Study on loess liquefaction potential evaluation based on physical indexes and the depth limit

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SUMMARY:

Loess is widely distributed in the Loess Plateau of China, where there is the largest area, 640000km^2, and the thickest deposit, more than 500m, of loess over the world. It has high liquefaction potential, which may be triggered by the effect of earthquake with the seismic intensity of Ⅶ degree or PGA of 0.1g. In this paper, two major physical indexes of influencing liquefaction potential of loess, initial void ratio and plastic index and the maximum depth of liquefiable loess deposit were figured out. The relationship between liquefaction stress ratio and initial void ratio, plastic index and depth has been established based on dynamic triaxial tests and computation analysis. Furthermore, the performance-based simple and practical method of evaluating loess liquefaction potential has been provided with four levels of non-liquefiable, slightly liquefiable, moderately liquefiable and completely liquefiable under the effects of different seismic intensities ranging from Ⅶ to Ⅸ degree.

Keywords: loess liquefaction, evaluation, void ratio, plastic index, depth

1. INTRODUCTIONS

Loess is a special soil with big pores and weak cementation (Wang Lanmin, 2003). Based on recent research of earthquake disasters and laboratory tests, the saturated, even the loess with high water-content has remarkable liquefaction potential and flow failure potential (Ishihara K, 1990, Wang Qian, 2012). In the 21st century, the megacities and medium-sized cities spread to the high terraces rapidly. Agricultural irrigation system in the loess region of China is significantly improved. Therefore, the water content of loess at high terraces is increased in many places and leads to increased risk of liquefaction of saturated loess under the effect of earthquake with a certain intensity. Furthermore, statistical data predicts that around 2020, the population in the loess area of China will reach more than 300 million, which will account for 22% of population of whole China. Thus, loess liquefaction will threaten the safety of both people and infrastructures and facilities.

The evaluation of liquefaction potential in loess area is to predict the probability and severity of the loess liquefaction. The anti-liquefaction measures for a loess site could be taken based on the evaluation results (Prakash S, 1998). The current loess liquefaction potential evaluation has two methods: one is to calculate the horizontal peak acceleration on liquefied ground using the result from triaxial test which applies random dynamic loads got from seismic risk analysis. Then evaluate liquefaction potential of the loess site with the earthquake effect of certain intensity by comparing the PGA of corresponding intensity (Wang Lanmin, 2003). Another is based on Seed's simplified method and seismic response analysis, which compares the shear stress of loess layer under certain earthquake intensity and the average shear stress under the effect of earthquake, then determine the loess field liquefaction potential by comparing seismic shear stress time-history of site with corresponding intensity of earthquake. The two methods are all based on the dynamic triaxial tests (Wang Lanmin& Mo Yong, 2009). Although the result is accurate, this kind of work is both time-consuming and difficult for engineers.

As a typical special soil, loess usually has certain grain size, density and humidity that can be measured with simple procedures. So the application of these simple characteristics of loess liquefaction for evaluation of loess liquefaction potential has an obvious merit. Hence, the object of this research is to establish a method to evaluate loess liquefaction potential using properties such as plastic index, relative density, initial void ratio etc.

In the research the first step is to determine the liquefaction shear stress and number of cycles ratio of saturated loess through the dynamic triaxial test, then compare the different initial pore ratio and plastic loess liquefaction stress ratio under different seismic intensity, thus it could draw the quantitative relationship between the saturated loess liquefaction shear stress ratio and the main property of the loess liquefaction index, and establish the evaluation method of saturated loess liquefaction potential and the depth limit[4].

2. SAMPLES, TEST METHODS AND RESULTS

In the research the undisturbed loess samples were secured from different sites in Lanzhou, Guyuan and Tianshui. Lanzhou site is located in the east of the city, which is on the Ⅳ level terraces of Yellow River, the loess samples is typical Q3 loess which is loose and homogenous; Shibei tableland site of Guyuan is located in the rear edge of the sliding plane during Haiyuan earthquake. On the Shibei tableland, the strata of different depth are all belong to Q3 series, the samples are all typical Q3 loess except at 14-17 meters depth, where loess contains lots of sand. The Tianshui site is in the rear edge of liquefaction landslide of Wenchuan earthquake. The samples are all Q3 loess. To study the effects of a single property index of saturated loess, some remolded loess samples are also used. The property index as is shown in table 2.1.

Table 2.1 Sample Physical Indexes

Samples	Depth (m)	Initial void ratio	Water content (%)	Grain composition (%)			Ip	Comments
				clay	silt	sand		
LZ-1	4	1.1	4.5	17.3	68.2	14.5	9.4	Undisturbed loess
LZ-2	——	0.7	10.0	17.3	68.2	14.5	9.4	Remolded loess
LZ-3	——	0.8	10.0	17.3	68.2	14.5	9.4	Remolded loess
LZ-4	——	0.9	10.0	17.3	68.2	14.5	9.4	Remolded loess
LZ-5	——	1.0	10.0	17.3	68.2	14.5	9.4	Remolded loess
LZ-6	——	1.2	10.0	17.3	68.2	14.5	9.4	Remolded loess
GY-1	4	1.2	5.4	17.3	73.2	9.5	11.2	Undisturbed loess
GY-2	8	1.1	8.7	20.7	71.7	7.6	11.1	Undisturbed loess
GY-3	12	1.1	11.3	25.2	65.3	9.5	9.8	Undisturbed loess
GY-4	16	0.7	5.8	13.2	34.9	51.9	5.1	Undisturbed loess
GY-5	20	0.9	11.4	24.2	69.4	6.4	7.6	Undisturbed loess
QS-1	4	1.0	16.5	30.5	62.8	6.7	13.0	Undisturbed loess

The test instrument is the WF-12440 HCA which is made in the UK. The machine is pneumatic-driving to get cell hydraulic pressure and apply dynamic loading with a servo control which can ensure to get desired pressure during the test process; the vertical load was provided by pneumatic actuator. The system can realize collaborative dynamic control of four types of stress (inner confining stress, outer confining stress, axial stress and back pressure) to control the magnitude, frequency and direction of the principal stresses to simulate of the actual status of soil stress. The back pressure was provided through the pneumatic-driving hydraulic pressure to improve the saturation rate and the speed of saturation during test (figure 1). The system can realize the five axis of digital close-loop feedback control by improving the control accuracy and stability of the test and try to minimize the system error.

The test method is in strict accordance with the national standard "the soil test regulations

(SL237-1999)". The specifications of specimen preparation are Φ 50 mm x 100 mm, the remolded loess samples are compacted layer by layer. Test process is composed of three stages: consolidation, saturation and cycle shearing. Saturated method with low back pressure shows that the method can reach saturation rate of more than 90% for loess in a short period of time (usually less than 90 min) and the deformation of sample during saturation is little. Consolidation pressure during the sample consolidation is 100 kPa, 150 kPa and 200 kPa with the consolidation ratio of Kc = 1.0. The frequency of sine load of dynamic loading is 1 Hz for all samples. The criteria for liquefaction damage is set as strain ε_d = 3%, and dynamic pore water pressure coefficient U_d/σ_0' > 0.2 (Wang Lanmin et al. 2000).

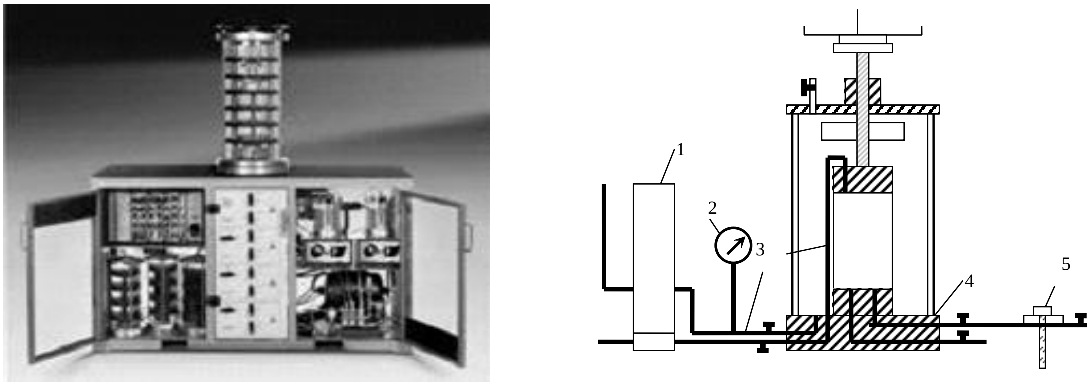
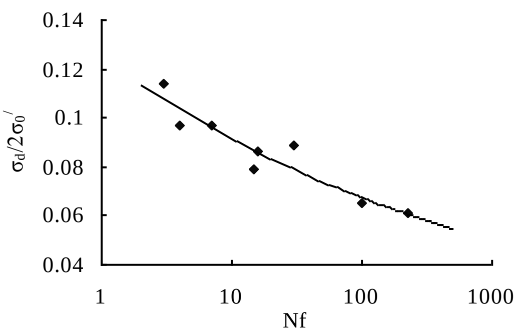
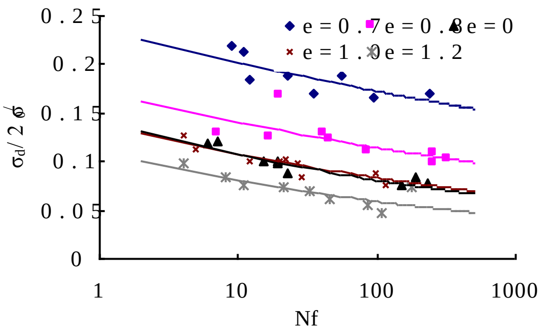


Figure 1. The WF-12440 HCA and the framework of back-pressure system

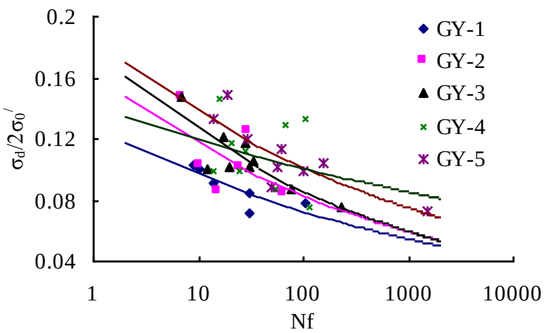
The liquefaction stress ratio ($\sigma_d/2\sigma_0'$)-number of cycles (Nf) curve presents dynamic triaxial liquefaction test results, as shown in figure 2 shows.



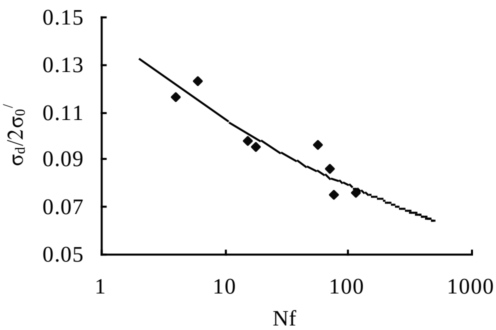
(a) Lanzhou undisturbed loess



(b) Lanzhou compacted loess



(c) Guyuan undisturbed loess



(d) Tianshui undisturbed loess

Figure 2. The results of dynamic triaxial test

The figure shows that the saturated loess liquefaction stress ratio decreases with the increase of the number of cycles. This can be fitted with an exponentiation function as equation (2-1), a, b are fitting parameters.

$$\frac{\sigma_d}{2\sigma_0'} = a \times N_f^{-b} \tag{2-1}$$

3. QUANTITATIVE INFLUENCE OF PHYSICAL INDEXES

3.1 Influence of initial void ratio

In the study, the disturbed loess from Lanzhou site is chosen in order to minimize the interference of other physical indexes. The liquefaction stress ratio ($\sigma_d/2\sigma_0'$)-number of cycles (Nf) curves of the saturation disturbed loess with different initial void ratio are shown in figure 3.

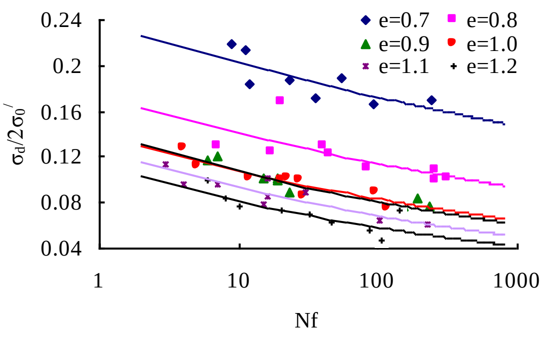


Figure 3. The relationship between ($\sigma_d/2\sigma_0'$) and (Nf) of different compacted loess

It can be seen in figure 3, the liquefaction stress ratio of the disturbed loess increase with the decrease of initial void ratio under the same number of cycles. The relationship between liquefaction stress ratio and initial void ratio of the disturbed loess is obtained as shown in Fig.4. According to the results, we can conclude that the initial void ratio (e) had insignificant influence on the liquefaction stress ratio when $0.9 \le e \le 1.0$, and it had much significant effect when $e \le 0.9$ or $e \ge 1.0$. Combined with the Fig.3, to make the Nf=10, the liquefaction stress ratio of the loess of e=0.8 is 1.3 times of that with e=0.9, and the liquefaction stress ratio of the loess of e=0.7 is 1.44 times of that with e=0.8, so the liquefaction stress ratio increased significantly with decrease of void ratio when $e \le 0.9$.

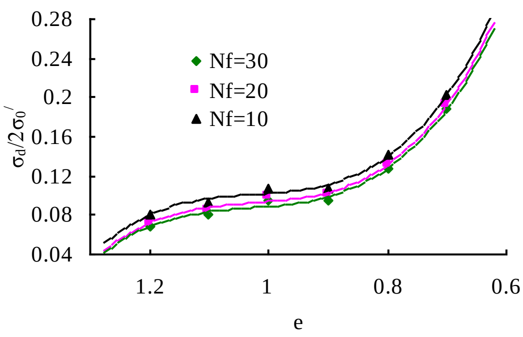


Figure 4. The relationship between ($\sigma_d/2\sigma_0'$) and (e) of different compacted loess

The relationship between liquefaction stress ratio and initial void ratio can be fitted using cubic polynomial function as equation (3-1), $\sigma_d/2\sigma_0'$ is the liquefaction stress ratio, e is the initial void ratio, a, b, c, d are fitting parameters.

$$\frac{\sigma_d}{2\sigma_0'} = ae^3 + be^2 + ce + d \tag{3-1}$$

3.2 Influence of plastic index

The plastic index reflects the role of the grain composition of the soil. The cementation of the fine grain is believed to raise the liquefaction stress of the saturated loess. In the study we choose the undisturbed loess samples from Lanzhou, Guyuan and Tianshui city to examine the influence of the plastic index, in order to ensure that the structure of the loess is not damaged. The test results are shown in figure.5. According to the figure, under the similar number of cycles, the liquefaction stress ratio of the Tianshui loess which had a cemented structure is the largest, whereas the Lanzhou loess whose structure was weakly cemented is the smallest, and the results from Guyuan loess fall in between. The increase of plastic index results in a stronger structure of the loess, increasing liquefaction stress.

The relationship between liquefaction stress ratio and plastic index under different seismic intensity is obtained from test results of figure.5 and is given as figure.6. The relationship can be fitted using an exponential function as equation (3-2), in which a and b are fitting parameters. It can be observed from figure 6 that with the increase of plastic index, and the liquefaction potential diminished largely due to increase of the cementation of the fine grains, the tendency of the structure collapse of the loess is diminished.

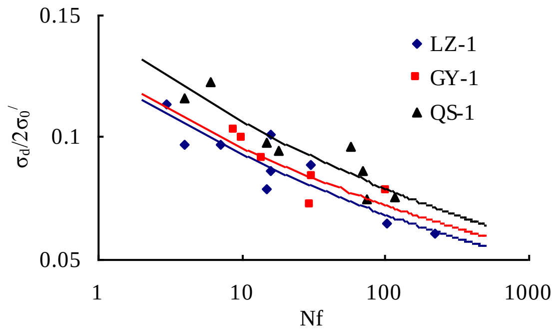


Figure 5. The relationship between ($\sigma_d/2\sigma_0'$) and (Nf) of different undisturbed loess

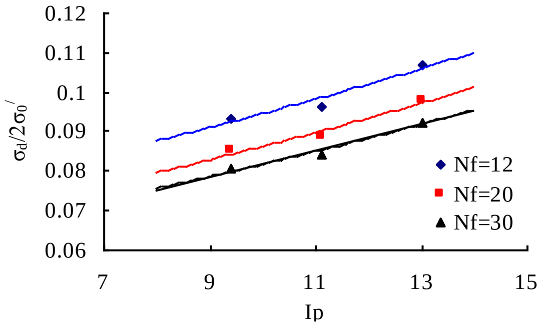


Figure 6. The relationship between ($\sigma_d/2\sigma_0'$) and (Ip) of different undisturbed loess

$$\frac{\sigma_d}{2\sigma_0'} = ae^{b*Ip} \qquad (3\text{-}2)$$

$\sigma_d/2\sigma_0'$ is the liquefaction stress ratio, Ip is the plastic index, a, b are fitting parameters.

3.3 Influence of depth

The impact of depth on the liquefaction stress is mainly due to vertical overburden pressure of the soil. In the study, the influence of the vertical overburden pressure is examined based on the test results of loess at different depth from Guyuan site.

As seen in figure 7, the vertical overburden pressure of Guyuan loess increase with the depth with little influence form other initial physical indexes. We can compute the vertical overburden pressure with equation (3-3), which is used to calculate its liquefaction stress. The liquefaction potential evaluation results of Guyuan saturated loess using the Seed's simplified liquefaction evaluation method show that the maximum depth for liquefaction occurring are 20.8m, 28.8m and 38.5m under the seismic intensity of Ⅶ, Ⅷ and Ⅸ. The depth limit is related to the seismic intensity and the initial physical indexes of the loess, it increases with the seismic intensity, and decrease with the decrease of initial void ratio or increase of the plastic index.

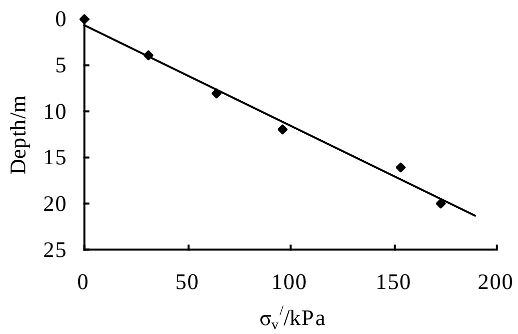


Figure 7. The depth versus vertical overburden pressure of the saturated loess

$$\sigma_v' = ah + b \qquad (3\text{-}3)$$

$\sigma_v^{/}$ is the effective gravity stress, h means the depth, a, b are fitting parameters.

4.LIQUEATION POTENTIAL EVALUATION METHOD BASED ON PHYSICAL INDEXES AND DEPTH

4.1 Calculation and evaluation results of liquefaction potential

The earthquake shear stress $\tau(t)$, the liquefaction resistance strength τ and the earthquake equivalent shear stress τ_e have been used to evaluate the liquefaction potential of the saturated loess. We set a parameter A which means the number of the peak of $\tau(t)$ is greater than τ as follow (Wang Lanmin 2011):

If $\tau(t) < \tau$ and $\tau_e < \tau$， unliquefiable.

If A is less than the equivalent number of cycles, and $\tau_e < \tau$, light liquefiable.

If A is greater than the equivalent number of cycles, and $\tau_e < \tau$, moderate liquefiable.

If A is greater than the equivalent number of cycles, and $\tau_e \geq \tau$, completely liquefiable.

If A is less than the equivalent number of cycles, and $\tau_e \geq \tau$, it could be unliquefiable, light liquefiable or moderate liquefiable according to the magnitude of A.

In the above-mentioned assessment method, the strength of loess deformation, τ, which is resistance to liquefaction and the equivalent shear stress, τ_e, of earthquake can be calculated respectively by equation (4-1) and equation (4-2). The results are shown in table 4.1.

$$\frac{\tau}{\sigma_v'} = C_r \frac{\sigma_d}{2\sigma_0'} \qquad (4\text{-}1)$$

$$\tau_e = 0.65K \frac{a_{max}}{g} \gamma h \qquad (4\text{-}2)$$

In the equations, $\sigma_v^{/}$ is the effective gravity stress, Cr and K are reduction coefficient, $\sigma_d/2\sigma_0^{/}$ is the liquefaction stress ratio, a_{max} means design earthquake acceleration, g is acceleration of gravity, γ means density, h means the depth.

Table 4.1 Results of Liquefaction Stress and the Equivalent Shear Stress of Different number of cycles

Samples	σv′/kPa	τ/kPa			τe/kPa		
		Nf=12	Nf=20	Nf=30	Nf=12	Nf=20	Nf=30
LZ-1	49.04	2.14	2.03	2.05	3.78	9.18	17.84
LZ-2	46.58	1.75	1.66	1.57	3.80	9.24	23.45
LZ-3	43.89	2.60	2.48	2.35	4.17	10.16	19.74
LZ-4	41.68	2.77	2.63	2.53	4.40	10.70	20.78
LZ-5	39.72	3.83	3.72	3.55	4.64	11.29	21.93
LZ-6	37.86	5.86	5.68	5.59	4.92	11.96	23.22
GY-1	31.11	1.74	1.62	1.57	3.00	7.30	14.18
GY-2	63.76	4.28	4.02	3.79	5.99	14.58	28.31
GY-3	96.01	6.80	6.39	5.99	8.65	21.04	40.86
GY-4	153.86	10.8	10.52	10.15	12.40	30.16	58.58
GY-5	172.77	13.68	13.06	12.34	13.56	32.98	32.98
QS-1	42.12	2.60	2.48	2.33	4.28	10.40	20.20

According to the above-mentioned evaluation method of loess liquefaction potential, we evaluated the liquefaction potential of saturated loess and the compacted loess under different seismic intensity through comparing the shear stress time history τ(t) at the saturated loess site with the related calculated result in table 4.1. The evaluated results are shown in table 4.2.

Table 4.2. Liquefaction Potential under the Effect with Different Seismic Intensity

Samples	The number of τ(t)≥τ			Liquefaction potential evaluation		
	Seismic intensity					
	7	8	9	7	8	9
LZ-1	46	52	81	completely liquefiable	completely liquefiable	completely liquefiable
LZ-2	48	56	94	completely liquefiable	completely liquefiable	completely liquefiable
LZ-3	25	28	78	completely liquefiable	completely liquefiable	completely liquefiable
LZ-4	22	23	70	completely liquefiable	completely liquefiable	completely liquefiable
LZ-5	11	15	44	moderate liquefiable	moderate liquefiable	completely liquefiable
LZ-6	6	13	35	slightly liquefiable	moderate liquefiable	completely liquefiable
GY-1	23	38	71	completely liquefiable	completely liquefiable	completely liquefiable
GY-2	14	28	62	completely liquefiable	completely liquefiable	completely liquefiable
GY-3	8	24	46	moderate liquefiable	completely liquefiable	completely liquefiable
GY-4	6	19	38	slightly liquefiable	moderate liquefiable	completely liquefiable
GY-5	2	9	28	non-liquefiable	slightly liquefiable	moderate liquefiable
QS-1	29	41	58	completely liquefiable	completely liquefiable	completely liquefiable

4.2 Liquefaction potential evaluation methods based on major physical indexes and depth

According to the above-mentioned tests, calculation and analysis, we could propose a method of evaluating liquefaction potential of saturated loess based on physical parameters and the maximum depth of the loess, which is summarized in table 4.3.

Table 4.3 Physical Parameters and the Minimum Depth of Liquefaction Potential Evaluation

Liquefaction	Seismic intensity		
	7	8	9
non-liquefiable	e≤0.9 & h≥20m	——	——
slightly liquefiable	a）e≤0.7 & h≥5m or b）e≤0.8 &16m≤h≤20m	e≤0.9 & h≥20m	——
moderate liquefiable	a）0.7≤e≤0.8 & h≥5m or b）e≤1.1，Ip≥9.8 &16m≤h≤20m	a）e≤0.8 & h≥5m or b）e≤0.9 &16m≤h≤20m	e≤0.9& h≥20m
completely liquefiable	others	others	others

5. CONCLUSIONS

The following research achievements are gained:

1) The liquefaction stress ratio of the saturated loess increases with the decrease of initial void ratio, the relationship between of them can be fitted as a cubic polynomial function.
2) The relationship between liquefaction stress ratio and plastic index can be fitted as an exponential function. The liquefaction stress increases with increase of I_p .
3) The vertical overburden pressure of the loess increase with the depth increase, it can be fitted by using liner function, however, the initial physical indexes has little influence on it.
4) A method to evaluate loess liquefaction potential using the physical indices and depth limit has been established based on dynamic triaxial test and computing results.

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