

Review of Elastic Wave Scattering from Tunnel Structures

Kaixiang Fan¹, Yusheng Shen^{1,*}, Bo Gao¹

¹Southwest Jiaotong University, Chengdu, China

Abstract

Shallow buried mountain tunnels are prone to earthquake damage under the action of strong earthquake. With the great development of rail transit in China, more and more tunnels will be built in high seismic intensity areas. It is of great scientific research and engineering significance to carry out research on anti-shock damping technology of shallow buried mountain tunnels in high seismic intensity areas. In essence, the dynamic response of tunnel structure under earthquake belongs to the scattering of elastic waves. In this paper, the research status of the scattering of elastic waves by tunnel structure is summarized, aiming to provide reference for similar research.

Keywords

Tunnel engineering; Shallow buried; Seismic response; Scattering of elastic waves; review.

1. Introduction

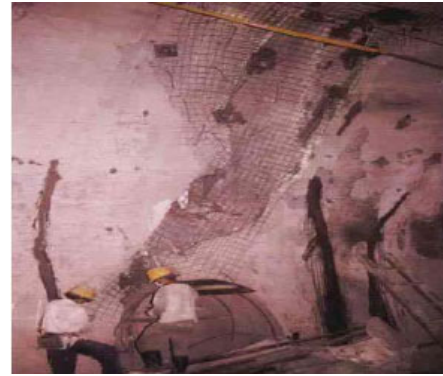
In the 21st century, mankind is faced with six major challenges: population growth, land desertification, energy shortage, reduction of water resources, environmental deterioration and climate warming[1]. With the rapid development of China's economy and accelerated urbanization, the resulting "urban syndrome", such as urban population saturation, land scarcity, crowded building space, traffic congestion, environmental pollution and urban waterlogging, has become increasingly prominent[2]. With the outstanding advantage that it does not occupy ground land resources, tunnels and underground engineering are playing an increasingly important role in dealing with many major challenges such as "population growth", "resource shortage", "environmental deterioration" and "traffic congestion"[3-4].

According to statistics, earthquakes of magnitude 7 or above on the Chinese mainland account for 1/3 of the earthquakes of magnitude 7 or above on the global mainland, and the number of deaths due to earthquakes accounts for 1/2 of the global total. In more than 300 cities in the country, half in the basic earthquake intensity for VII to VII degrees above the earthquake zone, 23 millions more than the population of cities, more than 70% VII and VII degrees of earthquake zones.

Typically, underground structure seismic performance is superior to the ground structure[5], but since the 1995 kobe earthquake in Japan, Taiwan chi-chi earthquake in 1999, the wenchuan earthquake in 2008 and 2013 ya since the earthquake, a large number of underground structure in different degree of damage, overturns the underground structure is a good seismic performance of the traditional concept of a natural, shows that the tunnel under the action of earthquake resistance to shock problems also need high attention. The main failure modes of tunnels and underground structures after earthquake are collapse of central columns, cracking blocks of lining, collapse of the inverted slope at the entrance of the cave, longitudinal, circular and oblique cracks and water seepage, water gushing, groundwater accumulation, steel bar distortion and even fracture, overall tunnel collapse and closure, etc. Typical failure types after earthquake are shown in Fig. 1.



The central column collapse of Daikai Station after the Hanshin Earthquake in Japan



Lining blocks of Chi-Chi Earthquake Tunnel in Taiwan



Invert slope damage at the entrance of Longdongzi Tunnel caused by Wenchuan Earthquake



Segment cracking and water seepage of Chengdu Metro Line 1 caused by Wenchuan Earthquake

Fig 1. Damage of tunnels and underground works under several typical strong earthquakes [5-6]

Because the tunnel and underground works have high cost, long construction period, damage is difficult to repair or repair the cost is high, traffic interruption of earthquake disaster rescue caused by immeasurable losses and other characteristics, as one of the main structures of the national lifeline project, we must learn from the previous earthquake disaster experience. Therefore, it is of great significance to study the dynamic response mechanism of tunnels and underground structures under earthquake.

2. Scattering of Elastic Waves in Elastic Media

The essence of the so-called wave function expansion method is to separate the variables of the wave equation, construct the scattered wave field by using the wave function which can satisfy the governing equation, and obtain the expanded wave function coefficients from the boundary conditions, so that the problem can be solved. In 1973, Chinese-American scholars Yih-hsing Pao and Chao-Chow Mow [7] made pioneering use of wave function expansion method and integral transformation method to study the dynamic stress concentration problem of full-space holes under elastic wave incident. Figure 2 shows the diagram of typical plane wave incident. They reproduce more than ten years of research results, published authoritative works of the Diffraction of Elastic Waves and Dynamic Stress Concentrations, "(Diffraction of Elastic wave and Dynamic Stress concentration)", the book not only systematically elaborates the basic principle of wave mechanics, this paper introduces the due to obstacles exist

Diffraction of steady state and transient wave method, is presented in different geometry obstacles on the numerical results of Stress concentration, and points out several important problems of wave mechanics and development direction, With the publication of the book, research mushroomed.

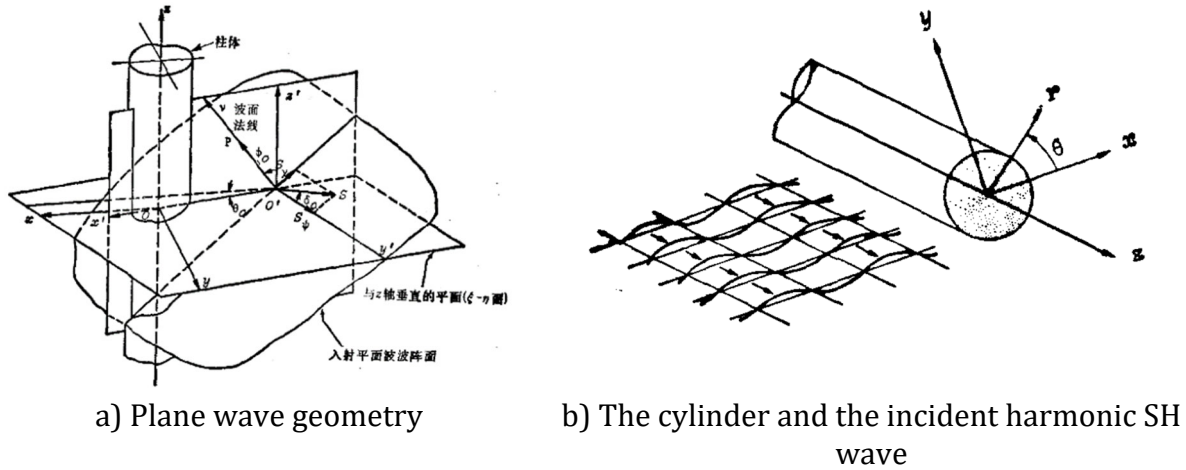


Fig 1. Typical plane wave incidence[7]

Lee V W is undoubtedly the first to be mentioned among many scholars who study elastic wave scattering from underground structures based on wave function expansion method. Since the mid-1970s, Lee and his collaborators Trifunac, Cao, Karl, Todorovska, Liang and others have carried out detailed and in-depth studies on elastic wave scattering and dynamic stress concentration, and achieved fruitful results, which are still active in the research front line. Trifunac [8] (1971) firstly used the wave function expansion method to obtain the exact analytical solution of the incident SH wave in a two-dimensional semicircular valley in an elastic half space. Lee [9] (1977) generalized the solution of PAO and MOW [7] to half space by using wave-function expansion method combined with mirror image method, and studied the scattering of incident plane SH wave by two-dimensional cavity in uniform elastic half space.

Lee and Trifunac [10] (1979) used a similar method to obtain the analytic solution of the scattering of a lining tunnel in a uniformly elastic half space under the incident SH wave in the plane, as shown in Fig. 3. Later, the scattering of incident waveforms by other scholars was studied, but it was found that because P and SV waves would transform on the scattering surface, the processing of scattering boundary conditions was much more complicated than that of SH waves, so the wave function expansion method combined with the mirror image method was not applicable.

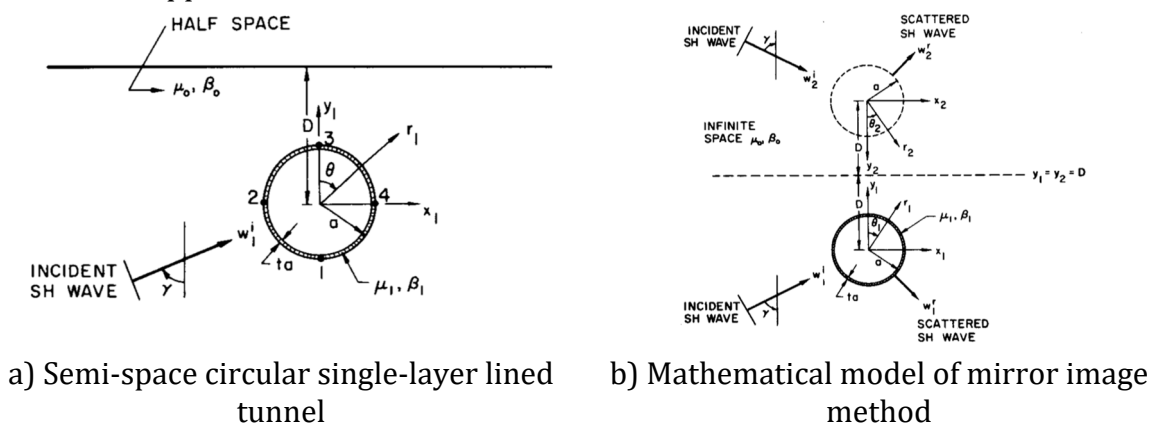


Fig 2. Scattering of incident plane SH waves by two-dimensional tunnels in space [10]

Sheidl and Ziegler [11] (1978) an article for this field of research provides a new train of thought, they suggest that with a large radius arc approximated obstacles of half space near the boundary, this allows the straight boundary of the scattering wave into a large circular arc boundary scattering, thus waveform transformation are applied to solve the problem can use the mathematical formula, they use this method to study the half space circular rigid inclusions under the effect of Rayleigh surface wave scattering problems. Inspired by the idea, Lee and Cao [12] (1989) through the study found that using the Sheidl and Ziegler [11] in this paper, the mathematical method of numerical solution is not convergence, the applicability of the method is limited, so they are using finite Fourier series to replace Sheidl and Ziegler [11] not convergent series method in this paper, at the same time, by adopting the idea of a large circular arc approximation straight boundary (great circle hypothesis), and studies a series of elastic wave scattering problems in elastic half space, achieve more satisfactory results, as shown in figure 4 - a. With the deepening of the research, Lee and kar1 [13] (1992199 3) of the above method is improved, the half space are measured by using large circular arc approximation straight boundary, on the basis of combining the wave function expansion method, using Fourier - Bessel series to replace the original Fourier series, cavity in homogeneous elastic half space are given for incident plane P and SV wave scattering analytical solution, optimized the original on the mathematics theory and get a more accurate solution, as shown in figure 4 - b. Davis, etc. [13] in Lee (2001), on the basis of research results, such as the great circle boundary scattering component has carried on the detailed analysis, thought the scattered waves are caused by the incident wave straight boundary reflection wave and scattering wave produced by the approximate circular arc, but due to the great circle is an approximate boundary, and the value of the reflection wave under the condition of a given incident wave is certain, so when calculating the scattering of the great circle should have reflected wave components separated, the circular arc of the resulting scattering error relative Lee and others methods, Davis used this method to solve the analytic solution of planar SV wave scattering by underground caverns and pipes. By comparing the numerical results with other literatures and engineering examples, it is found that this method can achieve high accuracy, as shown in Fig. 4-C. Luo(2010) [15] used the classical wave function expansion method and a new decoupling method to study the scattering problem of a two-dimensional semi-circular cavity under SH wave incident in half space.

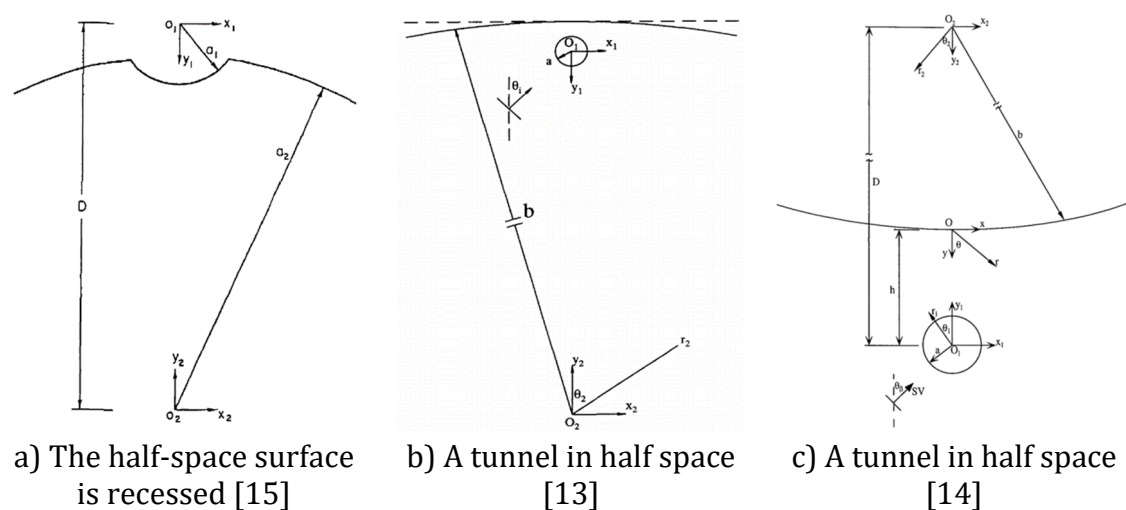


Fig 3. Scattering of elastic waves from local topography under large circular arc hypothesis

In contrast, the wave function expansion method used by domestic scholars to study the scattering of elastic waves from underground structures started relatively late. Since 2003, Liang Jianwen et al. [16-29] (2003,2004,2005,2006,2013), based on the research of Lee et al., used the Fourier-Bessel series expansion method to study the analytical solution of elastic wave scattering of single hole, parallel double hole, underground cavern group and corresponding lining cavern in semi-infinite space, as shown in Fig. 5.

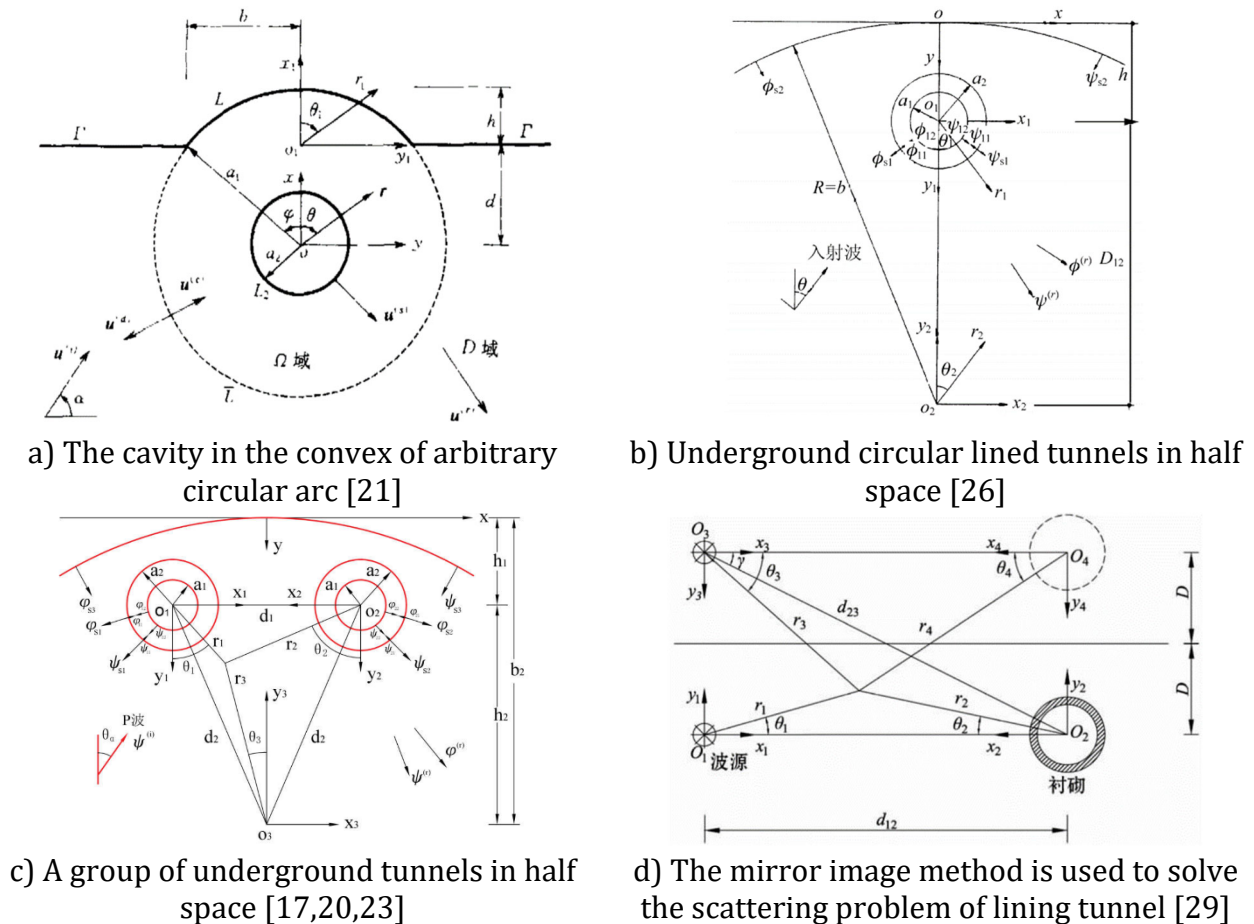
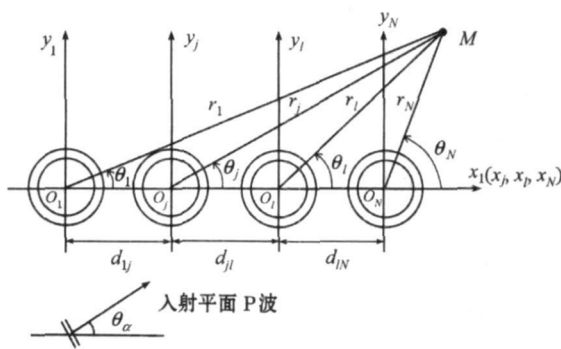
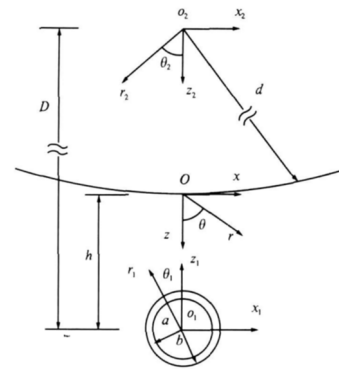


Fig 4. Scattering of elastic waves by an underground tunnel in a single phase half space

Xu Pingping[30] (2008) used the wave function expansion method and Graf addition theorem to obtain the analytical solution of plane P-wave multiple scattering by deep circular lining groups, as shown in Fig. 6-a, according to the boundary conditions that the displacement and stress at the interface between the lining group and the surrounding medium are continuous and the inner boundary of the lining is completely free. Xu Pingjun[31] (2009) used the wave function expansion method combined with the hypothesis of large circular arc to analyze the influence of the dimensionless incidence frequency, lining thickness and burial depth on the dynamic stress concentration factor inside the lining and the normalized horizontal and vertical displacements on the surface of half space when the plane P-wave was incident vertically, as shown in Fig. 6-b.



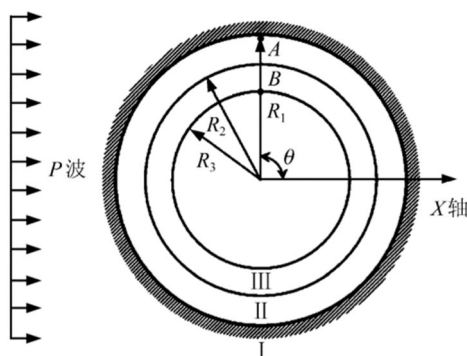
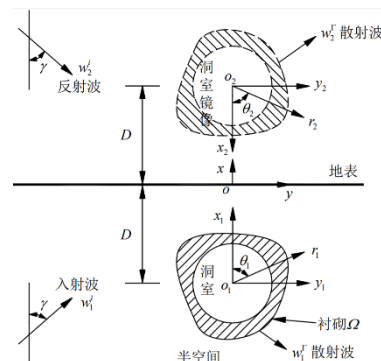
a) Deep buried circular lining group [30]



b) Semi-space elastic medium with circular lining [31]

Fig 5. Scattering of elastic waves by lining (groups) in a single phase medium

Wang Changbai et al. [32] (2011) derived the analytical solution of the diffraction problem of a deep-buried double-lined circular cavity in infinite medium under the action of plane P wave by using the wave-function expansion method, as shown in Fig. 7. He Ying[33-34] (2014,2015,2016) used the wave function expansion method and the boundary dispersion method to give the semi-analytical solution of the surface dynamic stress and the dynamic stress of the lining of the underground cave with arbitrary cross-sectional shape to the plane SH wave scattering, as shown in Fig. 8

**Fig 6.** Deep buried compound lining tunnel [32]**Fig 7.** Lined cavern of arbitrary shape and its mirror image [34]

Fu Jia[35] (2016) used wave function expansion method to solve the analytical solution of dynamic response of embedded rigid lining tunnel in uniform half space under incident SH wave in plane, as shown in Fig. 9. Wang shuai shuai [36-39] (8, 2014201, 6201, 7201) using Fourier - Bessel series expansion method system to study the deep and shallow buried single-phase set damping layer composite lining of tunnel surrounding rock medium in plane P wave, SH wave and SV wave and the Rayleigh wave under the action of elastic wave scattering and dynamic stress concentration problem, elaborated the tunnel engineering in setting up the damping mechanism of damping layer and the optimal design parameters are given, the model is shown in figure 10 ~ as shown in figure 12.

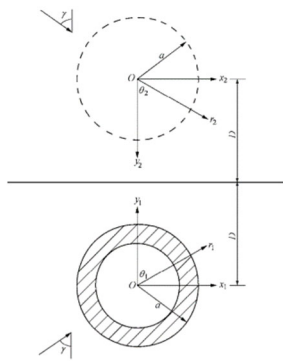


Fig 8. Half-space rigid lining and its mirror image [35]

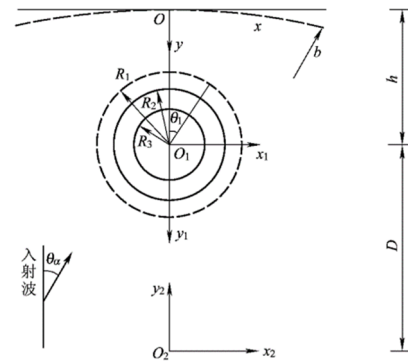


Fig 9. Half space double lined caverns [37]

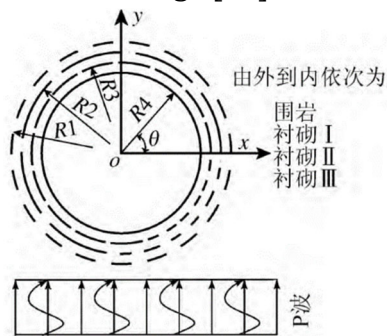


Fig 10. Deep buried compound lining cavern [40]

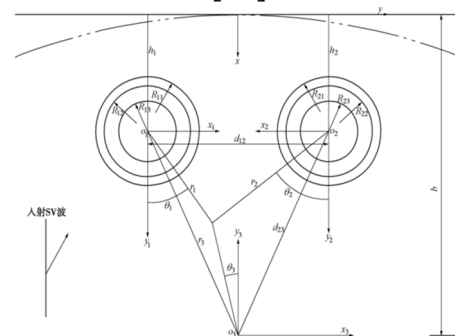


Fig 11. Double - layer double - hole lining cavern model drawing [39,41]

3. Conclusion

Summing up the tunnel damping resistance research status both at home and abroad can be found, though the tunnel resistance to shock absorption technology has made a lot of research results, but at present our country has not been specifically for mountain tunnel seismic design specification, at present our country mountain tunnel seismic design method is based on the railway engineering anti-earthquake design specification (GB50111-2006) in the seismic coefficient method is put forward, only consider the function of the horizontal seismic force. The Code for Seismic Design of Urban Rail Transit Structures (GB50909-2014) issued in 2014 proposes that subway stations and intervals can be analyzed by reaction displacement method or reaction acceleration method. These seismic analysis methods do not consider the incident direction and frequency of seismic waves, as well as the scattering of elastic waves by underground tunnels, etc. In the future, the seismic wave scattering theory can be used to further study the anti-shock design of composite lining.

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