EASY STATIC LOAD TESTS: EXPERT RESULTS

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Test equipment has been developed to record automatically both the displacement of the pile head and the load applied during a conventional maintained load pile test. Some systems also have, in addition, been fitted with the facility for maintaining the applied load, as set by the operator, at very constant levels.

The advantages are both commercial and technical, but a well trained operator has to be in attendance to control the test. Since typical test specifications in the UK require more than 19 hours to complete, it became inevitable that at least one equipment operator remained on site to expedite the test for its duration. Although electronic measurement and data logging of load tests may be more safe than previous direct observation of dial gauges. A single person remaining on a construction site alone is not to be recommended, even if they are just supervising the test.

Further development of the testing system produced equipment which will perform the entire test specification as required without operator intervention. To achieve this, full automation is employed. The patented method particularly addresses the safety requirements and by using additional sensors, detects any uncharacteristic behaviour of the pile under test or of the reaction system and the equipment takes appropriate action in a controlled and safe manner.

The quality of test data returned from these automated systems is a key element when analysing pile behaviour with models such as *CEMSOLVE*™ and *TIMESET*™. These analysis methods often indicate ground disturbance resulting from installation technique and have allowed pile design to be optimised using actual field data rather than theoretical considerations alone.

An additional feature is remote access, this allows the data recorded to be transferred and the progress of the test to be viewed from practically any location. This permits experts to view the data 'live' and allows rapid diagnosis of any problems with the expected pile behaviour.

Introduction

The manner in which static load testing of piles is performed has changed substantially in the last decade. Previously, an entire test would be performed manually; with the load applied by a hand operated hydraulic pump and using a pressure gauge or a load column to determine the load. The displacement of the pile head was recorded generally using dial gauges. It was rare to find any degree of automation in this area.

Automation of the entire system has progressed through several different stages:

1) initially the displacement of the pile head was measured and recorded automatically using a datalogger arrangement;

2) electronic load cells were brought into use and logged automatically;

3) hydraulic control systems were then developed to maintain the load truly constant at regular intervals without manual intervention,

4) by assessing the measured data, the test was controlled automatically according to a prescribed specification.

Automatic measurement of pile head displacement and load

The development of dataloggers allowed the introduction of displacement sensors and load cells which are measured electronically. Digital recording of these measurements may be made at regular intervals.

Many suitable electronic displacement sensors are commercially available, allowing total displacements of up to 250 mm to be measured with excellent resolution. The only difficulty in making a choice is the wide variety of transducers to choose from. The preferred and most reliable sensors in the author's experience, have proven to be resistive elements that employ a carbon strip such as those from Penny & Giles.

Several different manufacturers provide dedicated data collection hardware with programmable functionality. Such equipment is capable of reading up to 160 sensors per datalogger, sometimes using multiplexers (automatic channel selectors). Typically data can be transferred from these loggers by direct link, modem interface or various telecommunication devices. Often 500000 data points can be stored and remain in memory for retrieval when convenient. It has been the experience of the author that for static loading tests, recording of displacement and load every one minute provides both suitable and ample data for most applications.

The automatic recording of pile head displacement revealed other deficiencies in the overall pile testing scenario. The most important consideration was the application of truly constant load.

Typical data required from a conventional static load test are the record of displacement of the pile head and the load applied. Although the manual reading and recording of dial gauges employed in a static loading test should present no insurmountable difficulty in terms of accuracy and regularity, it is the application of the load that generally is the source of poor quality data. This is principally because of the need to attend to a manual hydraulic pump continuously to maintain the load with any order of constancy. Inaccuracy is further exacerbated by the fact that sometimes a pressure gauge is employed to derive the force applied, using suitable calibration charts.

If manual load control is attempted, it is found generally that if the load is measured using a hydraulic pressure gauge which can be resolved only to the nearest 1%, the actual load control resulting is unlikely to be better than 2%.

To assess the consequences of a 2% variation of load on a test pile, consideration need only be given to the elastic behaviour of the pile shaft which may easily be around 5-10 mm at the maximum test load. The load variation will produce a variation of recorded displacement of up to 0.2 mm. For consistent interpretation of the displacement-time behaviour it has been found that the load control accuracy needs to be an order or magnitude better than can be achieved manually[1].

Two examples are presented below of typical displacement-time behaviour, recorded automatically under "nominally constant" load. Although every effort was exercised to perform the load tests in the best possible manner, and restore the load to the desired value before the readings were taken, the displacement-time graphs show erratic behaviour.

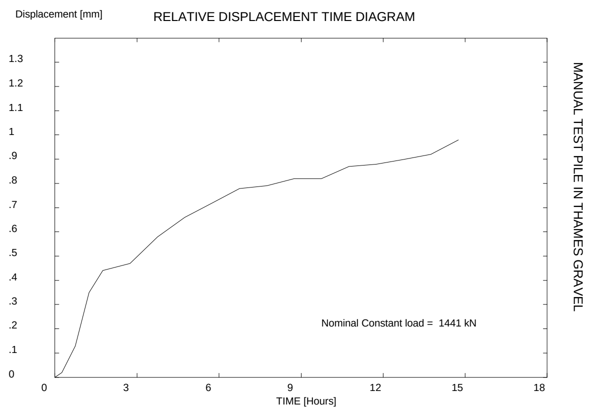

Figure 1 Manually restored load during testing of a 425 mm diameter pile 15 m long based in Thames gravel

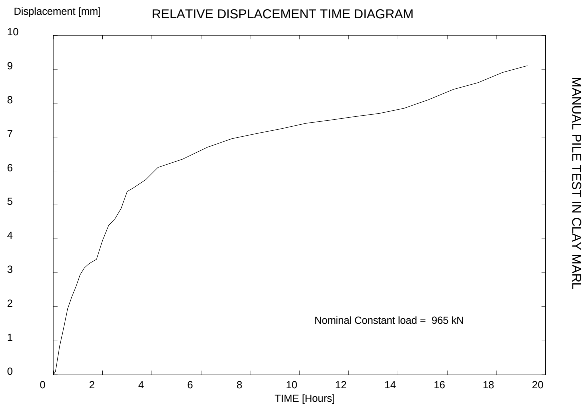

Figure 2 Manually restored load during testing of a 600 mm diameter pile 12 m long in firm clay Marl

Automatic load control

In contrast to manually controlled load application, the alternative is to employ an electronic load cell and a computerised load maintaining arrangement; the logger can be programmed so that the magnitude of load applied is checked every few seconds and a correction to the applied load actioned if the deviation is greater than an arbitrary figure, say 5 kN or 0.1%. It should be noted that reliance is placed on the resolution of the load measuring system to maintain the applied load constant to within 0.2% for most typical test loads.

Air driven hydraulic pumps are used. These work on a differential area piston principle, applying air to the large surface area of the air drive piston which is mechanically connected to a smaller hydraulic piston, so converting pneumatic energy into hydraulic power.

The significance of constancy of load application becomes clear when the resulting displacement-time characteristic is reviewed. Two examples are presented below in Figure 3 and Figure 4 where the load has been held constant, one is for a pile in clay the other for a pile in sand and gravels.

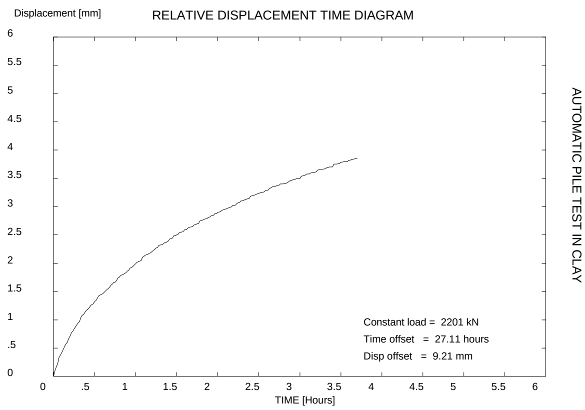

Figure 3 Relative displacement time of a pile in Clay under constant load

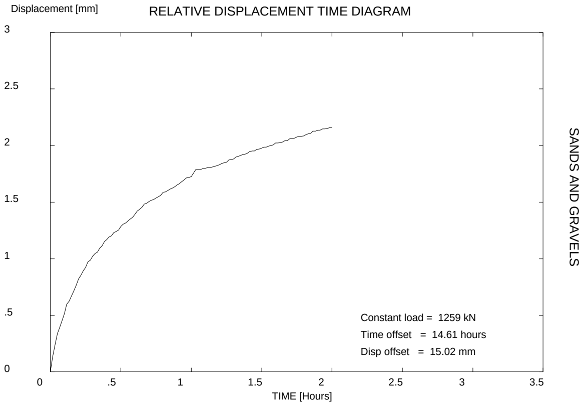

Figure 4 Relative displacement-time of a pile in sands and gravels under constant load

The consistently smooth deformation pattern has permitted the development of mathematical models which can be made to match the data, such as *TIMESET,* England(1992, 1999)*.* This has only been possible with the application of loads which have been maintained constant within very narrow tolerance.

To illustrate the *TIMESET* analysis method the data shown in the previous Figure 3 and Figure 4 have been modelled mathematically by the two relevant linear-fractional functions as shown below. The matching curve is represented by the addition of the two functions marked 'Ts' and 'Tb'.

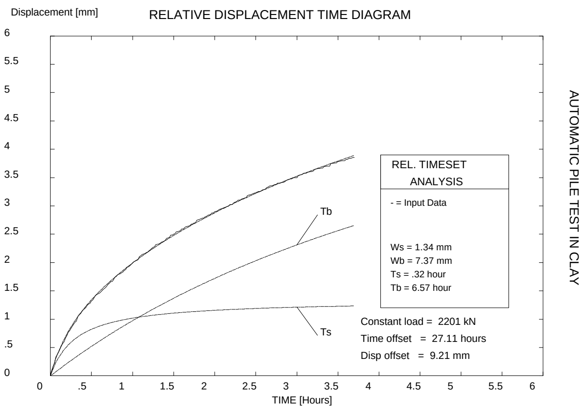

Figure 5 Relative *Timeset* analysis of an pile in Clay

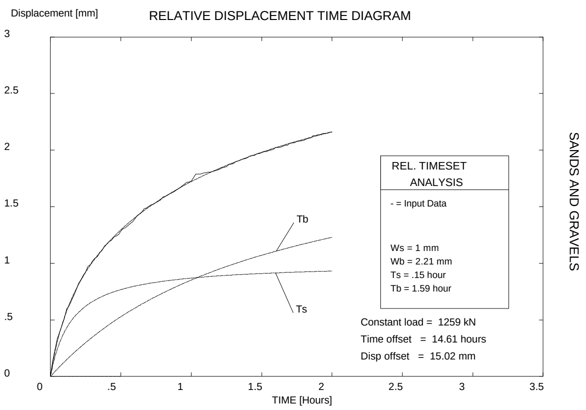

Figure 6 Relative *Timeset* analysis of a pile in sands and gravels

The purpose of this form of displacement-time analysis was initially to allow the forecasting of long term deformation that would result if the load was maintained indefinitely to allow pile behaviour analysis to be independent of the duration of each load hold. However, it transpires that the pile behaviour under constant load also reveals information about the mechanisms controlling the pile behaviour. Further, departure from the modelled behaviour can be recognised and can be of great assistance with interpretation of data.

The ability to recognise departure from an expected deformation-time pattern, allows for example, the evaluation of the suitability of the settlement measuring reference frame. A stable datum is particularly important to achieving accurate measurement of vertical movements. An assembly and a simple reference beam arrangement have been developed so that they are reasonably immune to temperature induced variations.

The results from a large number of tests, typified by the two examples above, is that the method is generally applicable and is not associated with specific soil types. Further, it can be deduced that permeability does not have a great influence on the deformation-time behaviour observed under these test conditions.

Although a considerable amount of pile test data have been recorded in the past, complete analysis has usually been difficult because, in general, poor quality impeded such close examination. The development of automated static loading test systems has allowed better analysis to be made and simple behavioural models have been developed, such as *CEMSOLVE* to characterise foundation behaviour both in time England (1992) and under load, Fleming (1992), in a manner independent of the testing programme.

CRP (constant rate of penetration) tests are however of significantly less value when maintained load tests are capable of delivering this enhanced information. It transpires that CRP test enhance pile capacity and underestimate the load-settlement characteristic.

Development of complete automation of the test

After several thousand static load tests performed with automatically maintained load and automatic measurement and recording, it has become possible to detail anomalous behaviour resulting from failure of an element of the testing arrangement. Structural failure of the test pile or of the anchor piles or failure/problems with the equipment can usually be identified precisely. A challenge has been to design a data monitoring and control system which could evaluate the safe progress of the test, calculate the settlement rate of the pile head, and decide in a manner superior to that possible by manual observation, whether the test should progress to a different load, pause or stop safely.

Although 95% of the tests performed to date could be adequately and safely controlled using the existing sensors (four displacement sensors on the pile head and one load cell), to catch the remaining 5%, additional information relating to the integrity of the reaction system is needed.

In addition to the displacement sensors measuring the pile cap displacement, a fifth sensor is employed to monitor the deformation of the reaction system to ensure its safety and also monitor the extension of the jack. As a precaution, an electronic bunting arrangement ensures detection of any unauthorised access to the area and automatically pauses application of any further load should its integrity be violated.

A remote control facility has also been integrated into the new systems by radio communication link using a digital mobile phone. This allows progress/control of the test to be viewed remotely.

It is not desirable for a single operator to be in attendance on site on his own, as may often be the case during the night; this specific aspect is overcome with the completely automatic system because all the anticipated atypical responses of the system are sought in the measurements being made. Thus the controlling computer can decide on the reliability of the arrangement and whether it is safe to proceed. In the unlikely but possible failure of the reaction system or test pile, the action taken by the automatic system is organised to ensure safe progress of the test and it can report telephonically that a specific event has occurred.

The automatic load testing system is illustrated diagrammatically in Figure 9.

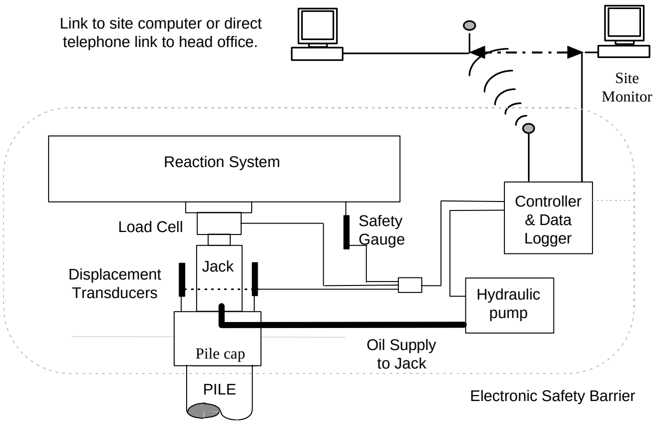

Figure 9 Load test equipment diagram

The fifth gauge can be conveniently mounted with magnetic clamps, between the body of the jack and the underside of the reaction beam, as illustrated in Figure 7.

Some engineers, and Specifications, insist on secondary measurement of the pile head displacement during a test which is independent of the reference frame and using precise levelling. This is a wise precaution, however, it should be appreciated that the accuracy that can be achieved with the use of optical precise levels is low in relation to small pile head deflections. Attempts to check the position of the reference frame often cause measurable disturbances when the staff is placed upon it.

An alternative solution to precise levelling, is the use of the fifth displacement sensor which measures movement between the pile head and the underside of the reaction system. It can give a much better estimated pile head movement than could ever be achieved by using levels - and the data is measured in synchronism with the displacement sensors on the pile head.

Figure 8, by way of example, shows the pile head displacement from the average of the 4 gauges between the reference frame and the pile head and

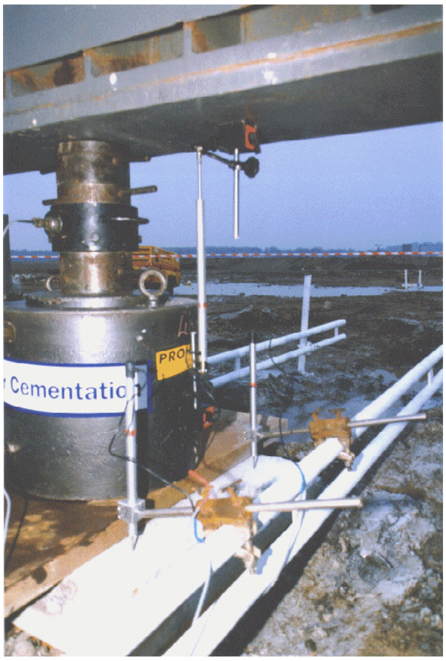

Figure 7 Displacement sensors on the pile head

also the results from the fifth gauge, which is measuring the displacement of the underside of the reaction beam with respect to the pile head.

In order to reproduce the pile head displacement from the fifth gauge alone, it would be necessary to assume that the reaction beam followed a linear elastic behaviour. The modulus of elasticity would also need to be estimated or this may be derived from previous experience or from the initial loading data. It then remains to subtract the elastic deformation of the reaction beam from the recorded data to obtain a check of pile settlement.

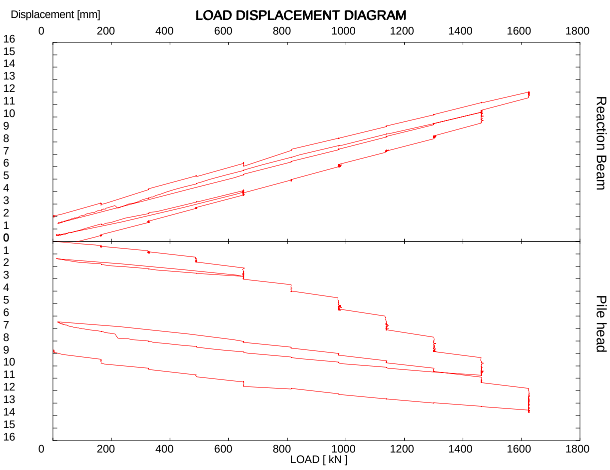

Figure 8 Fifth gauge measuring the pile head and the underside of the reaction beam.

While it may be argued that this alternative measurement with respect to the reaction beam might not be as accurate as direct measurement with respect to some arbitrary fixed point, the displacement of the pile head is overestimated slightly as a result of the reaction beam movement under load. The result is generally more informative than can be achieved with levelling.

Automatic control according to a specified schedule

Most specifications require several specific load steps to be applied and these are to be maintained for minimum intervals of time or until a defined settlement rate has been achieved.

This requires a software program to be generated with the required load steps with loading intervals precisely defined, taking account of the specific settlement rate. The computer program can then control the test load precisely; making the required load changes as required.

Load changes are performed by successively increasing the load in small increments over a short time period until the desired next constant load level is achieved. If the settlement rate during the load change exceeds a specified maximum value the system waits for the imposed condition to be met before proceeding any further.

The computer software intercepts specific fault conditions by monitoring of the data at regular intervals (typically every 2.5 seconds). The following is a summary of the potential conditions which trigger a “fail-safe” situation in which no further hydraulic fluid is pumped:

1. **Eccentric loading:** If the difference between the measured displacement by any two of the displacement transducers exceeds 50% of the value recorded, an undesirable condition may be occurring with unintentional lateral loads being applied to the pile. In extreme cases this may result in structural damage or failure. The fail-safe also detects a misreading from one or more of the sensors.

2. **Changes of applied load**: If the applied load drops by 10% when it should be held constant, a fault condition is detected. This can be caused by abrupt failure of the reaction system or failure of the foundation under test. Depletion of consumables such as hydraulic fluid and compressed air fail safe intrinsically and their supply is not monitored. The effect of problems with the hydraulic pumping will generally be that the load applied will fall and once below the 90% threshold the system will cease to attempt to pump any additional hydraulic fluid.

3. **Battery Voltage:** If the 12 volt battery supplies fall below 10V, the test is discontinued and priority is given to storage of data in a completely passive mode.

4. **Actual Load applied exceeds a maximum allowed:** If the recorded load exceeds a preset maximum, which may be the maximum tolerable by the reaction system, the maximum rating of the jack, or the maximum rating of the load cell, the system shuts down.

5. **Recorded displacement exceeds a preset maximum:** This fail-safe is triggered if the condition is met. It is preset generally as 10% of the pile diameter. This scenario would occur if the pile head has excessive displacement.

6. **Disconnection of equipment electrical leads:** this condition is detected to ensure the reliable connection to all the sensors.

To ensure the settlement rate calculation is appropriate, measurements taken for the previous 8 minutes are used to determine the velocity of the pile head, provided the load has been successfully held constant within a specified boundary. This boundary is slightly larger than that used in the load maintaining control algorithm.

To cover all the hazardous situations experienced, consideration needs to be given to a gradual failure of the reaction system. Failure of the reaction system can for example be either an anchor pile pulling out of the ground, or structural failure of the reaction assembly. If the upward movement of the reaction system is gradual, the load applied may be maintained and the additional displacement sensor is relied upon to detect this scenario and prevent excessive jack travel.

The area surrounding a pile test is normally cordoned off using bunting and often a fine wire conductor system is employed to detect any unauthorised access. This wire is selected so that it will break electrical continuity easily. When such a condition arises the operation of the system is designed to fail safe.

When any of the safety violations are detected, the program is configured so that a digital mobile phone may be put into operation and calls the operator or Head Office to report the current situation. Complete control of the loading and testing system is accessible over a serial data communication line and all the test data can also be transferred so that an appropriate schedule for the completion of the test may at any stage be updated.

10 completely automatic load test systems are now deployed and regularly in use in the UK and Ireland. Providing an easy and simple method for expediting all of the 500 tests Cementation perform each year. An independent test house also operates one of these systems under license with Cementation providing the remote control and night time supervision.

Test equipment justification

The initial cost justification for using the datalogging systems was not based on technical reasons, but was instead centred on the time employed in producing the report and in its quality. The production of the report with computer logged data is practically instantaneous regardless of the quantity of data and requires no typing of data or manual production of graphical displays, thereby minimising possible errors due to manual handling of the data.

As confidence in the ability of the system to operate under battery power increased, a further commercial benefit was found in the fact that the equipment could be left unattended, particularly at night, during which the test could be continued automatically.

Typical tests specified according to current recommendations can readily take nearly 20 hours to complete, England et al (1994); and overnight operation is unavoidable. Where these or longer duration tests are specified, the automatic equipment may be left unattended to progress the test safely. The cost of maintaining engineering attendance is significantly reduced. Further, a single operator can set up and run several tests simultaneously without fear of confusion or error.

Progress of the tests runs according to prescribed testing regimes, thereby significantly enhancing the quality of data returned.

Remote access to the recorded data means that the results can be analysed "live" expeditiously by the most appropriate person. This ability to perform back analysis of the test data and diagnose any changes required to the testing regime is of great value.

Advantages

Some of the advantages of employing the equipment described in this paper are:

I. Simultaneous readings of all transducers may be displayed every 2.5 seconds, with recording at intervals of between 10 seconds and 10 minutes.

II. An operator can be located at a safe distance away from the kentledge or reaction system.

III. Printing and plotting of all data is available directly from the computer: minimising clerical effort for producing reports.

IV. Data are compatible with a suite of programmes for back analysis, allowing accurate and reliable interpretation of the results and characterisation of the factors affecting pile performance.

V. Automatic system control allows for unattended operation if required. This is particularly suitable for overnight tests, although security attendance may be required.

VI. The principal merit of employing the test equipment is found in the analysis of the test results recorded, this is attributable to the high quality of data and the constancy of load applied.

VII. The response to potentially hazardous situations as detected by the computer software is immediate; thereby minimising the likelihood of any damage.

Conclusions

Test equipment has been developed and has found acceptance in the industry. The quality of data recorded from pile tests in terms of load, time and displacement of the pile head has been significantly improved in a cost effective way.

Constancy of load application, which is a vital issue in test analysis, continues to be unmatched by any manual method. The load changes are controlled precisely at predetermined rates, and the risk of over-stressing any components of the loading system and the potential for premature failure of the surrounding soil is reduced.

The equipment has been used for testing various pile types, pile groups and also for testing surface foundations. The systems have been employed for both vertical and lateral loading tests requiring application of constant loads.

Because the quantity of data recorded is augmented with this equipment, recording typically 1000 sets of readings, it has been possible to take advantage of methods of modelling pile behaviour, both in time and under load, which allow test data to be conveniently and accurately represented by a small number of parameters. This in turn permits the results to be compared against design on a regular basis and stored for future reference.

It is of great interest to note how such a simple development has led to a much greater appreciation of overall pile behaviour. By comparison with the design expectation, both the accuracy of forecasting and understanding of the influence of installation method have been enhanced.

U.K. Patent No. 2323174 PCT in application
Cementation Trade Marks: "*CEMSOLVE*", "*TIMESET*"

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