Settlement Analyses of Homogeneous and Non-Homogeneous Granular Pile with Linear, Non-Linear and Average Deformation Modulus

Dr. Pooja Gupta[1], Prof. J.K. Sharma[2], Prof. K.S. Grover[3]

[1]*Department of Civil Engineering, Poornima Institute of Engineering & Technology, Jaipur, Rajasthan, India*
E-mail: pooja.gupta@poornima.org
[2]*Department of Civil Engineering, Rajasthan Technical University, Kota, Rajasthan, India*
E-mail: jksharma@rtu.ac.in
[3]*Department of Civil Engineering, Rajasthan Technical University, Kota, Rajasthan, India*
E-mail: kdsgrover@gmail.com

Abstract

The use of Stone columns or granular piles for ground improvement is found most flexible and cost effective technique in comparison to other methods. The inherent advantage of using granular piles is its ability to adjust the applied load and thereby redistribute the load on the constituent soils. The present study deals with the comparative settlement analysis of homogeneous and non-homogeneous floating granular pile with effect of linear variation, non-linear variation and average values of deformation modulus from top to tip of the granular pile. The behavior of non-homogeneous granular pile is analysed based on elastic continuum approach in terms of settlement influence factor. It was observed from the present analysis that the reduction in settlement of a non-homogeneous floating granular pile is approximately in range of 10 to15% in comparison to settlement of homogeneous granular pile. This reduction in settlement depends on the degree of non-homogeneity and relative length of granular pile. It was also found that by average analysis the values of settlement influence factors are under estimated in comparison to the exact analysis.

Keywords: Granular pile, Settlement Influence factor, Non-homogeneity, Deformation modulus, Average analysis.

1. Introduction

The behavior of homogeneous and non-homogeneous granular pile is analyzed by various researchers and practicing engineers for ground improvement. Successful implementation of granular piles/stone columns in different geotechnical projects have already been exposed throughout the world. Baez & Martin [1] investigated the application of granular piles in increasing the resistance to liquefaction and minimize the settlements following it. Madhav & Nagpure [2] presented design charts for rapid determination of equivalent soil parameters of stone column reinforced ground based on area ratio, column and soft soil characteristics. Lee & Pande [3] reported a numerical model to analyze elastic as well as elastoplastic behavior of granular pile reinforced foundations by assuming the granular piles dispersed within the in situ soil and a homogenization technique was invoked to establish equivalent material properties for in situ soil and granular pile composite. Sivakumar et al. [4] investigated the load deformation performance of specimens of soft clay reinforced with single sand columns with various lengths by conducting laboratory experiments.

Priebe [5] extended the formulation of Priebe[6] to floating piles. Two approaches have been suggested assuming that the balancing of stress takes place solely either in the upper treated zone or in the lower untreated zone. Shivashankar [7] presented results from a series of laboratory plate load tests carried out in unit cell tanks to investigate the improvement in stiffness, load carrying capacity and resistance to bulging of stone columns installed in soft soils. Siva Kumar et al.[8] proposed a laboratory model study on the settlement performance of isolated pad footings bearing on reinforced sand deposits under the influence of a fluctuating groundwater table.

Etezad [9] presented an analytical model to predict the bearing capacity of soft soil reinforced with stone columns under rigid raft foundation subject to general shear failure mechanism. The causes of non-homogeneity of granular pile are discussed by Madhav M R, et al.[10] and Gupta P and Sharma J K [11]. Grover K.S et al. [12] analyzed the effect of stiffening on a single granular pile for both types of piles viz. floating and end bearing.The response of non-homogeneous floating granular pile in non-homogeneous soil is evaluated by Sharma and Gupta[13] to study its true behaviour. The objective of the present study is to conduct a comparative settlement analysis of homogeneous and non-homogeneous floating granular pile with the consideration of effect of linear variation, non-linear variation and average values of deformation modulus from top to tip of the granular pile.

2. Method of Analysis

The elastic continuum approach is used to analyze the behavior of a homogeneous and non-homogeneous granular pile in an ideal elastic soil mass. The analysis is based on finding out the stress system, {τ}, along the soil-granular pile interface which satisfy the compatibility of displacements along the interface for no slip or yield condition [10].

The compressible granular pile of length, L, and diameter, d, acted upon by load P. The granular pile is characterized by its deformation modulus E_{gp} increasing linearly and non-linearly with depth as mentioned in equations (1) and (2) respectively. The load on granular pile is distributed by mobilization of shear stresses on GP-soil interface. The deformation modulus Egp (z) at any depth z, from the top of the granular pile is

$$E_{gp}(z) = E_{gp0}\left\{1+\alpha\frac{z}{L}\right\} \tag{1}$$

$$E_{gp}(z) = E_{gp0}\left\{1+\alpha\frac{z}{L}+\delta\left(\frac{z}{L}\right)^2\right\} \tag{2}$$

From equation (1) and (2), E_{gp0} is the deformation modulus at ground surface, α and δ are linear and non-liner non-homogeneity parameters respectively and can be expressed from equation(1) as:

$$\sim\ = \frac{\left\{\frac{E_{gp(z)}}{E_{gp0}}-1\right\}}{\left(\frac{z}{L}\right)} \tag{3}$$

and from equation (2) α and δ are expressed as:

$$\sim\ = \frac{\left\{\frac{E_{gp(z)}}{E_{gp0}}-1-¢\left(\frac{z}{L}\right)^2\right\}}{\left(\frac{z}{L}\right)}$$

$$\text{¢} = \frac{\left\{ \dfrac{E_{gp(z)}}{E_{gp0}} - 1 - \sim \left(\dfrac{z}{L} \right) \right\}}{\left(\dfrac{z}{L} \right)^{2}} \qquad (4)$$

Where Egp(z) is the deformation modulus of the granular pile with linear and non-linear variation as shown in figures 1 and 2 respectively.

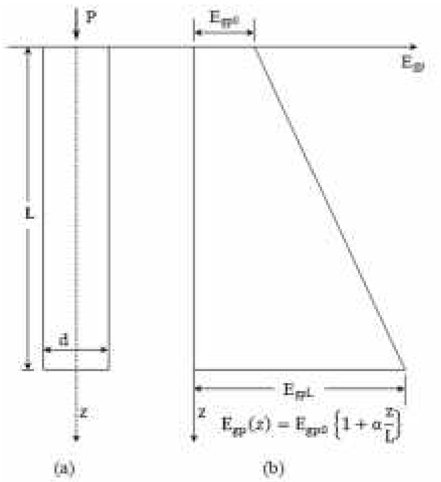

Fig. 1(a) floating granular pile (b) linear variation of deformation modulus with depth

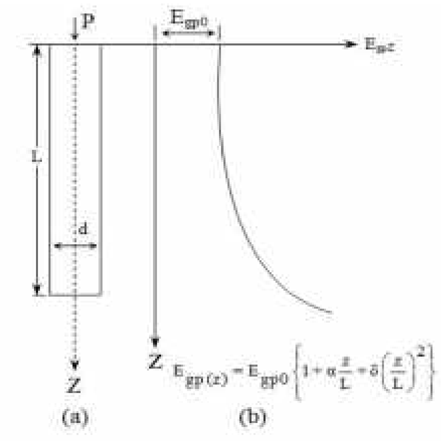

Fig.2 (a) floating granular pile (b) linear variation of deformation modulus with depth

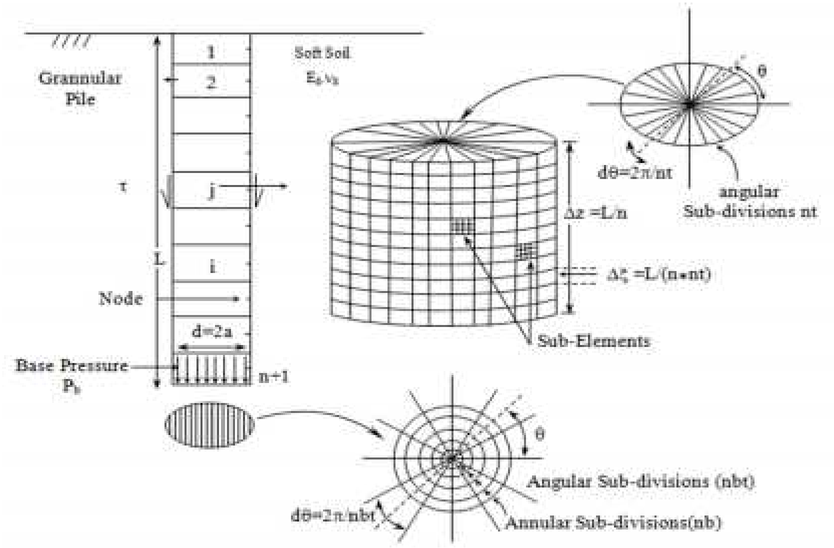

Fig.3 Granular Pile discretisation Scheme

Figures 1(a) and (b) show respectively floating granular pile and linear variation of deformation modulus with depth. Similarly Figures 2(a) and (b) depicts the floating granular pile and non-linear variation of deformation modulus with depth. The surrounding soil and the base are represented by their deformation moduli and Poisson's ratios as E_s & ν_s respectively. The discretisation used for the integration of Mindlin's equation is shown in Fig.3.The relative stiffness parameter is defined as the ratio of the deformation modulus of the granular pile at ground level to that of the soil i.e., K_{gp0} (= E_{gp0}/E_s). The elastic continuum approach is used to analyze the behavior of a homogeneous and non-homogeneous granular pile in an ideal elastic soil mass. The basic assumptions in the analysis are:

1. The base of stone column/granular pile is assumed to be smooth and rigid across which the load is uniformly distributed [10].
2. The disturbance effects in the in-situ soil due to the installation of granular piles are ignored and considered as homogeneous.
3. The settlement of granular pile depends on its deformation modulus and geometry besides the magnitude of load. Based on the various studies the consideration of non-homogeneity of granular pile is appropriate and close to in situ behavior. Non-homogeneity of granular pile is considered in terms of its deformation modulus with the linear to non-linear variation.

The essential steps of the analysis are-

2.1 Soil Displacements:

GP is discretised into ‘n’ cylindrical elements acted upon by shear stresses,τ, and with the base having a uniform pressure, P_b. The soil displacements of the nodes on GP periphery and the centre of each element are evaluated based on the influence of the elemental shear stresses. Thus, soil displacements equations for a floating granular pile

$$\left\{\rho^{s}\right\} = \left\{\frac{S^{s}}{d}\right\} = \left[I^{sp}\right]\left\{\frac{\tau}{E_{s}}\right\} \tag{5}$$

Where $\{S^s\}$ and $\{\rho^s\}$ are soil displacement and normalised soil displacement column vectors respectively. $\{\rho^s\}$ is of size (n+1) for floating granular pile. $\{\tau/E_s\}$ is a column vector of size (n+1) for the normalised shaft stresses and normal stress on the base. $[I^{sp}]$ is a square matrix of soil displacement influence coefficients of size (n+1) for displacement of n number of nodes on periphery of shaft of granular pile and $(n+1)^{th}$ base node on centre due to influence of each ‘n’ number of shaft stresses on n nodes and base pressure of $(n+1)^{th}$ node based on Integration scheme of Mindlin’s equation.

2.2 Pile Displacements:

Granular pile displacements are based on the equilibrium relation for an infinitesimal element of granular pile obtained as given by Sharma and Gupta [11].

$$\left[I^{pD}\right]\left\{\circ\, p\right\} + \left\{Y\right\} = \left\{\frac{2}{E_{S}}\right\} \tag{6}$$

Where $[I^{pD}]$ is a square matrix of size, (n+1) of pile displacement influence coefficients and {Y} is a column vector of size, (n + 1) as mentioned by Sharma and Gupta [13].

3. Results and Discussion:

Results are presented for the following ranges of non-dimensional parameters: for analysis of non-homogeneous granular pile in homogeneous soil: L/d = 10–40, $K_{gp} = E_{gp}/E_s$ = 10–1000, α = 0–4, δ = 0–4, ν_s=0.5. Relative stiffness, K_{gp}, of granular pile, lies between 10 and 100 but for the better understanding of the problem, analysis is carried out up to K_{gp} = 1000. The agreement between the results from the present analysis with those from Poulos et al. [14] has been very close (Table 1).

Table 1 Comparison of results from the present analysis with Poulos [14]

Parameters	Settlement Influence Factor (I_{sp})	Reference
(a)Floating Granular Pile L/d=10, K_{gp}= 100, ν_s= 0.5	0.189	Mattes and Poulos (1969)
(b)Floating Granular Pile L/d=10 K_{gp}= 100, ν_s= 0.5	0.1891	Present Analysis

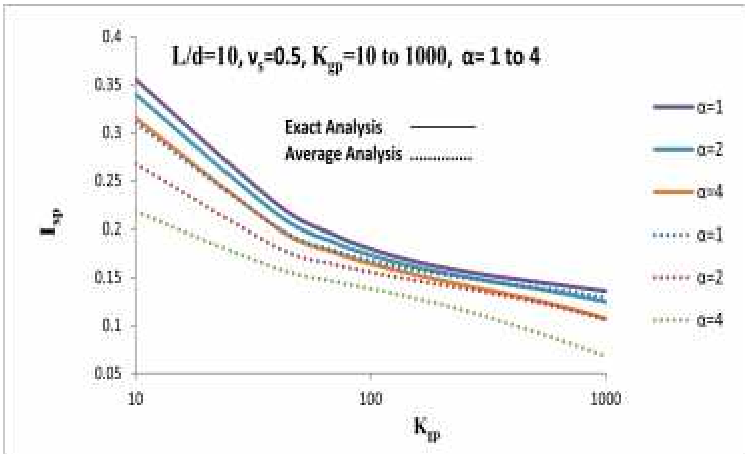

Fig.4 Comparative Variation of settlement influence factor, I_{sp} with relative stiffness, K_{gp} for Floating Granular Pile - effect of non-homogeneity parameter, α. (L/d=10)

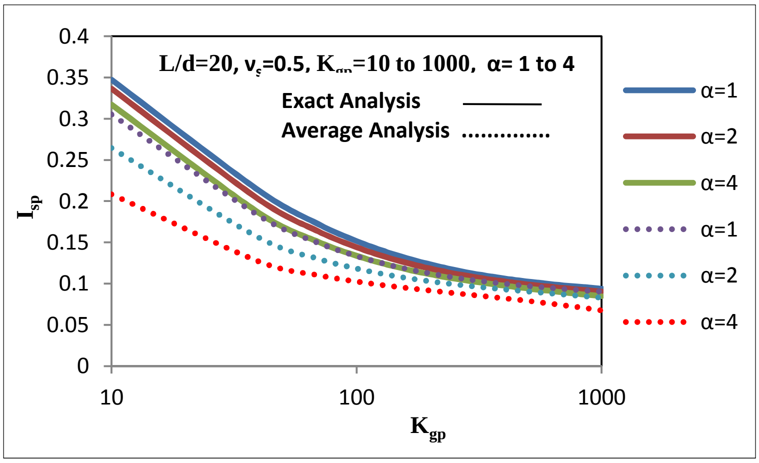

Fig.5 Comparative Variation of settlement influence factor, I_{sp} with relative stiffness, K_{gp} for Floating Granular Pile - effect of non-homogeneity parameter, α (L/d=20).

Figures 4 and 5 depict that with the increase of relative stiffness parameter, K_{gp}, settlement influence factor, I_{sp}, decreases for all values of linear non-homogeneity parameter, α. Settlement influence factor, I_{sp} decrease with increase of α. For a given degree of non homogeneity parameter,α, a longer GP (L/d=20) would have a relatively smaller modulii at all depths compared to a shorter one (L/d=10). Figures 4 and 5 also shows that with the average analysis, settlement influence factor, $I_{sp,}$ is under estimated while the exact analysis is appropriate.

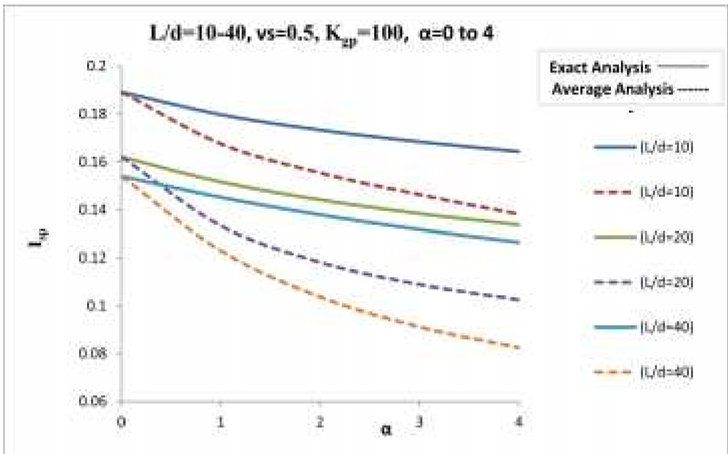

Fig.6 Comparative Variation of Settlement influence factor, I_{sp} with linear non-homogeneity parameter, α, for Floating GP-effect of relative length, L/d.

The decrease in settlement influence factor with non-homogeneity parameter, δ for all values of Kgp is less for longer GP in comparison to a shorter granular pile as shown in fig.6. The same trend had been reported by Madhav et al. [10] in variation of settlement influence factor, I_{sp} and non-homogeneity parameter, α with effect of relative length, L/d. Figure 6 also gives the clear idea of under estimated values with the average analysis in comparison to the exact analysis.

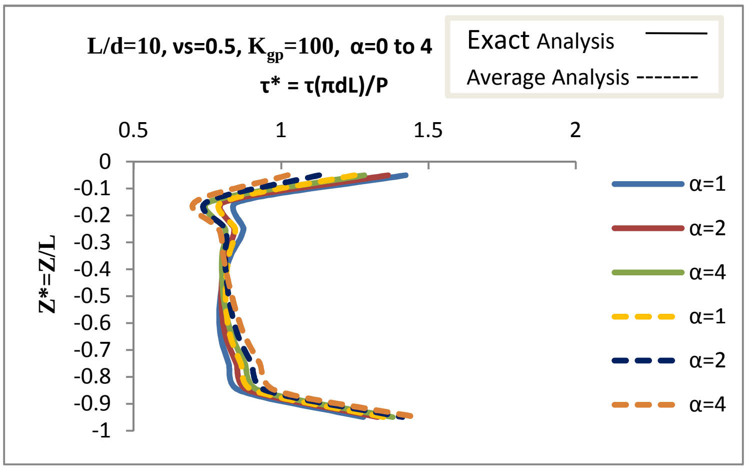

Fig.7 Comparative Variation of normalised shear stress, τ* with normalised depth, Z* with effect of linear non-homogeneity parameter, α.

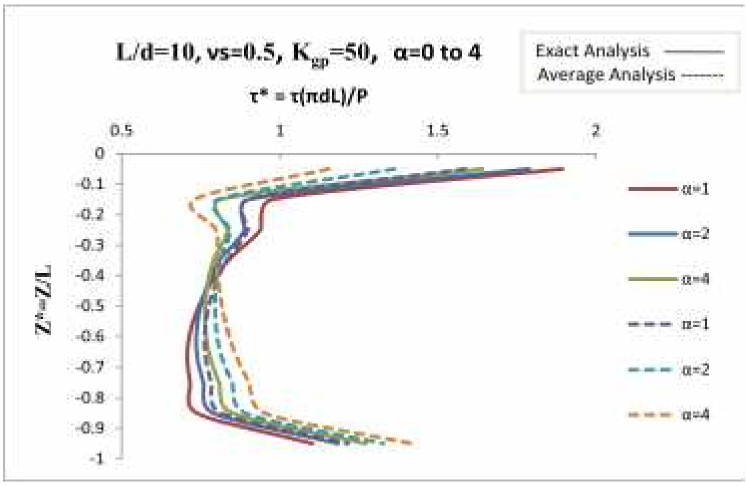

Fig.8 Comparative Variation of normalised shear stress, τ* with normalised depth, Z* **with effect of linear non-homogeneity parameter, α, (L/d=20, K_{gp}=50).**

With the increase of non-homogeneity of GP, shear stress decrease with depth in the upper portion of GP approximately over half of its length and increase in the lower half of granular pile as shown in figures 7 and 8. Thus load is transferred to the lower part of granular pile. This results in decrement of settlement of granular pile. The areas of decrement of normalised shear stress in the upper half of GP between any value of α and α=0 (homogeneous GP) are approximately equal to area of increment in the lower half portion for the same values of δ. Thus, non-homogeneity of floating GP redistributes the shear stress along GP- soil interface. In the lower half of granular pile shear stresses increase more in average analysis in comparison to exact analysis due to lesser average deformation modulus in the lower half part of granular pile.

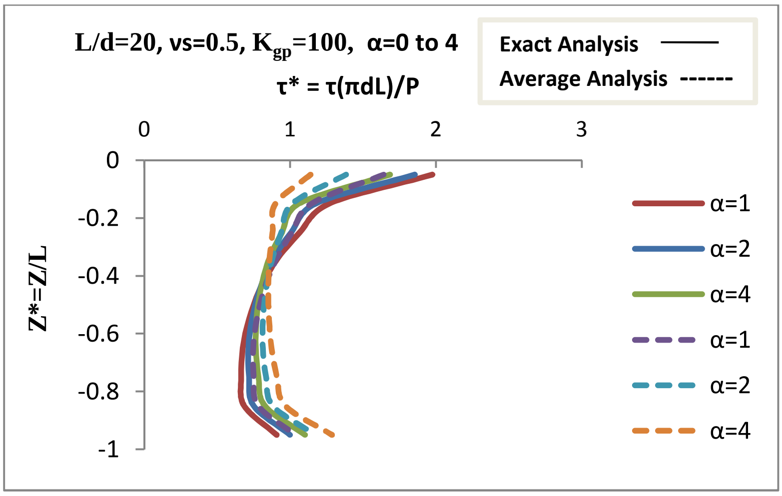

Fig.9 Comparative Variation of normalised shear stress, τ* with normalised depth, Z* with effect of linear non-homogeneity parameter, α. (L/d=20, K_{gp}=100)

Figures 9 shows the almost similar trend of shear stresses with depth as shown in figures 7 and 8. The reduction in shear stresses in the upper region of longer granular pile is more in comparison to shorter one due to longer compressible upper part of longer granular pile for the same values of linear non-homogeneity parameter, α.

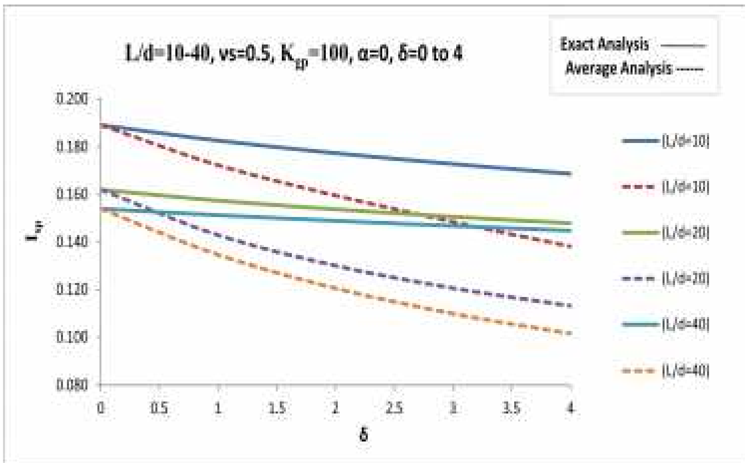

Fig.10 Comparative Variation of Settlement influence factor, I_{sp} with non- linear non-homogeneity parameter, δ, for Floating GP-effect of relative length, L/d.

Figure 10 clearly shows that the rate of decrease of settlement influence factor, I_{sp} with non-linear non-homogeneity parameter, δ, in case of short granular pile is slightly more due to higher values of modulus of deformation of GP at shallower depths.

4. Conclusion

Formulation of pile displacement matrix for linear and non-linear variation of deformation modulus is developed using finite difference technique. The reduction in the settlement of a floating non-homogeneous granular pile with linear and non-linear deformation modulus are in range of 10 to 15% depending on degree of non-homogeneity and relative length of granular pile with respect to the settlement of homogeneous granular pile.

With the increase of relative stiffness parameter, K_{gp}, settlement influence factor, I_{sp}, decreases for all values of linear and non-linear non-homogeneity parameter, α and δ respectively.

It is also observed that with increase in the relative length of the granular pile, rate of decrease of settlement is decreasing as non-homogeneity increases.

With increase in relative length, L/d from 10 to 20 for linear non homogeneity parameter, α=4, the decrease in settlement is about 25.7%. Similarly for non-linear non-homogeneity parameter, δ=4 this decrease is 18.11%. Non-homogeneity of granular pile affects the variation of shear stresses along granular pile –soil interface with depth. Depending on degree of non-homogeneity the shear stresses along granular pile –soil interface get transferred from the top to lower portion of the pile and to the pile base.

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