Desiccation Assessment in Puddle Clay Cores

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SYNOPSIS. The embankment dams to Banbury Reservoir and Lockwood have a history of high level leakage, clay core repairs and TWL restrictions. Current TWL restrictions posed a risk of damage to the kneeler beam of Banbury Reservoir during storms, whilst on Lockwood Reservoir undermining of the kneeler beam and associated slabing due to exposure to wave action was actively occurring. In seeking relaxation of the restrictions to mitigate damage, and to recover potential storage capacity, Thames Water were requested by the AR Panel Engineer to complete a desiccation assessment. This paper describes the principles and techniques adopted for the desiccation assessment of the clay cores, including laboratory testing of high quality samples and the installation and monitoring of two arrays of GeO flushable piezometers. Visual inspection did not identify desiccation cracks within the cores, although there is evidence that the cores have previously been desiccated to greater depth. The potential of desiccation processes is highlighted, with the monitoring of pore pressures within the clay cores demonstrating the seasonal activity and depth within the clays cores to which suctions can be experienced.

INTRODUCTION

Top Water Level (TWL) restrictions to Banbury Reservoir and Lockwood Reservoir posed a continued risk of damage to the internal slabing of Banbury Reservoir during storms, whilst on Lockwood Reservoir undermining of the slabing due to exposure to wave action was actively occurring. In 2003 Thames Water sought the relaxation of the restrictions to mitigate the risk and with the added benefit of recovering raw water storage within the Lee Valley. A desiccation assessment was requested by the AR Panel Engineer in advance of any trial raising of the reservoir levels. The initial desiccation assessment was undertaken in March 2004, with monitoring of soil suctions at a selected site on each reservoir continuing until May 2005.

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RESERVOIR DESCRIPTION

Inaugurated in 1903 Banbury Reservoir and Lockwood Reservoir are both non-impounding storage reservoirs formed by continuous earth embankments, with a central puddle clay core keyed into the underlying London Clay Formation. Located within the flood plain of the Lee Valley the reservoirs were founded on “soft” Alluvial soils. The puddle clay cores were constructed using the underlying alluvial clays of very high to extremely high plasticity. The shoulders or “Filling” comprises a mixture “clayey Gravels” and “gravely Clays”, Figure 1. Both reservoirs experienced considerable settlement, up to some 10% of the core height above surrounding ground level in the 40 to 50 years post construction.

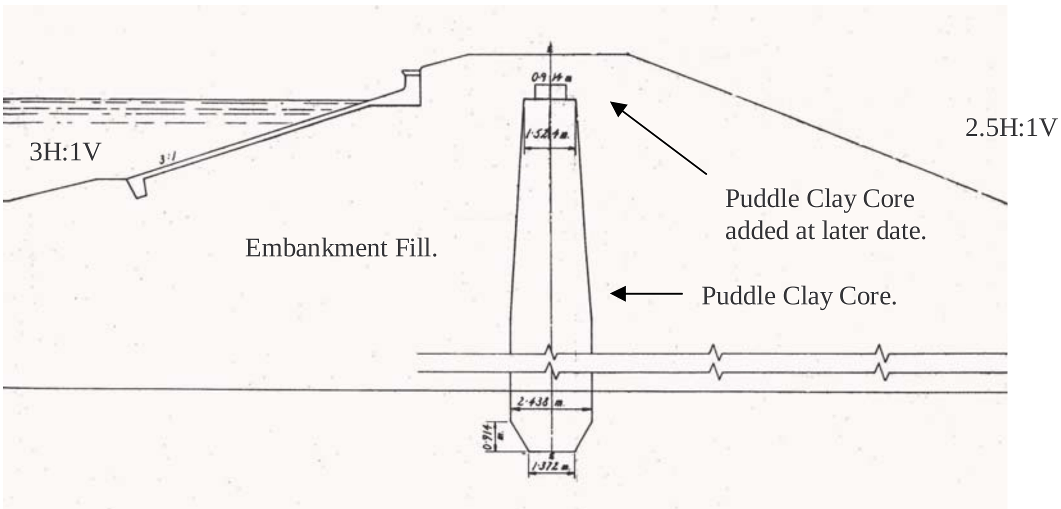

Figure 1: Representative Embankment Cross Section of Lockwood Reservoir

During the Second World War the reservoirs were kept at a lower water level, Lockwood requiring repairs at two locations due to bomb damage. It is suspected that during this period the top of the puddle clay cores may have “dried out” to the extent that leakage occurred during refilling. Raising of the clay cores was undertaken on Lockwood Reservoir during 1943 to 1945 and on Banbury Reservoir between 1957 to 1958. No specific information has been found with respect to the selection of the material for raising the cores. Whilst it is anticipated that a key with the existing core would have been provided (as the case for the raising of the clay core to the Warwick Reservoirs undertaken during a similar period) this is not shown on record drawings.

Occurrences of leakage continued throughout the 1960's to the 1980's with a series of investigations undertaken and TWL restrictions applied. A number of remedial works were subsequently completed during the 1970's to 1980's including asbestos sheet piling, grouting and core remoulding (Ray and Bulmer, 1984.)

THE ASSESSMENT OF DESICCATION

A soil is desiccated when it has either (i) soil suction in excess of that, which would be expected or (ii) a moisture deficit.

Soil Suction

Traditional assessments of desiccation make use of suction measurements to identify its presence. The stresses on an element of soil in the ground are made up of vertical (σ_v) and horizontal (σ_h) total stresses and the pore water pressure (u) at the depth of the element.

$$p' = (\sigma_v + 2\sigma_h) / 3 - u$$

When an element of soil is removed from the ground the total stresses are reduced to zero and the pore water pressure becomes negative (i.e a suction). If the sampling is perfect and the sample is truly undisturbed the soil suction will be equal to the effective stress in the ground (p'). If the soil is desiccated the measured suction will be greater than the expected in situ effective stress. This is evident as a bulge in the soil suction/depth plot (Figure 2).

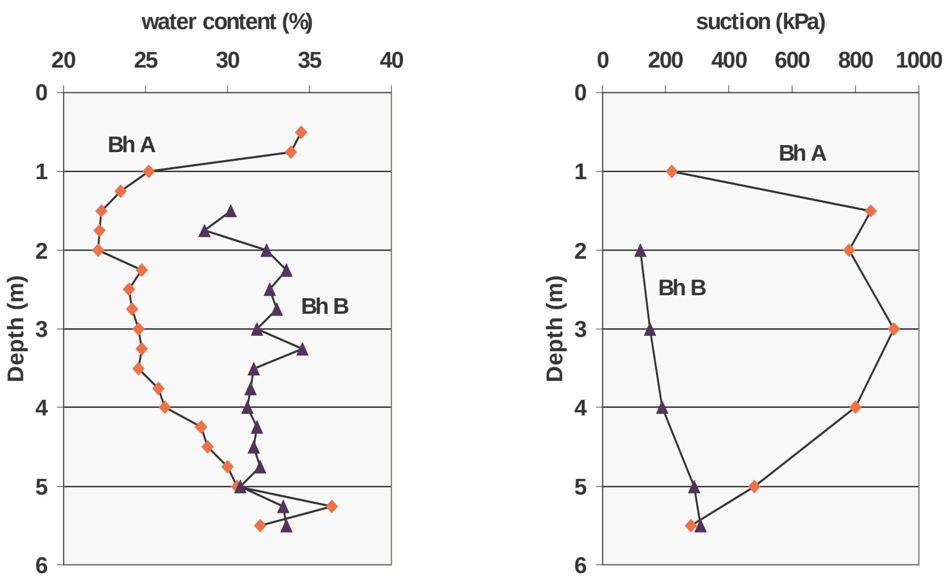

Figure 2: Typical profiles of water content and suction in a desiccated location (A) and a normal location (B), after BRE (1996.)

IMPROVEMENTS IN RESERVOIRS

In an embankment the initial stress condition on an element of soil in the ground is complicated by the fact that it lies above the natural ground surface and above the natural water table. Therefore there are no significant horizontal stresses on the soil, particularly at shallow depths. Moreover the compaction, which occurred when the core of the embankment was constructed, would have introduced an inherent suction into the clay. The magnitude of the suction measured now may provide an indication of desiccation, whether current or historical.

Moisture Deficiency

Soil moisture deficit (in mm) is defined at the amount of water per unit surface area, which the soil surface will absorb before further precipitation cannot be stored in the profile (i.e the soil has reached it's field capacity, although it is not necessarily saturated in this state). Volumetric water content (θ) represents the volume of water in an element of soil and is defined as follows:

$$\theta = (S_r.e) / (1+e)$$

Where, S_r is the degree of saturation and e is the void ratio.(Note: In a saturated soil the volumetric water content is equal to the porosity, n)

The moisture deficit for an element of soil is the difference between the volumetric water content at field capacity and the desiccated volumetric water content. The soil moisture deficit is measured over the whole profile and is the difference between the volumetric water content profile at the field capacity and the desiccated volumetric water content profile, Figure 3.

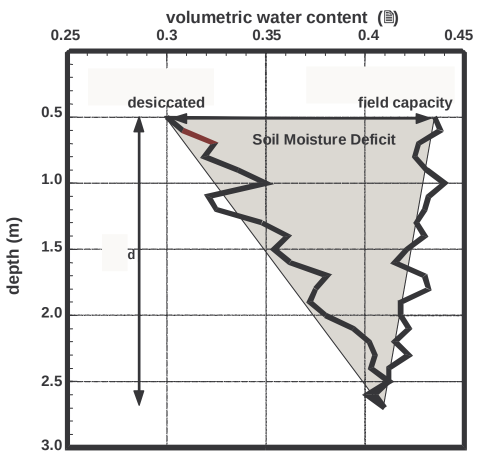

Figure 3: Illustration of Soil Moisture Deficit in the ground for a desiccated profile and a profile at field capacity.

Void ratio and degree of saturation are mutually dependent. Therefore in the absence of direct measurements of volumetric water content it is acceptable to represent moisture deficit in terms of the degree of saturation estimated from the measurements of the bulk density, water content and specific gravity (G_s).

$$\gamma_{bulk} = .\ \gamma_{water}.(G_s+S_r.e) / (1+e)$$

$$S_r = (w.G_s) / [G_s(1+w).(\gamma_{water}/\gamma_{bulk})-1]$$

FIELD SAMPLING AND LABORATORY TESTING

Samples of the clay core were retrieved using thin walled "Shelby" sample tubes. To improve recovery and reduce the amount of disturbance each 1m tube was only pushed 0.5m into the clay core. Samples were extruded using a hydraulic jack with a leveling platform, with the direction of extrusion consistent with the sampling direction.

Standard laboratory testing was undertaken including;

- Gravimetric Water Content
- Atterberg Limits
- Bulk Density
- Suction

In addition the degree of saturation was inferred from the measurements of bulk density and water content, using assumed values of specific gravity. Suctions were measured using suction probes adopting the technique presented by Ridley et al (2003).

The results of the laboratory testing from the samples obtained at Chainage 600 on Lockwood Reservoir are shown in Figure 4 (a to d). The results for bulk density, degree of saturation and water content all indicate that there has been some desiccation at an elevation of 13m to 13.5m. This is consistent with the bulge in the graph of suction verses depth and coincident with the restricted top water level. It should be noted that the suction measurements provide only a representation of the suction at a point in time. The investigations were undertaken in March 2004 and the suctions are only considered representative of end of winter.

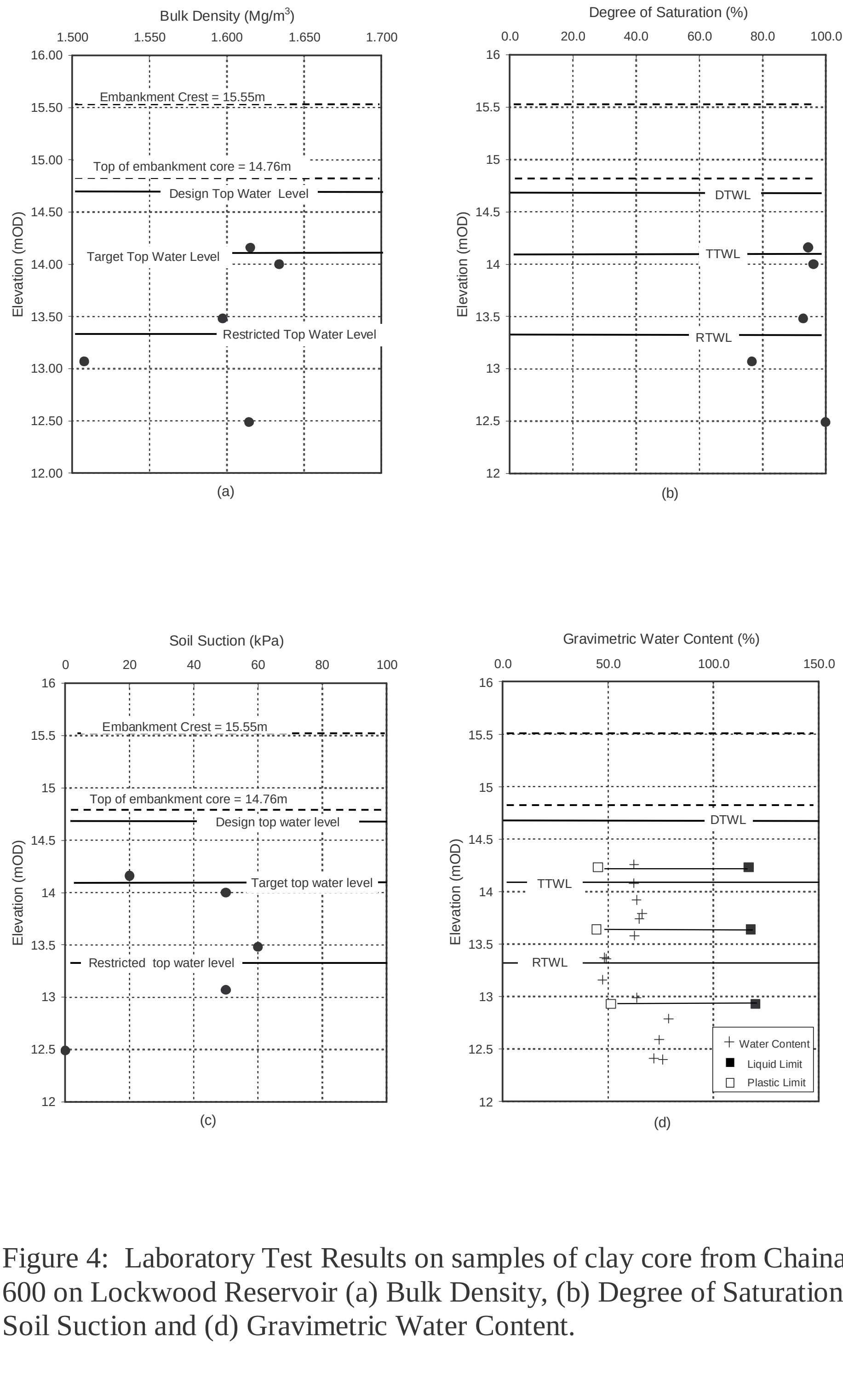

Figure 4: Laboratory Test Results on samples of clay core from Chainage 600 on Lockwood Reservoir (a) Bulk Density, (b) Degree of Saturation, (c) Soil Suction and (d) Gravimetric Water Content.

SUCTION MONITORING

With the suction measurements undertaken on the samples only providing a reference of the end of winter conditions within the clay core GeO flushable piezometer's were installed to investigate the seasonal behavior of suctions within the clay core. Although GeO piezometers are widely used in investigating embankments and slopes, this was the first application of the instruments within the clay core to an embankment dam.

GeO Piezometers were installed at Chainage 600 on Lockwood Reservoir at three depths;

- between the Design TWL (14.69mOD) and Target TWL (14.09mOD),
- between the Target TWL (14.09mOD) and Restricted TWL (13.37mOD),
- below the current Restricted TWL (13.37mOD),

This is shown on Figure 5. A similar array was also installed on Banbury Reservoir at Chainage 300. The monitoring period for the GeO piezometers ran from April 2004 through to May 2005, during which period the reservoir level's in both Lockwood Reservoir and Banbury Reservoir was maintained close to the restricted TWL's with no significant operational drawdown experienced. The results of the monitoring are shown in Figure 6 (a to c).

At all depths the GeO Piezometers show strong seasonal response, with suctions reaching a maximum at the end of summer. The response from the GeO Piezometers at 1.04m and 1.64m depth recorded suctions in excess of 90kPa. The GeO Piezometer at a depth of 2.48m, approximately 0.7m below the current Restricted TWL, approached a suction of 80kPa.

Although not presented herein the suctions of the array of GeO Piezometers installed at chainage 300m on Banbury Reservoir showed a similar seasonal response. Suctions approached 80kPa above the Restricted TWL and 30kPa below the Restricted TWL.

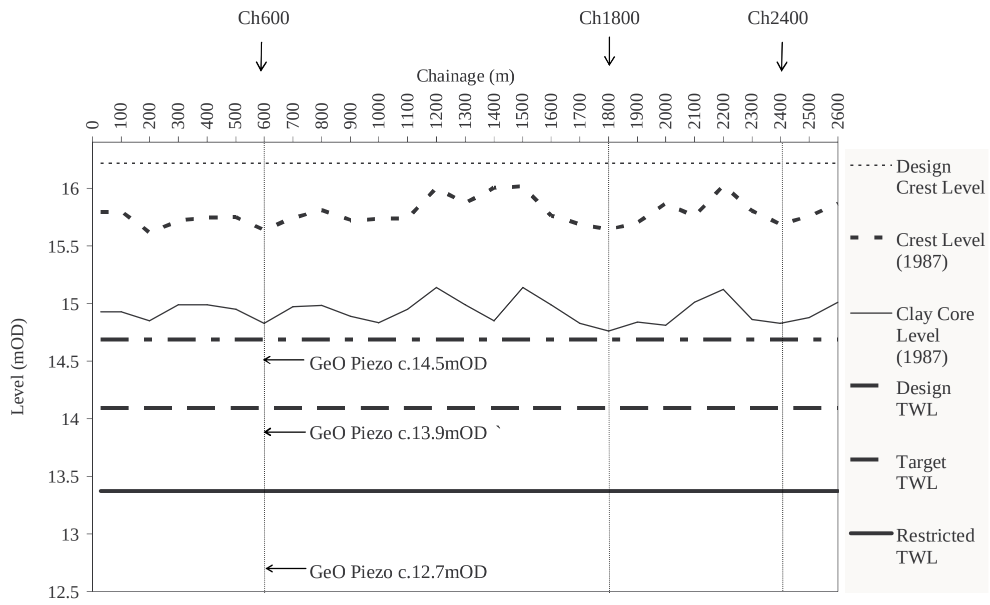

Figure 5: Long Section for Lockwood Reservoir, showing TWL, Clay Core Level and locations of the GeO Piezo's.

DISCUSSION

There is an obvious link between suction and the development of desiccation cracks. Visual inspection of cores retrieved during the investigations considered that there had been previous desiccation and this is consistent with the historical observations of leakage and remedial works.

The monitoring record from the GeO Piezometers has provided confirmation of the seasonal behavior as might be expected and has also provided an initial indication of the magnitude of the suctions and depths to which they may be experienced. Whilst monitoring results will vary from year to year, further research would be required to establish;

- to what depth are the seasonal variations in the core effective
- how much above 100kPa were the suctions experienced

The latter may be addressed by the measurement of suctions from undisturbed samples taken at different seasonal periods, i.e. at the end of winter and at the end of summer.

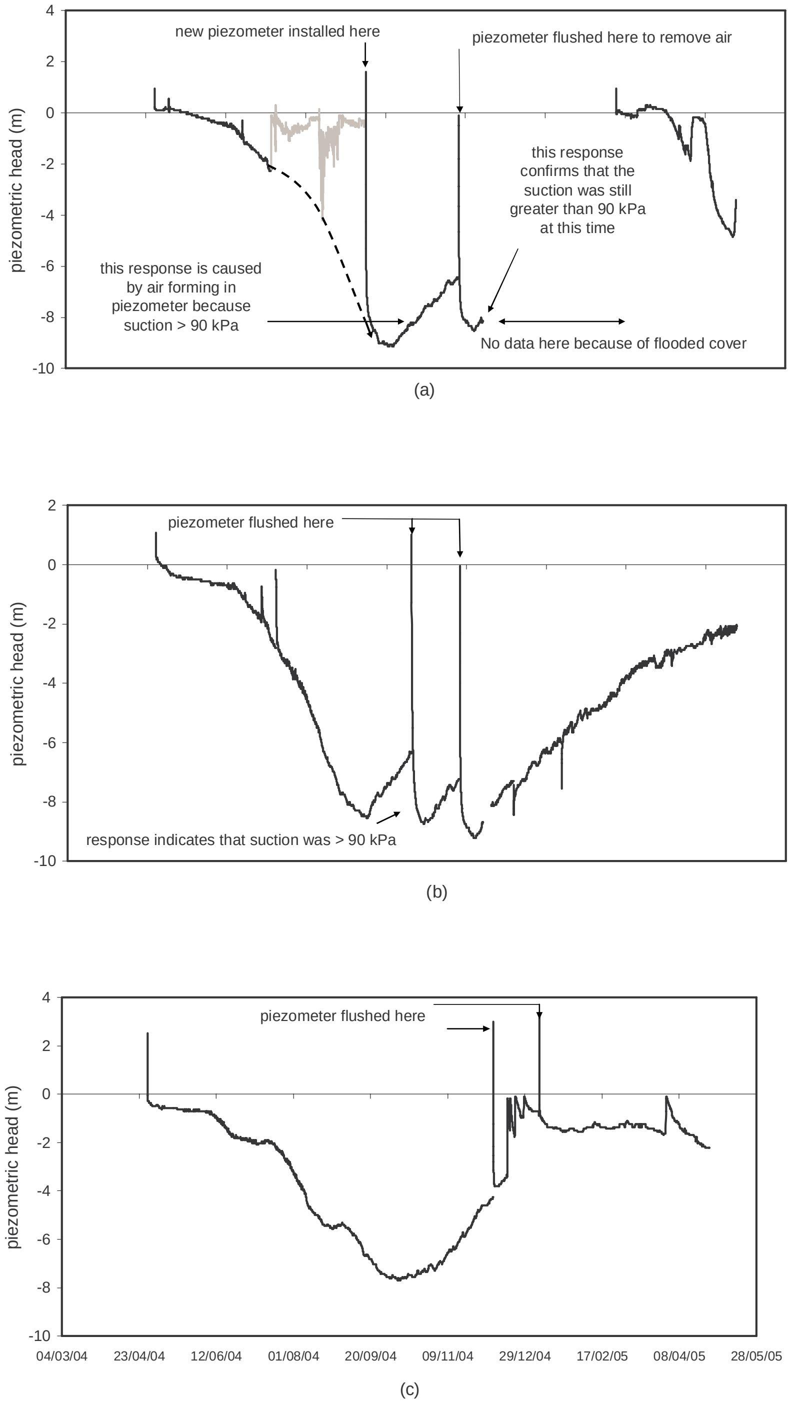

Figure 6: GeO Piezo Suction Measurements at Chainage 600 on Lockwood Reservoir (a) depth 1.04m between Design TWL and Target TWL, (b) depth 1.64m between Target TWL and Restricted TWL, and (c) depth 2.48m below Restricted TWL.

Whilst at Banbury Reservoir and Lockwood Reservoir there were no physical indications of cracking of the clay core, as would result in high level leakage, there is clearly the potential for cracking to occur as a result of desiccation. It is therefore reasonable to anticipate that high level leakage could occur in the future, particularly upon refilling after reservoir drawdown and / or during drought event years.

Owners need to be aware of this mechanism, with high plasticity clays more likely to suffer desiccation and potential settlement, and to recognize that increased surveillance is clearly very important during such periods. Whilst high level leakage occurring from desiccation may not necessarily be a threat to the safety of a dam it will restrict operational performance until the leakage has been addressed.

ACKNOWLEDGEMENTS
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