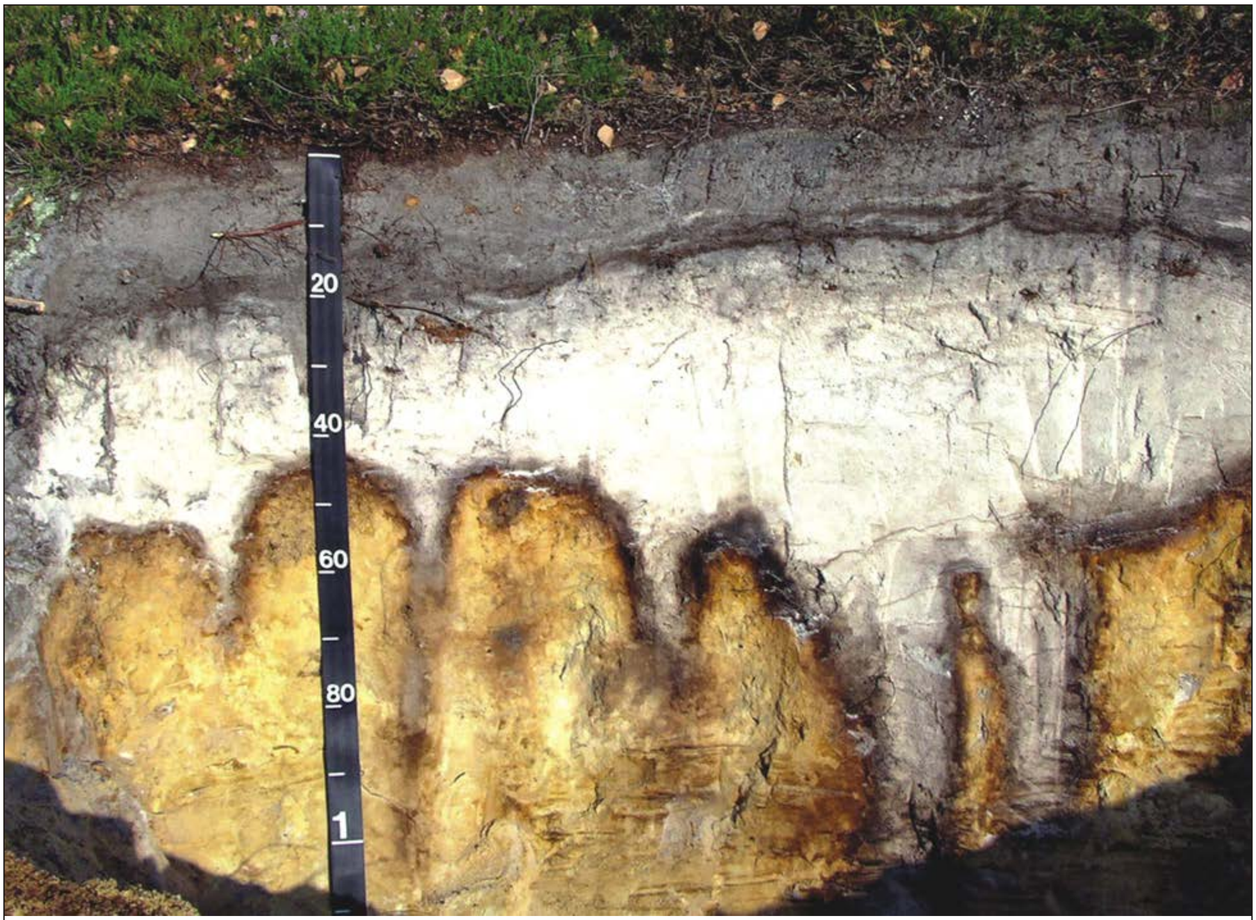

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Research Article
Comparison Between Particle Size Distribution as a Predictor of Pedotransfer Functions using Laser Diffraction and Sedimentation Methods

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Abstract

Background and Objective: Particle size distribution (PSD) is the main predictor variable used in Pedotransfer functions (PTFs). Verification of PTF requires a specialized database. These databases contain PSD measured by sedimentation methods either using pipette or hydrometer method. Recently, laser diffraction method (LDM) is widely used for particle size distribution measurement. The aim of the research was to validate usage of laser diffraction method instead of pipette method for estimating soil saturated hydraulic conductivity, using PTFs. **Materials and Methods:** Soil saturated hydraulic conductivity (KS) was measured by constant head method technique and calculated by PTFs. The calculated PTFs were based on PSD measured by laser diffraction method (LDM) and by pipette method (PM) for estimating KS. Saturated hydraulic conductivity (KSPM) was calculated by pipette methods (PM), while KSLDM was calculated by LDM, using PTFs. **Results:** The results observed that lower clay fraction measured by LDM than that measured by the PM, while higher silt fraction measured by LDM than that measured by PM. In spite of, there is no agreement between the PSD obtained by LDM and PM. However, it didn't change soil type texture. The root mean square error (RMSE) of KSLDM (2.41×10^{-6} m sec^{-1}) was relatively close to RMSE of KSPM (2.63×10^{-6} m sec^{-1}). **Conclusion:** LDM technique can be successfully used for estimating soil hydraulic properties using PTFs, without any modification or recalculations for silty loam and silty clay loam soils under study.

Key words: Particle size distribution, laser diffraction method, pipette method, pedotransfer functions (PTFs), saturated hydraulic conductivity

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Particle size distribution (PSD) is one of the most important soil physical parameters. It was often used in soil, geological and geomorphological laboratories[1]. PSD is typically defined by size distribution or mass fractions (sand+silt+clay %) of primary soil particles. It is the most important characteristic affecting: Pore geometry, total pore volume (porosity), pore size distribution, solid surface area, hydro-physical and thermo-physical characteristics. PSD effects on many soil physical processes taking place in the soil. This statics property is commonly used for their classification and determination of some hydraulic and thermal properties. Recently, various new methods for particle size distribution have been developed, such as, (electroresistance particle counting, time of transition, laser diffraction method (LDM) and optical estimation of PSD using image analysis)[2,3]. These methods are covering a wide range of particle sizes and rapidly analyzing for small samples[4]. However, PSD is still measured by hydrometer or pipette methods as classical and an accurate. Despite, it is consuming both time and money especially for determination of clay fraction particles having a diameter less than 2 µm. A particle diameter measured by laser diffraction method (LDM) is equivalent to that of a sphere giving the same diffraction as particles. The PSD assessment by LDM has been successfully carried out by soil scientists for some time[5-7], however, its application has not replaced the classical laborious sedimentation methods. The comparisons between sedimentation methods and LDM have been performed by several authors. Eshel *et al.*[8] found that in 40 out of 42 soils analyzed LDM yielded a smaller clay fraction than pipette method. Also, Di Stefano *et al.*[9] demonstrated that sand content measured by sedimentation method could be assumed equal to that determined by LDM technique, while clay fraction measured by LDM was lower than that measured by the sedimentation method. The efficiency of laser diffraction method is widely based on a dispersing agent. Moreover, Polakowski *et al.*[10] reported that shape of sand particles affects the results of particle size distribution obtained by laser diffraction method. Few studies evaluated the efficiency of PSD measured by LDM in PTFs. Lamorski *et al.*[11] found that a particle size distribution estimated by LDM might be directly used for PTF developments without any recalculations about their sieve-hydrometer counterparts. PSD, soil bulk density and soil organic matter are commonly used as predictor variables in PTFs. PTFs can be categorized into two main groups namely point PTFs and continuous PTFs, where the first allows for estimation of soil water content for some selected soil water potentials, while latter describe whole soil water retention curve (SWRC) by parameters of some SWRC functional representation (e.g., van Genuchten function[12]). Other categorization of PTF may be done about techniques used for PTFs development: Mathematical regression, neural networks (NNS), support vector machines (SVM), k nearest neighbors (k-NN) or other techniques can be used. The PTFs were often developed using statistical regression[13]. The PTFs are widely used for estimating soil thermal parameters and soil hydraulically properties[14] based on various physical and chemical soil characteristics. Shein *et al.*[15] reported that PTFs developed by mathematical regression, depending on: Soil bulk density, organic matter, clay and sand contents and the efficiency of PTFs depended on the correlation between these parameters and Ks. Hydrus 1-D program or (Rosetta program) is one of PTF software program uses a neural network. The Rosetta program can be used for prediction the parameters of van Genuchten and saturated hydraulic conductivity depend on pore-size model Schaap *et al.*[16]. So it is important to estimate the efficiency of PSD obtained by LDM, for predicting soil hydraulic conductivity using PTFs. The objectives of this study were: Firstly, investigate the agreement between PSD measured by laser diffraction method and by pipette method, secondly, to validate the usage of laser diffraction method instead of pipette method for estimating soil water transfer, using PTFs and thirdly, to compare measured values of saturated hydraulic conductivity KS, with calculated values by PM and LDM to determine LDM efficiency.

MATERIALS AND METHODS

Soil samples: Soil samples were collected from silty loam and silty clay loam sod-podzolic soils (Retisols), which represent the major group of agricultural soils in Moscow region, Russia. Fifteen soil samples were collected at Zelenograd field laboratory of Soil Science Institute (Fig. 1). Three soil profiles were excavated and then divided into three genetic horizons for each profile, horizon A (0-30 cm), horizon EL (30-40 cm) and horizon B1 (40-50 cm). Additionally, five undisturbed soil samples were collected at a different depth for each profile. Saturated hydraulic conductivity was measured by the direct method and by PTFs based on PSD obtained by LDM and by PM.

Soil physical properties: Soil physical characteristics were determined including organic matter which was measured by high-temperature catalytic oxidation using Express analyzer

AN-7529 according to Nelson and Sommers[17]. Also, soil bulk density (ρ_b) was determined by the core method according to Klute and Dirksen[18].

Particle size distribution: Particle size distribution was measured by two methods:

Laser diffraction method (LDM): The LDM is based on the phenomenon that particles of a given size diffract light at a certain angle that increases with decreasing particle size and the intensity of diffracted beam at any angle is referred to measure particles quantity. Particle size distribution is inferred from light intensities measured at detector as a function of angle based on Mie theory Eshel *et al.*[8]

Particle size distribution analysis was performed using helium-neon laser with a wavelength of 633 nm as a light source using Analysette-22 as Fig. 2 according to Eshel *et al.*[8]. Sodium pyrophosphate solution at concentration of 4% (analytical grade) was used as a liquid dispersing agent. It prepared in the Lab (25 mL of sodium pyrophosphate in a liter of distilled water).

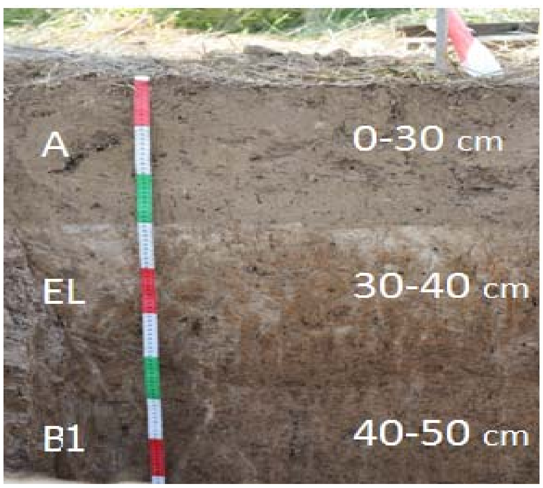

Fig. 1: Soil horizons of sod-podzolic soils

Pipette method (PM): Particle size distribution was measured according to pipette method based on Stock's law. Sodium pyrophosphate solution 4% was used as a dispersing agent as described by Gee and Bauder[19]. The PSD was determined as used in the main international data based: Sand>0.05 mm, silt (0.002-0.05) mm and clay<0.002 mm.

Saturated hydraulic conductivity (KS): Saturated hydraulic conductivity was measured according to Klute and Dirksen[18], using constant head method technique based on Darcy's law Eq. 1:

$$\frac{Q}{A.t} = Ks\frac{\Delta H}{l} \quad (1)$$

Where:

Ks = Saturated hydraulic conductivity (m sec^{-1})
Q = Volume of water passing through the soil (m^3) at time t
A = Cross-sectional area of soil column (m^2)
$\Delta H/l$=A hydraulic gradient

Calculation saturated hydraulic conductivity: Rosetta program implemented five hierarchical pedotransfer functions (PTFs) for estimation of water retention curve and saturated hydraulic conductivity using limited (soil texture) to more extended (particle size distribution, bulk density and one or two water retention points) input data. Rosetta uses a neural

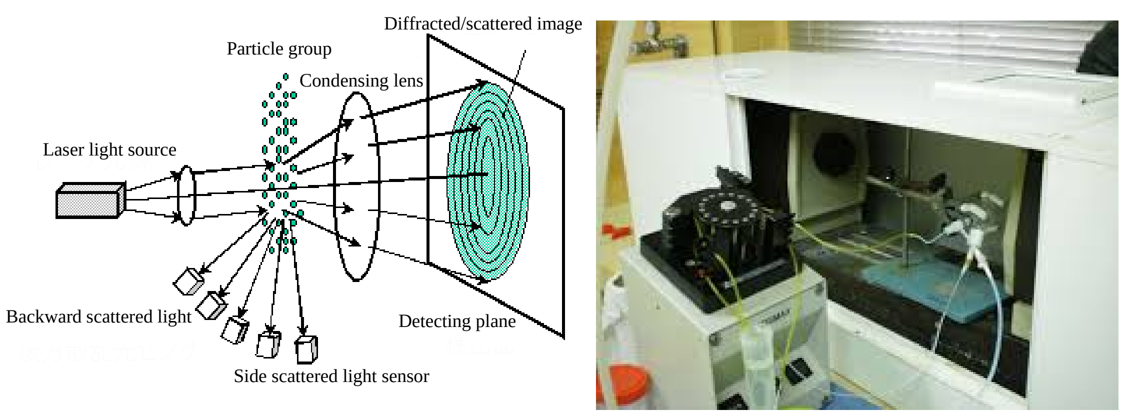

Fig. 2: Methodology and equipment of laser diffraction Analysette-22

network and bootstrap approach Schaap *et al.*[16] for prediction parameter and uncertainty analysis respectively. It is able to estimate the parameters of van Genuchten[12] model (Eq. 2) and saturated hydraulic conductivity Ks, as well as unsaturated hydraulic conductivity K(h), based on Mualem[20] as (Eq. 3) pore-size model Schaap *et al.*[16].

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + \left(\alpha \left| \psi_m \right| \right)^n} \right]^m \quad (2)$$

$$K(h) = Ks.S_e^L \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (3)$$

$$m = 1 - \frac{1}{n}$$

where, n>1. Se, is the effective saturation computed as Eq. 4:

$$Se(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \quad (4)$$

Where:

θ_r, θ_s = Residual and saturated water contents, respectively
Ks = Saturated hydraulic conductivity
α = Inverse of air-entry value (or bubbling pressure)
n = A pore-size distribution index and pore connectivity parameter l in hydraulic conductivity function

This equation was estimated by Mualem[20] to be about 0.5 as an average for many soils.

Rosetta used for calculation saturated hydraulic conductivity using particle size distribution and soil bulk density, particle size distribution (PSD) measured by both PM and LDM methods, two values of saturated hydraulic conductivity KSPM and KSLDM were calculated based on PSD measured by PM and LDM methods. All PTFs give KS in m sec^{-1}.

Statistical analysis: The efficiency of the laser diffraction method was determined using the determination coefficient (R^2) and root mean square error (RMSE) according to Kobayashi and Salam[21]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(y_i - \hat{y}_i \right)^2}{\sum_{i=1}^{n} \left(y_i - \bar{y}_i \right)^2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(y_i - \hat{y}_i \right)^2}{N}}$$

Where:

y_i = The measured value
$\hat{y}_i$ = The predicted value
$\bar{y}_i$ = The average of the measured value of y
N = The total number of observations

Software tools were Microsoft Excel 2007, Hydrus-1D version 4.8, Rosetta database program and SPSS program version 16 probability was 95% for the statistical analysis.

RESULTS AND DISCUSSION

Comparison between PSD obtained by LDM and PM: The results demonstrated that mean value of sand, silt and clay fractions measured by PM were 4.56, 68.65 and 26.79%, respectively. While the mean values for those measured by LDM were 2.94, 82.33 and 14.73 %, respectively. The relative error for sand, silt and clay fraction, that measured by PM and by LDM were 1.62, 13.68 and 12.06%, respectively. The fraction of sand measured by PM was relatively close to that measured by LDM. While the clay fraction measured by LDM was 1.8 times lower than measured by PM. On the other hand, the silt fraction obtained by LDM was higher than obtained by PM. The highest value of R^2 was 0.854, for a sand fraction. While, R^2 value was lower for silt and clay fractions, its values were 0.48 and 0.75 respectively. Moreover, the lowest value of RMSE was 2.24 for a sand fraction. While it values were higher for silt and clay fractions 13.8 and 12.4, respectively. The RMSE for measured silt by LDM was 6.16 times larger than for measured sand. Moreover, RMSE for measured clay by LDM was 5.5 times larger than for measured sand and therefore, the ability of LDM for measurement sand fraction (large particles) is better than measurement fractions of silt and clay. This result is agreement with Di Stefano *et al.*[9]. Also, Beuselinck *et al.*[22] indicated that there was not a unique relationship between the PSD obtained by LDM and pipette method. Moreover, the different mineralogy and particles shape strongly affected the differences between the two methods.

The difference between two methodologies sources can be due to causes inherent to the methods and therefore vary for different soil samples. First, the pipette method is based on a stokes law is used to deduce particle size distribution. Also, it depends on soil particle density, viscosity and density of suspension, while in LDM is independent on soil particle density and viscosity. Second, the differences in physical and chemical properties of soil particles have a different effect on two measurement systems. PM assumes that all particles are rigid, spherical, smooth and having the same density, while in LDM technique, the laser beam is affected by a color of the sample, which influences the refractive index. Third, particle's shape changes size measurement and angle of reflection for a particle according to Polakowski *et al.*[10].

Comparison between measured KS and calculated KSPM and KSLDM: Figure 3 shows that the measured KS variations were from 9.99×10^{-6}-6.1×10^{-7} (m sec^{-1}) for silty loam and silty clay loam soils, respectively. While variations of calculated values of KSPM and KSLDM using PTFs (Rosetta program) were between (4.08×10^{-6} and 5.22×10^{-6} m sec^{-1}) to (5.94×10^{-7} and 1.26×10^{-6} m sec^{-1}), for silty loam and silty clay loam soils, respectively. Mean value of calculated KSLDM (2.9×10^{-6} m sec^{-1}) was 1.5 times higher than for calculated KSPM (1.83×10^{-6} m sec^{-1}). That is because silt fraction measured by LDM was higher than measured by PM, while clay fraction measured by LDM was lower than measured by PM due to increasing the calculated KSLDM, these results agree with Di Stefano *et al.*[9].

Measured and calculated Ks: The results of statistical analysis showed R^2 for calculated KSPM was 0.94, which was higher than calculated KSLDM was 0.855. However, RMSE value of calculated KSLDM was relatively close to calculated KSPM were 2.41×10^{-6} and 2.63×10^{-6} m sec^{-1}, respectively. Variance between calculated KSPM and KSLDM was low and the difference between PSD measured by both PM and LDM were insignificant for calculation saturated hydraulic conductivity. The reason of that may be using the same dispersing agent lead to reduce the difference between PSD measured by PM and LDM and did not change the type of soil texture. Also, sedimentation methods determine higher values of PSD fine grain fractions (silt and clay) due to the distribution of the solid phase density in different granulometric fractions in their different origins and composition. The differences may reach several times that can cause serious errors in the PTF determination and its use.

PSD measured by LDM in PTFs validation: Combined portions of sand, silt and clay in a soil determine its textural classification. Sand particles range in size from 0.05-2.0 mm, silt ranges from 0.002-0.05 mm and the clay fraction is made up of particles less than 0.002 mm in diameter, were measured both PM and LDM. Once the sand, silt and clay percentages of soil are known, the textural class can be read from the textural triangle according to (USDA soil taxonomy). Also, the soils have the same texture having the same soil hydraulic characteristics such as saturated hydraulic conductivity and drainage. The soils under study were silty loam and silty clay loam according to the textural triangle as Fig. 4. In silty loam soils the range of silt and clay (%) were from (73-88%) for silt (%) and from (0-30%) for clay (%). While, in silty clay loam soils the range of silt and clay (%) varied from (60-73%) for silt (%) and from (25-40%) for clay (%). Clay content measured by either PM or \LDM was in the range from (14.7-26.7%). Moreover, silt measured by either PM or LDM was in the

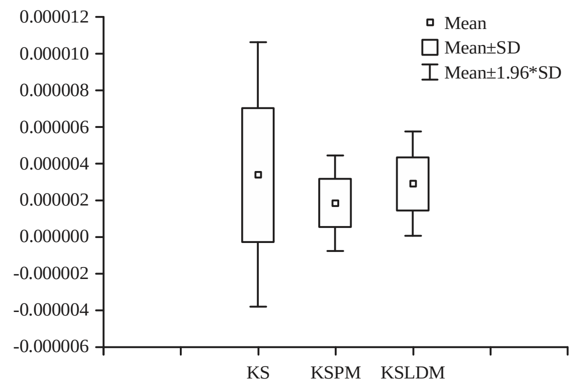

Fig. 3: Statistical analysis of saturated hydraulic conductivity measured KS and calculated (KSPM) and (KSLDM) using Rosetta program

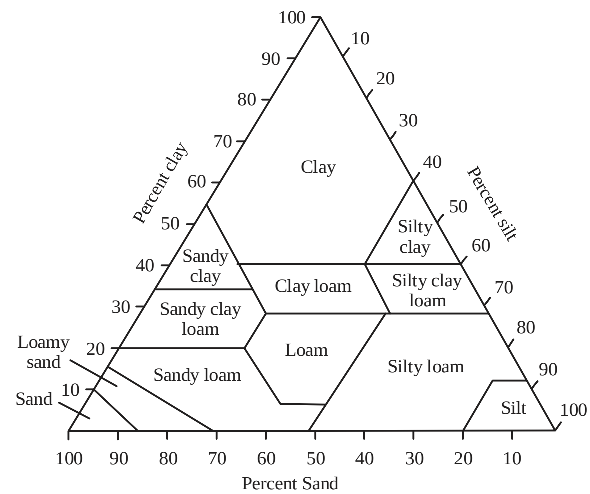

Fig. 4: A soil textural triangle is used to determine soil textural class from the percentages of sand, silt and clay in the soil

range from (68-88%), where those were the same ranges of both silty loam and silty clay loam soils. The variance between PSD measured by PM and LDM was insignificant, where it did not change the type of soil texture. Sequence mean value of KSLDM was relatively close to mean value of KSPM for soils under study and didn't take into account the method of PSD measurement.

CONCLUSION

Laser diffraction method is widely used to ascertain a particle size distribution. The LDM is more efficient for measuring sand fraction than silt and clay fractions. There is no agreement between the PSD obtained by LDM and PM. Variance between calculated KSPM and KSLDM based on PSD measured by PM and LDM, not only depend on the method of PSD measurement but also soil texture. The PSD measured by LDM may be utilized in calculating saturated hydraulic conductivity using PTFs without any modification or recalculations for silty loam and silty clay loam soils. Rosetta program is strong tool used to calculate soil saturated hydraulic using PSD that measured either by PM or by LDM.

SIGNIFICANCE STATEMENTS

This study discovers the possibility of the use laser diffraction method instead of pipette method for measuring particle size distribution. It uses as a predictor for predicting soil saturated hydraulic conductivity, using pedotransfer functions. It can be beneficial for saving both time and money, also measure rapidly soil hydraulical properties. This study will help the researcher to uncover the critical area of possibility uses particle size distribution measured by laser diffraction method in pedotransfer functions that many researchers were not able to explore. Thus, a new theory of uses particle size distribution measured by laser diffraction method as a predictor of pedotransfer functions for estimating soil hydraulic conductivity have arrived.

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