GEOMETRICAL EFFECT ON THE BEHAVIOUR OF EMBANKMENT ON SOFT GROUND

ALI SOBHANMANESH

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To my lovely wife, your courage and compassion have taught me humility

To my beloved parents

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ABSTRACT

Many embankments constructed on soft ground are susceptible to failure and large settlements due to its low strength soil condition. Geosynthetics are used effectively as a reinforced material to increase the shear strength, and stiffness of the reinforced embankment and consequently, to reduce the total and differential settlements. In the first part of the study, four different cases of embankments with and without reinforcement, constructed on soft and stiff grounds were studied through small-scale physical modeling using centrifuge test and numerical modeling using finite element simulation. Comparison between the results using both finite element models and centrifuge tests was carried out to validate and identifies the reliability of the finite element method. In centrifuge test, a model scale with various sizes was simulated to a constant full-scale dimension using different acceleration fields. The results show the different deformation behavior for these different embankment cases and indicate the significant effect of the geosynthetics reinforcement on increasing the stability of embankment. The comparison analysis presents a good agreement between results of these two methods. It validated the finite element technique in analysis of different embankment cases. The second part of the study focus on the geometrical effects on the behavior and failure mechanism of embankments. Two full-scale case history embankments in Malaysia and Canada, the Muar trial embankment and Vernon highway embankment were verified. Three dimensional effects on Muar trial embankment were evaluated by comparing the results of two and three-dimensional analysis, in terms of predicted displacements, lateral movements, excess pore pressure, factor of safety, and failure height of the embankment fill. Moreover, this study attempt to evaluate the boundary limits for the applicability of two and three-dimensional analyses by determining the suitable geometry configuration of embankment in utilizing the geotechnical analysis. The ratio of the calculated failure height of three to two dimensional Finite Element analyses ($H_{f,3D}/H_{f,2D}$) has been determine for embankment cases with different base aspect ratio of the length to width (L/B). Two shape-factor equations related to the bearing capacity of spread footings and safety factor of embankments also utilized to account for the geometrical behavior of the embankment regards to its geometrical configuration. Results of three-dimensional analyses have better agreement with the actual field measurements. It is concluded that neglecting the three dimensional effects could mislead the design of the embankment in some condition. In conclusion, it is recommended that for "long embankment" with the length to width ratio more than two ($L/B > 2$), it may appropriate to use two-dimensional analysis as the three-dimensional safety factor converges to two dimensional safety factor. For "short embankment" with the length to width ratio less than two ($L/B < 2$), three dimensional effects on the embankment behavior becomes considerably great and should be considered as important factor in design and analysis of embankments.

ABSTRAK

Kebanyakan tambakan yang di bina di atas tanah liat lembut terdedah kepada Kebanyakan benteng yang dibina di atas tanah lembut terdedah kepada kegagalan dan enapan besar disebabkan keadaan tanah mempunyai nilai kekuatan yang rendah. Geosintetik digunakan dengan berkesan sebagai bahan pemgukuh untuk meningkatkan kekuatan ricih, dan kekukuhan benteng bertetulang dan seterusnya, untuk mengurangkan enapan jumlah dan perbezaan. Dalam bahagian pertama kajian ini, empat kes benteng yang berbeza iaitu dengan dan tanpa menggunakan tetulang,yang dibina atas tanah dasar lembut dan tegar telah dikaji menggunakan model fizikal berskala kecil melalui ujian centrifuge dan model berangka menggunakan simulasi unsur terhingga. Perbandingan diantara keputusan menggunakan kedua-dua model unsur terhingga dan ujian centrifuge telah dijalankan untuk mengesahkan dan mengenal pasti kebolehpercayaan kaedah unsur terhingga. Dalam ujian centrifuge, skala model dengan pelbagai saiz telah disimulasikan kepada dimensi sebenar yang tetap menggunakan medan pecutan yang berbeza. Keputusan menunjukkan berlaku kelakuan ubah bentuk yang berlainan bagi kes-kes tambak yang berbeza dan menunjukkan kesan yang ketara terhadap tetulang geosyntheic di dalam peningkatan kestabilan benteng. Analisis perbandingan menunjukkan hubungan yang baik di antara keputusan kedua-dua kaedah. Ini mengesahkan penggunaan teknik unsur terhingga dalam analisis untuk kes benteng yang berbeza. Bahagian kedua kajian ini memberi tumpuan kepada kesan geometri terhadap tingkah laku dan kegagalan mekanisme benteng. Dua kes benteng berskala penuh di Malaysia dan Kanada, Benteng Percubaan Muar dan Benteng Lebuh Raya Vernon telah disahkan. Kesan tiga dimensi di Benteng Percubaan Muar dinilai dengan membandingkan hasil analisis dua dan tiga dimensi, dari segi anjakan, ramalan pergerakan sisi, tekanan liang berlebihan, faktor keselamatan, dan ketinggian kegagalan benteng. Selain itu, kajian ini telah menilai had sempadan yang sesuai untuk analisis dua dan tiga dimensi dengan menentukan konfigurasi geometri benteng yang sesuai dalam menggunakan analisis geoteknikal. Nisbah ketinggian kegagalan yang dikira menggunakan dua dan tiga dimensi analisis Unsur Terhingga ($H_{f,3D}$ / $H_{f, 2D}$) telah ditentukan melalui kes-kes banteng yang mempunyai nisbah yang berbeza untuk aspek asas panjang dan lebar (L / B). Dua persamaan faktor bentuk yang berkaitan dengan keupayaan galas asas dan faktor keselamatan benteng digunakan untuk mengambil kira kelakuan geometri benteng terhadap konfigurasi geometri itu. Keputusan analisis tiga dimensi mempunyai kesamaan yang lebih baik dengan ukuran sebenar di tapak. Ia menyimpulkan bahawa dengan mengabaikan kesan tiga dimensi, boleh mengelirukan reka bentuk benteng dalam beberapa keadaan. Kesimpulannya, adalah disyorkan bahawa untuk "benteng panjang" dengan nisbah panjang ke lebar lebih daripada dua (L / B> 2), ia boleh memperuntukkan untuk menggunakan dua analisis dimensi kerana faktor keselamatan tiga dimensi menumpu kepada faktor keselamatan dua dimensi. Untuk "benteng pendek" dengan panjang ke lebar nisbah kurang daripada dua (L / B <2), kesan tiga dimensi ke atas tingkah laku benteng menjadi agak besar dan boleh dianggap sebagai faktor penting dalam reka bentuk dan analisis benteng.

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LIST OF SYMBOLS

A_m	-	Local acceleration of model
A_r	-	Radial acceleration
B	-	Width of embankment
C	-	Cohesion of the soil
C_a	-	Adhesion of the soil to the geosynthetic
C_v	-	Coefficient of uniformity
c, $\bar{c}$	-	Total and effective cohesions, respectively
D	-	Diameter of footing
DR	-	Thickness of failed region
d_g	-	Average grain size
E	-	Shear, or frictional, efficiency of geosynthetic to soil
E_g	-	Coefficient of elasticity of grain material
e	-	Void ratio
FS	-	Factor of safety
F_r	-	Number of revolution per unit time
H	-	Embankment height
H_{allow}	-	Allowable height of embankment

Hf	-	Failure height of embankment
H_m	-	Height of model
H_p	-	Height of prototype
h_i	-	Height of water above base of circle for each slice
K_a	-	Coefficient of active earth pressure = $\tan^2 (45 - \phi /2)$
k_x	-	Horizontal Permeability
k_y	-	Vertical Permeability
L_{arc}	-	Length of the failure arc
L_m	-	Length dimensions in the model; Suffix m = model
L_p	-	Length dimensions in the prototype; p = prototype
L_{reqd}	-	Required anchorage length behind the slip plane
m	-	Number of geotextile layers
n	-	Number of slices
N	-	Scale factor or gravity level
N_c	-	Bearing capacity factor
N_i	-	$W_i \cos \theta_i$
$\overline{N}_i$	-	$N_i - u_i \Delta x_i$, in which
Pa	-	Rankine active pressure
q_{allow}	-	Allowable bearing capacity
q_u	-	Unconfined compression strength of soil
R	-	Radius of the failure circle

R_a	-	Radius of rotating arm
S	-	Distance travel along circular path
T_{act}	-	Actual stress in the geosynthetic
T_i	-	Allowable tensile strength of various geotextile layers
T_v	-	Consolidation time factor
t	-	Time travel
t_m	-	Model time
t_p	-	Prototype time
V	-	Vertical external load
V_r	-	Radial velocity
V_s	-	Volume of sand
u_i	-	$h_i \gamma_w$ = pore-water pressure
W	-	Weight of failure zone
W_i, $\overline{W}_i$	-	Total and effective weight of each slice
X	-	Moment arm to center of gravity of failure zone
y_i	-	Moment arm of geotextile layers
γ	-	Unit weight of embankment soil
γ_m	-	Model unit weight
γ_p	-	Prototype unit weight
γ_w	-	Unit weight of water
$\overline{\square}$	-	Artificial gravity induced by centrifugal forces

θ	-	Angle of pile inclination/about center of rotation
θ_i	-	Angle of intersection of horizontal to tangent at center of slice
Δl_i	-	Arc length of each slice
Δx_i	-	Width of slices
ϕ	-	Friction angle of the soil
ϕ, $\bar{\phi}$	-	Total and effective angles of shearing resistance, respectively
σ_c	-	Cohesive force between sand grain
σ_g	-	Crushing strength of grain materials
σ_v	-	Average vertical stress = γH
σ_{vm}	-	Model vertical stress
σ_{vp}	-	Prototype vertical stress
δ	-	Friction angle of the soil to the geosynthetic
δ_{req}	-	Required friction angle of geosynthetic to soil
ε	-	Maximum error developed in centrifugal machine
ρ	-	Soil density
ω	-	Angular velocity

LIST OF ABBREVIATIONS

ASTM	-	American Standard Testing Method
BIS	-	Bureau of Indian Standards
BS	-	British Standard
BSI	-	British Standards Institution
CRE	-	Constant Rate of Extension
CSPE	-	Chlorosulfonated Polyethylene
CU	-	Consolidated Undrained
EPS	-	Expanded Polystyrene
EPWP	-	Excess Pore Water Pressure
FD	-	Finite-Difference
FE	-	Finite Element
H_F	-	Failure Height
HDPE	-	High Density Polyethylene
ISO	-	International Organization for Standardization
LCD	-	Liquid Crystal Display
LDPE	-	Low Density Polyethylene
LL	-	Liquid Limit
LVDT	-	Linear Variable Different Transducer
MC	-	Mohr-Coloumb
MHA	-	Malaysian Highway Authority
PA	-	Polyamide
PET	-	Poly- Ester

PI	-	Plasticity Index
PL	-	Plastic Limit
PP	-	Polypropylene
PVC	-	Polyvinyl Chloride
PRC	-	People Republic of China
UK	-	United Kingdom
UKM	-	Universiti Kebangsaan Malaysia
ULS	-	Ultimate Limit State
USA	-	United States of America
UTM	-	Universiti Teknologi Malaysia
SS	-	Soft Soil Constitutive Model
2-D	-	Two-dimensional
3-D	-	Three-dimensional

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Embankments are needed in construction of many industrial structures. Today, a large number of industrial structures and embankments are constructed in areas with low strength grounds such as harbor and river inlets zones. Many embankments constructed on such soft grounds are susceptible to failure and large settlements due to the incompatible weak condition of the ground soil.

Many conventional methods and ground improvement techniques have been used in the past to increase the shear strength of the soft soils. In the conventional method of construction, the soft soil is replaced by a suitable soil or it is improved by preloading, dynamic consolidation, injected additives, lime/cement mixing or grouting prior to the placement of the embankment. Other options such as staged construction with sand drains, the use of stabilizing berms and piled foundations are also available for application. All of these methods have a degree of applicability, but it is clear all suffer from being either expensive, time-consuming, or both. Hence an alternative method such as soil reinforcing by geosynthetics materials, which is a fast and economical technique, could cope with this problem to some extent.

The utilizing of geosynthetics as ground reinforcement has enhanced the concept of ground improvement and being used for a wide range of applications e.g. slope stabilization, construction of retaining structures, bridge abutment walls and embankments. As a deformable material, geosynthetics have the effect of not only increasing the strength and ductility of soil, but also creating a more flexible structure. In the construction of geosynthetic reinforced soil structures, successive layers of free draining soil are compacted between sheets of reinforcement. This procedure results in a stable composite structure that can extend to significant height. Such structures can undergo fairly large deformation without catastrophic collapse and often without their serviceability be affected. From a mechanical standpoint, reinforcing soil provide the benefit of stiffening earthwork structures without increasing their mass.

The other important issue in designing and analyzing of the embankment construction on soft ground is to consider the correct behavior of embankment and define all possible failure mechanisms. The behavior of embankments is originally three-dimensional (3-D) but in many cases two-dimensional (2-D) analysis can give an acceptable and reasonable results. In general, two-dimensional (2-D) analysis can be categorized into two types: (1) 2-D plane stress which is usually applied for stress analysis of thin plate structure by assuming the stress in the direction perpendicular to the plate is equal to zero and (2) 2-D plane strain which is defined as the strain state in the direction perpendicular to the plane is equal to zero. Most researches assumed plane strain condition for numerical simulations of reinforced earth structures.

1.2 Statement of Problem

There are many problems and issues concerning the modeling and analyzing of reinforced embankment on soft ground as described in following:

1.2.1 Problems related to reinforcement mechanism

There are many factors that affect the mechanism and behavior of geosynthetic reinforced soil / embankment, but the most important ones are:

- Characteristics of soil
- Characteristics of geosynthetic reinforcement
- Interaction between soil and reinforcement

In construction of embankments, the characteristics of soil are very important and have a significant influence on stability and failure height of embankment. If the soil has weak geotechnical characteristics (soft soil), it causes many limitations and problems, i.e. the weak shear strength of soil considerably reduces and limits the height of embankment fill and the deformability, compressibility and low permeability of soil induce excessive settlements because of developing of excess pore water pressure due to construction of embankment on such a compressible soils. The characteristics of geosynthetics also have a great influence on behavior of the model. With regards to the characteristics of geosynthetic reinforcements, different reinforcement mechanisms e.g. membrane type, shear type, and anchorage (pull-out) type should be considered. Moreover, soil–geosynthetics interface plays an important role in the reinforced structures.

Aforementioned factors have been studied by many researchers but despite the large number of experiences related with using geosynthetics to enhance the stability of embankments and other geotechnical projects, the reinforcement mechanisms and its interaction with the adjacent soil are not completely well-defined. Analytical analyses based on failure modes are simplified and do not provide an integrated picture of stress-strain and deformation behavior of the complete system. The mechanism of load transferring among different elements, includes embankment fill, foundation soil, reinforcement and soil-reinforcement interaction is complex and is influenced by the properties of the individual elements as well as the relative magnitudes of the properties with respect to each other (Varadarajan, 1999).

1.2.2 Problems concerning the modeling of embankment

As mentioned before, analytical methods cannot furnish a comprehensive mechanism of reinforced embankment system on soft ground. Therefore other methods of modeling such as physical modeling by means of full-scale or small-scale (centrifuge test) modeling and numerical modeling by means of finite element (FE) or finite difference simulations are needed to give a deeper insight of the behavior of these structures. Due to economical and time concerns, centrifuge test is considered as a preferable technique in physical modeling but there are many factors that affect the behavior of embankment in a centrifuge test, which makes some errors and differences compare to the results of the prototype. These factors are:

- Radial gravity of centrifuge tests
- Different geometry of embankment in each stage of construction due to the different gravitational acceleration field
- Interaction between the side wall of the model box and the model
- Limitation payload capacity of centrifuge apparatus

In numerical simulation of centrifuge test, most of researchers have considered FE simulations based on prototype full-scale dimensions without considering the above factors. Therefore, numerical simulations utilizing small-scale dimensions of centrifugal models with considering the above factors are essential for a realistic comparison between the numerical results and centrifugal measurements and to minimize the differences between these two modeling methods.

1.2.3 Problems concerning the geometrical behavior of embankment

The other issue that should be considered as the most important factor that affects the analysis of embankments is geometrical effects (2-D and 3-D behavior) of embankment. Generally, as a simple and quick approach, most researchers have assumed two-dimensional (2-D) plane strain condition, while there can be a difference between the assumption shape of the failure surface in 2-D and 3-D analysis. As shown in Figure 1.1, for 2-D analysis an infinite cylindrical surface is considered while for 3-D analysis a finite curved surface is assumed which is closer to the actual failure surface in many cases. Consequently, direction of maximum stress and sliding of soil can not be recognized by 2-D analysis in some cases, which leads to inaccurate design of embankments on soft grounds.

Usually in the factor of safety approach, with a few exceptions, two-dimensional analysis yields conservative results compared to three-dimensional analysis ($FS_{2D} < FS_{3D}$), while with increasing width of the failing soil wedge assumed in a 3-D analysis, FS_{3D} converges to FS_{2D}.

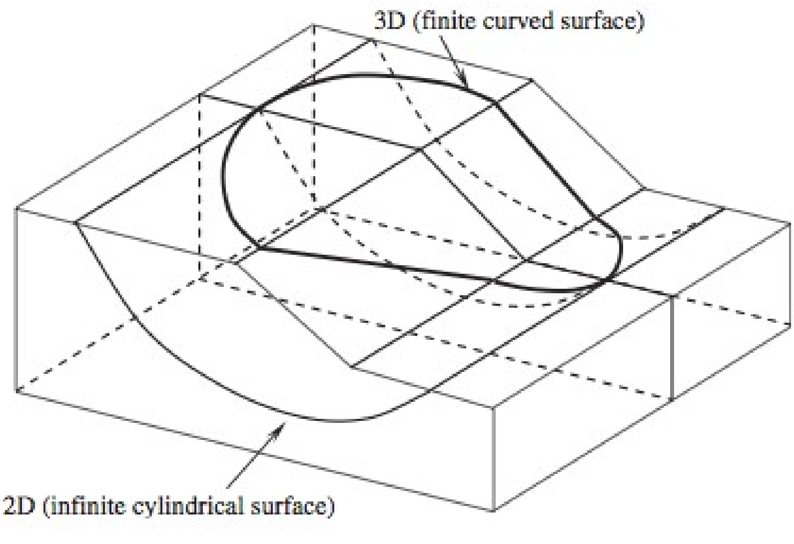

Figure 1.1 Assumption shape of the failure surface in 2-D and 3-D analysis

Based on above explanations, it can be conclude that, 2-D analysis can give proper results in *linear fill* cases (long embankments) in which the length of the fill is much larger than the width such as roadway embankments, while gives a conservative and less accurate results compare to 3-D analysis in a *area fill* (short embankment) in which the length and width of the site are approximately equal. Therefore, define a proper behavior of embankment based on its geometrical aspects is very important in analysis of such structures. Moreover, 3-D analysis has been rarely considered in previous works and researches and the field is still open for further studies of 3-D behavior and geometrical effects on behavior of embankments on soft ground.

1.3 Objectives of Study

The major aim of this thesis is evaluation of geometrical effects on the behavior and failure mechanism of embankment and to define that under what geometry configuration, the failure mechanism is three-dimensional.

In order to attain aims of this thesis, following objectives had been fulfilled:

1. To determine the influence of important parameters on the deformation behavior and failure mechanism of embankment.

2. To evaluate the geometrical (3-D) effects on deformation behavior and failure mechanism of embankment on soft ground.

3. To define the suitable geometry configuration of embankment, for utilizing in geotechnical analysis (2-D or 3-D analysis).

4. To perform numerical modeling, utilizing small-scale centrifugal model dimensions and considering important factors of centrifuge test in FE simulation.

1.4 Scopes of Study

This thesis is divided in two parts: The first part deals with the evaluation of important factors on the behavior of reinforced embankments by physical (small-scale centrifuge tests) and numerical modeling (finite element simulation) of assumed cases. The second part describes the geometrical behavior and 3-D effects on behavior of embankments by FE simulation of case-history embankments. The scope of this research comprised of different types of geotechnical modeling and analysis with considering different materials in order to achieve the objectives of this study. Following scopes and limitations had been covered:

1. Hypothetical analysis of initial embankment model on soft ground was performed based on limit equilibrium analysis of different failure elements (e.g., bearing capacity analysis, global stability analysis, elastic deformation analysis, pull-out or anchorage analysis, lateral spreading analysis).

2. Four cases of embankment models based on different type of foundation soil and reinforcement condition were considered in centrifuge test and finite element analysis. Moreover, two case-history embankments namely 'Muar trial embankment and Vernon highway embankment' were considered in parametric and geometric analyses.

3. In modeling of four embankment cases, Kaolinite and compacted sand were used as soft and stiff foundations respectively. Clayey-sand was utilize as embankment fill material and a proper textile was considered as a reinforcement material. These materials were considered based on the available compatible materials regards to the models of this study.

4. Geotechnical laboratory tests were performed to define the properties of materials of the study. These tests include direct shear test, compaction (proctor) test, mini-vane shear test and tensile strength test. The characteristics and properties of case-history embankments considered based on the previous works of other researchers on these embankments.

5. Small-scale physical modeling by means of centrifuge test was performed in a mini-centrifuge apparatus of Universiti Kebangsaan Malaysia (UKM). This apparatus did not enable a comprehensive quantitative study of the models due to its small capacity and payload limitation, which affected the results of this study. The small size of the strongbox makes it possible to study a small embankment model with a fill slope of 1:1 only and limited boundary conditions. Furthermore, It did not equipped with necessary measurement sensors, transducers, cells and gauges. Finally, the effect of step loading cannot be studied completely, because in-fight loading was not possible with this apparatus.

6. Numerical modeling by means of two-dimensional (2-D) and three-dimensional (3-D) finite element simulation were carried out. "PLAXIS 2-D" and "PLAXIS 3-D FOUNDATION" programs were used for finite element simulation and analysis.

7. 2-D and 3-D parametric and geometric analyses were performed on considered cases and two full-scale case-history embankments.

1.5 Research Significances

The weak and compressible condition of soft ground leads to embankment failure and collapse, which cause wasting of budget, time and consequences in stopping or postponing the project. Therefore, the study of the construction of embankments on compressible soft soils has been a frequent task for geotechnical engineers all over the world and considering a proper and developed method of designing and analyzing of embankments on soft ground is very important and necessary.

Totally, utilizing the 2-D plane strain analysis seems to be conservative in some cases, which result in inaccurate strength of subsoil foundations. This can lead to an inappropriate designs of embankment over soft ground and cause catastrophic failure and collapse. To deal with this issue, three-dimensional analysis is essential and significant to evaluate the influence of geometric conditions and investigate the 3-D effect on deformation behavior and failure mechanism of embankments on soft grounds. Considering 3-D effect especially in analyzing the short embankments can contribute in increasing the stability of work by giving more accurate and realistic results.

Moreover, the parametric study of this research can give a better insight to the researchers and engineers about the influence of important variables on the deformations and displacements of embankment in two and three-dimensional (2-D and 3-D) analyses.

Finally, The results of this research study can be a useful guidance for engineers in actual and industrial field of embankment construction. It shows the proper method of deign and analysis (2-D or 3-D analysis) based on the basal aspect ratio of length to width (L/B) of embankment.

1.6 Thesis Organization

Chapter 1 presents an introduction of thesis research about construction of embankments on soft grounds, including background of the research, statement of problems, aim and objectives of study, scopes of study and significance of this research.

Chapter 2 gives a review of construction of embankment on soft ground, reinforcing the embankments by geosynthetics, 2-D and 3-D failure mechanism, geotechnical modeling and their application in analyzing the embankments e.g analytical, physical and numerical modeling and finally an overview of some case-history embankments built to failure in Malaysia and Canada.

Chapter 3 explains the methods and technics that used in this research to fulfill the objectives of study include geotechnical laboratory test methods, small-scale physical centrifuge test and numerical finite element simulation and analyses for different embankment case models.

Chapter 4 present and discuses the results obtained from physical and numerical modeling and analysis for various case embankments with different shear strength of foundation and reinforcement condition and to compare these results to validate the finite element analysis.

Chapter 5 describes the results obtained from 2-D and 3-D geometric and parametric analyses of two full-scale case-study embankments to investigate the 3-D effect and compare the 2-D and 3-D results.

Chapter 6 depicts useful conclusions based on results of this research study especially on utilizing the three-dimensional analysis in construction of embankments on soft grounds. Moreover, this chapter provides recommendations for further research works.

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