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BEHAVIOR OF MAT FOUNDATION FOR A TEN-STORY BUILDING: FIXED BASE VS THREE-DIMENSIONAL SOIL MODEL

ZACHOWANIE SIĘ PODŁOŻA Z MATĄ DLA BUDYNKU DZIESIĘCIOPIĘTROWEGO: STAŁA BAZA A TRÓJWYMIAROWY MODEL GRUNTU

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Abstract

Soil is an anisotropic, heterogeneous, and inelastic complex material. It is difficult to represent the exact behavior of soil by numerical modelling in practice. Conventionally, soil is simplified to an idealized model where it is considered isotropic, homogeneous, and behaves elastically under loads. The idealization, in this case, is done using the proper elastic modulus, Poisson's ratio, and unit weight of soil depending upon the soil type. Although the exact soil behavior is simplified, using Finite Element Analysis (FEA) a more effective result can be obtained. A superstructure was modelled using ETABS using a fixed-base system and the base reaction forces were obtained. A mat and a soil element on which the mat was laid were modelled as a flexible-base system in Midas GTS NX. The base reactions obtained from ETABS were applied to the mat in the soil model to determine the settlements and, consequently, the spring stiffness. The superstructure was then modelled again, incorporating springs under the respective columns. Convergence in settlement, and base reactions were reached by iteration, and the final results from the flexible-base system were then compared with the fixed-base system. The center column settled the most, about 60 mm, and there was a decrease in settlement by 15% between the first model and the final iterated model. The base reaction for center columns decreased by 24% in the flexible base system compared to the fixed base system. However, an increase in base reaction was observed for both side and edge columns. There was an extremely erratic change in grade beams under a flexible base system, which shows that the superstructure elements are also affected by the change in the base system. It is recommended to use this approach, for the analysis of structures considering flexible base systems instead of fixed bases because it enhances the accuracy of analysis with feasible time consumption and less complex effort.

Keywords: Elastic modulus, Poisson's ratio, Finite Element Analysis (FEA), Midas GTS NX, settlement, spring stiffness etc.

Streszczenie

Gleba jest materiałem złożonym anizotropowym, niejednorodnym i nieelastycznym. W praktyce trudno jest dokładnie odwzorować zachowanie gleby za pomocą modelowania numerycznego. Konwencjonalnie glebę upraszcza się do wyide-

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environment

alizowanego modelu, w którym uważa się ją za izotropową, jednorodną i zachowującą się elastycznie pod obciążeniem. Idealizacja w tym przypadku odbywa się za pomocą odpowiedniego modułu sprężystości, współczynnika Poissona i masy jednostkowej gruntu w zależności od rodzaju gruntu. Chociaż dokładne zachowanie gleby jest uproszczone, można uzyskać bardziej efektywne wyniki za pomocą analizy elementów skończonych (FEA). Konstrukcja nośna została wymodelowana za pomocą ETABS przy użyciu systemu stałej podstawy i uzyskano siły reakcji podstawy. Matę i element gruntu, na którym została położona, zamodelowano jako układ o elastycznej podstawie w programie Midas GTS NX. Reakcje bazowe uzyskane z ETABS naniesiono na matę w modelu gruntowym w celu określenia osiadań, a co za tym idzie sztywności sprężystej. Następnie ponownie wymodelowano konstrukcję nośną, włączając sprężyny pod odpowiednimi kolumnami. Zbieżność osiadania i reakcji bazowych została osiągnięta przez iterację, a końcowe wyniki z systemu o elastycznej podstawie zostały następnie porównane z systemem o stałej podstawie. Kolumna środkowa osiadła najbardziej, około 60 mm, a między pierwszym modelem a ostatecznym modelem iterowanym nastąpił spadek osiadania o 15%. Reakcja podstawy dla kolumn centralnych zmniejszyła się o 24% w systemie z podstawą elastyczną w porównaniu z systemem z podstawą stałą. Zaobserwowano jednak wzrost odczynu zasadowego zarówno dla kolumn bocznych, jak i krawędziowych. Nastąpiła bardzo nieregularna zmiana belek niwelacyjnych pod elastycznym systemem bazowym, co pokazuje, że zmiany w systemie bazowym mają również wpływ na elementy konstrukcji nośnej. Zaleca się stosowanie tego podejścia do analizy konstrukcji z uwzględnieniem elastycznych systemów bazowych zamiast stałych baz, ponieważ zwiększa to dokładność analizy przy możliwej czasochłonności i mniejszym wysiłku.

Słowa kluczowe: moduł sprężystości, współczynnik Poissona, analiza elementów skończonych (FEA), Midas GTS NX, osiadanie, sztywność sprężyny itp.

1. INTRODUCTION

Foundation could be either shallow or deep depending on the bearing capacity of soil and the load from the superstructure. Shallow foundation can be chosen when the demand of the superstructure, the load, can be met by, the bearing capacity of the soil, from shallow depth usually when the depth of foundation is equal or less than the required width. Shallow foundation can be of different types like single footing, combined footing or mat foundation-which is a special type of combined footing. Whereas deep foundation system is considered when the bearing capacity of the soil is not enough at shallow depth. The simplified distinction is when the depth of foundation is four times the width of foundation, the system is called deep foundation. Pile foundation is one of the most common examples of deep foundation system. Mat foundation is adopted when the bearing capacity of soil is not sufficient for individual column footing because of overlapping of footing area. Mat foundation spreads the load over a large area and allows more settlement.

Settlement occurs when a load is applied on the soil, and it is very important for the engineers to be able to predict its settlements. A settlement is comprised of two types, elastic settlement and consolidation settlement. Consolidation settlement can be of two types, primary consolidation and secondary consolidation. The elastic settlement is the immediate settlement that occurs when a load is applied. Settlement mainly depends on the soil properties. For example, when a load is applied on sand, the settlement that occur is only elastic due to the deformation of the soil body. Whereas, the clay soil will have both elastic settlement and consolidation settlement, the deformation of soil particles followed by drainage of water. And in the long term the secondary consolidation will occur when the soil particles will rearrange themselves after the water is drained out. The settlement also depends on the inter-particle properties.

Compared the bending moments between conventional approach and FEM. A raft was modelled in SAFE and the superstructure was modelled in STAAD. The bending moment in x and y direction as well settlements were converged. Bending moment was found to be lesser in FEM than conventional approach for loose and medium soil, however, the difference is not much for stiff soil and between the centre column spaces for all types of soil (Limkar et al., 2017). A New Approach for Estimating Thickness of Mat Foundations under Certain Conditions by (Al-Shayea, Zeedan, 2012) estimates the thickness of the mat foundation for engineering practice. The mat thickness was estimated using FEM analysis of soil, mat, and superstructure in STAAD PRO, where the mat was analysed as a 3D finite element plate, and the soil and the superstructure were considered as elastic materials with different elastic properties using Poisson's ratio and elastic modulus. The following insights were found in the paper: The distribution of stress on the foundation is affected by both mat rigidity and soil type; for rigid plates, moment is more important than shear; for flexible plates, shear is more important.

Cement columns in peat soil were compared between an analytical model and a finite element (FE) model. The FE model was done using PLAXIS 3D foundation software, and for the analytical model, Brom's analytical methods were used. The analytical model consistently predicts less settlement than the FE model (Banadaki et al., 2012). Settlements of hydro-digesters on mat foundation were both measured and analysed using numerical analysis tools by (Shah et al., 2006) two digesters were modelled using FE software, where the superstructures were analysed in STAAD Pro and the subsurface soil model was analysed in Plaxis software. Springs were incorporated into the superstructure model, which used the subgrade modulus from the soil model as the spring stiffness of the springs. The results from both the models were iterated and converged before analyzing the results. It was seen that the FE model predicted more settlement, but it was close to the measured values.

The modulus of subgrade reaction, k. In this study, a value of k was computed using Vlasov's model from a concentrated load, which was then used in the Winkler's model. The value of k from Vlasov's model and the corresponding value for maximum displacement were converged by the process of the iteration method. An equation for k was developed, which can be computed if the properties of the soil as well as the geometry are known (Daloglu et al., 2000). In Practical Subgrade Model for Improved Soil-Structure Interaction Analysis: Software Implementation by (Horvath, Colasanti, 2011), they proposed an improved model for plate-like structures coupling of the virtual springs underneath the mat foundation. The paper uses both the Modified Kerr mechanical model (Horvath, Colasanti, 2010) and the Reissner model to introduce a new method called the Modified Kerr- Reissner Model (MK/R), which is done by introducing a tensioning thin membrane between layers of springs and using an equivalent single layer of elastic and isotropic soil instead of the multi-layered soil which was introduced by Reissner's Model.

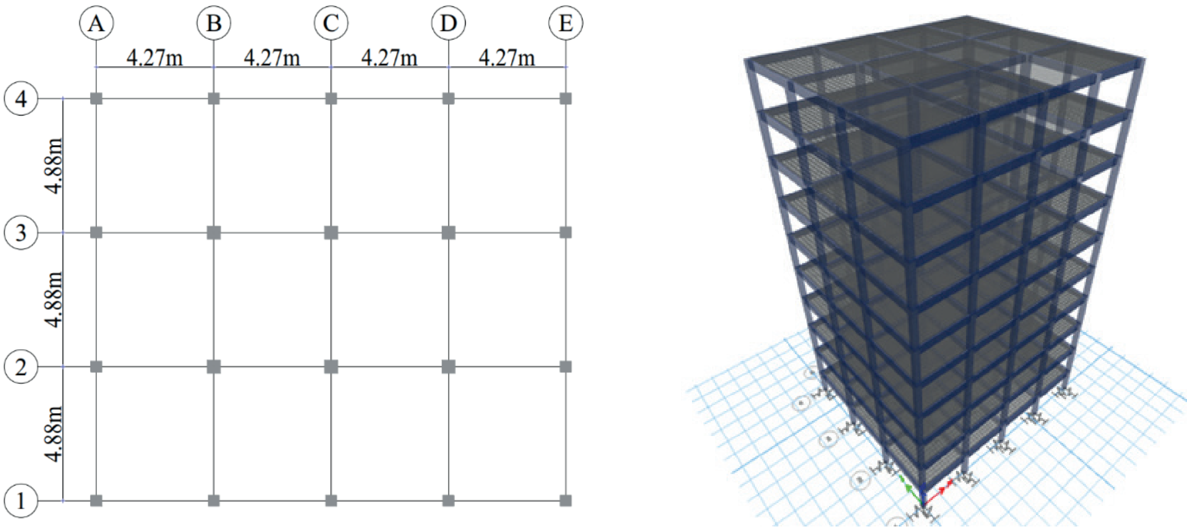
A three-stage design approach to ensure an optimum design system. The three stages are: finding the number of piles, location of the piles; and a detailed analysis to confirm the optimum number of piles for practical design. It was also noted that increasing the number of piles after a certain point gives no additional benefits to the structure (Poulos, 2001). the applicability and accuracy of various approaches offered for determining the coefficient of subgrade reaction, k. The geotechnical parameters of a site on the Tabriz Marl were used as a baseline, and settlement study findings from different methods were compared to those obtained from advanced soil model analyses utilizing Safe and Plaxis software. The soft soil model was shown to be the best governing model for Tabriz Marl, and the Vesic relation among the techniques of determining k_s leads to low inaccuracy when compared to the soft soil model. It is also suggested that mean elasticity modulus should be used to obtain more accurate findings from these methods (Sadrekarimi, Akbarzad, 2009).

Three soil samples were taken from the research area at various elevations. A variety of tests were carried out to determine some of the soil's prerequisite qualities. The use of piles, regardless of raft thickness, results in a significant reduction in foundation settlements. The use of piled rafts can also be used to reduce raft settlements as well as material resources by reducing raft thickness. Midas GTS NX has proven to be effective software for analyzing piled raft foundations (Saini, Goyal, 2019).

2. METHODOLOGY

A 10-story residential building will be modelled in ETABS, and linear static analysis will be carried out to determine the base reaction of the columns under vertical load. The behavior of mat foundation system will be analyzed using the finite element method. As a result, a mat on soil model will be created in Midas GTS NX. The settlement will be then determined for the superstructure's base reaction force. Using the base reaction force and settlement, the spring stiffness (coefficient of subgrade reaction) will be calculated, and the superstructure will be modelled using springs under each base column. The new base reaction will be obtained and used in the FE model to determine the new settlement, and hence another spring stiffness will be calculated and used in the spring model. The process will be repeated and the settlement, spring stiffness, and base reaction will be determined using this incremental iteration process. These parameters will be compared with the original fixed base system.

The plan's X span was 17 m, with 5 columns spaced at 4.27 m intervals and 4 columns spaced at 4.88 m intervals in the Y direction for a total span of 48 ft. Each story height was 3 m, with a foundation level 2.44 m below the existing ground level and a total height of 29.87 m. A reinforced concrete structure was considered for the superstructure analysis. The concrete material was to be elastic and isotropic.



a) Plan view b) 3D view

Fig. 1. Building interpretation

Table 1. Lateral loads parameters (BNBC-2020)

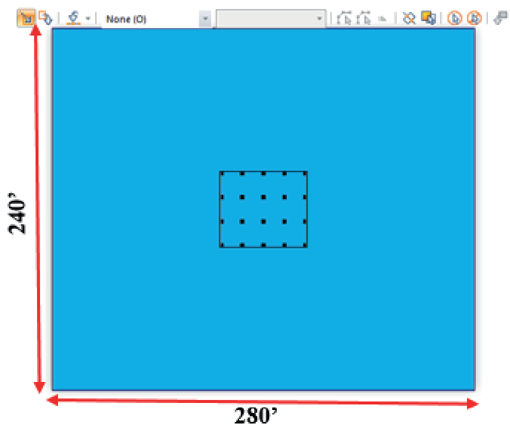
Wind load		**Seismic Load**	
Windward coefficient, C_{pw}	0.8	Response reduction factor, R	8
Leeward coefficient, C_{pl}	0.5	System over-strength factor, Ω_0	3
Wind Speed, V (m/s)	65	Deflection amplification factor C_d	5.5
Exposure type	B	Importance factor, I	1
Importance factor, I	1.0	0.2 seconds spectral acceleration, S_s	0.5
Gust factor, G	0.85	1 second spectral acceleration, S_1	0.2
Directionality factor, K_d	0.85	Site class	F
Topographic factor, K_{zt}	1.0	Site co-efficient, F_a	1.35
		Site co-efficient, F_v	2.7

Five layers of soil were modelled using an idealized soil strata from Dhaka (Dhanmondi Area), in Midas GTS NX software using the Mohr-Coulomb plasticity model. The soil strata are given below.

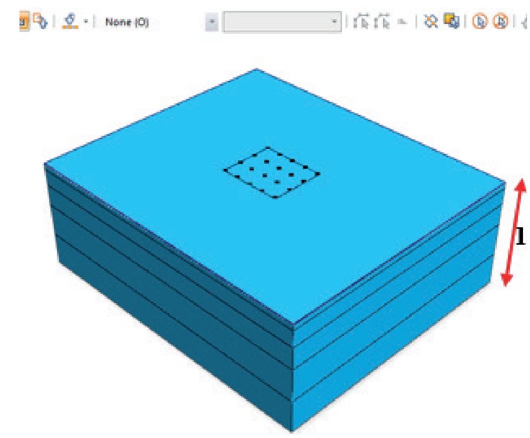
Table 2. Properties of soil with layer thickness

Thickness	**Soil Types**	**Soil properties**	
1.5 m	Soft Clay	$\gamma = 19$ kN/m^3, $E = 12.5$ MPa, $C = 25$ kN/m^3	$\varphi = 0°$, $\upsilon = 0.4$
4.5 m	Medium Stiff Clay	$\gamma = 19.5$ kN/m^3, $E = 29$ MPa, $C = 35$ kN/m^3	$\varphi = 0°$, $\upsilon = 0.35$
6.0 m	Stiff Clay	$\gamma = 20$ kN/m^3, $E = 49$ MPa, $C = 58$ kN/m^3	$\varphi = 0°$, $\upsilon = 0.3$
9.0 m	Medium Dense Sand	$\gamma = 20$ kN/m^3, $E = 35$ MPa, $C = 0$ kN/m^3	$\varphi = 30°$, $\upsilon = 0.3$
9.0 m	Dense Sand	$\gamma = 20$ kN/m^3, $E = 120$ MPa, $C = 0$ kN/m^3	$\varphi = 40°$, $\upsilon = 0.3$

An 85 m × 73 m (five times the mat dimension in both directions) soil body was modelled using Midas GTS NX software with depth taken as 30 m as per the above soil strata.



a) Plan of the model



b) Three dimensional view

Fig. 2. Soil Model in Midas GTS NX

For meshing the built-in auto mesh feature was used for both mat and soil model. The auto mesh feature in Midas GTS NX generates a combination of hybrid mesh of hexahedral, pentahedral and tetrahedral elements in both two-dimensional and three-dimensional elements.

The analysis for the superstructure was done in ETABS, whereas the soil and mat were analyzed in Midas GTS NX. The procedure of the numerical analysis was as below:

- Base reactions (F_o) under each base column were generated from the ETABS Model using a rigid base system.
- The base reactions were then transferred to the soil model in Midas GTS NX to obtain the resulting vertical displacements under each column (x_o).
- Using the expression, $F = k/x$, we obtained the spring stiffness or coefficient of subgrade reaction (k_o) obtained from these values.
- The spring stiffness was used in the ETABS model under each base column to analyze the superstructure as a flexible base system. This generated new base reactions and vertical displacements.
- The new base reactions were then used in the soil model in MIDAS GTS NX to obtain the new displacement.

A new spring stiffness was calculated again and the procedure continued until the parameters were converged.

3. RESULTS AND DISCUSSSIONS

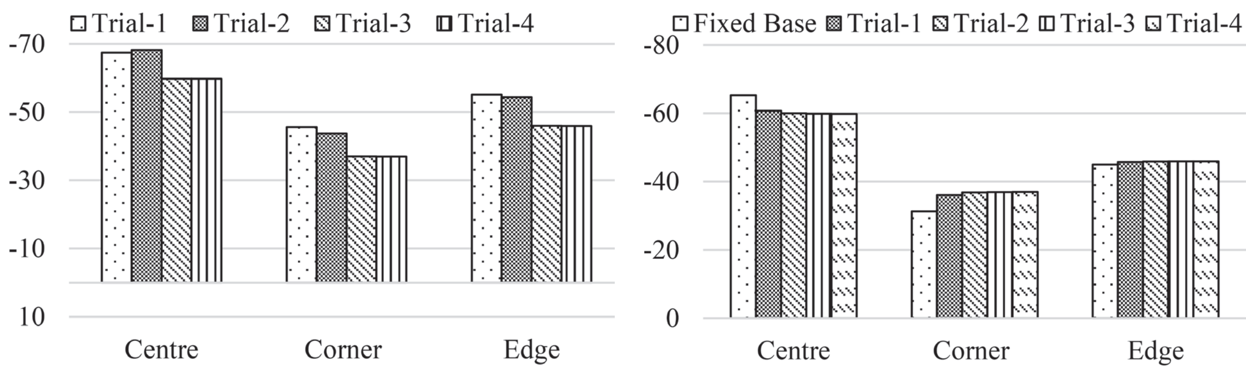
The convergence in parameters such as settlement, base reactions, and spring stiffness will be represented and discussed. Furthermore, the behavior of the superstructure's elements will be displayed and discussed, which could be a basis for future work.

Differential vertical settlement was encountered when spring was used in the superstructure model than fixed support. However, the settlement difference between the original model (fixed support) and the spring model was around 15% for center columns (after convergence) in comparison to finite element model (FEM).

Table 3. Comparisons of settlement (mm)

Trial	Centre columns		Corner columns		Edge columns	
	ETABS	Midas GTS NX	ETABS	Midas GTS NX	ETABS	Midas GTS NX
Fixed base 0		−65.26	0	−31.30	0	−44.97
Trial-1	−67.39	−60.70	−45.58	−36.05	−55.18	−45.76
Trial-2	−68.22	−59.96	−43.73	−36.83	−54.35	−45.89
Trial-3	−59.75	−59.83	−37.02	−36.94	−45.97	−45.92
Trial-4	−59.78	−59.81	−36.98	−36.96	−45.95	−45.93

The conventional modelling of a superstructure using fixed support cannot account differential settlement between the columns. It can be seen that the difference in settlement between the center columns and the corner columns is around 24 mm. Thereby flexible foundation should be modelled to encounter the differential settlement.



a) Settlement (ETABS) b) Settlement (Midas GTS NX)

Fig. 3. Convergence in settlement (mm) between Midas Model and ETABS Model

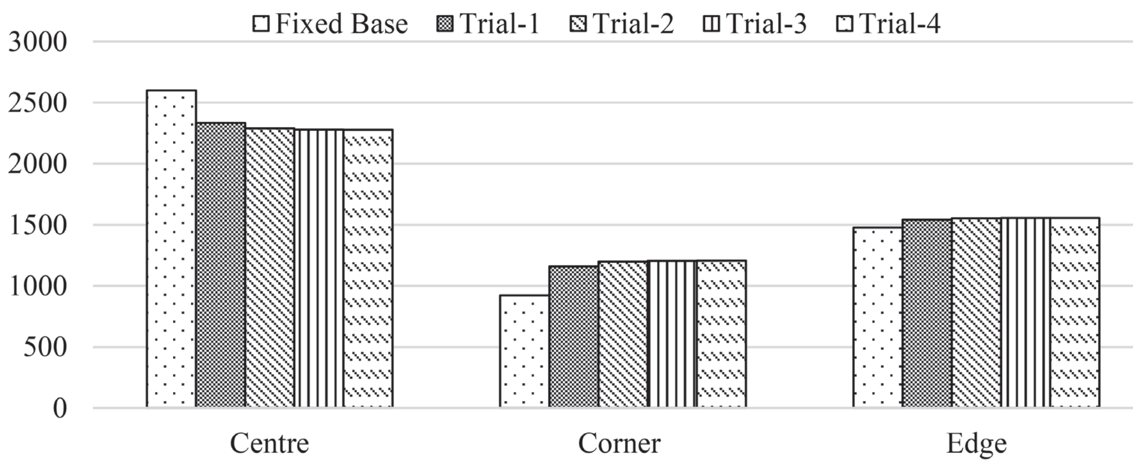


Fig. 4. Graphical representation of convergence in base reactions (kN)

In most conventional practice, the soil flexibility is totally ignored, and it is assumed that the superstructure is supported on a fixed base. This results in overestimating the foundation or worse, underestimating the soil settlement and base reaction. Therefore, it is necessary to analyze the support as a flexible support. This is done by considering virtual springs underneath the superstructure as developed by Winkler. However, Winkler's model assumes constant spring stiffness for the entire area of the foundation system, which again leads to the same problem of both underestimation and overestimation in the foundation system. Therefore, it is critical to use different spring stiffness according to the superstructure and substructure response.

Table 4. Comparisons of spring stiffness (kN/mm)

Trial	Centre columns	Edge columns	Corner columns
Fixed base	39.88	32.85	29.48
Trial-1 38.46		33.71	32.17
Trial-2	38.19	33.85	32.57
Trial-3	38.13	33.88	32.63
Trial-4	38.12	33.89	32.65

The analysis shows that the spring stiffness for the corner columns increased by around 10% whereas, the center columns decreased by as much as 5% and the side columns were not affected much. The base reaction was significantly affected by the change in support. The base reaction for corner columns increased as much as 24% by the introduction of springs in the support instead of fixed support which is concerning. The side columns were least affected by conversion of fixed base to flexible base. The base reaction for corner column also increased by 15%.

4. CONCLUSION

The purpose of this study was to understand the behavior of soil under both fixed base systems and flexible base systems and to find a state-of-the-art solution to analyze mat foundation systems. The new approach to analyzing the mat foundation can be more accurate and efficient at the same time. The settlement in both the soil model and the spring model converged. The maximum settlement in the flexible foundation was reduced to 60 mm from 68 mm, which is not very much. The main concern, however, is the differential settlement, which could be eliminated by knowing the exact settlement from FEM. The change in base reaction was drastic in the flexible base system compared to the fixed base system. In some cases, there would be under design of mat foundation systems if the conventional fixed base system was used. Because the settlement was nearly the same in both models, the spring stiffness changed as the base reaction changed. Again, there would be under design in the mat foundation if a fixed base was to be used in the foundation system. The superstructure's elements' behavior also changed by changing the base system. When the base is changed to flexible, some elements experience increased moment or a reverse in moment direction, or both. This is a big concern, and more study must be done in the future to understand more about the superstructure's elements' behavior under a flexible base system.

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