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Relating 1D Compressibility of Kaolin Clay with S-Wave Velocity and Electrical Conductivity: An Instrumented Consolidometer Study

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ABSTRACT

Objective – Non-Invasive and minimally invasive testing techniques for geotechnical engineering purposes, nowadays, are developing progressively. Nonetheless, due to the particulate nature of soil, there exists a transitional zone where the conventional testing (macro-level) is studied simultaneously in micro-level using non-destructive techniques. The incorporation of the conventional testing in parallel with non-destructive testing is to establish the correlation between well-known testing program under controlled conditions with innovative techniques. For this purpose, the current paper as part of an ongoing research the current paper presents the one-dimensional consolidation characteristics of kaolin in cement-treated condition with concurrent bender element and electrical conductivity (EC) measurement in an instrumented consolidometer.
Methodology/Technique – Kaolin slurry at twice liquid limit was mixed with 5 % cement cured for 7 days which undergoes 2.5 to 1000 kPa vertical Stress. Shear wave velocity Vs was measured to quantify the small-strain stiffness of soil using bender element transducers triggered by GDS bender element master signal conditioning unit in a frequency range 1-100 kHz. Electrical conductivity and temperature was measured using HANNA commercial probe. The shear wave velocity was analysed using the conventional techniques (visual picking).
Findings – Results indicate that the Vs increases with applied stress whereas the EC decreases.
Novelty – S-wave and EC have strong relationship with the compressibility behaviour of cemented kaolin clay.
Type of Paper: Review

Keywords: Kaolin; Shear Wave Velocity; Electrical Conductivity; Consolidation, Instrumented Consolidometer; Cement-Treated Kaolin

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1. Introduction

One-dimensional consolidation is a process of squeezing the porewater from fully saturated cohesive soils at vertical, top and bottom, drainage condition (Whitlow, 1990).It is the combination of two coupled phenomena in which the rate of water flow is controlled by the permeability and compressibility of the soil fabric controls the change in volume for a given change in load (Fam & Santamarina, 1996). This phenomenon, in its laboratory form, was introduced by Terzaghi in 1920. Since then one-dimensional consolidation has been a

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subject for many studies primarily on fine-grained soil under variable testing conditions. As a well-established test in geotechnical engineering, the mechanical interpretations of the test results are in macro-level whereas the micro-level interpretations are still illusive (Santamarina, Klein, & Fam, 2001). On the other hand, non-destructive testing in geotechnical field has been gaining importance in recent years to overcome the sampling disturbance of the original soil. Nonetheless, due to the particulate nature of soil, there exists a transitional zone where the conventional testing (macro-level) is studied simultaneously in micro-level using non-destructive techniques (Carlos & Moheb, 1995). Past researchers have proposed various approaches of relating the one dimensional conventional result interpretations with means of non-destructive techniques. One of the first examples conducted on Kaolinite, Bentonite and Silica floor have indicated a good correlation between one dimensional consolidation results with shear wave velocity and complex dielectric permittivity (Fam & Santamarina, 1996). Another innovative technique was implemented by Comina et al (Comina, Foti, Musso, & Romero, 2008) in consoildometer cell. In this study a 3D electrical resistivity tomography has proven effective in detecting both resistive and conductive target inclusions with good precision, as well as in monitoring porosity variations affecting the electrical conductivity on Ticino sand. In a recent paper by Kang et al (Kang, Kang, & Bate, 2014) a floating consolidometer was developed to measure the stiffness anisotropy on kaolinite using bender element transducers. Referring to studies on the electrical properties of soil, Saarenketo (Saarenketo, 1998) obtained a strong correlation between the electrical conductivity and moisture content of silty and clayey soil, while Ahire et al (Ahire, Chaudhari, Ahire, & Patil, 2013) established resilient correlation with physical properties of black clay. As part of an ongoing research the current paper presents the one-dimensional consolidation characteristics of kaolin in cement-treated condition with concurrent bender element and electrical conductivity (EC) measurement in an instrumented consolidometer.

2. Design of Instrumented Oedometer Cell

The instrumented consolidometer is a floating ring-type Oedometer made of high quality material to withstand an aggressive environment, especially for saline soil, and high imposed load. The initial height of the soil specimen inside the ring is 100 mm and the diameter is 100 mm.The instrumented consolidometer, attached to a conventional frame with lever arm ratio of 1:5, consisted of one pair bender element transducers, electrical conductivity-temperature probe incorporated inside the ring figure1. Bender element was connected to data acquisition system. Details of each component are elaborated in the following sections.

2.1 GDS Bender Element

Bender element (BE) transducers and data acquisition system were supplied by GDS Instrumentation Company. The dimensions of each bender element transducer are 10 mm by 5 mm by 2 mm (length by width by thickness). Transmitter transducer was inserted in the top and the receiver in the bottom platen to avoid disturbance caused by the movement of the cap. Sinusoidal waves (10 V) were triggered manually in a frequency range 1-100 kHz with a sampling frequency rate of 2000 k samples per second per channel. BE data acquisition system, which works as one unit figure 1, consisted of bender element external control box functioned with a transducer power supply; signal conditioning, amplification of the source supply and switches between circuits (i.e P-wave and S-wave). S-wave was measured throughout this experimental program while P-wave was not retrieved due to the high moisture content of the soil samples. The input GDSBES v2.2.7 software was installed in PC which is connected to BE unit. The output files were saved in BES excel format which compatible with GDSBE. GDSBE software was used to analyse the output data using excel GDS Bender Elements Excel Add-In V1.18 (GDSBEAT) and compared with visual picking observations.

2.2 Electrical Conductivity

Direct electrical conductivity (EC) DC probe type, manufactured by Hanna, was attached at the top cap and inserted 50 mm inside the soil specimen. It is made of stainless steel with a conical tip to provide a minimal disturbance and smoother penetration through the specimen. EC is measured in mS/cm with a resolution of 0.01 mS/cm in a conductivity range of 0-4 mS/cm where it can measure up to 9 mS/cm with a lower accuracy.

3. Materials and Experimental Methods

Manufactured kaolin clay (Malesia grade FM) was used in this study and its physical properties are shown in table 1. The kaolin was mixed with 5 % Portland cement by dry weight in twice liquid limit (148%). Kaolin was first dried in oven to ensure complete dry condition. Distilled water was added to the dry kaolin and mixed in automatic mixer for 10 minutes and then kept in a closed container to allow mellowing for 24 hours. Then the cement was added to the slurry and mixed in the mixer for 2 minutes only to avoid mixture hardening. Doubled filter papers were placed in the top cap and bottom platen to facilitate the drained water. The ring was lubricated with silicon grease to avoid the side friction between the cap and the side wall.

Table 1: Physical and chemical properties of Kaolin clay

Moisture content	0
Plastic limit	36
Liquid limit	74
Particle density	2.6
pH (30% solution)	3.5-6
Brightness (GE)	75-82%
325 Mesh residue	< 0.2%
Average particle size	3-5.5 µm
Alumina (Al_2O_3),	33-39%
Silica (SiO_2),	45-50%
Iron Oxide (Fe_2O_3),	< 1.5%
Potash (K_2O),	< 2.5%
Magnesia (MgO),	< 1%
LOI at 1025 C	10.5-13%

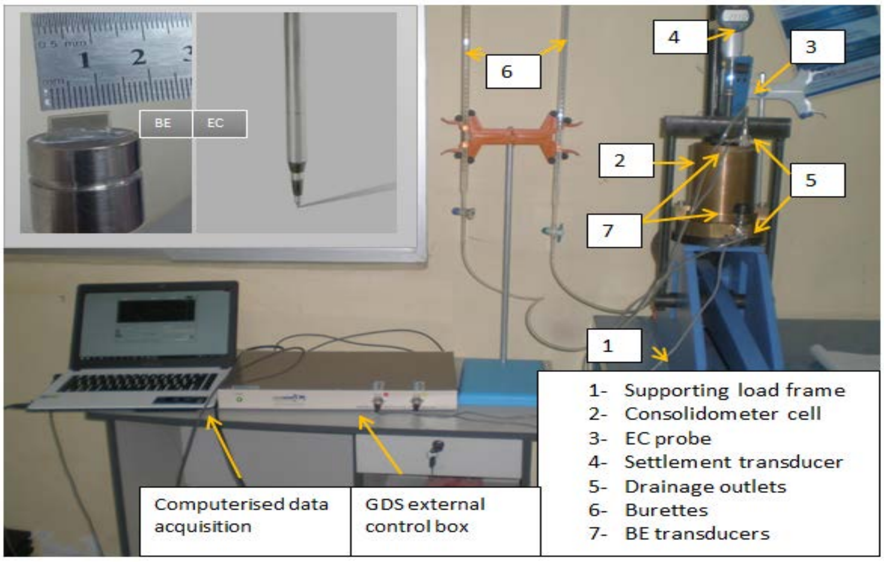

Figure 1: Instrumented Consolidometer Set Up

The pourable mixture was placed inside the floating ring carefully in three layers which was knocked after each layer to ensure free entrapped air bubble specimen. While the drainage outlets at the top and bottom caps were kept closed during the seven days of curing period, no settlement has occurred and the specimen height remained at 100 mm. After the curing time has elapsed the cell was positioned on the loading frame. The loading steps in the current test were 6.25 kPa, 12.5 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa and 1000 kPa respectively. Each loading step was sustained until the primary consolidation have ceased. After that the final sample was taken and dried in oven for 24 hours to determine the final moisture content. As shown in figure 1, two scaled burettes were attached to the drainage outlets. The drained water was reserved to monitor the permeability for each loading stage.

4. Results and Discussion

The EC of the distilled water was measured zero as it is virtually free of impurities that may contribute the EC value. However, the EC value of the plain mixture-kaolin and water- prior to cement addition was 0.21 mS/cm which indicates that the kaolin is not ionic-free. Before discussing the S-wave and EC relationship in curing time period it is worth mentioning that the first measurement of EC was taken after almost 15 minutes which is the time required for mixing and sample preparation. The S-wave was traced after almost 3 hours. When the cement was mixed with water reaction has occurred and emission of free ions has contributed to the increment of EC of the mixture. Cement compounds, when mixed with water; undergo a process called hydration in which a chemical reaction between water and cement compounds take place. Tricalcium silicate compound is the responsible of the early strength whereas the dicalicium silicate will contribute more to the later strength (Peterson, Neumann, & Livingston, 2005). The tricalicium silicate reaction with water is given by equation:

$$\text{Tricalicium silicate } 2Ca3\ SiO5\ +\ 7H2O +\ \text{water}\ (H2O) = \\ (\text{calcium silicate hydrate})3CaO.\,2SiO2.4H2O\ +(\text{calcium hydroxide})3Ca\ (OH)2\ \ +\ \text{heat}$$

The chemical reaction between water and cement-soil matrix results in cations and ions exchange which contribute to EC values increment. The mechanism of clay soils and cement based stabilisation includes four different processes (Prusinski & Bhattacharja, 1999). Cation exchange initiates the stabilisation process by developing the double layer diffusion. Flocculation and agglomeration alter the structure of the clay from plastic to granular soil. The hydration and pozzolanic processes contribute to the rapid and slow strength respectively.

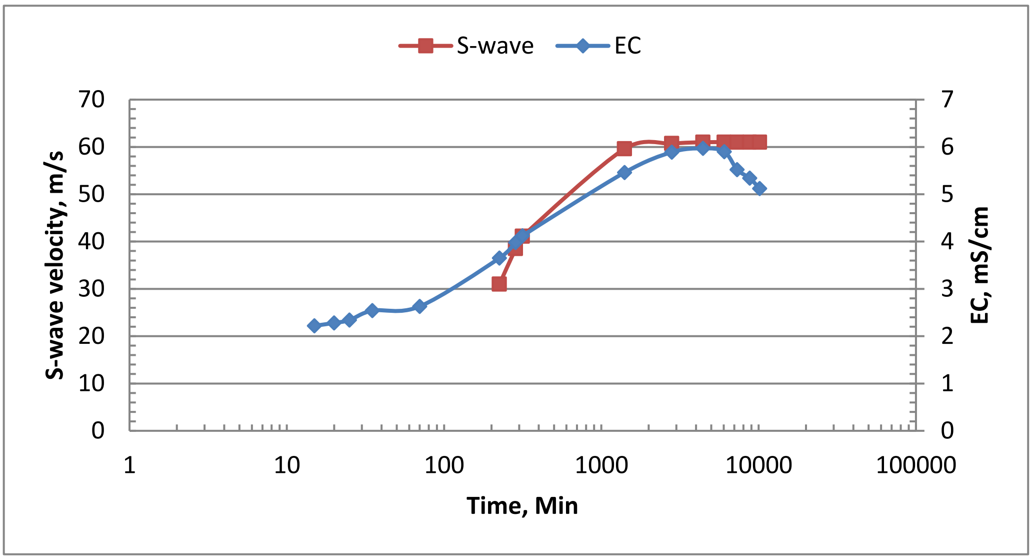

Figure 2: S-wave and EC behaviour during the Curing time

On the first curing day, the rapid increment in EC indicates that the cation exchange and hydration process was very active. At the same time, the S-wave rapid increment indicates that the flocculation and agglomeration process have successfully altered the formation of the interparticle to more granular condition. During the following curing days, the EC showed a slower increment up to 5 days and starts to decrease in further time, while the S-wave values remained almost stationary. It can be concluded that, at the first curing day for the specified dosage of cement, the flocculation and agglomeration process was proportional to the activation of the cation exchange.

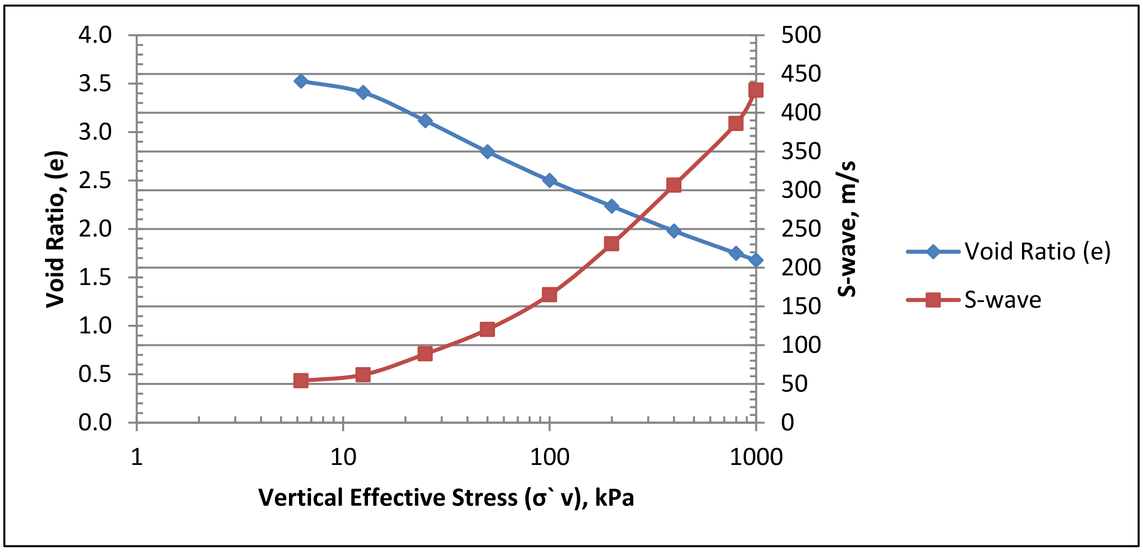

Figure 3: Void ratio (e) vs S-wave With Respect to Vertical Applied Stress ($\sigma`_v$)

Figure 3 shows the relationship between the void ratio (e) and S-wave velocity during the loading stages. When the vertical applied stress increased, it forces the porewater to flow out through the drainage path. As a result, the void ratio will be reduced subsequently. Accordingly, the solid particles were brought closer to each other causing rearrangement of the particles interaction. Based on previous studies results it is well-known that the S-wave propagates faster through the solid particles and denser mediums. Thus, when the void ratio deceased, the S-wave increased. Figure 3 shows a strong correlation between the S-wave and void ratio. It is worth noted that around 20% decrement of the S-wave when the first load applied due to the redistribution of the porewater and the rearrangement of the cemented soil-structure interaction. Similarly, figure 4 shows the relationship between the EC and the void ratio. In general, the EC decreased as the void ratio decreased. However, at the initial stresses (6.25-50 kPa) the EC decreased in slower rate (0.27 mS/cm) compared to the void ratio (0.73). It is assumed that the specimen under test was still in a very liquid state whereby the drained water did not affect much the EC values. Meaning that the surrounding mixture film around the EC sensor is still sustained almost the same initial condition. But during the middle stresses (50-200 kPa), the EC decreased rapidly by 2 mS/cm compared to the void ratio 0.57. After that the EC showed slight decrease (0.32 mS/cm) compared to the void ratio 0.55 for the remaining applied stresses. The bender element is enhanced when the frequency input frequency reaches the resonant frequency (Fonseca, Ferreira, & Fahey, 2009; Lee & Santamarina, 2005). The resonant frequency is coupled between the soil and bender element transducer. However, the stiffness of soil changes under applied stress, hence the resonant frequency changes as well. Lee and Santamarina claimed that the “arrival time is not affected by the input frequency but the ability to detect the arrival time can change dramatically”.

Figure 4 shows the received signals for S-wave with vertical applied stress. The frequencies that have been selected for this study were 1, 2, 4, 10 and 20 kHz. During the curing time and at lower stresses, small frequencies were used and bigger frequencies were used for higher applied stresses. Based on this experimental work it has been found that the frequency selection for S-wave is dependent on the S-wave velocity. Thus for higher S-wave velocities

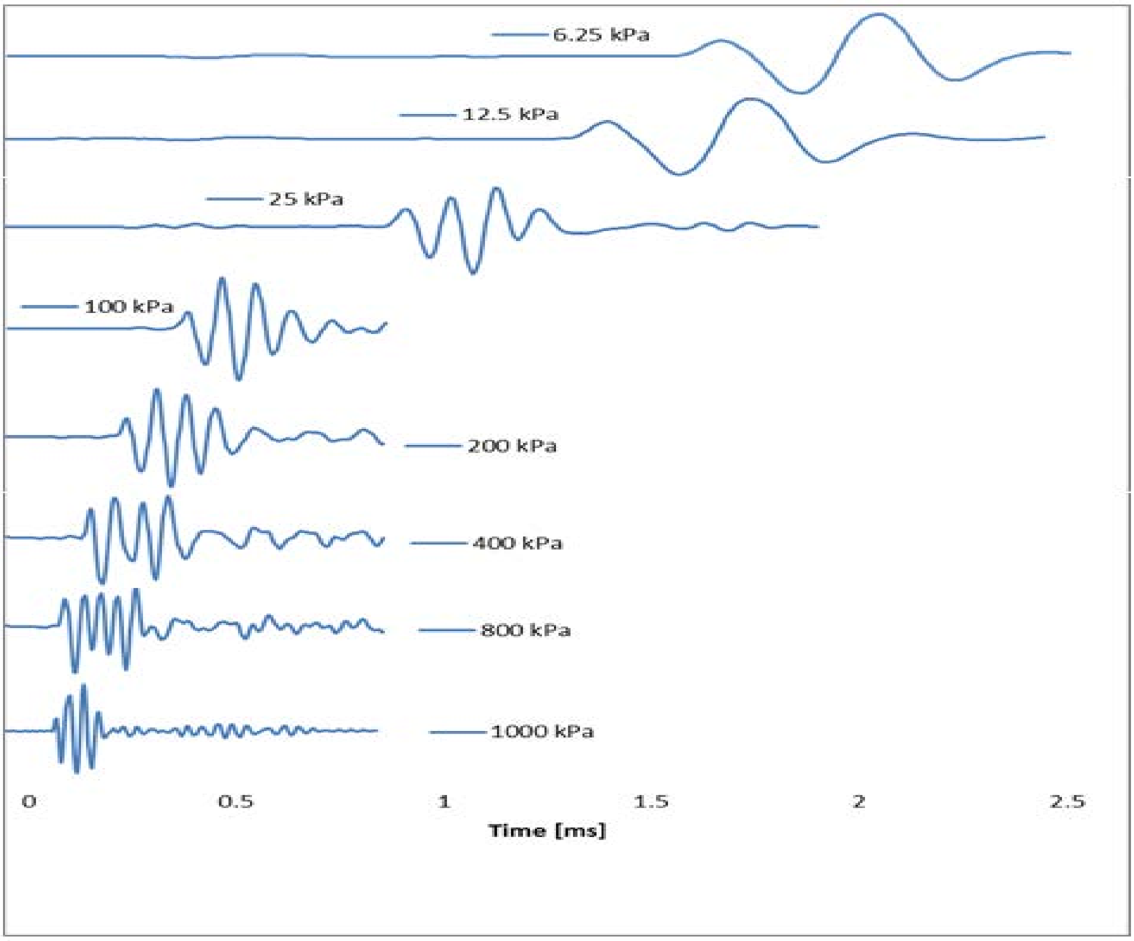

Figure 4: Typical S-Wave Response for Different Stresses

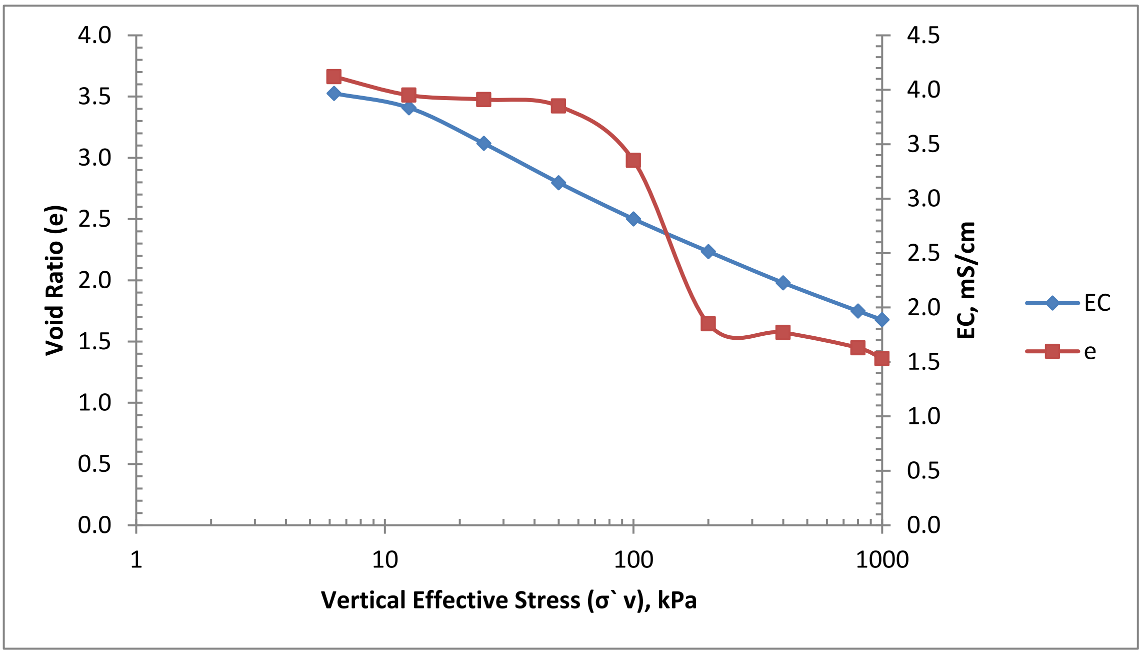

Figure 5: Void Ratio (e) vs EC With Respect to Vertical Applied Stress (σ_v)

higher frequencies should be used. Note that comprehensive details about the frequency selection for clay soil with an instrumented conolidometer basis are still under study.

5. Conclusion

Based on experimental work so far it can be concluded that:

- During the curing period the S-wav and EC increased speedily in the first day due to the cation exchange and hydration process. After that, the S-wave remained constant while EC continued increasing in slower rate and started to decrease. These results reveal the mechanism incurred between the soil-water-cement in micro level.
- S-wave velocity propagated faster when the void ratio decreased due to the interparticle interaction allowing the S-wave to propagate faster through the medium.
- EC showed three interrelated phases with respect to the applied vertical stress in which slight decrease was measured during the initial small stress. While bigger decrease was observed during the middle range of stress and small decrease observed in the remaining stress.
- It can be concluded that S-wave and EC have strong relationship with the compressibility behaviour of cemented kaolin clay.

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