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Influence of surcharge on cone penetration test results and the inspection of various approaches for capturing its effect: a case study

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Abstract

Studies in recent decades demonstrate the significant effect of stress configuration (e.g., vertical stress and lateral confinement) on the shear strength or, in this study, the cone penetration test (CPT) results. Addition of a surcharge over the ground changes the stress condition, and consequently, the CPT tip resistance. In this study, the results of different CPTs conducted before and after backfilling with various thicknesses in a land development project were reviewed while focusing on the trend of an increase in CPT penetration resistance due to the additional surcharge. Both pre- to post-fill stress ratios and soil type affect the rise in corrected q_c values after backfilling. Moreover, there has always been a sudden increase in q_c values around the pre-fill surface in all studied cases. In this study, another approach was derived from the reanalysis of CPT data from a specific site for predicting the post-fill corrected q_c from pre-fill results by considering the above-mentioned factor. Likewise, post-fill results were predicted by depth-normalized pre-fill CPT results using Robertson's normalization method. The proposed approach in this study showed a better match with the site data compared to the normalization method, especially at and around the pre-fill surface.

Keywords: CPT, Land development, Backfilling, Normalization, Post-fill q_c

Introduction

In situ testing offers immediate and continuous profiling of subsurface materials. Furthermore, these tests provide the geo-stratigraphy and quick and reliable assessment of soil properties during the site exploration [23]. Among others, the cone penetration test (CPT) is known as the most widely adopted ground investigation method that can describe the physical properties and mechanical characteristics of a subsoil profile developed in practice and the literature in previous decades (e.g. [16, 18, 41, 44, 48]). CPT involves pushing an instrumented cone penetrometer into the ground and measuring the cone tip resistance (q_c) and sleeve friction (f_s) at selected depths (e.g. [23, 39]).

In last decades, different studies have attempted to provide appropriate and dependable correlations between in situ measurements and liquefaction susceptibility (e.g. [1, 18, 44, 51]), the physical characteristics of soils, including soil behavior type (SBT), density and grain size (e.g. [15, 27, 35, 42, 44, 46, 47]), and hydro-mechanical characteristics

of soils with applications in constitutive models (e.g. [2, 4, 6, 11, 19, 37, 36]). Therefore, CPT has been established as a routine, reliable, affordable, and expedient means for site characterization, stratigraphic profiling, engineering requirement evaluation of projects, and geotechnical design (e.g. [23]).

According to Moss et al. [29], additional effective stress (for example, due to a surcharge load) can have a significant influence on CPT results. This influence, if not assessed properly, can lead to an incorrect interpretation of soil properties for engineering purposes such as liquefaction triggering analysis, elasticity modulus estimation, and the like. Based on previous reports, normalizing CPT measurements is essential for a realistic and reliable evaluation of CPT results affected by overburden stress (e.g. [8, 12, 17, 20, 21, 23, 29, 30, 32, 42, 47, 52]). To compare the soil behavior from different depths, the cone resistance is often normalized (or corrected) to common effective overburden stress of 100 kPa [52]. Some studies developed stress normalization methods for cone tip resistance [29, 33, 34] by considering correcting f_s by merely extending the same factors (used for q_c) to $f_{s,1}$. Overburden stress affects different soils in a wide variety of ways [29]. The response of cohesive soils to overburden stress depends on the over-consolidation ratio and undrained shear strength whereas it relies on relative density, lateral earth pressure, compressibility, and particle characteristics in cohesionless soils. Although reviewing all these factors is beyond the scope of this study, some of the main efforts on normalizations with respect to overburden pressure are reviewed based on study objectives in the following section. More discussions in this field are presented by Moss et al. [29], Sadrekarami [47] and Robertson [45]. This study attempts to capture the rise in the q_c values as a result of backfilling (without performing any compaction works in between) using the stress normalization procedures introduced in the literature and, in the end, proposes a new approach through which CPT results after backfilling can be predicted from the geometry, ground condition and the CPT results before backfilling.

Normalization of CPT results

One of the major applications of the CPT is the determination of soil stratigraphy and SBT using the chart depicting the normalized cone resistance vs. the normalized friction ratio introduced by Robertson [42]. The early charts using corrected cone resistance (q_t) and friction ratio (R_f) were proposed by Douglas and Olsen [9] and later developed by Robertson et al. [38], Robertson [39] and Robertson [45]. Different researchers and engineers have widely used these charts in geotechnical fields. In recent years, several studies have introduced various stress normalization methods [5, 8, 29, 32, 45, 47, 50]. Olsen and Mitchell [33, 34] corrected the tip resistance and sleeve friction as follows:

$$q_{c,1} = C_q q_c, \quad C_q = \left(\frac{p_a}{\sigma_{v'}} \right)^c \quad (1)$$

$$f_{s,1} = C_f f_s, \quad C_f = \left(\frac{p_a}{\sigma'_{v0}} \right)^s \quad (2)$$

where q_c , f_s , p_a , and σ'_{v0} represent raw tip resistance, raw sleeve friction, atmospheric pressure, and c , s , C_q , C_f , $q_{c,1}$, and $f_{s,1}$ denote dimensionless tip and sleeve normalization exponents, dimensionless normalizing factors, corrected tip resistance, and sleeve

friction, respectively. Throughout this paper q_c , $q_{c,1}$, f_s , $f_{s,1}$, p_a , and σ'_{v0} shall be in a same unit of pressure.

In Robertson's method, the SBT is based on normalized CPT parameters as follows. CPT parameters are normalized by the effective overburden stress to produce dimensionless parameters (i.e., Q_t and F_r) where

$$q_t = q_c + u_a \times (1 - a) \quad (3)$$

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \quad (4)$$

$$F_r = \frac{f_s}{q_t - \sigma_{v0}} \times 100\% \quad (5)$$

where q_t , u_a , a , f_s , σ_{v0} , and σ'_{v0} are CPT corrected cone resistance [7], pore water pressure, the net area ratio (from laboratory calibration), sleeve friction, in situ total vertical stress, and in situ effective vertical stress, respectively.

Moreover, Jefferies and Davies [14] identified that the soil behavior type index (I_c) could represent SBT zones in the $Q_t - F_r$ chart where I_c is essentially the radius of concentric circles that define the boundaries of the soil type.

Additionally, Robertson and Wride [41] modified the definition of I_c to apply to the $Q_{tn} - F_r$ chart of Robertson [39], as defined in Eqs. (6) and (7):

$$I_c = \left[(3.47 - \log Q_{tn})^2 + (1.22 + \log F_r)^2 \right]^{0.5} \quad (6)$$

The contours of I_c (as shown in Fig. 1 on the $Q_{tn} - F_r$ SBT_n chart) can be used to approximate SBT boundaries. In this regard, Jefferies and Davies [14] suggested that the SBT index I_c could also be used to modify empirical correlations that vary with soil type.

It is noteworthy that the definition of I_c suggested by Robertson et al. will be used throughout the current study.

Likewise, Robertson [42] and Zhang et al. [54] presented a normalized cone parameter with a variable stress exponent (n):

$$Q_{tn} = \left(\frac{q_t - \sigma_{v0}}{p_a} \right) \cdot \left(\frac{p_a}{\sigma'_{v0}} \right)^n \quad (7)$$

$$n = 0.381 \times I_c + 0.05 \times \frac{\sigma'_{v0}}{p_a} - 0.15 \leq 1.0 \quad (8)$$

where $\frac{q_t - \sigma_{v0}}{p_a}$ and $\left(\frac{p_a}{\sigma'_{v0}} \right)^n$ represent dimensionless net cone resistance and the stress normalization factor, respectively. In addition, n and p_a denote the stress exponent that varies with SBT_n and the atmospheric pressure in the same units as q_t and σ_v , respectively. Note that when $n = 1$, $Q_{tn} = Q_t$. Zhang et al. [54] suggested that the stress exponent (n) could be estimated using the SBT_n index (I_c).

To the best of our knowledge, no study has so far described the effect of surcharging on CPT data derived based on site investigations. In many practical projects (land development works in particular), thick fill layers cannot be placed in one construction attempt, but they are put in several smaller phases. After each phase, the overall quality of the ground shall be tested by CPT and checked against the final requirement of the project, which is usually defined by minimum q_c values vs. depth. To ensure that interim CPTs (before the placement of the final sub-layer of the fill) are properly assessed, the constructor and consultant of the project need to convert pre q_c to post q_c values (after the completion of the fill). This study aimed to provide an overview of a specific site in order to describe the effect of surcharging on the q_c before and after surcharging. Furthermore, the site data were used to evaluate the application of the normalization method proposed by Robertson [39] in order to predict the post surcharge q_c from pre-fill CPT results. In this regard, a new approach was proposed and evaluated using numerous CPT data from the site.

The effect of surcharge: case study

In a land development project near the United Arab Emirates coasts in the Persian Gulf, several series of backfilling works were planned over an area of more than three million m^2 . Most newly developed lands were artificial islands dredged in the middle of the sea although some smaller parts were in the vicinity or on top of natural islands or geological formations. The subsoil consists of multiple layers of silty sandy gravel to highly silty sand with the N_{SPT} values of 20–40. There is also an approximate 1-m-thick loose layer with the N_{SPT} of 2–4 in some parts of the site. An average soil profile of the project (before backfilling) is provided in Table 1 based on the boreholes performed on the area.

After the completion of the backfilling and other necessary earthworks on the surface, different compaction methods were employed to densify the newly filled materials depending on the soil type and reclamation depth. During and at the end of the work, several series of CPTs were performed on the virgin ground after the backfilling of the soil and execution of the compaction in order to assess the quality of each step of the project. First, the CPTs in the research were performed on the native ground before the placement of the fill (pre) and after backfilling although before compaction execution (post). However, as mentioned above, CPT results (tip resistance in

Table 1 Average soil profile of the project (before backfilling)

Elevation [m]	Description	Natural gravimetric water content (%)	Atterberg limits (%)		Grading [% of total mass]		
			LL	PI	Gravel	Sand	Silt/Clay
+ 3.0 to + 0.5	Medium dense sand	15	25	7	38	42	20
+ 0.5 to – 0.5	Medium dense sandy gravel	27	30	8	43	35	22
– 0.5 to – 2.5	Medium dense to loose gravel	22	30	10	64	25	11
– 2.5 to – 6.5	Dense sandy gravel with seams of weathered calcar-enite	23	30	7	45	43	12
Below – 6.5	Bedrock	20					

particular) are a function of several parameters which might change during the work, including the surcharge.

The natural ground condition of the above-mentioned project was inspected by CPT before and after additional backfilling prior to conducting the compaction phase. The results of CPTs performed on the natural ground were compared to those of CPTs conducted after placing an additional soil layer. The former and latter series of CPTs are called pre- and post-fill CPTs, respectively. No ground improvement was found at the time of performing CPTs. Therefore, any changes in the results were due to the weight of the backfilled layer. Pre and post CPTs were executed in reasonable proximity (in the range of 5–10 m). However, it should be noted that even a few meters distance could lead to some variations in the subsoil profile.

In the following section, the pre-fill CPT tip resistance ($q_{c,pre}$) is used to predict the expected post-fill CPT results ($q_{c,post}$) as a function of soil type and backfilling height using a technique introduced in the literature (i.e., normalization for the stress level) and a proposed method.

Site inspection and subsoil conditions

The areas concerned in this study consisted of medium dense silty sand on the top. The sandy silty gravel with the seams of extremely weathered calcarenite was found starting from the elevation of around -2 m downward. Since the studied CPTs were covering a quite large area, there were some fluctuations in the ground conditions. The details of the subsoil condition are presented in Figs. 2 and 5. The groundwater table is averagely at an elevation of +0.5 m.

For the investigated area, the backfilling height was averagely 3 m over a land with natural elevations of +1.25 to +3.25 m above the mean sea level.

CPT results

In Fig. 2, CPT tip resistances before and after placing the surcharge on top of the natural surface are presented by gray and black curves. As shown, q_c has increased after backfilling. To find the effect of backfilling on q_c values, a comparison should be made between pre and post CPTs in each pair.

Figure 2 elaborates on one pair of CPTs (case N5, pre and post) in more detail. q_c , f_s , F_r , Q_{tn} , and I_c of these CPTs are used for further analysis of the proposed method in this study. Based on data analysis, the normalized Q_{tn} and F_r are calculated as per Robertson's chart Fig. 1.

As illustrated in Fig. 2, f_s has been less affected after backfilling compared to q_c . Moreover, q_c starts from 0.0 MPa (the so-called “entry effect”) at the pre-fill ground level although this value is considerably larger than 0.0 MPa at the same elevation but in post-fill CPT. This jump should be also reflected in the predictions of post-fill CPTs from pre-fill results.

Estimating soil unit weight from CPT

The total unit weight (γ) of soil layers is needed for estimating the overburden stress (σ_v). The correct evaluation of total and effective overburden stresses is important in many correlations between CPT results and geotechnical parameters [43]. The unit weight is

best measured by obtaining undisturbed samples. However, obtaining undisturbed samples in all soil layers can be difficult and costly for many soils and low-risk projects. An alternate approach is to directly estimate the soil unit weight from CPT results. Different equations have been proposed for calculating the unit weight of soil layers by compiling an extensive database for various soils and site measurements (e.g. [22, 24–28, 43, 49]). Among them, Eq. (10), which was proposed by Robertson and Cabal [43], was adopted to estimate the unit weight of soil layers in the present study.

$$\frac{\gamma}{\gamma_w} = 0.27 \times \log(R_f) + 0.36 \times \log\left(\frac{q_t}{p_a}\right) + 1.236 \quad (10)$$

where R_f is the friction ratio and equals $f_s/q_t \times 100$. Moreover, γ_w and p_a represent the unit weight of water and atmospheric pressure in the same units as γ and q_t , respectively.

Figure 3 shows the estimated γ using Eq. (10) and the CPT data of before and after surcharging. As depicted, the unit weight of soil layers is not affected by surcharging. However, all analyses in this study were conducted based on the estimated γ using Eq. (10) and CPT data.

Prediction of post-fill CPT tip resistance

Using existing methods

As discussed in Sect. 2, many studies have introduced different methods for normalizing the overburden pressure (e.g. [8, 12, 17, 21, 29, 33, 34, 42, 52]).

In this study, the pre and post CPT results were normalized for depths (or pressure) according to Robertson [42], which is the most widely used normalization method, as per Eqs. (4) to (8). Therefore, the normalized tip resistances (Q_{tn}) of pre and post CPTs must be theoretically equal. Considering that the soil is mainly granular and regarding the time between the construction of the fill and the post CPTs, it is not unrealistic to assume that the excess pore water pressure has been dissipated by the time of post CPTs.

Subsequently, the normalized pre CPT again was reverted to non-normalized q_c values using the same method but with the vertical stresses of the post CPT condition calculated from the post-fill overburden pressure. This procedure estimates the q_c values of post CPT tests based on pre CPT results and the surcharge due to backfilling thickness or overburden pressure. The dotted lines in Fig. 5 represent the expected q_t values after backfilling, which can be called 'predicted q_t '. Based on the finding, the predicted CPT

Fig. 3 Calculated saturated density of soil based on CPT results as per Eq. (10) for pre and post CPT results of case N5

tip resistance could not properly estimate the actual post CPT tip resistance (the solid black line) and was less than that value in most cases.

Proposed prediction method

In the assessment of CPT results, the increase in the corrected tip resistance (q_t) seemed to be a function of initial and post-fill stresses, along with soil types. Hence, factors regarding stress levels and soil type must be introduced for estimating the post CPT q_t .

On the other hand, the most noticeable changes in q_t values were close to the surface irrespective of the soil type. In all studied cases, the q_t values of the post-fill condition ($q_{t,post}$) at around the pre-fill surface were considerably higher compared to the pre-fill condition ($q_{t,pre}$). Typically, q_t starts from zero at the surface. This could be due to the movement of earthwork equipment on the pre-fill ground surface. However, changes in the stress condition and additional surcharge in the post-fill test (from zero to $\Delta\sigma'$) at that elevation have probably a prominent influence on this increase. In Fig. 4, this jump in the tip resistance of case N5 is shown by the dashed arrow.

Based on the performed analysis, Eq. (11) can be used to convert the pre-fill to the post-fill CPT tip resistance:

$$q_{t,post} = k_{\sigma} k_s q_{t,pre} + q_o \quad (11)$$

where k_{σ} and k_s are dimensionless multiplying conversion factors for predicting post-fill q_t with respect to stress levels and soil type.

The influence of surcharge on the post-fill q_t attenuates by increasing the depth. This effect can be determined using the pre- to post-fill stress ratio ($\sigma'_{v,pre}/\sigma'_{v,post}$) where $\sigma'_{v,pre}$ and $\sigma'_{v,post}$ are vertical effective stresses in pre- and post-fill conditions. Depending on the groundwater table, $\sigma'_{v,post}$ can be easily calculated based on the fill height and the expected unsaturated and/or submerged unit weight of the fill material. To make any noticeable change in the stress condition and/or the soil structure, additional stress

Fig. 5 Solid gray and black curves show the q_t values of pre and post CPTs ($q_{t,pre}$ and $q_{t,post}$). Dotted and dashed curves present the prediction of $q_{t,post}$ using the normalization method and the methods proposed in this study

Fig. 5 continued

should be a significant portion of natural stress. Based on the studied cases, no meaningful change was observed in q_t if the stress ratio ($\sigma'_{v,pre}/\sigma'_{v,post}$) exceeded 45%. Therefore, Eq. (12) was proposed for k_σ based on the best fit in the results. It should be noted that this equation is valid only where the stress ratio is less than 0.45. For the stress ratio > 0.45 , $k_\sigma = 1$.

Fig. 5 continued

$$k_{\sigma} = 1 + \left(0.45 - \frac{\sigma'_{v,pre}}{\sigma'_{v,post}} \right) \quad (12)$$

$$\sigma'_{v,post} = \sigma'_{v,pre} + \Delta\sigma' \quad (13)$$

Soil type was also found to affect the post-fill q_t . Layers with higher fine contents experienced less or no resistance development. One reason could be the immediate settlement and densification occurring only in granular soils. Additionally, even if no densification happens in sandy soils, increasing the surcharge leads to an increase in effective vertical and horizontal stresses in underlying layers which, consequently, increases the CPT tip resistance. However, due to extremely low permeability, the additional

surcharge is carried by the pore water pressure and has minor or no influence on effective stresses and thus on the post-fill q_t in fine-grained soft soils. In the assessed CPT results, no meaningful change was detected in q_t values for layers with I_c values more than 2.05 (sand or silt mixtures as per Roberson [39] and [42]). Moreover, higher resistance development can be expected in q_t can be expected when I_c values are lower. Therefore, Eq. (14) was implemented in this study for the soil type prediction factor.

Table 2 Ground elevations of pre and post CPTs

CPT cases	Ground elevation (m)		Height of surcharge (m)
	Before backfilling	After backfilling	
N5	+ 1.34	+ 4.70	3.36
N8	+ 1.10	+ 4.70	3.60
N14	+ 1.45	+ 4.70	3.25
M2	+ 1.85	+ 5.30	3.45
M4	+ 1.54	+ 4.68	3.14
M9	+ 1.64	+ 4.62	2.98
M14	+ 2.24	+ 4.41	2.14
P1	+ 2.10	+ 4.49	2.39
Q10	+ 2.73	+ 4.54	1.81
R3	+ 3.22	+ 5.15	1.93
R4	+ 3.10	+ 5.12	2.02
R6	+ 2.81	+ 4.92	2.11
S11	+ 2.57	+ 5.14	2.57
S14	+ 2.97	+ 5.20	2.23
S15	+ 2.78	+ 4.59	1.81
T7	+ 2.76	+ 4.60	1.84
T9	+ 1.25	+ 4.48	3.23
T12	+ 2.75	+ 4.58	1.83
Z11	+ 1.48	+ 4.70	3.22

$$k_s = 1 + (2.05 - I_c) \quad (14)$$

Both stress and soil type (k_σ and k_s) should only be applied on depths starting from the pre-fill ground surface to where the stress ratio ($\sigma'_{v,pre}/\sigma_{v,post}$) is less than 45%. In the depths with higher stress ratios, pre and post-fill q_t results ($q_{t,pre}$ and $q_{t,post}$) were in the same range or represented no noticeable variation between pre and post CPTs.

k_σ and k_s are multiplying factors and cannot properly predict the post-fill cone resistance at the pre-fill ground surface (and shallow depths) after backfilling. Accordingly, the term q_o was added to compensate for the jump in the cone tip resistance in this study based on the reviewed cases as mentioned earlier. Equation (15) is found to estimate the q_o value reasonably compatible with actual post-fill results. found to estimate found to estimate

$$q_o = n\Delta\sigma'(1 - k_\sigma)^m \quad (15)$$

This component decreases rapidly by depth for the studied soil type. n and m are dimensionless fitting parameters (fitted to get the best match in the studied CPT pairs), which are proposed to be 200 and 2, respectively. $\Delta\sigma'$ denotes differential effective stress due to the fill in the same unit as q_t .

Figure 5 displays the calibration capacity of the proposed approach for estimating the post q_t values for all tests listed in Table 2. As shown, the approach can estimate $q_{t,post}$ based on $q_{t,pre}$ for almost all CPTs. However, further field data must be employed for further validation and fine-tuning of the proposed approach.

Fig. 6 Soil behavior type of CPT results of case N5 for **a** before and **b** after backfilling CPTs, as well as pre-fill CPT results converted to post-fill using **c** normalization method and **d** the approach introduced in this study

As has been highlighted by Moss et al. [29], overburden stress differently affects various soils. Therefore, applying the proposed approach must be inspected for CPT measurements for different subsoils.

Although the proposed method could predict the post-fill q_t from the pre-fill date and the added surcharge, the CPT results in Fig. 5 demonstrate some pairs of pre and post-fill CPTs exist which show no comparable tip resistances over some depths (e.g., the CPTs of cases M14, Q10, R3, and S15). This is due to the heterogeneity of the ground or inclined soil layers which is naturally observed in site inspection reports.

Unlike tip resistance, no meaningful change was observed in the sleeve friction (f_s) in all studied CPTs. This could be explained by the subtle independency of cohesion to the load configuration. Therefore, the same sleeve friction of pre-fill CPT was assigned for further analyses of post-fill CPT results in this study (which are predicted from pre-fill results). Figure 6a and b show the soil behavior type chart (SBT chart) of Robertson [39]

for the pre and post-fill CPT results of top 1.5 m from the pre-fill ground surface (+ 1.34 to − 0.16 m) for case N5. In Fig. 6c and d, the SBT charts of the predicted post-fill data from the pre-fill values are plotted using the normalization method and the proposed approach. Soil behavior types are more or less in the same ranges since the same sleeve frictions are used in charts a, c, and d. Nevertheless, using the proposed approach (Chart d), the SBT chart of the predicted post-fill results provides a better prediction of actual post-fill CPT results (Chart b) compared to the normalization method (Chart c), especially the concentration of points on the top-left corner of zone 6 and the bottom of zone 7 while the predicted results are highly similar to pre-fill values using the normalization method. The additional surcharge was considered in the calculations of charts c and d.

Conclusion

In the studied pre and post-fill CPT results, tip resistance showed a significant increase, especially around the pre-fill surface while it gradually decreased by depth.

The maximum depth, around which the rise in q_c was almost stopped, was associated with the pre- to post-fill stress ratio ($\sigma'_{v,pre}/\sigma'_{v,post}$) of 0.45. Accordingly, the authors proposed not to consider any change in q_t values. The influence of the stress ratio was introduced by the stress factor (k_σ), which starts with 1.45 at the pre CPT surface and decreases by depth (or the stress ratio) to a minimum of 1.0. The soil type was also proved to have an influence on the growth of q_t so that the more granular soil led to further increases in q_c in the post CPT. Therefore, the soil type factor (k_s) was introduced while taking this effect into consideration, which is higher for lower I_c values with a minimum of 1.0. CPT results at the pre-fill surface or shallow depths represent a sudden growth. The term q_o is added to the factored pre-fill q_t for observing this jump.

Compared to predicting post CPT results through normalizing q_t values for depth (or stress), the proposed method seemed to be a more accurate and better fit to the actual post-fill results (for the soil type studied in this research), especially for shallow surfaces where the normalization method fails to demonstrate the increase in q_t values at shallow depths.

In the studied CPTs, there were highly minor or no noticeable changes in the sleeve friction (f_s). Hence, the sleeve friction of the pre-fill q_t , along with the predicted post-fill q_t was used to plot SBT charts. Although the SBT results were all more or less in the same zones, a better match was observed between actual and predicted post-fill data using the proposed method.

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