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BENTONITE-CONCRETE MIX FOR UFER GROUNDING

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

BENTONITE-CONCRETE MIX FOR UFER GROUNDING

By

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April 2014

Chairman: Chandima Gomes, PhD

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Based on the literature, Bentonite is one of the most efficient grounding improvement material. There are two commercially available types of Bentonite namely Sodium and Calcium Bentonite. However, previous studies have not considered the effect of type of Bentonite on its performance as grounding improvement material. In addition, there were insufficient information of Bentonite which is imperative to explain the effectiveness of Bentonite as grounding improvement material. Based on a series of experimental and theoretical work, both types of Bentonite were characterized and it was found that Sodium Bentonite was better due to its superior moisture absorption and retention capability, swelling capacity under hydrated condition as well as its significantly lower resistivity. Furthermore, the behaviour of backfill materials especially Bentonite under the application of high voltage which could be due to lightning and power system fault events was not studied extensively in the literature. Hence further characterisation of Sodium Bentonite with respect to its high voltage response which includes transient and high alternating voltage was done. Indeed the performance of Sodium Bentonite was found to be superior compared to other selected backfill materials such as sand and cement judging on its lower 50% impulse breakdown voltage as well as alternating breakdown voltage. These information together with the results of statistical studies done on the voltage at breakdown and time to breakdown of Bentonite were not available in the literature. On the other hand, Ufer grounding is an effective grounding practice provided that moisture is present. This is because concrete is the main component of Ufer grounding and previous studies have concluded that concrete exhibits significantly higher resistivity when the moisture content is low. The good properties of Bentonite as grounding improvement material as aforementioned may be able to improve the electrical properties of concrete which in turn will result in an improvement of Ufer grounding. Therefore, introduction of Bentonite into concrete mix of Ufer grounding at 0-70% proportions by volume was done at a site with soil resistivity of 121Ωm and its steady state ground resistance performance was investigated by adopting the Fall of Potential measurement method.

After one year of measurement of low frequency ground resistance of Bentonite mixed concrete encased steel cage, 30% Bentonite-concrete mix was found to be the best mix which yield the lowest average ground resistance with the least fluctuation as well. The best mix was found to be about 13% better than the standard concrete mix in terms of ground resistance. Therefore, the behaviour of the best mix was investigated at another site with soil of much higher resistivity at 1672Ωm. Sodium Bentonite was used instead of Calcium Bentonite henceforth due to its superior characteristics and the optimum mixing ration remains at 30% base on the resistivity variation of both type of Bentonite. After six months of monitoring, it was found that the performance of best mix was again superior compared to several other systems which include bentonite slurry, background soil and driven copper rod by judging on the ground resistance as well as cost factor. Hence it can be concluded that the best mix could be a good grounding improvement material which can also be used as fencing's foundation as the mechanical strength was not greatly reduced. In the final phase of this research, the best mix together with the standard concrete mix were installed in five sites with various soil resistivity to determine the correlation between ground resistance and the localized soil resistivity. Standard concrete mix was used as well due to its relatively good performance compared to other ratios of Bentonite-concrete mix except for 30%. These correlations would allow prediction of ground resistance of the best mix and standard concrete mix at a given soil resistivity and thus serves as a guide for future applications by engineers in designing grounding system using the best mix. Finally it was found that by comparing their respective correlations, the best mix is 16% better than the standard concrete mix. This difference is significant especially at sites with high soil resistivity.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

CAMPURAN BENTONIT-KONKRIT SEBAGAI PEMBUMIAN UFER

Oleh

SIOW CHUN LIM

April 2014

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Bentonit ialah antara bahan pembumian yang paling berkesan menurut kajian literatur. Terdapat dua jenis Bentonit komersial iaitu Natrium dan Kalsium Bentonit Walaubagaimanapun, kajian-kajian terdahulu tidak menyelidik kesan jenis Bentonit terhadap keberkesannya sebagai bahan pembaik rintangan bumi. Tambahan pula, literatur masih kekurangan informasi berhubung ciri-ciri Bentonit sebagai bahan pembaik rintangan bumi. Berdasarkan kerja-kerja eksperimen dan teori, kedua-dua jenis Bentonit telah dicirikan dan didapati bahawa Natrium Bentonit adalah lebih baik kerana mempunyai daya penyerapan dan pengekalan kelembapan yang tinggi selain kerintangan yang lebih rendah. Prestasi bahan-bahan pengisi seperti Bentonit apabila dibekalkan dengan voltan tinggi yang mungkin berpunca dari petir dan kerosakan sistem kuasa belum lagi dikaji dalam literatur. Oleh itu, pencirian Natrium Bentonit dari aspek tindak balas terhadap voltan tinggi yang meliputi keadaan sementara dan voltan tinggi ulang-alik telah dilakukan. Nyata prestasi Natrium Bentonit adalah lebih baik berbanding dengan bahan pengisi yang lain seperti pasir dan simen. Pembumian ufer ialah satu cara pembumian yang berkesan selagi adanya kelembapan. Walaubagaimanapun, keberkesanan pembumian ufer didapati amat rendah apabila kelembapan rendah. Oleh itu, penambahan Bentonit ke dalam campuran konkrit dalam pembumian ufer pada pelbagai nisbah yang berbeza telah dilakukan dan prestasi keadaan mantap rintangan bumi telah diselidik. Selepas pengukuran rintangan bumi selama setahun, didapati bahawa 30% campuran Bentonit-konkrit ialah kompaun optimum yang memberikan purata serta sisihan piawai rintangan bumi yang paling rendah. Oleh itu, prestasi campuran optimum itu dikaji pula di tanah yang mempunyai kerintangan yang lebih tinggi. Natrium Bentonit telah digunakan disebabkan keberkesanannya berbanding Kalsium Bentonit. Selepas penelitian selama enam bulan, didapati bahawa prestasi campuran optimum masih antara yang terbaik berbanding sistem yang lain. Oleh itu, dapat disimpulkan bahawa campuran itu berpotensi untuk dijadikan sebagai bahan pembumian yang baik. Tambahan pula, campuran optimum itu boleh juga digunakan sebagai tapak struktur seperti pagar kerana kekuatan mekanikalnya tidak terjejas

secara serius. Pada peringkat terakhir penyelidikan ini, campuran optimum tersebut bersama degan campuran konkrit telah dipasang di lima tapak dengan kerintangan tanah yang berbeza untuk menentukan korelasi atau hubung kait antara rintangan bumi dan kerintangan tanah setempat. Campuran konkrit turut dikaji kerana prestasinya yang secara relatifnya lebih baik berbanding nisbah-nisbah campuran Bentonit-konkrit yang lain kecuali 30%. Korelasi-korelasi tersebut akan dijadikan sebagai penentu rintangan bumi campuran-campuran tersebut pada kerintangan tanah yang tertentu dan ini akan menjadi rujukan untuk aplikasi-aplikasi di masa akan datang oleh jurutera yang akan mereka sistem pembumian menggunakan campuran optimum tersebut. Akhir sekali, campuran optimum adalah 16% lebih baik daripada campuran konkrit.

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I certify that a Thesis Examination Committee has met on 21 April 2014 to conduct the final examination of Siow Chun Lim on his thesis entitled "Bentonite-concrete Mix for Ufer Grounding" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the degree of Doctor of Philosophy.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

a	Radius of single vertical grounding electrode
A	Cross-sectional area
AC	Alternating current
ASTM	American Society for Testing and Materials
b	Atmospheric pressure
BS	British Standard
C	Capacitance
C_s	Corrective factor to calculate the effective human foot resistance
d	Depth of probe for soil resistivity measurement
$D_{\%}$	Percentage difference
DC	Direct current
DDL	Diffuse double layer
EDX	Energy Dispersive X-ray
EMC	Electromagnetic Compatibility
ESD	Electrostatic Discharge
E_{step50}	Maximum safe step voltage that a human can be subjected for body weight of 50 kg
E_{step70}	Maximum safe step voltage that a human can be subjected for body weight of 70 kg
FF	Fulguritic Formation
GI	Galvanized steel
GIM	Grounding Improvement Material
h	Absolute air humidity
HVAC	High voltage AC
HVDC	High voltage DC

I	Current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
k	Number of breakdowns
l	Length
L	Inductance
LPS	Lightning Protection System
LRM	Low resistivity material
MTDC	Malaysian Technology Development Corporation
$MgCO_3$	Magnesium (II) carbonate
$MgSO_4$	Magnesium (II) sulphate
N	Neutral conductor
Na_2CO_3	Sodium carbonate
Na_2SO_4	Sodium sulphate
NFPA	National Fire Protection Association
DC	Direct current
OPC	Ordinary Portland Cement
PE	Protective earthing conductor
PVC	Polyvinyl Chloride
r	Interprobe separation distance for soil resistivity measurement
R	Resistance
R_e	Earth resistance
RC	Reinforced concrete
RH	Relative humidity

t	Duration of lightning current exposure
T_r	Relaxation time
UPM	Universiti Putra Malaysia
PKOC	Palm Kernel Oil Cake
V	Voltage
V_{BD}	Voltage at breakdown
$V_{corrected}$	Voltage corrected to standard condition
$V_{50\%}$	50% breakdown voltage
Z	Impedance

LIST OF SYMBOLS

δ	Relative air density
σ	Conductivity
ϵ	Permittivity
ϵ_r	Relative permittivity
ϵ_0	Permittivity of free space
ρ	Resistivity
ρ_s	Resistivity of the layer between human feet and soil
μ_0	Permeability of free space

CHAPTER 1

INTRODUCTION

1.1 Background

Explosion of transformers, loss of livestock and even human life can all be either directly or indirectly attributed to improper grounding practices [1-2]. In the event of a ground fault, sizable amount of leakage current has to be dissipated away from transformers in substations. If such remedial process fails, it would generate ground potential rise which could be high enough to induce an insulation breakdown of oil in the tank. Such electrical breakdown can in turn, lead to the formation of an electrical arc which releases enormous energy causing ionization of oil vapor which ultimately effects an ignition of the oil vapor hence giving rise to an explosion. On the other hand, close proximity of livestock and human to metallic structures such as transmission towers with poorly implemented grounding are at great fatality due to high step voltage [2].

Therefore, it is safe to say that proper grounding is a key element in every electrified and electrifying system. It serves as a medium for neutralization of undesired charges or currents hence reducing ground potential rise in the form of step potential as well as touch potential [3]. In brief, a grounding system is a "limitless charge bank" because it is a medium for which infinite amount of charges is to be dispersed on. The efficiency of grounding system is highly dependent on the ground resistance which is governed by soil resistivity as well as geometry of the grounding system itself [4]. It is generally accepted that a grounding system fit for lightning protection is also qualified for grounding of power system, communication system and static electricity. Therefore, proper designing of grounding system for lightning protection will be sufficient for all of the aforementioned systems.

Grounding system can be further branched into several independent purposes namely signal grounding, power system grounding and transient grounding which encompasses grounding for lighting protection purposes. Generally, low ground resistance as well as impedance is ideal for any grounding system. Electrical engineers should design a grounding system such that the ground resistance is as low as possible with 10 Ω as the benchmark if one refers to IEC 62305. Common practices to achieve low ground resistance include deep-driving of grounding electrodes, installation of ufer grounding as well as backfilling with GIM (grounding improvement material) [3-5]. The first option may not be viable when the availability of soil depth is very limited. Under such circumstances, backfilling is the more preferable alternative. Till now, many materials have been researched in terms of their applicability as GIM [6-12]. Yet, the most superior is still one of the earliest used GIM which is Bentonite, and that sparked the interest of this research.

The application of backfill materials for improvement of grounding system performance has been in practice for several decades. Bentonite has been proven to be one of the most effective backfill materials thus far but yet no theoretical and thorough study has been done to explain it [7]. Furthermore, there are also several types of Bentonite produced industrially [13]. This fact was not regarded at all in the past researches on Bentonite as GIM. Therefore, Bentonite with different chemical composition should perform with different effectiveness as GIM. Several researches have found that Sodium Bentonite has greater swelling capacity compared to Calcium Bentonite under moistened condition [14-15]. Whether this difference will make Sodium Bentonite a better GIM than Calcium Bentonite remains to be seen. Therefore, the chemical composition of Bentonite will be analyzed in this research. In addition, the electrical and physical properties of the variations of Bentonite will also be investigated. The physical properties are characterized by swelling and moisture-absorbing capability of the two types of Bentonite whereas the electrical properties will be characterized base on their resistivity.

Backfill materials have been used as GIM without good understanding of their behavior under high voltage events which could be due to lightning as well as leakage current of substations. Thus far only sand was studied but even so, it was only to a limited extent. The high voltage response of common backfill materials such as sand, Bentonite and cement were not extensively studied in the literature. Therefore, there is a need to further characterize backfill materials especially Bentonite from the perspective of high voltage.

In usual practice, copper rod is selected as the grounding electrode. However at soil with high resistivity, the performance of concrete encased grounding electrodes also known as Ufer ground was found to be much better than copper rod [3]. On a side note, Ufer ground also performs much better than copper rod under highly corrosive environment as its resistance to corrosion especially due to sulphur rich environment is higher [16]. Concrete is the main material which is used in Ufer grounding and is relatively effective only with the presence of moisture [17].

When Bentonite is mixed with concrete it was thought that it would result in good improvement of grounding performance especially in the case of Ufer grounding. The inspiration came from the fact that Bentonite and cement have common physical and mechanical property to some extent. Both cement and Bentonite get hydrated in the presence of moisture content forming a paste which has improved conductivity. In order to produce concrete with practical strength, there are several rations which ought to be adhered to. Based on literature review on improvement of electrical property of concrete, only the proportion of cement is varied [18-19]. The proportion of gravels and sand are fixed constant. As certain ration has to be adhered to, it was decided that cement will be partially replaced with Bentonite rather than Bentonite being added into the mix. In this work, the performance and behavior of grounding electrodes encased in different composition of concrete and Bentonite were investigated under different soil conditions. Note that, the performance of Bentonite-mixed-concrete-encased-metal mesh as grounding system is not available in current literature. Therefore, the result of evaluation of such grounding system would be beneficial to electrical engineers. Apart from being invaluable information pertaining to Ufer grounding, such results can also be used to justify the application of Bentonite-mixed-concrete-encaged steel cage as a standalone alternative grounding practice.

Cement is the main material which binds the whole concrete together [20]. Different grades of concrete demonstrate different levels of strengths. These grades are classified based on the ration of concrete mix. Mechanical strength of concrete is extremely important when the Ufer design adopts the application of foundation of structures such as building and fencing. Bearing such in mind, there is concern that reduction of cement may result in reduction of mechanical strength of concrete. In order to address this issue, mechanical strength was also investigated to evaluate the suitability of introducing Bentonite into the Ufer grounding practice. If the reduction of mechanical strength is deemed to be significant, then the design should be applied in lighter structures such as fencing a part from being used as standalone grounding electrode.

It is therefore the ultimate aim of this research project to formulate a backfill material in the form of mix of concrete and Bentonite which maintains reasonably low ground resistance for a long time of usage. Once the optimum ration is obtained, its performance in various soil resistivity will be evaluated in order to establish an empirical formula correlating ground resistance with soil resistivity. Such empirical formula would serve as an apparent guide for future application of the best mix at certain specific dimension. In addition, it will also tell the extent to which the best mix performs better than the standard concrete mix.

1.2 Problem Statements

Bentonite has been widely used as backfill material for improvement of grounding system for a considerable time period. However there is no comprehensive study done on the reasoning behind the effectiveness of Bentonite as grounding improvement material. Understanding the characteristics of Bentonite is crucial in justifying its application. Apart from steady state ground resistance behavior of electrodes encased in raw Bentonite, no other electrical information is available on Bentonite. Even in such cases where the experiments were done, the chemical composition of Bentonite has not been studied and there are several types of "Bentonite" produced in the world. There is limited information on the behavior of backfill materials especially Bentonite under high voltage condition.

In addition, ufer grounding is another highly recommended grounding practice especially in site with high soil resistivity condition. However, the effectiveness of Ufer grounding at prolonged dry season maybe significantly lowered as concrete is a poor conductor when moisture is absent which gives rise to a need to address this issue. No improvised application of Bentonite with respect to improvement of ufer grounding has been done which means there is a vacuum in information regarding the mechanical or electrical properties of concrete mixed with Bentonite. Such information is crucial in justifying the application of such mix as ufer grounding. The lack of information on Bentonite is a major hindrance in developing various useful and commercializable materials for grounding using Bentonite as the base material. This two-pronged research is done mainly to characterize Bentonite as grounding improvement material as well as to propose a Bentonite-concrete mix aimed to improve the performance of ufer grounding system.

1.3 Objectives

The objectives of this research are to:

- characterize Bentonite as grounding improvement material from the electrical, physical and chemical perspectives of Bentonite
- investigate the behaviour of Bentonite under high voltage condition
- determine the best composition of Bentonite-concrete mix encasing steel cage in order to enhance the performance of ufer grounding system.
- formulate a correlation between ground resistance of the best mix and localized soil resistivity parameters

1.4 The scope of the study

Bentonite was characterized in terms of resistivity, swelling and moisture absorption capacity, and chemical composition tests. High voltage behaviour of Bentonite was investigated by comparing its time to breakdown, voltage at breakdown and 50% breakdown voltage with sand, cement, and air under the application of impulse and high alternating voltage. The best mix was determined by considering the variation of ground resistance and mechanical strength of the Bentonite-concrete mixes at different proportions.

1.5 Thesis Structure

This thesis contains eight chapters. **Chapter 1** presents the overview of this thesis together with the problem statements, importance of study, objectives and limitation of this study. **Chapter 2** details on various aspects and issues of grounding system with special attention to application of backfill materials and ufer grounding as well as ground resistance and ground impedance. **Chapter 3** elaborates on the characterization of Bentonite as grounding improvement material from the perspectives of electrical, physical and chemical. A series of experiments and measurements and theoretical study were done to investigate on several properties of different types of Bentonite and the results were used to explain the effectiveness of Bentonite as GIM. **Chapter 4** covers on the characterization of response of Bentonite under high voltage condition. Both transient and HVAC response of Bentonite will be discussed here. **Chapter 5** outlines on the determination of the optimum composition of Bentonite-concrete mix. Electrical and mechanical property of Bentonite-concrete mix will be investigated as well. The mechanical strength test is crucial in justifying its suitability as material for ufer grounding which utilizes the building foundation as the conductors. **Chapter 6** discusses on the performance of Bentonite-mixed concrete under high soil resistivity condition. In **Chapter 7,** an empirical formula correlating ground resistance of the proposed design with the soil resistivity was developed. This formula shall serve as an apparent guide for future application of the best mix in soil with different soil resistivity. Finally, **Chapter 8** conveys the general conclusions as well as future areas of study. Figure 1.1 depicts the overall framework of the thesis.

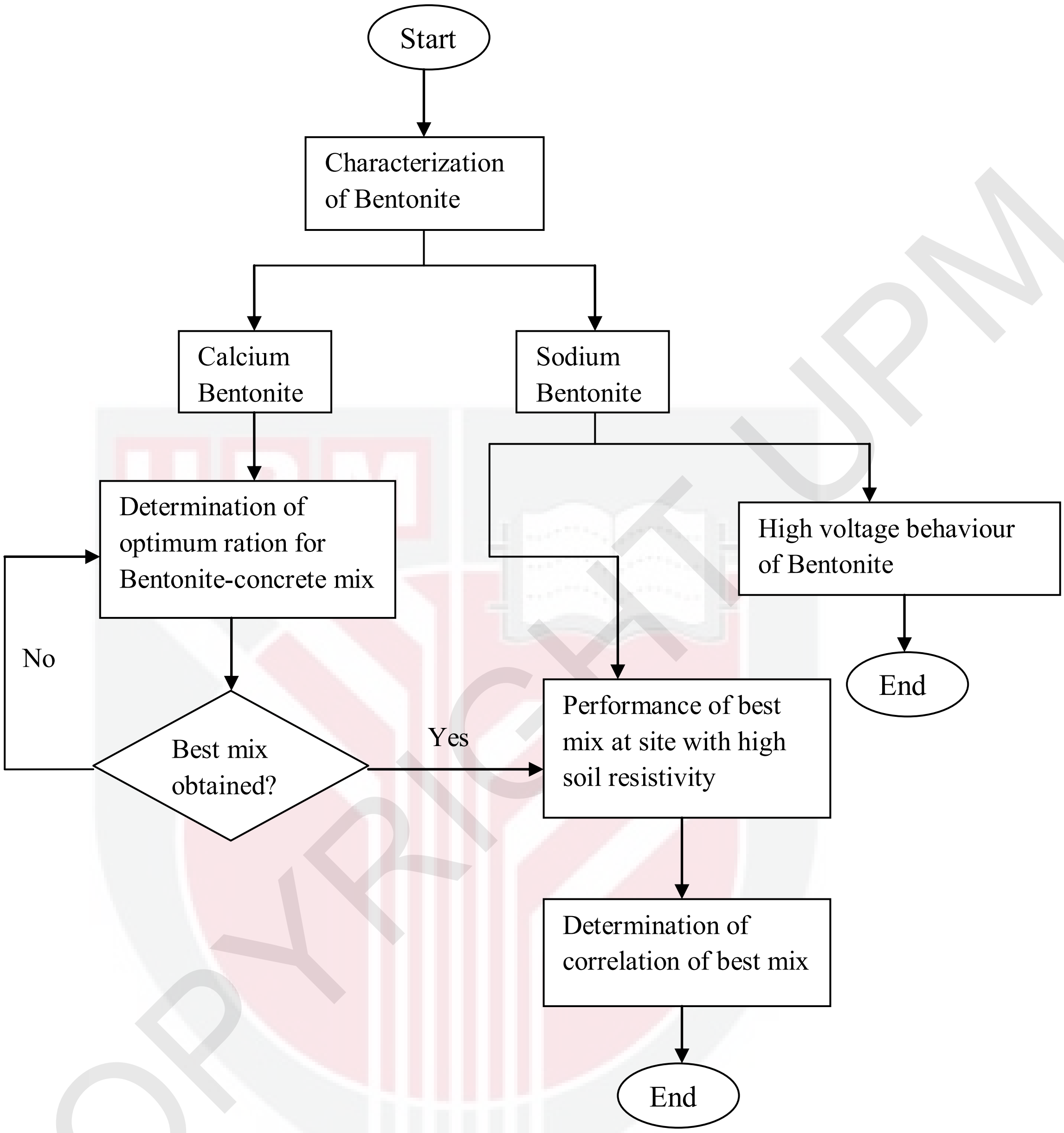

Figure 1.1 Overall framework of the thesis

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