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STABILITY ANALYSIS OF SLOPES IN HUNGARY

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MSc in Civil Engineering

PhD thesis

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1. INTRODUCTION

Due to natural characteristics, the slopes of hillsides in Hungary provide a major part of land available for utilisation and are frequently used as building sites. Activities reshaping nature keep increasing in scale and there is a growing need to adapt new areas to what is considered to be economical for utilisation, which entails cutting deeper and deeper into and building higher and higher embankments on sites located in hilly or mountainous terrain. To guarantee the safety and durability of man made objects is a high priority for engineers and calculating safe slope stability to satisfy the principle of reliability in dimensioning is one of the nicest and most complex jobs in earth sciences.

Shallow earth movements below the surface may arise without human intervention as the surface keeps changing due to natural forces and the impacts of weather. The recurring damage to the high bank areas along the Danube and Lake Balaton indicate how topical this issue is as such damage also tends to occur without human intervention, but human activity undoubtedly contributes to accelerating the formation and increasing the size of such phenomena.

Safe stability and failure probability play an important role particularly as regards slippages on flood protection dikes where preventing failure entails temporary action to ensure the stability of a dike whilst dike failure leads to the rapid inundation of the flood area.

The specifically high incidence of slope damage in 2010 and 2011 is clearly owing to above average rainfall in a period of close to eighteen months after autumn 2009. After that period of high precipitation earth movements were not restricted to areas with recognised propensity to show surface movements as unexplored and unresearched areas also became active.

Image 1: Formation of a slip surface at a high and low surface location (Sőtér Promenade, Kulcs, March 2011)

Civil engineers have duties at various levels with regard to surface movements: failures demand immediate intervention, restoration must start after the prevention of additional direct damage (so as to limit the size of the area affected by movement) and the development of procedures and methods with a sharp focus on prevention dominate calmer periods.

2. OBJECTIVES AND STRUCTURE OF THE DISSERTATION

2.1. Justification of topic selection and objectives

In addition to the current problem mentioned in the introductory, this dissertation aims to present the phenomena that arise in the course of slope stability problems and near-surface earth movements, to develop geotechnical evaluation methods and to promote the accuracy of calculating the safety factor and failure probability. Knowing these constituents can render the prevention of such phenomena and restoration if they do materialise less costly and more efficient.

Promoting the wide-spread use of geo-statistical methods is a long term goal. That includes (*inter alia*) the development of testing methodology for laboratory application and motivating the development of laboratory accreditation procedures in Hungary by development steps such as promoting the accuracy of evaluation methods or broadening the scope of ring trials to cover the determination of shear strength.

2.2. Composition of the dissertation

This dissertation elaborates five topics relating to the calculation of the stability of slopes and banks and their application in Hungary in five independent chapters:

- presentation of soil properties with statistical methods and recommending a new method of evaluation;
- an analysis and finite element modelling of the surface manifestation of slip surfaces based on layer slippages observed in Hungary;
- calculation of a slope of infinite length with granular soil using the principle of reliability;
- testing the stability of slopes reinforced with vegetation; and
- examining the additive features of the factor of safety.

Research methods are discussed separately in each chapter. Chapter 10 of the dissertation (Chapter 3 of the booklet of theses) provides a summary of elaborated theses. The thesis points of the dissertation are complete with references to papers containing my publication of my research findings collected separately from reference literature. The dissertation categorises calculations details, a description of finite element modelling and the related figures and images in appendices.

3. SCIENTIFIC FINDINGS OF THE DISSERTATION, THESES

Thesis No. 1

I recommend the application of a new method for determining the characteristic value of non-independent soil properties (tgφ' and c') for use in the statistical processing of direct shear test findings.

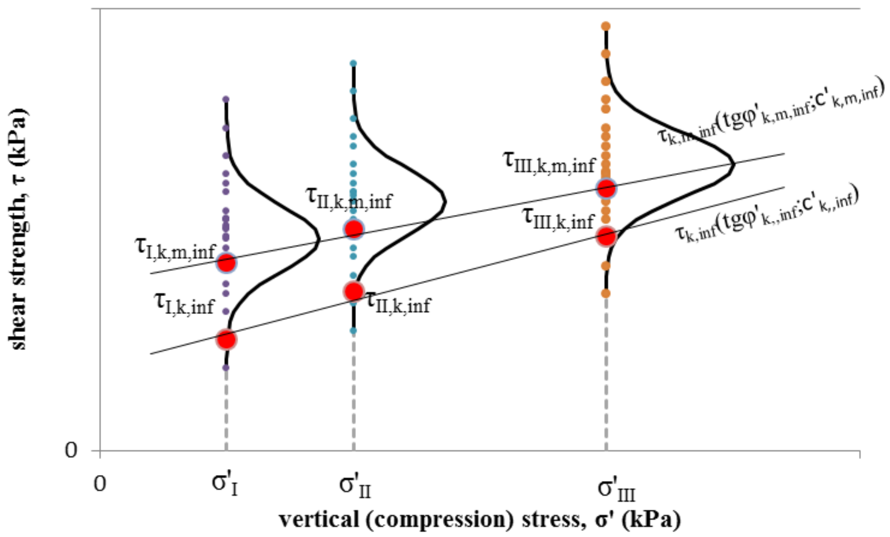

Figure 1: Principle of the method developed to determine the characteristic value of non-independent soil properties

Instead of performing statistical processing separately of the shear strength parameters (φ' or) tgφ' and c' established by tests, the evaluation proceeds (Fig. 1) as follows:

- **first, we determine the characteristic values (e.g. the average and extreme values of $\tau_{I,k,m,inf}$ and $\tau_{I,k,inf}$ a τ_I) from the shear strength values associated with compressive stresses,**
- **the angular coefficient and the axial section of the straight lines ($\tau_{k,m,inf}$ and $\tau_{k,inf}$) fitted to connect the points determined that way provide the characteristic values of shear strength properties (for the average values $tg\varphi_{k.m.inf}$ and $c_{k.m.inf}$; and for the extremes $tg\varphi_{k.inf}$ and $c_{k.inf}$).**

My comparison of the two methods showed that compared to the independent processing of shear strength parameters, the recommended method:

- offers stronger compliance with the approach to geotechnical design and the spirit of Eurocode;
- tends to yield higher values when calculating low characteristic values (for the estimation of both lower average and lower extreme values)

Publications related to the thesis: Kádár-Nagy-Takács (2010), Takács (2009, 2010, 2011, 2012a)

Thesis No. 2

An analysis of sliding blocks that occurred along the surface of Pannon clay in recent years I studied the findings of finite element stability tests performed in 18 sections at 10 sites and found with respect to the geometric position of the slip surface that:

- **the lower cut-out of the slip surface can be estimated accurately from soil stratification, slope geometry and the presence of ground (subsurface) water;**
- **the failures that occurred showed that the lower cut-out of the slip surface develops at a location which is easy to identify (.e.g. the toe of a bank, in a ditch) (except for sites where the difference between the weak plane and the line of the terrain is only a few degrees;**
- **stability tests based on detailed surveys can only provide approximations of the top cut-out of the slip surface;**
- **the failures that occurred suggest that the top cut-out of slip surfaces develops along several lines but mostly with a time delay due to the spatial variety of soils and secondary shifts.**

Publications related to the thesis: Farkas and Takács (2006a, 2010), Takács and Farkas (2010, 2012)

Thesis No. 3

I studied slope stability using traditional deterministic calculations and calculations based on the reliability principle by taking into account the following boundary parameters:

- slopes containing granular soil;
- slopes of infinite length;
- failure on planar slip surfaces.

I studied the accuracy of determining input data for each calculation and the effect of ignoring them.

Thesis No. 3.1

I have ascertained that using the characteristic value in the calculation yields a larger probability of failure by applying the safety factor k=1.35 than using soil property averages and the central safety factor k_c=1.5 for the purposes of the calculation. Applying Eurocode 7 (Hungarian national appendix) provides a higher degree of safety than the earlier calculation method.

Thesis No. 3.2

Performing calculations to show the relationship between the safety factor and failure probability, I found that the coefficient of variation of internal friction angle may not be omitted from dimensioning calculations as doing so would have a material impact on the result (Fig. 2).

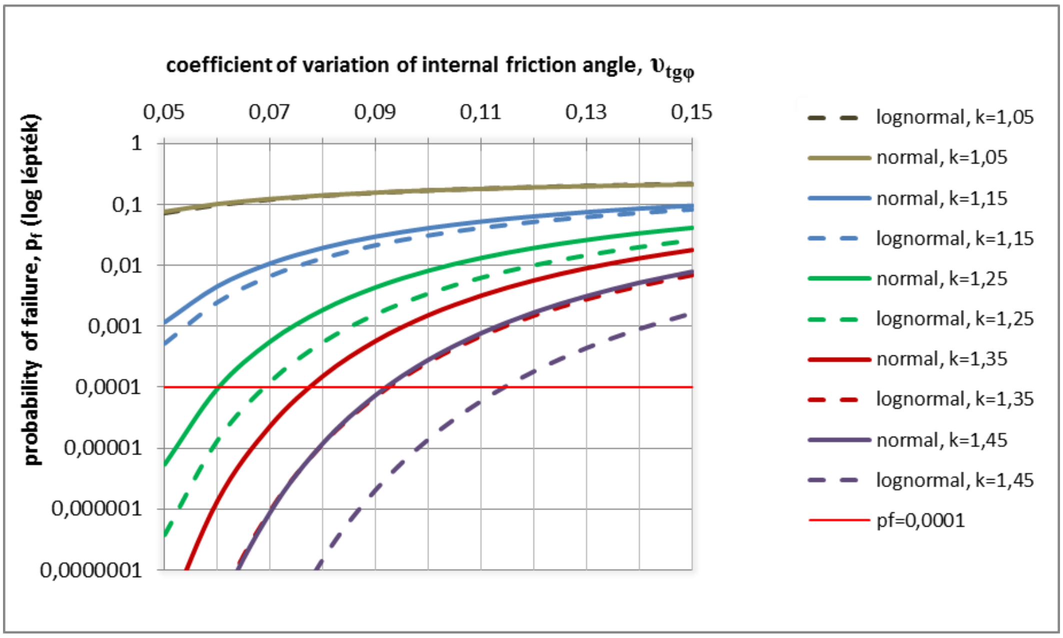

Figure 2: The relationship between the coefficient of variation of internal friction angle ($\nu_{tg\varphi}$) and the failure probability of slopes of indefinite length and granular soil (p_f) (assuming $\nu_{tg\alpha}=0$)

The type of distribution selected to describe the distribution of a specific soil property for the purposes of calculating failure probability is not indifferent. I have found that the failure probability associated with normal distribution is higher than the value specified for lognormal distribution in this theoretical exercise, except for safety factors close to k=1. On that basis I recommend that whenever choosing between the two distributions is uncertain, normal distribution should be selected for calculation purposes.

Thesis No. 3.3

I have shown that the maximum value the coefficient of variation of internal friction angle ($\nu_{tg\varphi}$) associated with the probability of failure $p_f \leq 10^{-4}$ (with the reliability index at $\beta \geq 3.72$) and the required safety factor at k=1.35 is 0.08 for normal distribution and 0.09 for lognormal distribution (Fig. 3). As regards these values, I have also shown that the maximum value the coefficient of variation of internal friction angle ($\nu_{tg\varphi}$) associated with the probability of failure $p_f \leq 10^{-3}$ (with the reliability index at $\beta \geq 3.09$) and the required safety factor at k=1.35 is 0.095 for normal distribution and 0.114 for lognormal distribution.

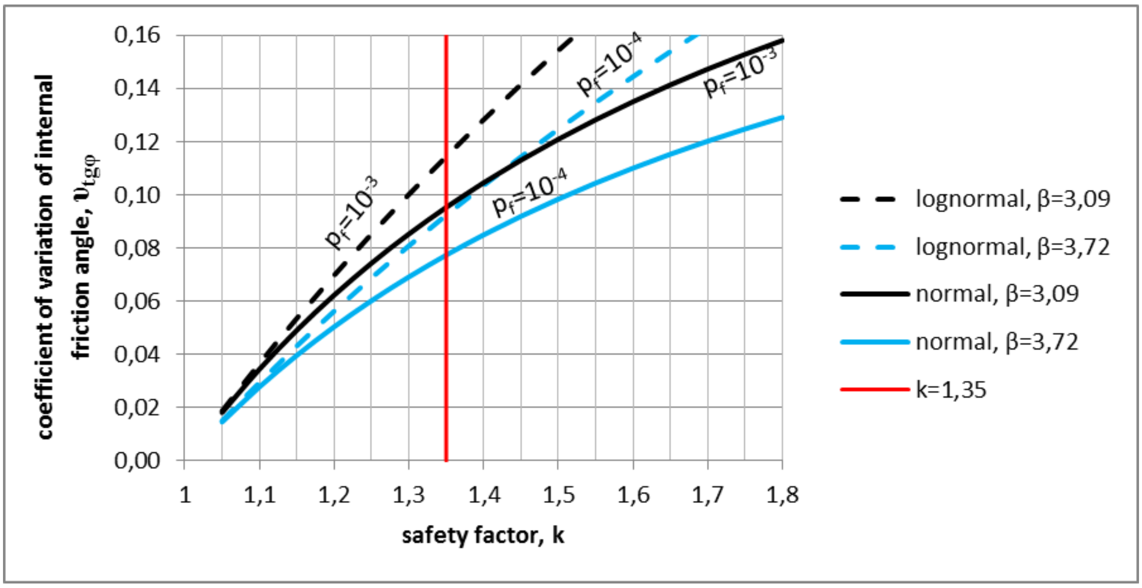

Figure 3: The maximum value of the coefficient of variation of internal friction angle ($\nu_{tg\alpha}=0$) in the safety factor function with different probabilities of failure ($p_f=10^{-4}$ and $p_f=10^{-3}$)

A series of tests performed to determine the angle of internal friction for granular types of soil seems to indicate that there is no problem with the shortfall of the coefficient of variation associated with the aforementioned probabilities of failure $p_f \leq 10^{-4}$and $p_f \leq 10^{-3}$.

Thesis No. 3.4

Taking both the coefficient of variation of internal friction angle and of the ratio of slope into account and assuming normal distribution for both variables, I have found (Fig. 4) that the maximum of the coefficient of variation of internal friction angle and the maximum of the ratio of slope may be determined using the following approximation:

$$\frac{\nu_{tg\varphi}^2}{a^2} + \frac{\nu_{tg\alpha}^2}{b^2} \leq 1.$$

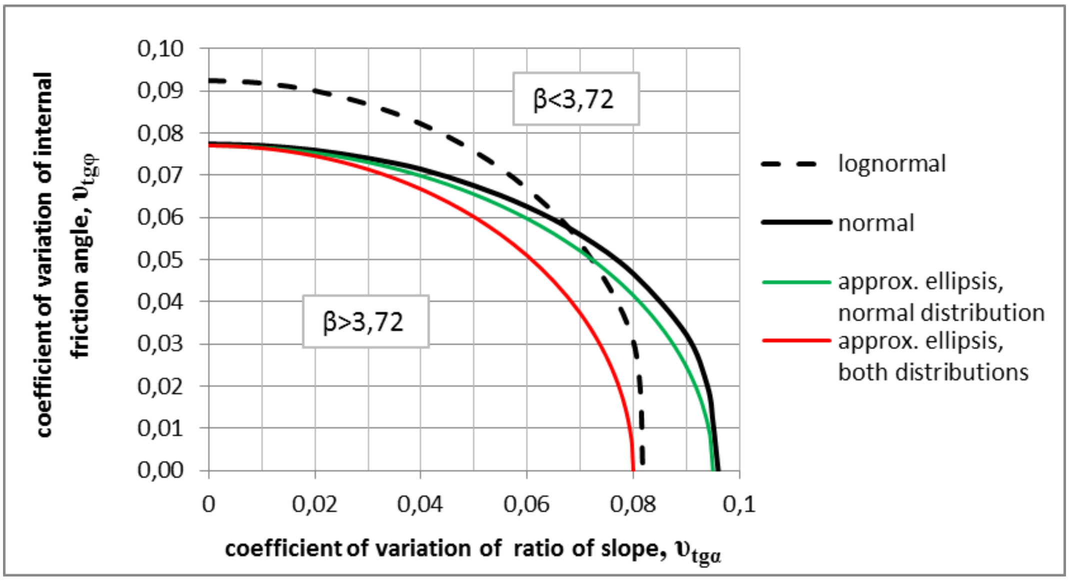

Figure 4: The maximum value of the coefficient of variation of internal friction angle (νtgα=0) in the safety factor function of the load bearing side with the safety factor (k=1.35) and the probability of failure ($p_f=10^{-4}$) given

That is to say, if the two variants are described in an orthogonal system of coordinates, the points satisfying inequality are located inside an ellipsis with a centre point at the origin of coordinates. If the respective values of ($\nu_{tg\varphi}$) and ($\nu_{tg\alpha}$) are larger than allowed, then there are two courses of action: increase the number of tested samples, or divide the layer if variations follow some rule.

The constant values in this exercise are a=0.08 and b=0.077.

If, however, the coefficient of variation of the ratio of slope is zero ($\nu_{tg\alpha} = 0$), then we get the method of calculation shown in Thesis 3.3.

Publications related to the thesis: Nagy and Takács (2012b, 2012c)

Thesis No. 4

I have prepared comparative tests using the finite element method to analyse the effect of vegetation on soil reinforcement and modelled the roots of vegetation and root cohesion (c_r).

Thesis No. 4.1

I have demonstrated that whenever root cohesion exists the safety factor tends to increase up to a marginal depth, over which the safety factor remains unchanged even if the root zone is thicker.

I have found that the marginal depth in granular soils up to which root cohesion couples with higher safety factor values shows a straight line relationship to root cohesion (Fig. 5).

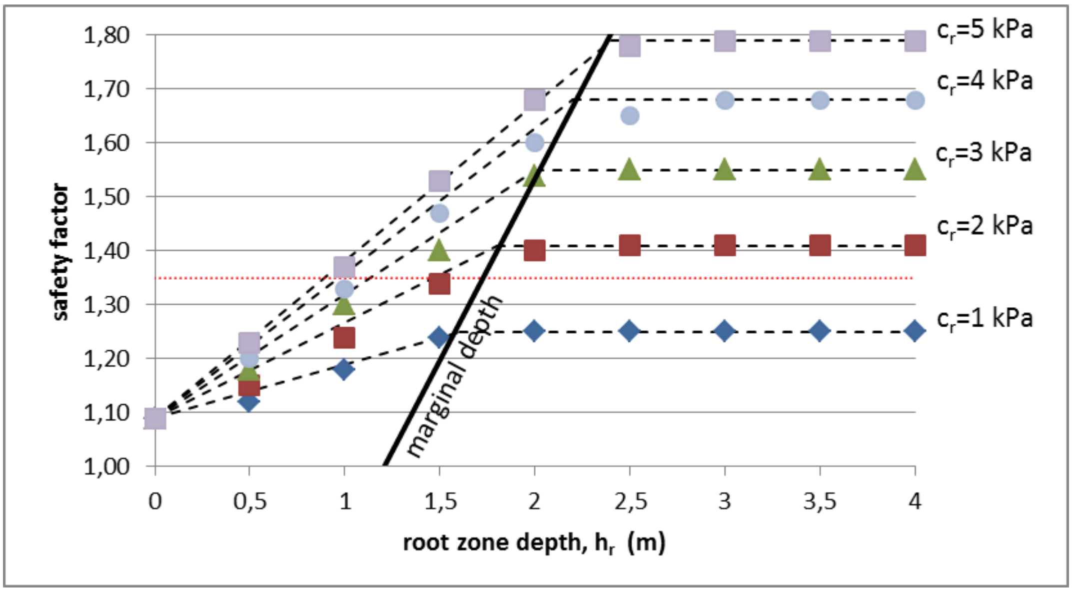

Figure 5: Safety factor variations as a function of root zone depth (h_r) with different root cohesion (c_r)

Thesis No. 4.2

I have plotted stability diagrams to demonstrate how safety factor values (Fig. 6) change in response varying root zone depths, provided shear strength and geometry remain unchanged.

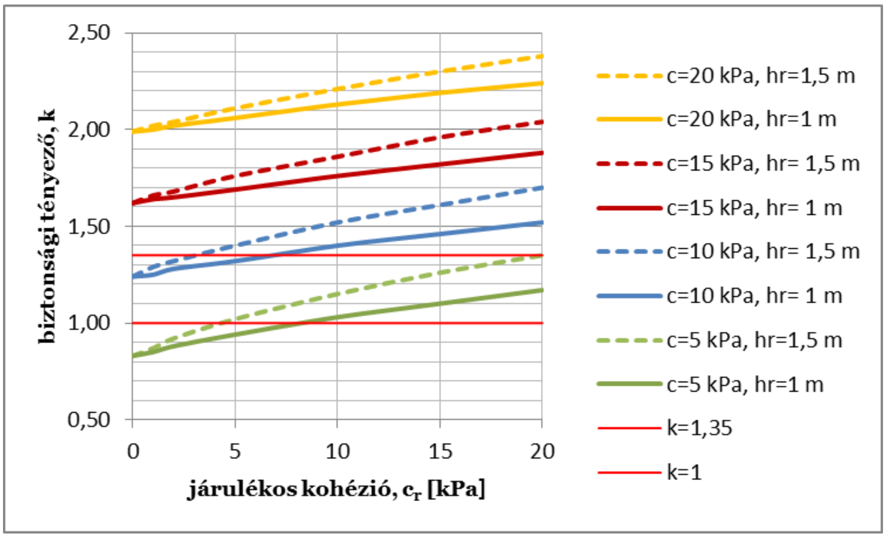

Figure 6: Stability diagram for H=10 m, 1:1 slope ratio and φ'=15º (Type III comparative tests)

I have shown that the stability factor N_c=c/Hγ may not be used to summarise and graphically represent calculated safety factors.

Using the results I have specified a range of shear strength characteristics where planting vegetation to a root depth of h_r=1.0-1.5 metres will increase the safety factor considerably (by more than 0.1).

Publications related to the thesis: Takács and Czap (2004), Czap and Takács (2010), Takács (2012b)

Thesis No. 5

Thesis No. 5.1

Based on the results of stability calculations presented in the dissertation, I have found that a simple addition of safety factor increments (Δn_i) will not capture the impact of various capital projects designed to improve stability on improving the stability factor, which is also relevant from the perspective of the national economy. Expressed in a formula:

$$\Delta n_B + \Delta n_C \neq \Delta n_{B+C}.$$

The calculation presented in the dissertation justifies that the following is true for each couple as well as all the three measures designed to improve safety:

$$\Delta n_B + \Delta n_C + \Delta n_D \neq \Delta n_{B+C+D}.$$

I generalised the same in mathematical form:

$$\sum \Delta n_i \neq \Delta n_{\sum i}.$$

Studying the multiplicative character of the safety factor I have found that it is not multiplicative.

Thesis No. 5.2

The calculations led me to assert that the incremental increase of the safety factor (Δn_i) arising from the simultaneous application of the two methods was higher than that arising from applying the methods separately:

$$\Delta n_B + \Delta n_C < \Delta n_{B+C};$$

to put it in general terms

$$\sum \Delta n_i < \Delta n_{\sum i}.$$

Publications related to the thesis: Nagy and Takács (2012a), Takács and Nagy (2012)

4. Utilisation of the results and additional research opportunities

Dimensioning on the basis of the principle of reliability is still in an early stage in the area of earth sciences Hungary. An increasing number of articles and studies of this nature are expected to get published in the near future. Sensitivity tests for a variety of geotechnical dimensioning jobs may be one of the easy-to-manage exercises.

Based on comparative tests I have ascertained that the uncertainty of input data influences the probability of failure substantially, which is why I recommend the specification of coefficients of variation for input parameters, especially as regards shear strength.

It is practical to perform an assessment of the impact of vegetation as part of the routine jobs relating to slope stability tests as analyses should not ignore this impact in certain cases. The presence of vegetation tends to improve stability (by increasing resistance), but it may also reduce it (by increasing load). Thorough and wide ranging studies are needed to justify that the roots of typical Hungarian vegetation tend to reinforce the soil of slopes and banks. I recommend a complex study of plant species, locations of occurrence, the depth of root zones, soil reinforcement and changing soil levels.

Other calculations and analyses also suggest to me that studying the non-additive character of safety factors is a fundamental issue of technical safety that requires more thorough analysis in the longer term. Such studies could provide useful outputs for analysing interventions aimed at improving stability as well as interventions and processes designed to reduce stability.

LIST OF PUBLICATIONS

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