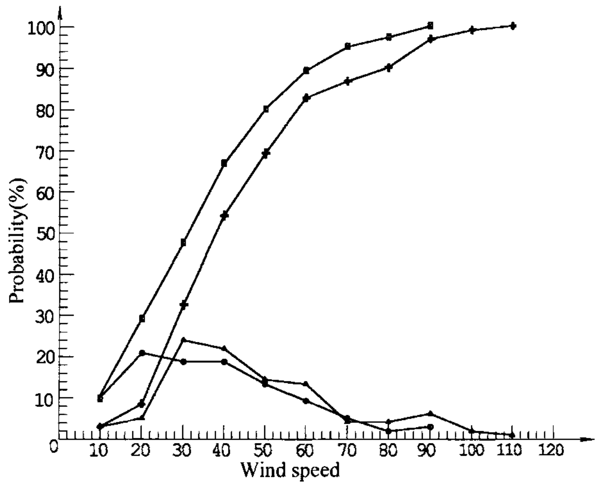

Fig. 1 Wind speed occurrence frequency /probability of typhoon

☒ Multiangled curve for win speed occurrence frequency of Typhoon No.9015

○ Multiangled curve for wind speed occurrence frequency of Typhoon No.9711

+ Multiangled curve for the density of wind speed occurrence probability of Typhoon No.9015

△ Multiangled curve for the density of wind speed occurrence probability of Typhoon No.9711

Table 5 Occurence frequency of wind speed of Typhoon No.9015

Wind speed(m/s)	Occurence frequency (times)	Cumulative frequency Nos(times)	Occurence frequency rate(%)	Cumulative frequency rate(%)
01 ~ 10	8	8	8.3	8.3
11 ~ 20	20	28	20.8	29.1
21 ~ 30	18	46	18.8	47.9
31 ~ 40	18	64	18.8	66.7
41 ~ 50	13	77	13.5	80.2
51 ~ 60	9	86	9.4	89.6
61 ~ 70	5	91	5.2	94.8
71 ~ 80	2	93	2.1	96.9
81 ~ 90	3	96	3.1	100.0
Total	96		100	

Table 6 Occurrence frequency of wind speed of Typhoon No.9711

Wind speed(m/s)	Occurence frequency (times)	Cumulative frequency NOs(times)	Occurence frequency rate(%)	Cumulative frequency rate(%)
01 ~ 10	3	3	3.1	3.1
11 ~ 20	5	8	5.2	8.3
21 ~ 30	23	31	24.0	32.3
31 ~ 40	21	52	21.9	54.2
41 ~ 50	14	66	14.6	68.8
51 ~ 60	13	79	13.5	82.3
61 ~ 70	4	83	4.2	86.5
71 ~ 80	4	87	4.2	90.7
81 ~ 90	6	93	6.2	96.9
91 ~ 100	2	95	2.1	99.0
101 ~ 110	1	96	1.0	100.0
Total	96		100	

(2) The determination of distribution model

1) The determination of the parameters of the distribution model for Typhoon No. 9015

The statistics (values) for 96 wind speed data sets on the typhoon were obtained as follows:

Mean value $m_X = 37.12$ m/s

Variance $\sigma_X^2 = 365.57$ m^2/s

Mean squared deviation $\sigma_X = 19.12$ m/s

According to Equation (7)

$$\begin{cases} \alpha = 0.0671 \\ k = 28.518 \end{cases}$$

Thus, we obtain the following probability distribution function and the density function for Typhoon No. 9015:

$$F_X(x) = \exp\{-\exp[-0.0671(x - 28.518)]\} \quad -\infty \leq x \leq \infty \tag{8}$$

$$f_X(x) = 0.0671\exp\left\{\begin{array}{l} -0.0671(x-28.518) \\ -\exp[-0.0671(x-28.518)] \end{array}\right\} \quad -\infty \leq x \leq \infty \tag{9}$$

2) The determination of the parameters of the distribution model for Typhoon No. 9711

By the same described above, the statistics values of the typhoon were obtained as follows.

Mean value $m_X = 44.98$ m/s

Variance $\sigma_X^2 = 419.84$ m^2/s^2

Mean squared deviation $\sigma_X = 20.49$ m/s

According to Equation (7):

$$\begin{cases} \alpha = 0.0626 \\ k = 35.760 \end{cases}$$

The probability distribution function and the density function for Typhoon No. 9711 are

$$F_X(x) = \exp\{-\exp[-0.0626(x - 35.760)]\} \quad -\infty \leq x \leq \infty \tag{10}$$

$$f_X(x) = 0.0626\exp\left\{\begin{array}{l} -0.0626(x-35.760) \\ -\exp[0.0626(x-35.760)] \end{array}\right\} \quad -\infty \leq x \leq \infty \tag{11}$$

(3) Calculation of the distribution curve for typhoon wind pressure

In the structural reliability calculation, the value of wind pressure was our concern, so we had to know the relationship between the wind pressure and the wind speed. This relationship is given in " Standard of Loads on Building Structures "(GBJ9 - 87, 1987) as $W = \frac{V^2}{1600}$, from which we can obtain the statistics (values) of wind pressure:

for Typhoon No. 9015:

Mean value $m_W = 1.09$ kN/m^2

Mean squared deviation $\sigma_W = 1.09$ kN/m^2

for Typhoon No. 9711:

Mean value $m_W = 1.53$ kN/m^2

Mean squared deviation $\sigma_W = 1.43$ kN/m^2

They accord with the Extreme Value I type distribution.

EVALUATION AND ANALYSIS FOR RELIABILITY OF BUILDING STRUCTURE

1. Establishment of the model of three-story-brick-concrete structure

An investigation of the houses along the coastal area indicated that the most typical are the two to four storeys brick-concrete houses, so a three-storeys-brick-concrete model house with girth but without structural pillars is built here (see Fig. 2), in which each storey was 3.2 m high.

Material selection: Grade C20, Grade MU 7.5 and Grade M5 were adopted for concrete, brick, and mortar, respectively. Table 7 gives the physics mechanics indexes for concrete (GBJ10 - 89, 1989). Table 8 gives the mechanics index for the brick wall (GBJ3 - 88, 1988).

Table 7 Mechanics index for C20 concrete

Concrete	Strength standard value (MPa)			Modulus of elasticity (MPa)
	Axis compressive strength	Bending strength	Tensile strength	
C20	13.5	15	1.5	2.55×10^4

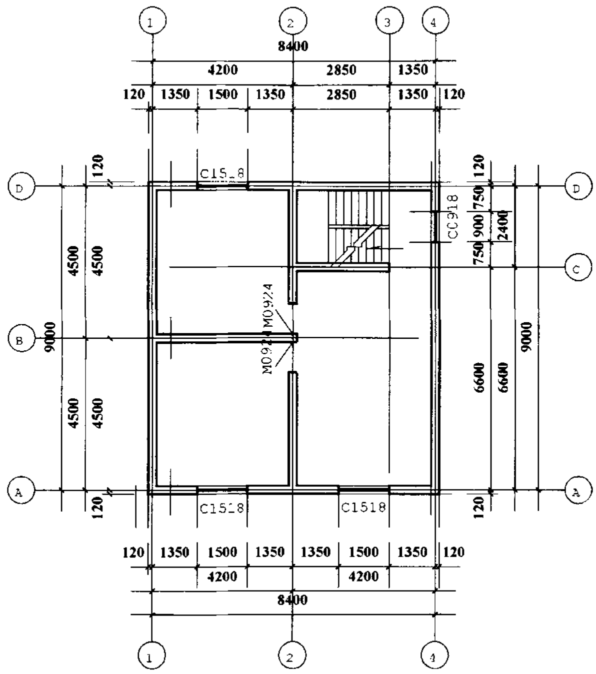

Fig. 2 Three-storey-brick structure

Table 8 Mechanics index for brick wall

Materials	Brick MU7.5						Mortar M5				Modulus of elasticity (MPa)
Compressive stress (MPa)	0.2884	0.5768	0.8652	1.1536	1.4420	1.7304	2.0188	2.3072	2.5956	2.8840	2.138×10^3
Strain (10^{-4})	1.3487	2.8565	4.5658	6.5391	8.8730	11.7295	15.412	120.6024	29.4754	49.0000	

The relation between compressive stress and strain in Table 8 was obtained from the logarithmic relation formula given in domestic research data:

$$\varepsilon = \frac{1}{\zeta \sqrt{f_m}} \ln\left(1 - \frac{\sigma}{f_m}\right) \tag{12}$$

For brickwork material, $\zeta = 450$; f_m is the average value of axis compressive strength for brickwork.

2. Load determination

When typhoon occurs, load generally includes structural dead weight, live load and horizontal wind load described respectively as follows:

1). Structural dead weight: Considering the existence of the surface plaster, the concrete dead weight is taken as 27.8 kN/m^3; the brick work dead weight is taken as 21.8 kN/m^3.

2). Live load: According to "Standard of Load on Building Structures" (GBJ9 - 87, 1987), the live load of floor is taken as 1.5kN/m^2; the live load of roof is taken as 0.7 kN/m^2.

3). Horizontal Wind load: According to "Standard of Load on Building Structures" (GBJ9 - 87), the wind load value is taken as:

$$W = \beta_z \mu_s \mu_z W_0$$

in which

β_z: Wind vibration coefficient, which need not be considered here.

μ_z: Wind load height coefficient. The low houses damaged by typhoon are generally located in the coastal spacious area, so the ground coarseness is class A, so $\mu_z = 1.38$

μ_s: Shape coefficient of wind load, whose values are as shown in Fig. 3:

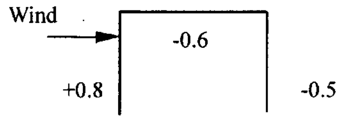

Fig. 3 Shape coefficient of wind load on structure

3. Structural analysis(Hu, 1997)

In order to reflect the state of stress and strain of the structural model and the destructive principle of the structural system accurately, a destructive point of the structure must be found by means of a combination of program analysis and experimental comparison. Concentrating on the structural model, we analyzed and compared the available method of finite element and found that most programs can analyze the structural stress and strain accurately(Chao et al., 1994). However, the analysis for a structural system needs a great deal of work. In this paper, we adopt the structural general software ABAQUS with analytical program, take material strength as a random variable and use 200 samples to analyze the stress and strain. After comparison with the results of an experiment on brick structural lateral force resistance (the experiment was a 1:0.5 model test), we found that when 0.15% horizontal displacement occurs to the structure, the structure collapses or cannot be loaded more (Zhuang, 1996). On the basis of this result, through statistical analysis, we came to the conclusion that the probability distribution of the wind resistance effect of the structural model accords with the normal distribution. The mean value is 8.13 kN/m^2 and mean squared deviation is 0.56 kN/m^2.

4. Structural reliability

The calculation theory for structural reliability is quite mature now and there are many programs available. As far as this calculation case is concerned, we have obtained the probability distribution of the resistance strength effect of the structural model and the typhoon load effect; therefore, the equation of ultimate state has its simple form(Jin, 1996a):

$$Z = B_R R - B_S S = 0$$

In which, B_R and B_S are variation coefficients of the resistance force effect and the load effect, respectively, which were considered during statistical analysis of the resistance force effect of the structural model and the load effect, and so need not be considered here. The resistance capacity, R, follows Normal distribution, while the load effect, S, follows Extreme I distribution.

The ultimate state function in Equation (13) has two random variables, whose distribution functions follow Normal and the Extreme I distributions. FORM (Jin, 1996b) may have sufficient calculation precision for this problem. The calculated reliability indexes and failure probability under Typhoon No. 9015 and No. 9711 are

for Typhoon No. 9015:

Structural reliability index $\beta = 3.58$

Structural failure probability $P_f = 0.0174\%$;

for Typhoon No. 9711:

Structural reliability index $\beta = 2.93$

Structural failure probability $P_f = 0.169\%$.

CONCLUSION AND SUGGESTION

The above-calculated results show that under the effect of Typhoon No. 9015, the structural reliability index $\beta = 3.58$, and failure probability $P_f = 1.7 \times 10^{-4}$. This β of 3.58 meets the requirements of the brick-stone structural reliability under the condition of domestic Standard (GBJ10 - 89). While under the effect of Typhoon No. 9711, both the structural reliability index $\beta = 2.93$ and the failure probability $P_f = 1.69 \times 10^{-3}$ exceeded the values stipulated by the Standard(GBJ10 - 89). The two calculated results indicate that the brick-concrete structural model in this paper can resist weak or medium strength typhoons but connot resist strong typhoons. Our domestic Standard does not stipulate the reliability indexes of the whole structural system, what we discussed here whether or not the structural reliability indexes can be met, just referred to the stipulated value of the standard of the reliability indexes of the structural members.

Our investigation showed that many houses built in the rural areas at present are still not as strong as the structural model built in this paper, and connot resist strong typhoons. We hope that what we have done can draw the attention of relevant government agencies to the crisis of the possibility of disaster in broad rural areas when strong typhoons hit them. We suggest that house builders in the rural areas should pay great attention to the design of the building, increase the stiffness of the lateral force resistant structural system, and strengthen the administration of building material purchase and the construction process.

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