Experimental Investigations and Numerical Simulations of Vibratory Compaction of Weakly Cohesive Soils

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Abstract: - The compaction of weakly cohesive soils presents particularities in terms of improving the geotechnical properties under the loads transmitted into the terrain. In this case, the evaluation of the compaction process requires the development of a roller-terrain interaction model whose constitutive parameters are directly correlated with information available from laboratory and in-situ experimental tests. A simulation model is implemented in Matlab on the basis of the mathematical equation of a Kelvin-Voigt lumped vibratory system. The simulation results are presented and compared to the experimental investigations results obtained for a road structure modernization project (Romania, DN 2, km 39+200, Movilița site).

Keywords: - compaction, vibratory roller, laboratory tests, field tests, simulation

1. INTRODUCTION

The term "weakly cohesive soil" concerns soils characterized by low shear strength and high deformability, such as sand or gravel whose strength depends on friction between particles. The aim of compaction of this kind of soil represents the improvement of characteristics properties consisting of: increasing shear resistance and bearing capacity; decreasing volume changes and settlement; decreasing permeability and ingress of water. Finally, the compaction is measured in terms of dry density achieved (under external applied loads).

In the case of the execution of large-volume road works, an experimental polygon is created in advance to establish the work technology and execution parameters, depending on the nature of the terrain. For this reason, it is necessary to know some characteristic parameters that are determined by different methods (static or dynamic), both in the laboratory, and in-situ.

Based on these results obtained through data processing, the geotechnical parameters necessary for the final verification of the executed works are calculated. Soil compaction is defined as the increase of bulk density or decrease in porosity of soil due to externally or internally applied loads.

This paper presents details about the determined parameters, the applied methods, as well as the Technical requirements in Romania, in the case of earthworks that involved weakly cohesive soils. The evaluation of the soil compaction performance and the development of the vibratory roller-terrain interaction model in the technological process of compaction imply the evaluation of the relationships between the specific significant parameters directly involved, based on datum available from both laboratory, and in-situ experimental tests.

2. GEOTECHNICAL SITE CHARACTERIZATION

The evaluation of the characteristic geotechnical parameters of the site that requires compaction is carried out according to the requirements of the NE-008-97 [1] which indicates a series of experimental tests, such as:

a) laboratory tests: oedometric test (STAS 8942/3-90 [2]), cyclic triaxial test (NP 125:2010, Annex B [3]), Proctor test (STAS 9850-89 [4]). On the basis of these laboratory geotechnical tests, the followings are determined: the time for complete compaction of the terrain (NE-008-97 point 2.14.), oedometric modulus of deformation, drawing the stress-strain curve and the time variation of the pore pressure, optimum compaction moisture and maximum dry weight or maximum dry density, compaction degree, Proctor curve;

b) in-situ tests: evaluation of the static modulus of linear deformation of soils (by calculation, based on the oedometric modulus according to STAS 3300/2-85 [5], point 3.4.5, or by direct measurement in-situ, by the plate loading test according to STAS 8942/3, evaluation of the settlement of soils under a single passing of the compactor (and by correlating with the values of the linear deformation modulus of the terrain, the experimental curves within figure 11 of NE-008-97 result), experimental evaluation of the layer thickness (according to NE-008-97 point 2.6 applying the procedure described in the NE-008-97, Annex 2.2., point 2).

3. IN-SITU TESTS FOR EVALUATION OF THE MAIN PARAMETERS THAT IDENTIFY THE STATE OF SOIL COMPACTION

Other parameters set evaluated using in-situ tests, enable the identification of the degree of field compaction, based on:

a) the correlation of parameters associated with the roller-ground system (by measuring the width of the contact area between the compactor roller and the ground, according to NE-008-97 and, then, by checking the values within the range indicated in NE-008-97 for the ratio of measured width divided by roll diameter, depending on the degree of compaction resulting from the Proctor test);

b) the duration of soil compaction and the effective consolidation effort (calculated on the basis of the specific settlement, according to NE-008-97 point 2.14, and the primary consolidation time obtained by the Casagrande semi-logarithmic representation method, according to STAS 8942/1-90, point 6.4, and respectively in-situ, by measurements of pressure doses to determine the pressure transmitted in the layer);

c) modulus of elasticity E_s, G_d and the damping ratio ζ of the ground (by tests of loading with the plate equipment on the ground to determine static modulus of linear deformation, according to NP125:2010 and then checking the values according to STAS 3300/1-85 Annex C, Table 9, or by calculation for the case of critical damping). The dynamic deformation modulus characteristic of the degree of soil compaction is usually determined for the deformation range (10^{-3} ...10^{-1}) cm/cm, through the cyclic triaxial test, for each loading cycle. The damping ratio can be determined based on the hysteresis curve (axial stress-deformation, on each cycle) according to NP 125:2010-Annex D, and directly, by in-situ measurements, according to the logarithmic decrement of the vibrations due to the free fall of a weight. It should be noted that vibration analysis technique can be improved by an appropriate choice of the damping ratio so that the resonance phenomenon effect to be minimized, aspect that have significant influence over the performances of the accelerometer such as precision, sensitivity and reliability [6]. The interpretation of in-situ geotechnical test data requires a unified approach so that soil parameters are evaluated in a complementary manner with laboratory results [7]. Thus, the maximum dry density and optimum moisture content of soils are obtained by the experimental standard and modified Proctor tests (as the saturation curve), through plotting of soil density vs moisture at a theoretical 100% saturation level (zero air voids). The values were within the range of ρ =(1.33-1.40) g/cm^3 for average moisture content of w_{av}=17.19%. The result of the granulometric analysis led to the identification of the soil type: dusty, sandy clay (40% clay, 36% dust and 24% sand). The static deformation modulus was measured by the static plate load test, identifying the value E_{st}=30 daN/cm^2.

The conditions for carrying out the on-site tests were identically to those on the site of the national road DN 2 Bucharest–Urziceni (km 39+200), through the construction of an experimental polygon at ICECON S.A. Bucharest and the use of a vibrating compactor type ABG - DD16 with two smooth vibrating rollers. Finally, the experimental investigations regarding the behavior of the compactor-terrain system in the compaction process led to the following results [8]:

- continuous rolling of the drum with the speed v=1.44 km/h, in the vibrating working regime;
- maximum stiffness of soil: k_{max}=5626700 N/m;
- settlement at maximum value of soil stiffness: $D_h(k_{max})$=1.024 cm;
- final density: ρ_{df} =1710 kg/cm^3;
- final compaction degree: D_f =95 %;
- loading-settlement curve (see Figure 1).

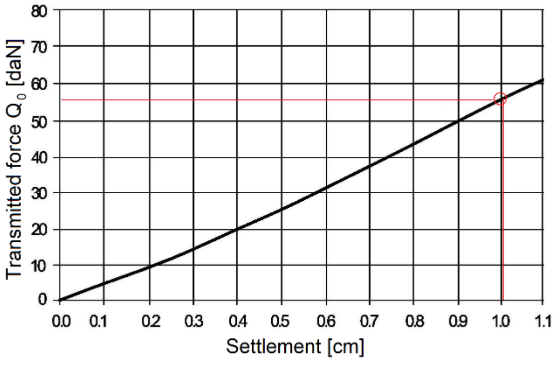

Figure 1. The variation of the force transmitted into terrain in respect to the achieved settlement (in-situ investigations)

4. CRITERIA FOR ROLLER-TERRAIN INTERACTION MODELS CONCEPTUALIZATION

The development of a new model of soil behavior in the compaction process (of weakly cohesive soils) associated with a roller-soil interaction model for this technological activity, assumes that the process takes place in a limited space and also has a limited duration [9-11]. This assumption implies the need to highlight the time dependence of the characteristic parameters of the terrain, having the settlement as a reference parameter Δh, also variable in time [8, 12]. We suppose that the main settlements usually occurred directly after the load was applied.

Based on the real data obtained through experimental determinations in the laboratory and in-situ, in order to identify the geotechnical characteristics of the land, the following models can be developed to analyze the performance of the technological process:

a) soil behavior model of the (static or dynamic) compaction process with descriptive characteristic parameters defined with predictable evolution depending on:

- the initial state of the soil to be compacted, defined by the initial characteristic parameters;
- the geometry of the contact between the roller and the soil, through the specific geometric parameters of the vibratory or static drum;
- the soil consolidation time under the pressure exerted by the compactor, through the settlement achieved at a given moment, as a common reference parameter which influenced another characteristic parameters of the soil [13, 14];
- the equivalent drum load of the compactor, by its static weight and the amplitude and frequency of the excited force generated by the vibration system.

b) roller-terrain interaction model of the compaction process defined by the next aspects:

- the action of the roller on the soil is quantified by the value achieved at a given moment in the process of compaction of the settlement;
- the action of the soil on the machine is quantified by the stiffness coefficient value achieved at a given moment in the compaction process of the terrain, non-linear with the settlement, and other important characteristic parameters that determine the working regime of the compactor depend [15, 16];
- the compaction technology that makes possible the increasing in quality of the compaction process, through the efficient use of compaction equipment enabling the carrying out of imposed technological tasks, through the general economic efficiency of the compaction process, by optimal choosing of the technological work scheme, the length L of the compaction area, v speed of the machine displacement for each passing etc.

5. NUMERICAL MODELING AND SIMULATION OF VIBRATORY PROCESSES BASED ON KELVIN-VOIGT LUMPED MODEL

5.1. Material and methodology

The internal damping and stiffness of a particular soil are associated with the mechanical models that can describe the viscoelastic characteristics of a material. Each of the mechanical models takes into account a certain form of stress or strain response for the material in various loading conditions [17, 18].

This paper studies the functional behavior of a vibratory compactor and the transmissibility and amplitude of the vibrations generated in weakly cohesion fill soils. Thus, from usually used models (Maxwell, Kelvin-Voigt, Zener, Burgers etc.) the Kelvin-Voigt model allows the prediction of the evolution of stress and strain within the weakly cohesion soil under arbitrary loading simulated scenarios, because of predominantly elastic characteristic of these soils with little influence of the natural viscosity in the global stress-strain characteristic. Modeling a vibratory process based on the Kelvin-Voigt model supposes an inertial dynamic excitation (Figure 2) in order to simulate the behavior of the compactor's vibratory roller along with the effect of its action on the material being compaction. The inertial harmonic excitation ($x=A\sin\omega t$) transfers energy into the soil, generating a dynamic response quantified by evaluating the viscous force $Q(t) = c\dot{x} + kx$.

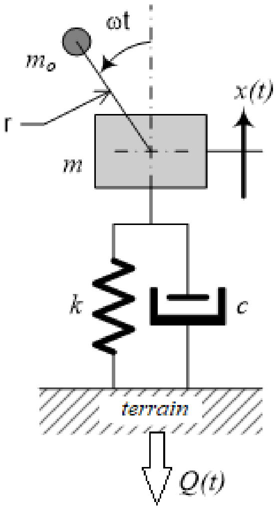

Figure 2. Kelvin-Voigt model for simulation of the effect of vibratory compaction process

There are two available analysis methods for simulation of multiple scenarios which are allowed on this rheological model [19, 20]:

a) harmonic excitation *x(t)* with a certain frequency applied ω to the mass m as action of the rotational motion of the mass m_0, disposed at eccentricity r, that generates the sinusoidal external force $F(t) = m_0 r\omega^2 sin(\omega t)$;

b) reaction force response $Q(t) = Q_0 sin(\omega t - \varphi - \theta)$ to the excitation $x(t) = Asin(\omega t - \varphi)$.

The dynamic response is evaluated taking into account the following factors:

- the dynamic behavior corresponds to the technological vibrations in permanent and stable work regime (usually, in post-resonance);
- the origin of time coincides with the moment when the dynamic force reaches its maximum value (with a positive value);
- the amplitude of the dynamic force $F(t)$ varies with the excitation pulsation ω when the vibration regime is changed from $\omega=0$ to $\omega \ggg p_{max}$ (highest value of the own pulsation);
- in the stable dynamic mode of operation, for $\omega > p_{max}$ (after resonance), when ω=constant, the dynamic force remains at a constant value.

We considered a vibratory roller, modeled as a vibrating system based on Kelvin-Voigt model, with discrete values for soil stiffness (k) and with the vibration excitation corresponding to work regime. The other two parameters, the viscous damping coefficient c and damping ratio ζ will be assigned by discrete values in order to model realistic compaction process, since after each pass of the vibratory compactor intermediate states (i) of the settlement of the soil layers have characterized by a continuous modification of their stiffness (until reaching the required degree of compaction, D_i [%]). Thus, each discrete value of the soil stiffness (k_i), obtained after the passage i, corresponds to a certain value of the coefficient of viscous damping (c_i), which indicates the response of the soil to the action of the dynamic force transmitted by the vibratory roller. The differential equation of motion for the terrain- roller interaction is given in Equation (1):

$$m\ddot{x} + c\dot{x} + kx = m_0 r\omega^2 sin\,(\omega t) \qquad (1)$$

The amplitude of the instantaneous displacement of the mass m, as a reaction response of the vibrating roller to the impact with the terrain (brought to the compaction degree D_i) has the form

$$A = \frac{\Omega^2 A_{st}}{\sqrt{(1-\Omega^2)^2 + 4\Omega^2\zeta^2}}, \qquad (2)$$

while the amplitude of the force transmitted into the terrain layer is

$$Q_0 = F_0^{st}\Omega^2\sqrt{\frac{1+4\Omega^2\zeta^2}{(1-\Omega^2)^2+4\Omega^2\zeta^2}}. \qquad (3)$$

The next terms in Equations (2) and (3) were used: Ω - pulsation ratio; A_{st} – static amplitude of the vibratory motion; F_0^{st} – static amplitude of the dynamic force

$$A_{st} = \frac{m_0}{m_0+m} r, \qquad (4)$$

$$F_0^{st} = kA_{st}. \qquad (5)$$

Transmissibility of the dynamic force of the vibratory roller into the terrain (within technological working condition) can be expressed by relation:

$$T = \sqrt{\frac{1+4\Omega^2\zeta^2}{(1-\Omega^2)^2+4\Omega^2\zeta^2}}. \qquad (6)$$

Since the value of the stiffness of the compacted layer increases with each pass (until reaching the maximum value corresponding to the maximum degree of compaction, after which it remains at constant value) it is defined as a dynamic stiffness (k_d). If the compaction is carried out with a compactor with a vibrating roller, the dynamic stiffness is higher than the stiffness k_s achieved in the case of using a static roller. According to the continuous variation of the vibration frequency of the drum the increasing of the dynamic stiffness coefficient of the compacted layer is obtained, calculated with the relation:

$$k(\omega) = k_d = \sqrt{(k_0 - m\omega^2)^2 + c^2\omega^2}. \qquad (7)$$

Next, the numerical simulation of a vibratory roller, modeled as a system with single degree of freedom was performed in Matlab for the input data:

- initial soil properties (experimentally investigations carried out): ρ_{dmax}=1710 kg/cm^3; ρ_{di}=1465 kg/cm^3; w_i=11.2%; E_{si}=139.4 daN/cm^2; G_{di}=46.5 daN/cm^2; ζ=0.283; D_i=85.67%;
- constructive and functional parameters of the vibratory roller: m=830 kg; m_0=1 kg; r=0.066 m; B=0.80 m; D_r=0.62 m; F_0=6480 N; f=48 Hz;
- constitutive parameters of the vibratory roller - soil interaction model: c=3x10^4 Ns/m; k=2x10^6, 4x10^6, 6x10^6, 8x10^6, 10x10^6 N/m.

5.2. Results

The results of simulation show soil behavior under continuous rolling of a vibratory compactor. It can be found that in the post-resonance regime for $\omega > \omega_n$, all amplitudes tend asymptomatically toward a constant value at A_{stable} = 0.8 mm, corresponding to a stable motion (Figure 3). In order to determine the resonance peaks, and to ensure a post-resonance regime, only the significant linear elastic behaviour was considered (neglecting the viscous effect). The variation of vibrations amplitude was simulated until

$\omega = 3\omega_n$, which means $\Omega = 3$, by two cases: for discrete increasing of the stiffness soil (Figure 3a) and for variation of the soil damping ratio (Figure 3b) as a measure of compaction degree.

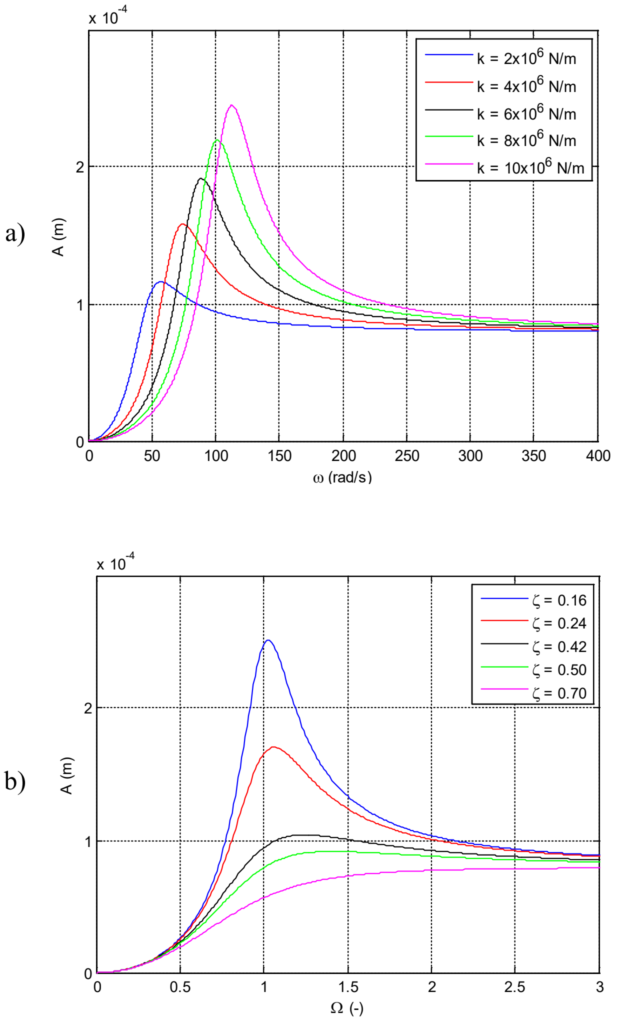

Figure 3. Variation of the vibration amplitude A versus Ω pulsation ratio, for discrete stiffness values (a) and, respectively, for discrete damping ratios (b)

Therefore, the variations of the specific parameters of the compaction process were highlighted depending on the improved properties of the terrain (in terms of stiffness and damping coefficient of the soil), only for the working frequency ($\omega = 2\pi f = 301.5929$ rad/s) of vibratory roller (Figure 4). Experimental investigations showed that the final compaction degree was achieved for the stiffness $k_{max} = 5.6 \times 10^6$ N/m. In the case of numerical simulation, for this stiffness value was obtained a settlement $\Delta h = A = 0.850$ mm, with 8.3% lower that the measured values (10.24 mm). This result ensures a verification of the numerical model, but it must be highlighted that, without some experimental data, it is difficult to simulate a terrain from the category of cohesionless soils.

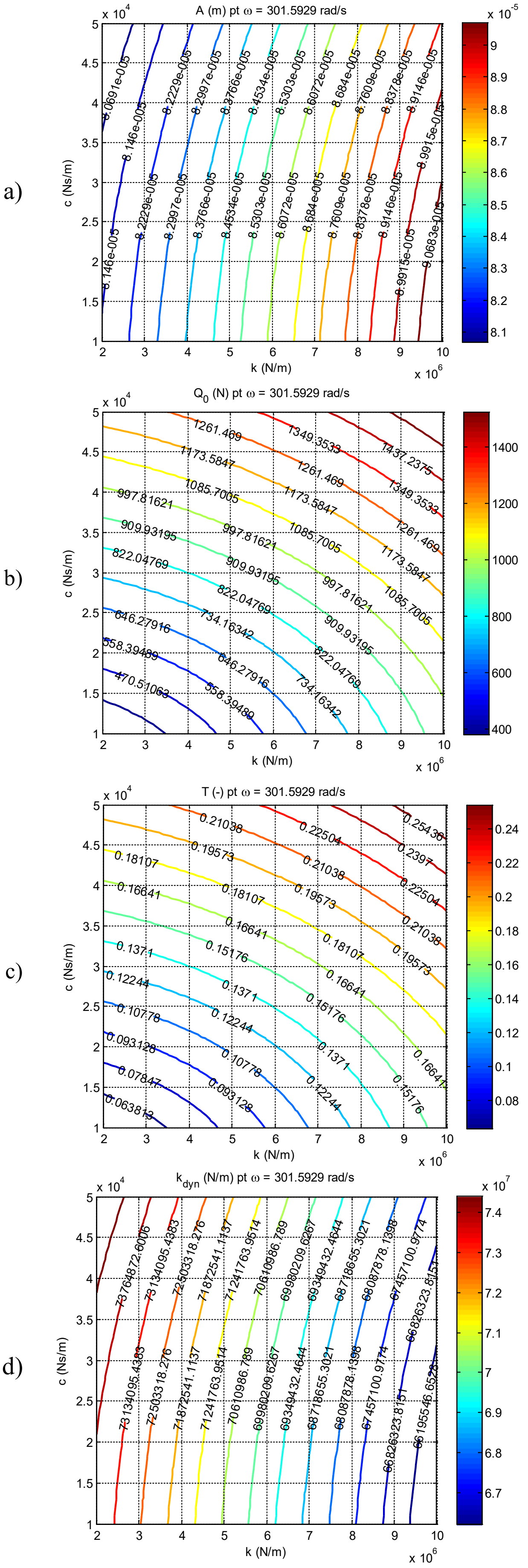

Figure 4. The variation of A, Q_0, T and k_{dyn} in respect to k and c for $\omega = 301.5929$ rad/s

6. CONCLUSIONS

Rheological models and mechanical systems adopted for vibratory motion analysis, associated to the technological compaction process, can offer the realistic information using numerical simulation if we take into account the experimental evolutions of the main parameters that describe changing of compaction state of the terrain, until the maximum compaction degree has been achieved. Based on Equation (1), and the laboratory and in-situ tests performed, the variation of the model parameters was correlated. In the post-resonance mode of operation, it is observed that the roller-terrain vibratory motion is stable, and the static amplitude of the motion, for all five cases of stiffness increasing, from $2x10^6$ to $10x10^6$ N/m (after 10 passes), leads to the evaluation of the improvement in settlement and, implicitly, in achieved degree of compaction. In the present study case, the maximum degree of compaction corresponds to maximum stiffness value, respectively, $D_i(k_{max})$, where $k_{max}=5,6x10^6$ N/m and $D_i=95\%$. The graphic representation (Figure 4c) highlights the very low effect of the transmitted force into terrain developed by the vibratory roller with the increase of the pulsation frequency. The dynamic stiffness of the soil acquires 15-20%increasing, for $\Omega=(2,5\ldots3)$, which highlights that, at excitation frequencies within post-resonance range, the stiffness $k=k_{dyn}$ is significantly higher than the static stiffness k_0. The simulation of the compaction effect developed at vibratory roller– cohesionless soil interaction, based on the Voigt-Kelvin linear lumped model, provides adequate information, especially when there are experimental results, so that it is possible to approach, in an unitary manner, the study of behavior of cohesionless soils.

In Romania, a research program is currently being carried out with the aim of implementing an intelligent system for the detecting, monitoring and processing of the technological vibration signals, in situ and in real time, so that the response curves of the interaction drum-terrain can be plotted using a specialized software. The final scope consists on ensuring the compaction degree, the dynamic rigidity and the dynamic modulus of the compacted terrain all these being in correlation with the laboratory tests, so that the quality of the compaction process is able to be fast verified in real time.

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