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Steel sheet piling used in the combined role of bearing piles and earth retaining members

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ABSTRACT: Steel sheet piling is traditionally perceived to be a temporary works earth retaining material. It is used to support excavations of which the cofferdam is perhaps the most common form. In this presentation the author discusses current trends in construction practice where reductions in time and cost can be achieved by using sheet piles as permanent load bearing walls. Sheet piles are by definition, structural units which when connected, one to another, form a continuous wall generally for retaining earth and/or water. They are found extensively in permanent applications forming seawalls, floodwalls, jetties and bulkheads - including quay walls for marine terminal facilities. Used in the above situation the sheet piling may utilise fully its earth retaining capacity but take little advantage of its inherent ability to support substantial vertical load. By developing the full carrying capacity of the section in terms of horizontal and vertical components of load the material is well placed to be considered for application into many other forms of construction. Consideration is given in this paper to a basic design approach which involves both geotechnical and structural considerations and their complicated interaction. Possible structural problems are identified, briefly explained and preventative measures are noted.

1 INTRODUCTION

Recent advances in installation technology have seen the introduction of hi-tech and innovative piledriving equipment which can achieve rates of installation and specified driving tolerances, which would not have been possible a few years ago. The ability to drive steel sheet piling to very tight tolerances and to meet strict standards of finish has led to an increase in the material being specified by engineers for permanent applications.

Engineers have taken advantage of these developments and have realised that substantial savings can be obtained in both construction time and cost by utilising the sheet piles ability to perform three functions namely:

a) Support the excavation initially.
b) Form part of the permanent works.
c) Reduce or eliminate the need for a separate foundation by carrying a portion or all of the superstructure load.

There are many areas of sheet piling application where these features are demonstrated. This paper concentrates on one particular area, namely Bridge Abutments where ongoing developments are seeing the material being used in a way that will be of interest to engineers at home and overseas. This particular category of structure is considered under the headings of:

a) Conventional Bridge Abutments
b) Integral Bridge Abutments

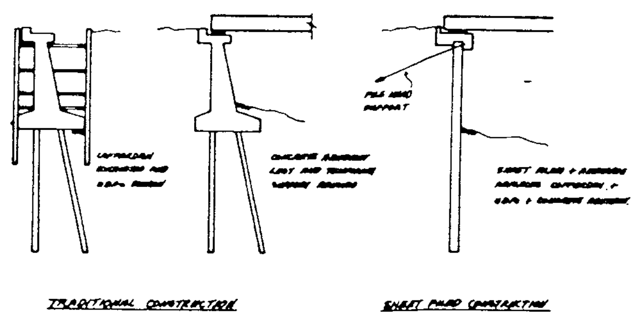

Figure 1.

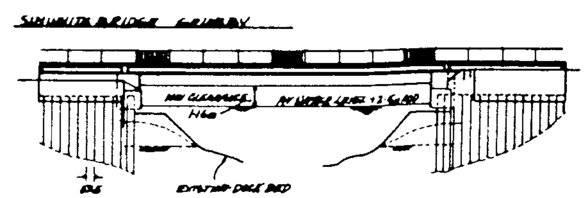

Figure 2.

2 CONVENTIONAL BRIDGE ABUTMENTS

Steel sheet pile bridge abutments have been constructed in the UK since the early 1970's. The high speed of installation and the relatively simple format of construction obtained by the use of this material has proven sheet piling to be a viable alternative to more traditional forms of construction. A typical example is shown in figure 1.

The use of sheet piling in the abutments of large and heavily loaded bridges where the piles replace the need for a separate abutment structure and foundation has firmly established the fact that sheet piles can carry substantial vertical loads in addition to their recognised earth retaining ability.

The Simwhite Bridge in Grimsby, South Humberside has abutments formed from 16.5 metre lengths of Larssen 25W sheet piles founded in firm to stiff clays (see figure 2). The heads of the piles are supported by the use of conventional tie rods going back to a sheet piled anchorage. The bridge constructed in 1988 supports loads from a dual carriageway which forms part of a major redevelopment of Grimsby Docks. The working load on the piles was 60 tonnes per linear metre of abutment or approximately 30 tonnes per pile. Dynamic testing during installation indicated that specified pile test loads would easily be achieved.

The maintained load tests which took place one month after pile installation were carried out on a group of four piles and also on a single pile. With the group test successful up to twice the working load, the single pile was then taken to just over three times the

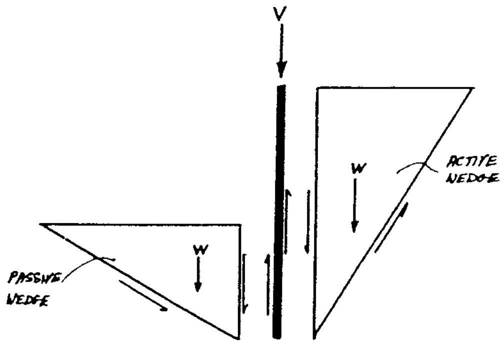

Figure 3.

working load (100 tonnes). At this load, total settlement was 7 mm with residual settlement of just 2 mm indicating that the pile was not near its ultimate bearing capacity. With the jacking system at full capacity no further testing could be carried out which was unfortunate as valuable information with respect to the initial design assumptions could have been obtained had the piles been tested to failure.

2.1 Design considerations and procedures

A sheet pile can support axial loads just like any other type of bearing pile provided it is driven into good bearing soils. Sheet piles can also be load tested in the same manner as other bearing piles using prescribed testing methods. However, as they are being asked to support both vertical and horizontal loads the influences of both must be considered.

2.1.1 Axial load

An axial load may for example enhance the passive earth pressure but may also increase the active pressure if the vertical movement of the sheet piling is larger than that of the active earth pressure wedge (see figure 3). Likewise if the piles go into tension the active earth pressure may decrease but the supporting passive pressure would decrease relatively more. In addition, consideration may be given to the possible change in the permissible vertical load due to the influence of the vertical component of the active earth pressure. On the other hand the passive earth pressure which slopes upwards acts as an additional support lower down the sheet pile (see figure 3)

2.1.2 Load carrying capacity

The calculation of the vertical load carrying capacity will be made for the combination of mobilised shaft and end bearing resistance when founding in dense cohesionless soils, soft rocks or extremely hard clays. For firm or stiff clays transference of load will be mainly by friction or adhesion. In order to assess the contribution to either shaft resistance or end bearing the surface or bearing area of the section under consideration must be obtained. The end bearing area if based purely on the cross-sectional steel is readily obtained for all steel sections.

2.1.3 Cohesive soils

In cohesive soils plug formation can be expected to occur in tubular piles and to some extent in H piles and sheet pile sections. With steel H and tubular piles, the basic shape of the section ie H or tube, does not change throughout the ranges of piles available. This is not the case for sheet sheet piles.

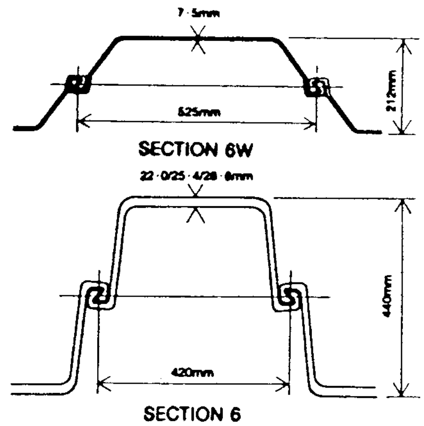

Figure 4.

Table 1.

LARSSEN U-PROFILE		FRODINGHAM Z PROFILE	
SECTION	80% PERIMETER (M)	SECTION	80% PERIMETER (M)
6W	1.22	1BXN	1.00
9W	1.30	1N	1.04
12W	1.38	2N	1.14
16W	1.45	3N	1.20
20W	1.54	3NA	1.26
25W	1.60	4N	1.29
32W	1.60	5	1.32
3	1.14		
4A	1.30		
6 122	1.50		
6 131	1.50		
6 188	1.5		

Some sections (see figure 4) are much deeper with almost parallel legs whereas others are shallower and have splayed legs. This variation of profile through the range of sheet piling makes a reasonable assessment of the area to be considered for possible development of a load bearing plug problematical. Obviously deep sections with near parallel legs are more likely to develop a fuller plug. Until the actual mode of formation of a dragged down plug is studied for sheet piling the approach to the estimate of the effective plug area should be conservative. Whatever area is assumed (50% of gross area is common) this and other design assumptions should be confirmed by a suitable load testing programme.

2.1.4 Cohesionless soils

It is generally accepted that plugging in cohesionless soils does not occur to any great extent. However if the formation of a solid load bearing plug is to be considered some estimate of area must be made. In tubular sections substantiation of possible plug formation can be obtained by plumbing down the interior of the pile. With sheet piling as with steel H piling this check is not possible and therefore assumptions are made which are again backed up by load testing.

When a plug is assumed the subsequent calculation of shaft resistance would be normally limited to the outer surfaces of the sheet pile section. Where plug formation is not considered a developed surface of up to 80% of the available perimeter may be adopted for British Steel sections as shown in Table 1.

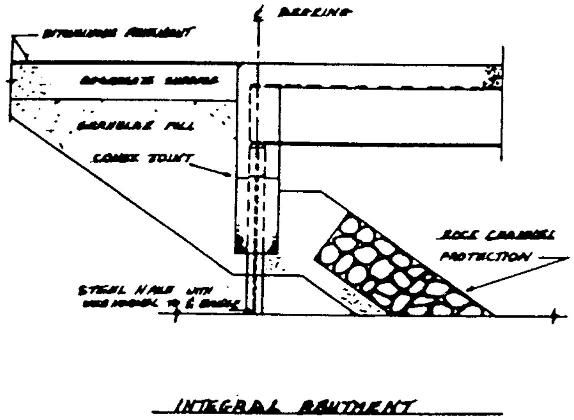

Figure 5.

2.1.5 Head restraint

Bridge abutment sheet piling is normally supported horizontally, usually at or near the pile head to provide restraint from the various combinations of loading induced by the bridge structure and also from earth pressure. The restraint may be provided by the use of tie rods with a sheet pile anchorage, ground anchors, or by using part of the deck structure to effectively strut between the abutments on short span bridges. The deck is then simply supported by the sheet piles through a capping beam which houses the bridge bearings.

3 INTEGRAL BRIDGE ABUTMENTS

3.1 Background

The use of integral bridge abutments has been the bridge engineers answer to the ever increasing damage and hence growing maintenance programme to bridges as they age caused by the use of de-icing salts. By definition, integral bridge construction is the practice of forming a bridge without deck joints.

The introduction of the concept of continuous span bridge design in the USA revolutionised bridge construction. Engineers then began to design bridges without deck joints over piers. Now the global trend in bridge construction, to eliminate as far as possible the need for joints at the piers and abutments has led subsequently to the deck being made integral with the abutment. Today, continuous bridge construction is commonplace in many parts of the USA and Australia.

The concept of integral abutments was first developed using a concrete abutment supported on a single row of steel bearing piles. Consideration is now being given to replacing the bearing piles with steel sheet piling. The role of the conventional sheet piled abutment therefore changes from what was essentially a propped retaining wall carrying vertical load to one which forms the abutments to become, along with the deck, a continuous frame portal.

3.2 Application

Typical integral abutments were constructed utilising a steel pile bent (H piles) with a concrete cap constructed integrally with the superstructure (see figure 5). The abutments supported on a single row of piles was considered flexible enough to accommodate longitudinal thermal cycling of the superstructure and dynamic end rotation induced by the movement of vehicles.

A move towards a more flexible single row of piles brings the suitability of steel sheet piling to the fore, especially since the sheet piles will not only provide a foundation but also retain the abutment fill. Sheet piles also remove the need for an earth embankment in front of the piles as is the case with an H pile solution. With the increasing use of sheet piling to form bridge abutments it was only a matter of time before an integral bridge format including a sheet piled abutment was proposed.

In 1990 a small bridge crossing of a brook (large stream) was constructed using integral sheet piled abutments in Suffolk on the East Coast of England. The bridge (see figure 6) has a span of just under 11 metres and uses a combination of steel sheet and box piles to form the portal frame legs and the foundation.

In many respects, there is little difference between the sheet piled approach and that for H pile integral abutments in this particular construction. The retaining capacity of sheet piles is utilised only to that of providing support over and above that given by the banks of the stream. The head of the pile is however, integral with the deck. The step forward into the use of a sheet piled integral abutment has been simplified in this way.

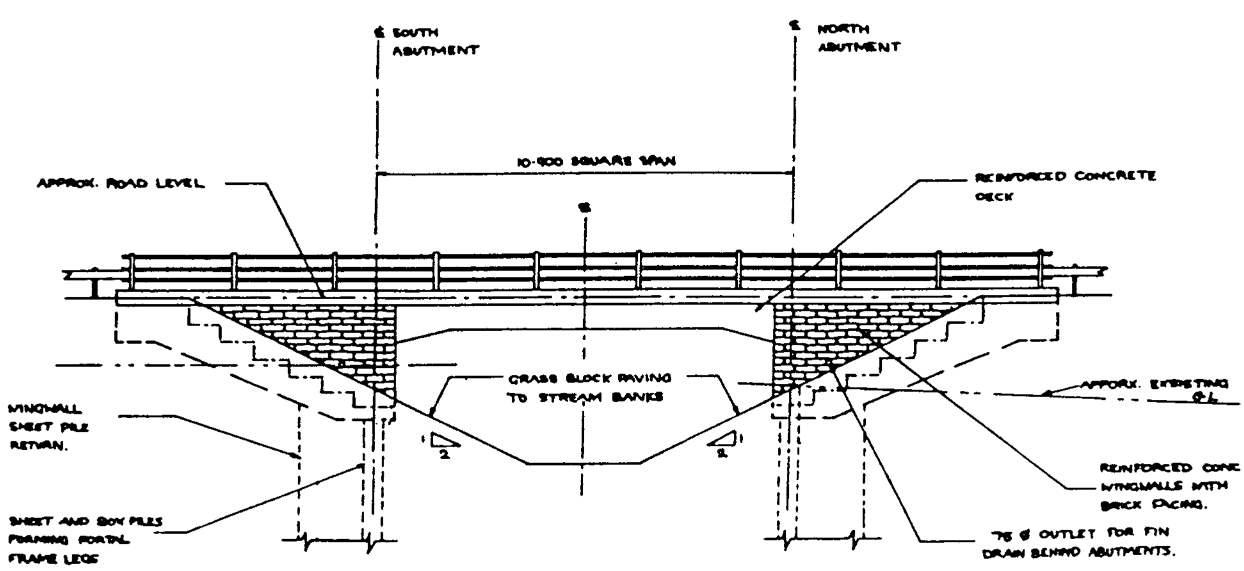

Figure 6. Chad Brook Bridge

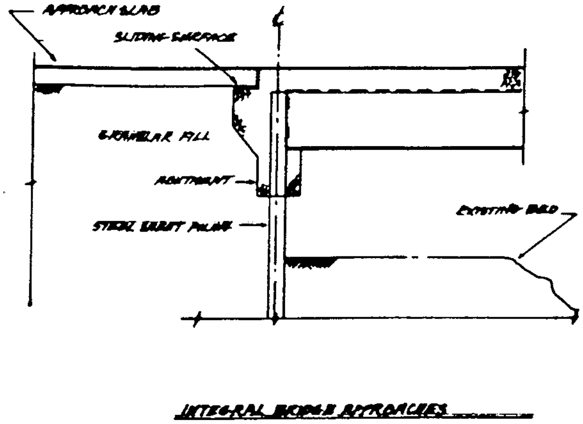

Figure 7.

3.3 Design considerations and procedures

3.3.1 Earth pressures

The earth pressures which act on retaining walls behind abutments or anchored sheet piled walls are normally calculated by classical earth pressure theories (Rankine or Coulomb). With their use it is tacitly assumed that the lateral movements of the wall will be sufficiently large to develop the full shear resistance of the soil along potential failure surfaces in the soil. When the wall displacement is not sufficient, for example where the wall is restrained by the structure, the earth pressure acting on the wall will be larger than active earth pressure. In addition increased earth pressures will also develop due to:

a) Compaction of the granular backfill behind the bridge abutment.
b) Combinations of loading on the bridge deck.
c) Thermal cycling effects on longer spans.

On small scale (up to 12.0m) single span structures it would appear reasonable for design purposes to assume that pressures are likely to approach the coefficient of earth pressure at rest parameter KO. On structures with longer spans a much more rigorous method of analysis is needed to model structure/soil behaviour. This should then be followed by insitu measurements to confirm initial design assumptions and to establish accurate design criteria.

3.3.2 Compaction of fill

Continued compaction of the soil and corresponding increase in earth pressures on the bridge approaches may be avoided by the use of approach or transition slabs (see figure 7).

3.3.3 Structure behaviour

The elimination of maintenance prone expansion joints subjects the now continuous deck to stresses induced by the response of the superstructure to thermal and moisture changes, settlement etc. In addition stresses will also be induced at the abutments due to the restraint provided by the backfill or existing soil against the cyclic movement of the deck. It is considered however, that on small span bridges these secondary effects are minimal and insignificant when compared to the damage that can be caused to the superstructure by the use of joints. The elimination of costly bearings and joints should result in savings in overall costs.

3.3.4 Method

To accommodate the step forward into this new way of using sheet piling modifications to existing methods of analysis are required or alternative approaches to design must be considered so that additional factors can be taken into account. The method adopted must consider the sheet piling element acting as a structural member of the portal frame in addition to it carrying horizontal earth pressures and vertical loads.

As with the first H pile integral bridges the design approach for steel sheet piles can be implemented on an experimental basis either formally or informally. Since the design of piles is usually based on nonscientific principles, small scale short span structures where thermal expansion and contraction forces are not considered an overly complicated design approach is not warranted. Major structures however, with long spans would require finite element analysis to formulate rational pile design criteria and to model the complex soil and pile responses adequately.

Suggested basic steps in the overall design approach are outlined below:

3.3.4.1 Step 1

The analytical model is a fixed base portal with a loading configuration as shown in figure 8A comprising KO Dead + Live Loads.

The initial portal frame analysis is based on a point of pile fixity assumed at 3.0m depth, see below.

(Hansen, J B 1961) suggests that in calculating a piles ultimate lateral resistance the point of virtual fixity of the pile for practical design purposes can be taken as:

a) 1.5m for compact granular soil or stiff clay
b) 3.0m for a soft clay or silt.

(Tomlinson 1971) points out that it is sometimes assumed that the depth to virtual fixity is equal to one-third of the depth of embedment. He also states that from considerations of comprehensive loading this criterion can be over conservative and goes on to suggest that values between 1.5 - 3.0m would be sufficiently accurate for cases of light horizontal loading.

The pile length (d) (see figure 8A) required to support the vertical loads is initially calculated.

3.3.4.2 Step 2

Next deflection is checked at point (A). Leg length (de) is varied until a proposed acceptable deflection limit of within 20 mm for the portal is achieved under the combined loads.

The pile length (d) which carries the vertical load is now added to (de) to get a total pile length = h + d + de for the permanent construction stage. This approach, where the pile length needed to resist the lateral loads is added to the lengths required to support vertical load, is conservative. However, the overall pile length obtained may be exceeded in any case by that required to satisfy the temporary construction stage.

3.3.4.3 Step 3

The pile length needed to meet the temporary construction stage requirements must now be assessed using conventional earth pressure theory. The longer of the pile lengths obtaired from 3.3.4.1 and 3.3.4.2 is adopted for the structure.

3.3.4.4 Step 4

With the pile length established (refer 3.3.4.2) detailed analysis considering various loading conditions is then undertaken. On small short span

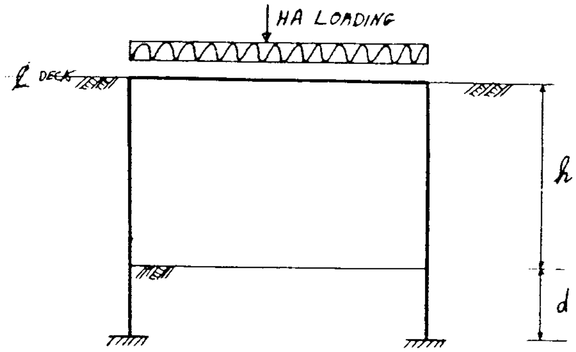

Figure 8A.

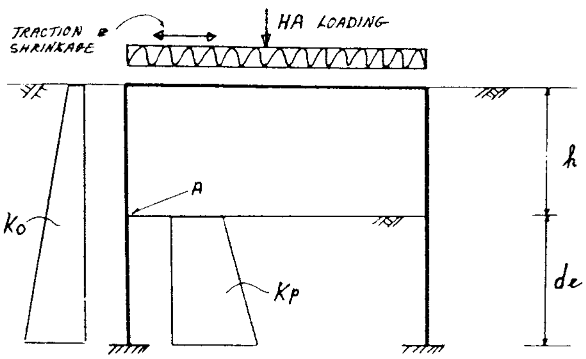

Figure 8B.

structures these would include:

a) Earth pressures + dead + live loads (HA load).
b) Earth pressures + HA load on bridge approaches.
c) Earth pressures + breaking/traction effects.

On longer spans the effects of expansion and contraction forces would also be considered.

4 POTENTIAL STRUCTURAL PROBLEMS AND RECOMMENDATIONS

4.1 Site investigation detail

Steel sheet piling when used in the area of permanent construction as described, involves both geotechnical and structural considerations and the complicated interaction of these two particular specialities. While the structural loads and material strengths are well known, the earth pressures which act on the sheet pile wall come from the soils and these are not well known. Therefore calculations carried out to assess earth pressures in addition to those to establish shaft and end bearing resistance based on soil data can in some cases be prone to large errors.

The error may arise from a number of factors such as boreholes taken away from the actual line of piling, minute sampling ratios, interpolation between boreholes, and misinterpretation of the soils investigation report. In addition assessments have to be made in relation to plug formation and mode of load transference from the piles to the soil. Therefore because of the difficulty of obtaining accurate input parameters and to substantiate the design assumptions, test loading of the driven piles is recommended.

It is essential therefore, in order to reduce as much as possible the risks associated with the estimation of soil loads that sound and comprehensive soil exploration procedures are adopted to establish the necessary parameters for use in the design analysis. Detailed sample testing is necessary to provide the designer with a comprehensive soils mapping of the site.

The analysis must be comprehensive taking into account all the potential changes of load which may take place during construction. This together with detailed engineering planning is necessary to ensure that all the various stages of construction are understood. Also allowance has to be made for necessary adjustments a contractor will have to make, such as the removal of temporary supports and the subsequent redistribution of forces that this will generate.

4.2 Construction difficulties

The construction must take place in whatever type of soil exists at the site although it would be unlikely to have a sheet piled format specified if conditions were not at least favourable as determined from early site investigation work. Even so, it is possible to have unanticipated soils present which could lead to construction difficulties. For example, undetected small quantities of soil strata such as very thin sand lenses could lead along with high water pressures to instability as excavation proceeds in front of the wall.

In the first integral abutments problems occurred such as pile cap cracking. This was addressed by increasing the pilecap size and by rotating the steel H piles to place the weak axis normal to movement. This measure was taken to reduce the resistance of the abutment pile foundation to the longitudinal movement of the bridge. In addition the foundation itself was limited to a single row of slender vertical piles. Developments of new forms of construction are inevitably going to lead to some instances of structural problems as mentioned above. However, the increased use of jointless bridge construction particularly in the USA indicates that initial teething difficulties have been overcome.

Very high standards are achievable in the finished structure. Potential difficulties will be avoided provided that a suitable pile section for the site conditions is adopted, along with the guidance of an experienced contractor using correct pile driving equipment and recommended installation procedures. It is not physically possible to eliminate all the uncertainties associated with this and other ground related forms of construction, however the best method of prevention against problems arising during or after construction is the use of good practice in the areas of design, construction and site exploration.

5 CONCLUSION

The practice of design and construction using sheet piling as part of the permanent works has become routine. Sheet piles are now common place in underground structures such as tunnels, subways, basements, underground car parks, pumping stations etc. Also for a number of years sheet piles have been used to form the abutments of short and long span bridges. Their recent application into integral bridge abutments has been a logical development prompted by the growing trend in bridge construction to adopt integral abutment construction as an efficient means of eliminating the ever growing maintenance syndrome associated with joints.

The general use of sheet piled integral abutments is likely to develop when comprehensive and conservative guidelines for their use becomes readily available and when their performance is documented. Bridge engineers will be able to justify their use when information on the likely stress levels developed on integral abutments is established and when fully described design details and procedures become available.

6 ACKNOWLEDGEMENTS

Detail of Chad Brook bridge reprinted with kind permission of:
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