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A Study on Shear Behaviour of Rock Joints

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Summary The shear strength characteristics of sandstone joints collected from a landslide site near Kangaroo Valley of Australia were investigated in the laboratory under Constant Normal Stiffness (CNS) condition. The joint surface profiles were characterised precisely using a digital Coordinate Measuring Machine (CMM) prior to testing. An initial normal stress (σ_{no}) of 0.56 MPa to 2.69 MPa was used during this study. It is observed that the peak shear stress of the joint increases with the increase in σ_{no}. However, the increase in normal stress during shearing was observed up to σ_{no} of 1.63 MPa for constant normal stiffness. The joint behaviour was dilatant for σ_{no} less than 1.63 MPa and compressive (negative dilation) for greater σ_{no}. A plot of peak shear stress and corresponding normal stress shows that a linear strength envelope is appropriate for CNS testing. The small cohesion intercept of the strength envelope resulted from the infill material (iron oxide). The mathematical model proposed in this study, predicts very closely the behaviour of natural joints tested in the laboratory.

1. INTRODUCTION

The shear behaviour of rock joints are generally investigated in the laboratory using the direct shear apparatus where the shearing takes place under Constant Normal Load (CNL) condition. Joints having non-planar discontinuities tend to dilate during shearing depending on the surrounding rock mass stiffness. Some of this dilation is inhibited by the overlying rock mass hence, an inevitable increase in normal stress occurs during shearing. Therefore, tests conducted under CNL condition for non-planar joints may not be representative of the actual field conditions. As suggested by several researchers (eg. Goodman, 1976; Lam & Johnstone, 1989; Skinas et al., 1990; Ohnishi & Dharmaratne, 1989), the shear behaviour of non-planar joints takes place under Constant Normal Stiffness (CNS) condition rather than under CNL condition. Laboratory test results reported by the above authors are based on artificial joints tested under CNS. Although the natural joints can be modelled in the laboratory using appropriate modelling parameters, results obtained from such testing may not represent the behaviour of the true field joints. This initiated the authors to conduct the laboratory tests on natural joints (non-planar interfaces) under CNS condition. In order to conduct laboratory tests on larger joint specimens, a large-scale shear apparatus was designed at the University of Wollongong to test joint specimens under both CNL and CNS conditions.

2. SAMPLING OF NATURAL JOINTS

The natural joints were sampled from a rockslide site near Kangaroo Valley of New South Wales, Australia (Fig. 1), where large areas of exposed joint surfaces are easily accessible for sampling. The continuing research under CNS at University of Wollongong, Australia is based on soft joint behaviour hence, natural sandstone joints recovered from Kangaroo Valley are ideal for this study. Laboratory investigations on the shear behaviour of model soft joints cast from gypsum plaster have been performed before. This study, in contrast, involves testing of natural soft joints recovered from the Kangaroo Valley rockslide site. The joints are composed of porous sandstone having an uniaxial compression strength (σ_c) of 19 - 21 MPa. A thin layer of compressed iron oxide (Fe_2O_3) exists on the joint surface. A close view of the orientation of the joint plane in the field is shown in Figure 2. A basic friction angle (ϕ_b) of 32° was observed for saw-cut surfaces of collected joints.

3. SPECIMEN PREPARATION

The field joints were cut at the site as a block and then transported to the laboratory. The laboratory specimens were prepared by cutting the joint to fit the top part of mould of size of 250x75x150 mm, and the bottom part of mould of size of 250x75x100 mm (Fig. 3).

4. JOINT SURFACE PROFILE

In order to assess the roughness of the joint profile, all joints surfaces were examined under a digital Ferranti (Mercury) Co-ordinate Measuring Machine (CMM) shown in Figure 4. The CMM is a manually driven which consists of a set of Renishaw probes and a MICRO 900 microprocessor. The basic frame of the machine is placed on a granite table. The machine can measure a minimum of 1 micron position resolution and can achieve accuracy with 95% confidence under normal working conditions.

Figure 1. Location of the rockslide site at Kangaroo Valley.

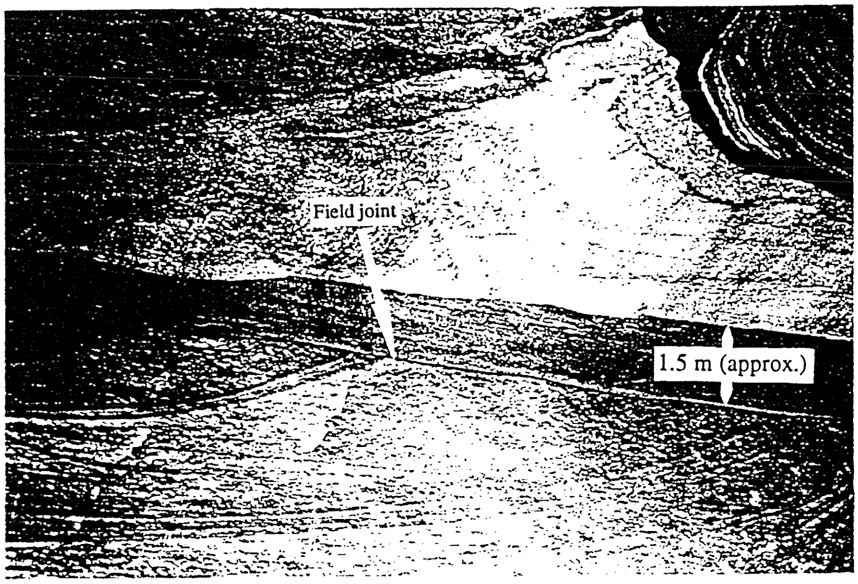

Figure 2. Orientation of joint plane in the field.

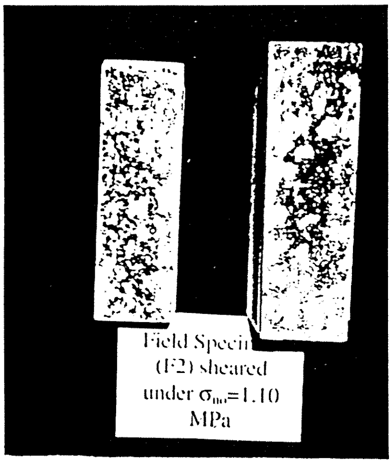

Figure 3. Prepared natural joint for testing.

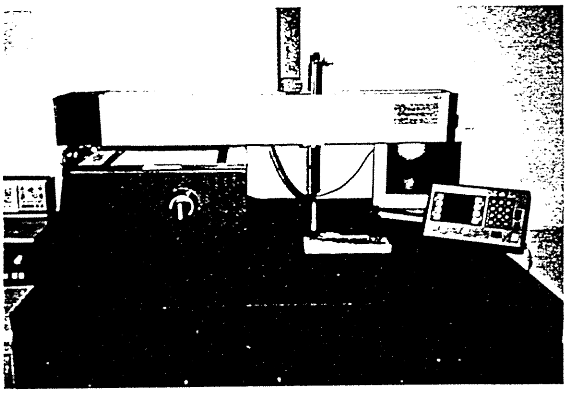

Figure 4. Digital Coordinate measuring machine (CMM).

The surface profiles of the field specimens were examined individually using CMM, and coordinates at any point were recorded using a touch trigger probe. All the measurements were taken with respect to a perfect datum, which coincided with the flat granite table of CMM. Two surface profiles of field specimens are shown in Figures 5 and 6. The average height of the joint asperities varied from 1.22 to 2.35 mm.

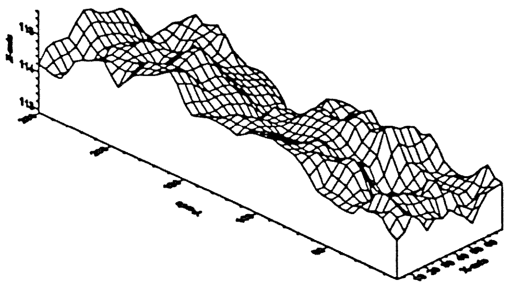

Figure 5. Surface profile of natural joint (F1).

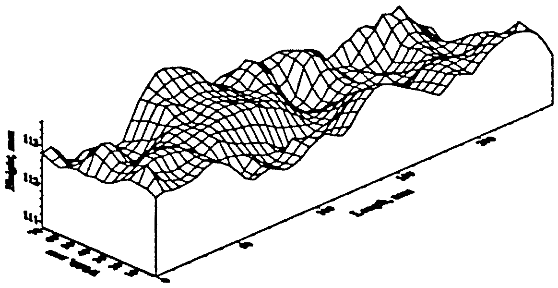

Figure 6. Surface profile of natural joint (F5).

5. LABORATORY TESTING

All the field joints were tested under a constant normal stiffness (k) of 8.5 kN/mm (or 0.45 MPa/mm for a joint surface area of 187.5 cm^2) and an initial normal stress (σ_{no}) varying from 0.56 MPa to 2.69 MPa, which represents the variation in normal stress observed in the field. The stiffness used in this investigation is representative of softer rocks eg. claystone, siltstone etc. However, in the field, the rock mass stiffness can vary from a low to a high value, depending upon the presence of joints. The specimens were sheared at a controlled strain rate of 0.50 mm/min. Further details about CNS apparatus and testing procedure are given elsewhere by the authors (Indraratna et al., 1998a).

6. RESULTS AND DISCUSSIONS

6.1 Shear Response

The variations in shear stress with horizontal displacement are recorded at 0.5 mm interval via a load cell which is connected to a digital strain meter. The shear stress response for the field joints under various σ_{no} is shown in Fig. 7. It is observed that as the σ_{no} is increased, the peak shear stress is also increased. At elevated σ_{no}, the shear stress vs horizontal displacement curves show a more well defined peak.

6.2 Normal Stress

The change in normal stress with shear displacement during shearing is monitored via a load cell connected to a digital strain meter. Figure 8 shows the variations in normal stress with displacement for all the tests performed on the natural joints. It is observed that the normal stress increases up to an initial normal stress (σ_{no}) of 1.63 MPa. A decrease in normal stress results for subsequent increase in σ_{no} which is attributed to full compression. Similar behaviour was also observed on plaster joint specimens tested under CNS condition (Indraratna et al., 1998a).

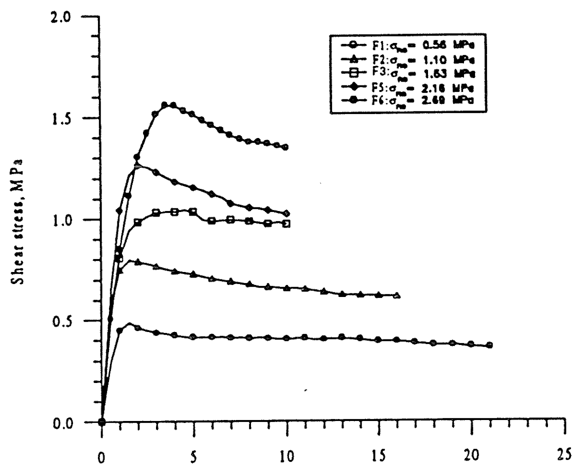

Figure 7. Variation of shear stress with horizontal displacement.

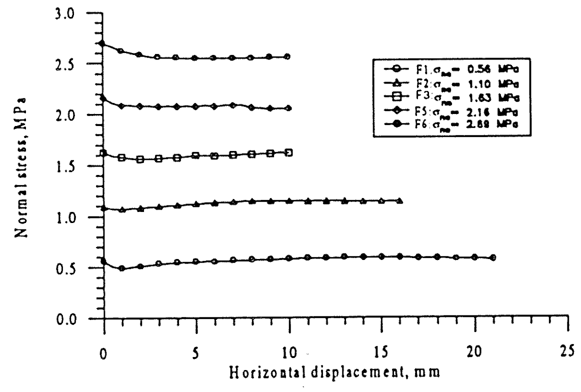

Figure 8. Normal stress vs horizontal displacement.

6.3 Dilation

The vertical movement of the joint interface was recorded by a dial gauge located at the centre of the specimen top. The variations of joint movement with horizontal displacements are shown in Fig. 9 for various levels of σ_{no}. It is observed that the joint dilates under σ_{no} of 1.63 MPa and the joint behaviour changes from dilation to compression for subsequent increase in σ_{no}. This indicates that the asperities shear completely at elevated normal stresses, thereby making the shear response similar to that of the CNL testing.

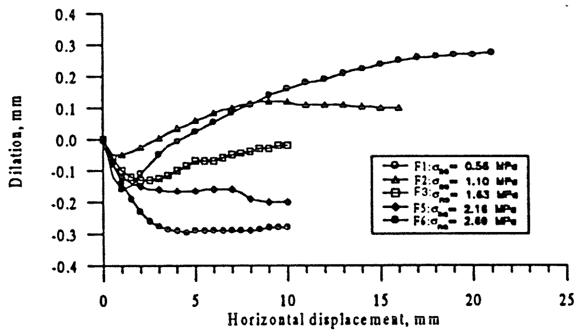

Figure 9. Variation in dilation with horizontal displacement.

6.4 Shear Strength Envelope

In order to obtain the strength envelope, the peak shear stresses corresponding to the normal stresses were plotted in Fig. 10 for various σ_{no} values. It is observed that a linear strength envelope is more appropriate for the sandstone joints tested under CNS, irrespective of the small variations in surface roughness. A small amount of cohesion (c) say, 0.25 MPa is found, possibly due to the trace of iron oxide between the interfaces.

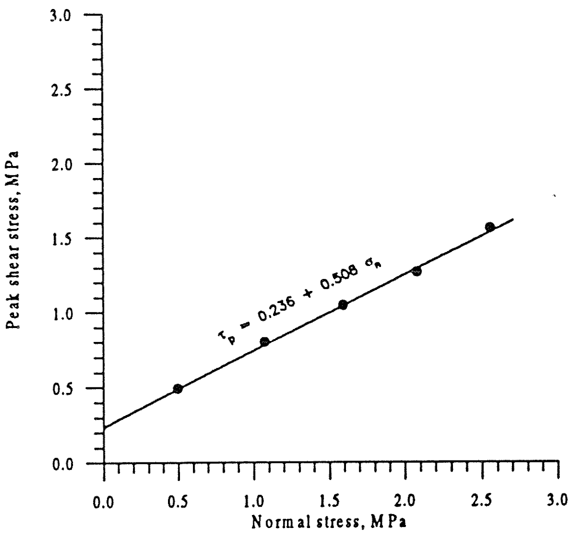

Figure 10. Strength envelope for natural joints (Kangaroo Valley) under CNS.

7. MATHEMATICAL MODELLING OF JOINT SHEAR BEHAVIOUR

7.1 Characterisation of Joint Dilation

In order to characterise the joint dilation during shearing of the specimen, Fourier transform technique (Spiegel, 1974) has been adopted in this study. The successful application of the Fourier series in the field of rock mechanics for saw-tooth joints has been discussed by Indraratna et al.

(1998b). Fourier series is normally used to define a continuous function $f(x)$ which is integrable along the period 2π, and has an integrable derivative at some interval (a, b). The following form of Fourier series is adopted here to characterise the joint profile for a prescribed period, T = b - a:

$$\delta_v(h) = \frac{a_o}{2} + \sum_{n=1}^{\infty}\left[a_n \cos(2\pi nh/T) + b_n \sin(2\pi nh/T)\right] \qquad (1)$$

where,

$$a_n = \frac{2}{T}\int_a^b f(x)\cos\frac{2\pi nx}{T}dx\text{, and} \qquad (1a)$$

$$b_n = \frac{2}{T}\int_a^b f(x)\sin\frac{2\pi nx}{T}dx \qquad (1b)$$

The Fourier series is calibrated to match the exact joint dilation with horizontal displacement, where the coefficients a_n and b_n are determined from the experimental data. It is assumed that for the natural joint, the dilation vs horizontal displacement curve is continuous for a given period as observed for saw-tooth joints. Based on this assumption, the current test data are used to calculate the Fourier coefficients for all the joints after shearing under different initial normal stresses, σ_{no} (Table 1). The value of a_o is observed to decrease with the increase in σ_{no}, thus indicating considerable shearing of asperities.

7.2 Variation in Normal Stress

Once the joint dilation [$\delta_v(h)$] with horizontal displacement (h) under a given initial normal stress (σ_{no}) is fitted to the Fourier series (Eqn. 1), the variation of normal stress under constant normal stiffness (k_n) can be determined by Eqn. 2:

$$\sigma_n(h) = \sigma_{no} + \frac{k_n.\delta_v(h)}{A} \qquad (2)$$

where, $\sigma_n(h)$ = normal stress at any horizontal displacement, h; σ_{no} = initial normal stress; k_n = normal stiffness; $\delta_v(h)$ = dilation corresponding to horizontal displacement, h; A = joint surface area.

7.3 Prediction of Shear Stress

The asperity angles tend to decrease with the increase in horizontal displacement as observed from the dilation behaviour. The higher the initial normal stress (σ_{no}), the more the asperity degradation occurs. Unlike in many previous joint models where the asperity angle (i) was regarded as constant, the Fourier analysis permits degradation of the asperity angle as a function of horizontal displacement, $i_{(h)}$. Subsequently, the shear stress response with the horizontal displacement can be calculated from Eqn. 3 as given below:

$$\tau(h) = \sigma_n(h)\tan\left[\phi_b + i(h)\right] \qquad (3)$$

where, $\sigma_n(h)$ is given by Eqn. 2; ϕ_b = basic friction angle; i(h) = inclination of the tangent to the dilatancy curve at any horizontal displacement, h.

Considering the fact that both $\sigma_n(h)$ and i(h) are continuous functions, the solution for 'peak' shear stress (τ_p) always exists, and it can be numerically determined using a computer subroutine.

8. VERIFICATION OF PROPOSED MODEL

The mathematical model which was previously applied to saw-tooth joints (Indraratna et al., 1998b) have been used to predict the shear behaviour of the natural joint under CNS condition. The Fourier Coefficients, surface profile properties, initial normal stress, normal stiffness and basic friction angle are used as input parameters in the computer program. The predicted output includes the shear stress with displacement, normal stress variation and peak shear stress. The shear behaviour of a typical field joint based on the predicted results is shown in Fig. 11. A comparison between the experimental and predicted results of peak shear stress and corresponding normal stress is summarised in Table 2. It is observed that the model prediction for peak shear stress and normal stress for the field joints is in good agreement with the experimental results, within acceptable accuracy. It is important to note that the model (predicted) peak shear stress is smaller than the laboratory value, as the work doneby the joint during dilation against the normal stress is underestimated in the proposed model. However, in the field it is difficult to obtain the intial asperity angles accurately. Therefore, a simplified form of shear strength model needs to be considered, where the natural joints are simulated as practically as possible.

Table 1. Fourier coefficients for field joints after testing.

Joint	σ_{no}, MPa	a_o	a_1	a_2	a_3	b_n
F1	0.56	0.25964	-0.17575	-0.04642	-0.02125	0
F2	1.10	0.13800	-0.06860	-0.04001	-0.00578	
F3	1.63	-0.14600	-0.03899	0.01799	0.01638	
F5	2.16	-0.31650	0.037840	0.00998	0.02544	
F6	2.69	-0.50600	0.063540	0.05661	0.03587	

Table 2. Comparison between predicted and laboratory results.

Joint	σ_{no}	Laboratory		Predicted	
	(MPa)	τ_{peak}, MPa	σ_n, MPa	τ_{peak}, MPa	σ_n, MPa
F1	0.56	0.48	0.50	0.44	0.68
F2	1.10	0.80	1.07	0.75	1.13
F3	1.63	1.04	1.58	1.06	1.60
F5	2.16	1.26	2.08	1.34	2.08
F6	2.69	1.55	2.55	1.68	2.56

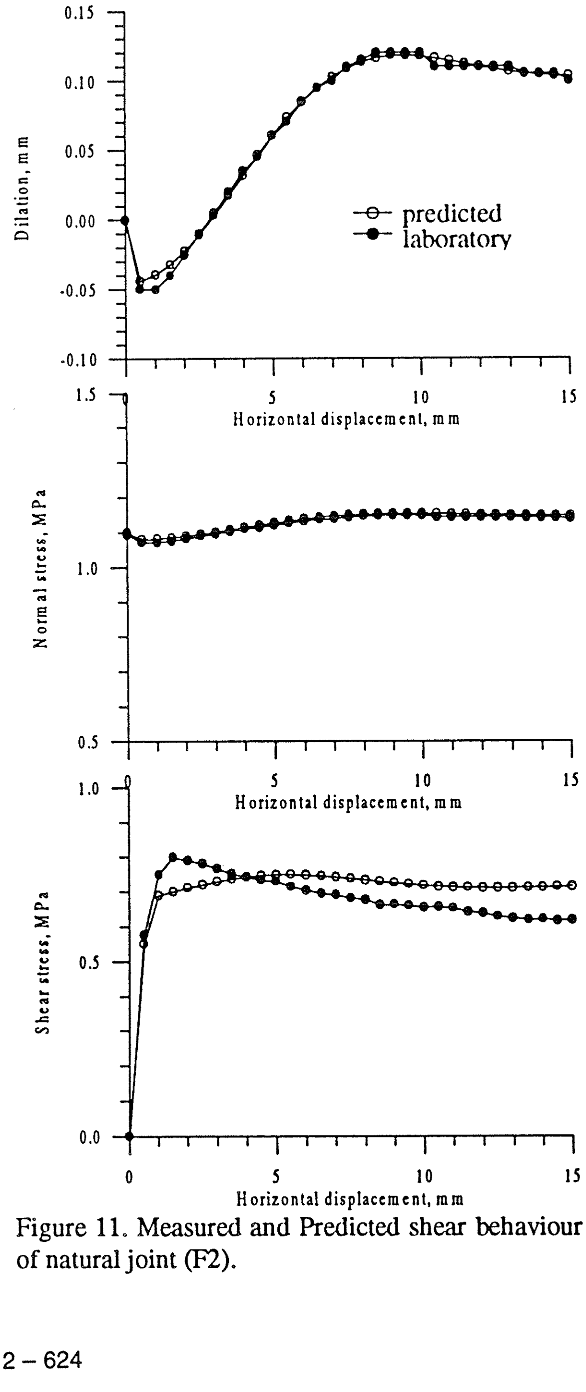

Figure 11. Measured and Predicted shear behaviour of natural joint (F2).

9. PRACTICAL APPLICATION OF THE CNS RESULTS

The CNS test results can be used in various field situations eg. stability analysis of the roof of underground excavations in jointed rock mass and rock slope with major discontinuities supported by fully grouted bolts.

By knowing the Fourier coefficients of a particular joint (Figure 12), the dilation behaviour of the joint system can be predicted at any normal stress. Once the dilation characteristics are known, normal stress and shear stress responses of the joint can be modelled accurately from equations 2 and 3, as mentioned earlier.

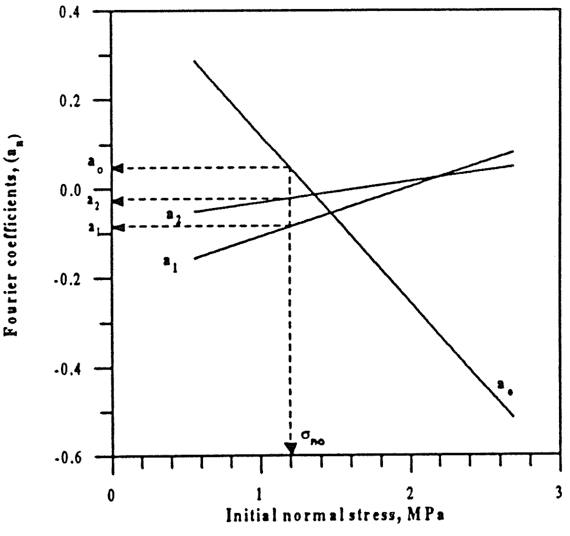

Figure 12. Fourier coefficients for various normal stresses.

10. CONCLUSIONS

The shear behaviour of the natural sandstone joints was investigated in laboratory under Constant Normal Stiffness (CNS) conditions, which are closer to the actual field situations. The natural joint surfaces are precisely characterised using a digital Coordinate Measuring Machine (CMM). Test results show that the peak shear stress of joint increases with the increase in initial normal stress (σ_{no}). The joint is dilatant under smaller σ_{no} say, 1.63 MPa thereby, increases the normal stress during shearing. The joint behaviour is fully compressive under elevated σ_{no}. A linear strength envelope is found to be appropriate for explaining the strength of field sandstone joints under CNS condition. The mathematical model proposed in this study can explain the degradation of the joint very closely. The predicted shear strength of field joints is compared with the experimental results and it is verified that the model predicts the laboratory behaviour within acceptable accuracy.

11. ACKNOWLEDGEMENT

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