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Circular Raft Footings Strengthened by Stone Columns under Dynamic Harmonic Loads

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***Abstract*—**Stone column technique has been successfully employed to improve the load-settlement characteristics of foundations. A series of finite element numerical analyses of harmonic dynamic loading have been conducted on strengthened raft footing to study the effects of single and group stone columns on settlement of circular footings. The settlement of circular raft footing that improved by single and group of stone columns are studied under harmonic dynamic loading. This loading is caused by heavy machinery foundations. A detailed numerical investigation on behavior of single column and group of stone columns is carried out by varying parameters like weight of machinery, loading frequency and period. The result implies that presence of single and group of stone columns enhanced dynamic behavior of the footing so that the maximum and residual settlement of footing significantly decreased.

***Keywords*—**Finite element analysis, harmonic loading, settlement, stone column.

I. Introduction

ONE of the important problems of weak soils is their high compressibility as well as low shear strength. Stone column is a most affordable technique for reducing the settlement and increasing the bearing capacity of foundations. Stone columns are columns including compacted sand or gravel embedded into soft foundation using various techniques. This method is usually used for soil improvement, such as for problematic soils which underlie structures that can tolerate excessive settlement, especially road embankments and storage tanks. Furthermore, it gives the advantage of accelerated consolidation settlements due to reduction in flow path lengths and the simplicity of its construction method [1].

Over the past year, the stone column has been used worldwide and represented successful results. Several modifications have been proposed to enhance the efficiency of this method such as addition of additives, encasing the stone columns with geogrid or geonet, use of special patterns of reinforcements to provide more confinement that increases the bearing capacity and reduces the settlement drastically without compromising its effect as a drain [2].

Since, the interaction between the soil and columns is not well realized, especially when the columns do not achieve a firm stratum but “float” in the layer of soft soil [3]. Therefore, to investigate the behavior of single and group of stone column, numerical studies were performed to more realize the interaction between the column material, geogrid and surrounding soil.

Ambily and Gandhi [4] performed a considerable work in experimental study of stone column. They investigated on the behavior of stone column based on various parameters such as shear strength of soft clay, spacing of columns, and loading condition in soft clay. Kirsch [5] simulated some field experiments in order to examine various parameters such as area ratio, improvement factor and influence of column length. Gniel and Bouazza [6] numerically simulated small scale laboratory tests in order to study the interaction between the geogrid, column material and surrounding soil. Ghazavi and Nazari afshar [7] were conducted numerical analysis to study scale effects on small stone columns tested in the laboratory. Malarvizhi and Ilamparuthi [8] studied the effect of geogrid encasement of stone column on load–settlement behavior of improved clay. McKelvey et al. [9] and Sivakumar et al. [10] investigated different types of failure mode in stone column including bulging, bending, punching and shearing.

This paper presents the results of numerical investigation accurately calibrated with laboratory measurements to study the load-settlement behavior of single and groups of stone columns in soft soil under harmonic dynamic loading.

II. Axisymmetric Finite Element Model

In the current study, a series of numerical analyses have been carried out to investigate the behavior of single and group stone columns in soft clay under harmonic dynamic loading. Initially, using PLAXIS software, an axisymmetric finite element analysis was executed on a single encased stone column in the laboratory to validate by some experimental tests from Ghazavi and Nazari afshar [7]. Furthermore, analyses were performed in prototype scale by validated model under harmonic dynamic loading in order to estimate the effects of single and group stone column on the bearing capacity of footings subjected to such loading. Additionally, some analyses carried out using harmonic dynamic loading on improved and unimproved footing in order to investigate dynamic behavior of single and group of stone column in comparison with unimproved ground [11]. Some sensitive analyses on harmonic dynamic loading frequency were done and results presented.

III. Description of the Model

In order to estimate the effects of the stone column in improving the settlement of foundations under harmonic dynamic loading, several numerical analyses of single and

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group reinforced stone columns have been carried out. The results of single and group stone columns subjected to harmonic dynamic loading are compared with the results of circular foundation without improvement. Sensitivity analyses have been performed to investigate the effect of harmonic dynamic loading frequency on the maximum and residual settlement of the improved footing.

Table I represents characteristics of analyses including load type and geometry of improvement layout. Material properties of soil, stone column and geotextile are presented in Tables II. Viscous dynamic damping was considered 5% of critical damping for dynamic analysis of the models under harmonic load.

TABLE I
SPECIFICATION OF PERFORMED ANALYSES

Test	Applied load	Properties of stone column				Steel plate diameter (m)
		Diameter (m)	Length (m)	Number of columns	Spacing	
Single stone column	Dynamic harmonic load	0.8	8	1	-	2
Group stone columns	Dynamic harmonic load	0.8	8	7	2.5D	6
Unimproved ground	Dynamic harmonic load	-	-	-	-	6

TABLE II
MATERIAL PROPERTIES OF PROTOTYPE MODEL

Parameters	Properties		
	Clay	Stone	Geotextile
Modulus of elasticity (kPa)	6000	80000	-
Poisson ratio (μ)	0.47	0.3	-
Cohesion (kPa)	15	0	-
Internal friction angle (φ)	0	46	-
Secant stiffness (kN/m)	-	-	35

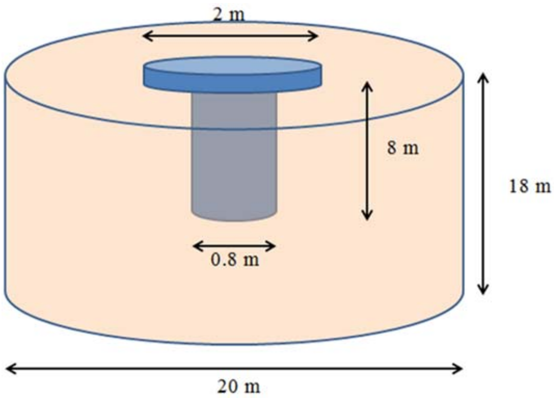

Fig. 1 Schematic model of single stone column used in the numerical modeling

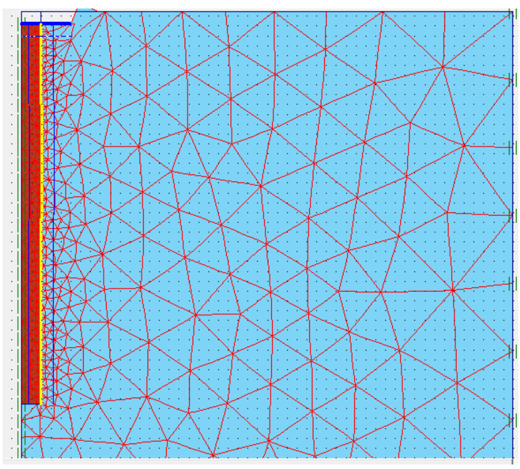

Fig. 2 Deformed mesh and bulging of single stone column under harmonic loading

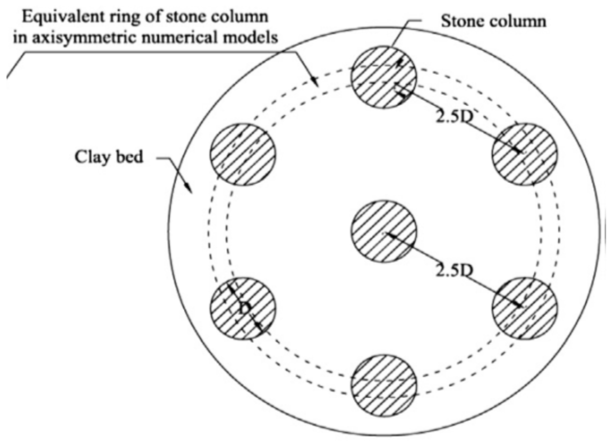

Fig. 3 Group stone column arrangement for analysis [7]

Fig. 1 indicates schematically the axisymmetric single stone column. The deformed mesh and bulging occurred due to static loading are represented in Fig. 2.

Fig. 3 indicates the 3D problem of groups stone columns simplified by a ring of stone column having an equivalent thickness, as can be seen [12], [13]. In order to determine the thickness of this ring, the area of the ring is assumed equal to the summation of cross sections of all six periphery stone columns. Vertical reinforcement is considered in both internal and external sides of the equivalent ring. In numerical analyses, the secant stiffness of geotextile used for equivalent ring is reduced to compensate real areas of reinforcement around periphery columns which is are more than two vertical sides of the ring.

IV. RESULTS AND DISCUSSION

Single and groups of stone columns as well as circular raft foundation without stone column were subjected to harmonic dynamic load of machinery foundation with maximum load of 1015 KN and various frequency including 5 Hz and 10 Hz. Figs. 4 and 5 represent the applying harmonic dynamic load pattern for the frequency 5 Hz and 10 Hz, respectively. Table III indicates important properties of device. The deformed mesh of group stone column and single under harmonic load is depicted in Figs. 6 and 7, respectively.

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Rayleigh viscous damping is employed for dynamic analyses. The damping matrix can be considered as the linear combination of the mass matrix and initial rigidity matrix of the structure [14] as:

$$[c] = \alpha[m] + \beta[k] \tag{1}$$

where α and β are constants:

$$\alpha = \xi\omega_1 \tag{2}$$

$$\beta = \xi / \omega_1 \tag{3}$$

where ξ is the critical damping specified as 0.05 in the current study and ω_1 is the initial circular frequency of mode 1. In order to obtain the initial circular frequency of mode 1, time of dynamic analyses in the stage that harmonic force were applied was considered more than duration of harmonic load (more than 1 sec); therefore, dynamic properties of the soil-stone column structures such as initial circular frequency of mode 1 was achieved in the free vibration phase [15]. However, numerical analyses were conducted by using dynamic harmonic load with different frequency and results are indicated at the point "A" beneath the plate for both single and group stone column (Figs. 6 and 7). Figs. 8 and 9 show load-settlement curves of improved footing under harmonic dynamic loading for the frequency equal to 5 Hz and 10 Hz in the case single and group stone column, respectively. It can be observed that in the case of group stone column and at the same load, footing under lower frequency of harmonic dynamic load indicates greater settlement because of the higher transformed energy. Furthermore, it can be seen that maximum settlement is increased by applying harmonic dynamic loading with lower frequency. This result is prospective due to higher energy level that imposed on footing at lower frequency.

TABLE III
DEVICE PROPERTIES AND SOIL DAMPING PARAMETERS

Press device properties			Soil dynamic and damping parameters	
Weight (ton)	Height (m)	Frequency (Hz)	T(sec)	ξ
65.5	15.5	5,10	0.876	0.05

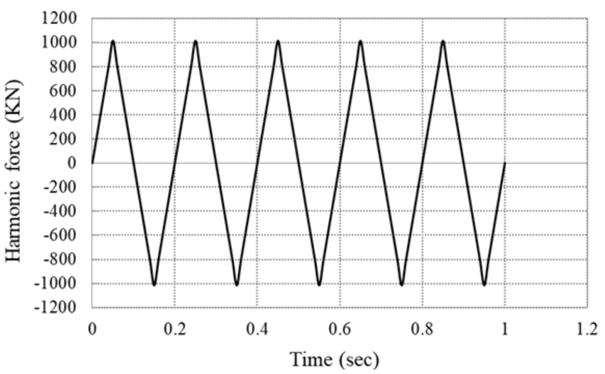

Fig. 4 Time history of the applying dynamic harmonic load for f=5 Hz

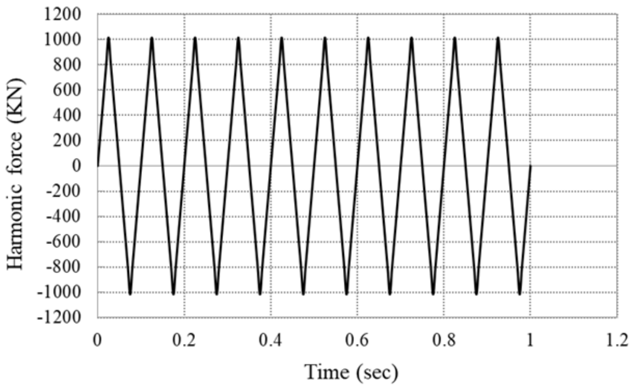

Fig. 5 Time history of the applying dynamic harmonic load for f=10 Hz

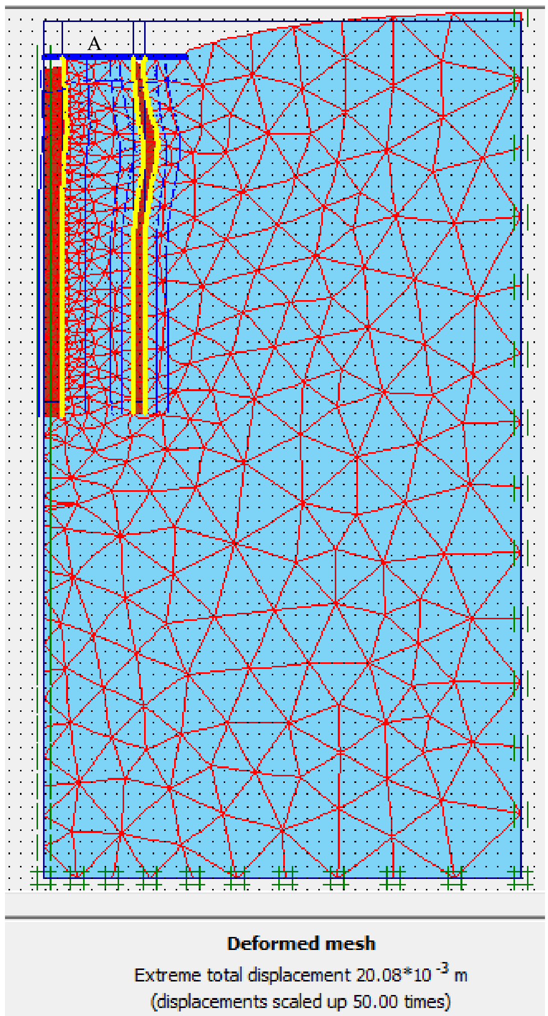

Fig. 6 Deformed mesh of group stone columns under harmonic load

Figs. 10 and 11 compare the load-settlement curves of the improved footing with unimproved one in the case of group stone column for the frequency equal to 5 Hz and 10 Hz, respectively. The result indicates that presence of group of stone columns enhanced dynamic behavior of the footing such that the maximum and residual settlement of footing significantly decreased. Additionally, in the case of single stone column, a comparison between load-settlement curves of the improved footing with unimproved are presented in Figs. 12 and 13 for the frequency equal to 5 Hz and 10 Hz, respectively. Table IV provides values of both peak and residual settlement of the improved footing and unimproved one. It declares that residual settlement of the group of stone columns under harmonic load and frequency equal to 5 Hz and 10 Hz was decreased 58% and 82%, respectively, with respect to the raft footing without stone column. Similarly, the maximum settlement of the improved footing decreased 60% in comparison with unimproved ground. So, using stone columns improved dynamic behavior of footing under the harmonic load with different frequencies.

TABLE IV
PEAK AND RESIDUAL SETTLEMENT OF THE IMPROVED AND UNIMPROVED FOOTING FOR F=5 HZ IN THE CASE GROUP STONE COLUMN

	Residual settlement (mm)	Maximum settlement (mm)
Improved ground f=5Hz	25	27
Unimproved ground f=5Hz	60	70
Improved ground f=10Hz	9	10
Unimproved ground f=10Hz	50	58

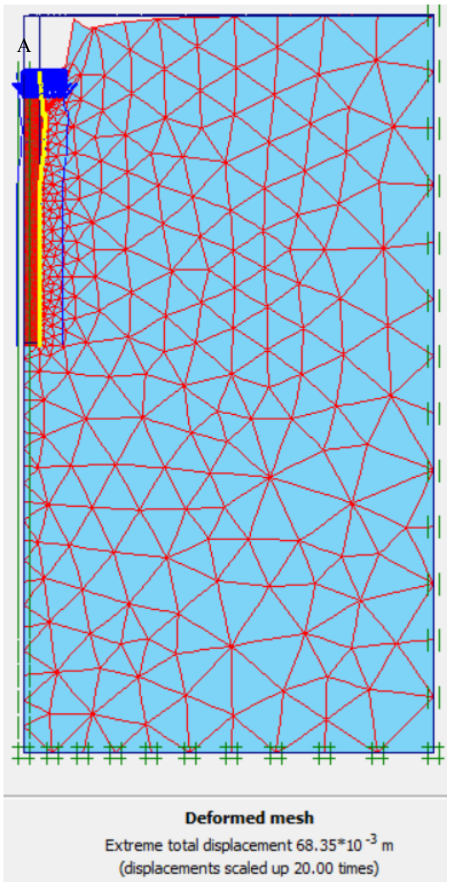

Fig. 7 Deformed mesh of single stone columns under harmonic load

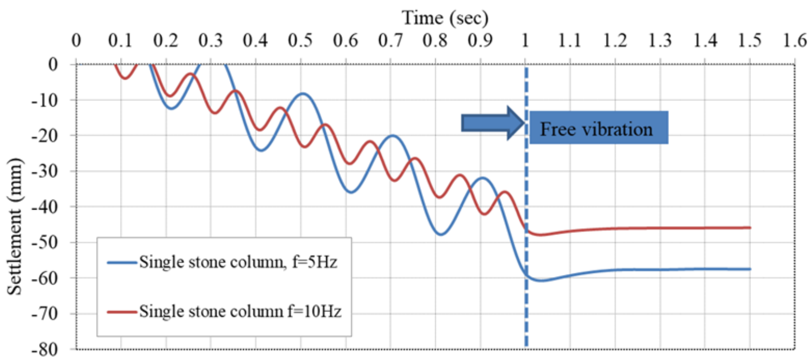

Fig. 8 Time history of surface settlement of improved footing via single column under harmonic loading and free vibration for f=5Hz and 10Hz

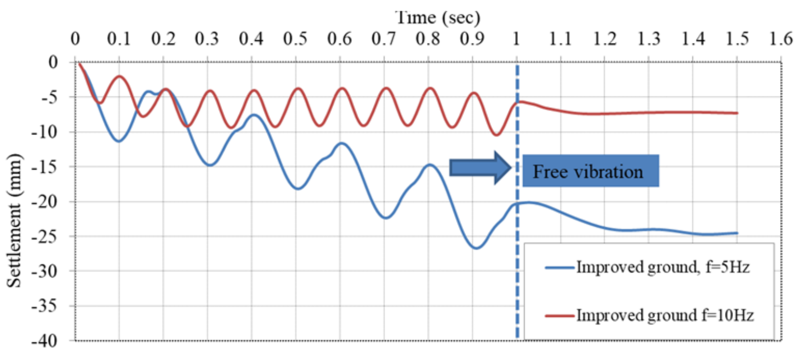

Fig. 9 Time history of surface settlement of improved footing via group stone column under harmonic loading and free vibration for f=5Hz and 10Hz

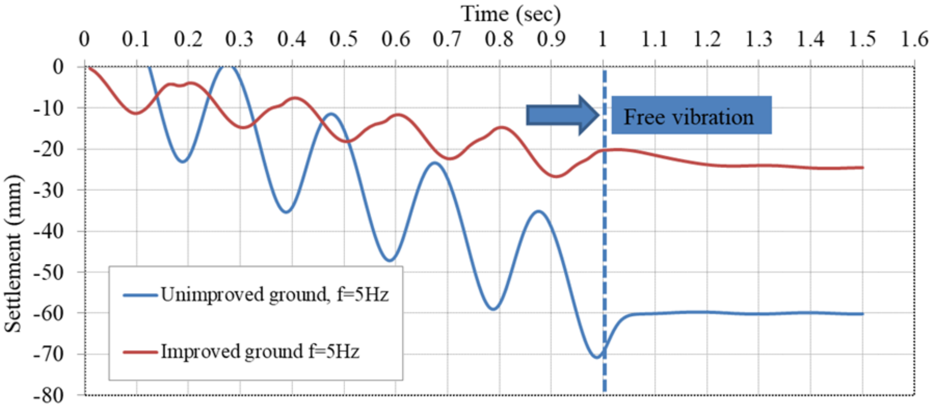

Fig. 10 Time histories of surface settlement with and without group of stone columns for f=5 Hz

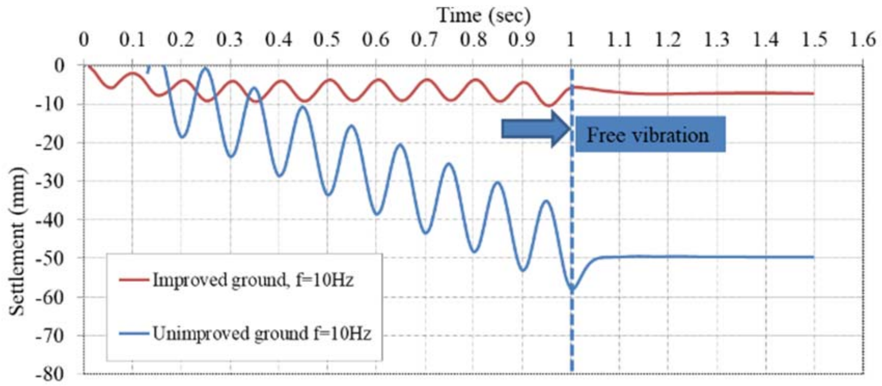

Fig. 11 Time histories of surface settlement with and without group of stone columns for f=10 Hz

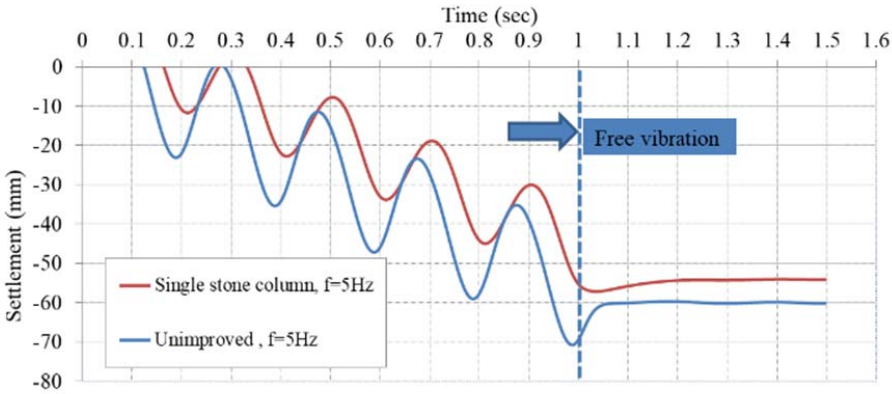

Fig. 12 Time histories of surface settlement with and without single stone columns for f=5 Hz

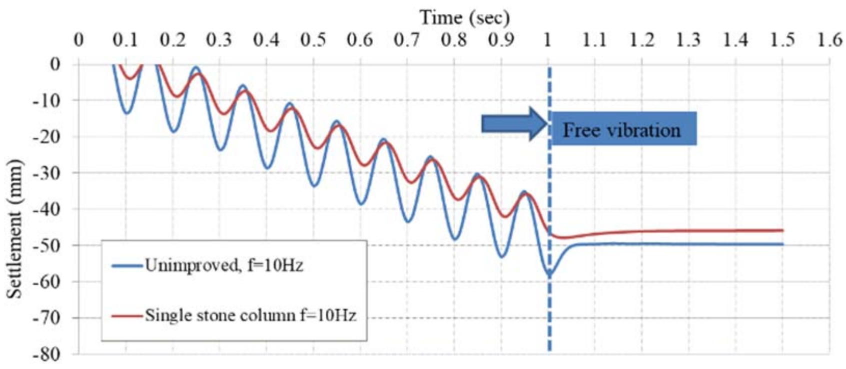

Fig. 13 Time histories of surface settlement with and without single stone columns for f=10 Hz

V. CONCLUSION

In this paper using finite element technique, the influence of single and group of stone column as strengthening elements of weak soft soils were calculated. The results of numerical investigation accurately calibrated with laboratory measurements to study the load-settlement behavior of single and groups of stone columns in soft soil under static and harmonic dynamic loading. Also, harmonic dynamic load of a machinery foundation was applied to both improved and unimproved footing. The result implies that presence of group of stone columns improved dynamic behavior of the footing so that the maximum and residual settlement of footing decreased significantly. Also, some analyses were done by applying various harmonic load with different frequencies in order to investigate the effect of frequency on the maximum and residual settlement of the footing. It can be concluded that at lower frequency, the maximum and residual settlement increased and the difference is more remarkable on the maximum settlement in comparison with residual settlement.

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