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King Sheet Piling (KSP) – a major advance in sheet pile retaining wall design and installation

King Sheet Piling (KSP) – un grand pas en avant dans la conception et l'installation de rideaux de palplanches

D A Baker*[1]

[1] *Balfour Beatty Construction Services UK, London, UK*
** Corresponding Author*

ABSTRACT The award-winning King Sheet Piling (KSP) retaining wall system is a radical yet simple innovation that changes 120 years of sheet pile wall design and installation practice. KSP was first used in over 25 km of retaining wall on the widening of the northern sector of the M25 London orbital motorway. With typical steel reduction of up to 35% and increased installation speed, the KSP system de-risked the demanding programme for the £1bn construction contract and delivered over £10M savings, shared equally between client and contractor. Increased productivity, ease of installation and superior alignment control improved constructability, adding to substantially reduced noise and vibration, enhanced safety and much reduced embedded carbon. The cost savings and reduced carbon go hand in hand, as recognised by the UK Government, which selected KSP use on M25 as one of four exemplar projects in the Infrastructure Carbon Review, published in November 2013. The paper describes the principles behind KSP and the constructability, environmental and sustainability benefits it offers. Key to the constructability improvement is inherent reduced clutch friction.

RÉSUMÉ. Le système primé de mur de soutènement KSP (King Sheet Piling) est une innovation à la fois simple et radicale, qui révolutionne 120 années de pratique de la conception et de l'installation de rideaux de palplanches. La première application de « KSP » vit le jour sur un tronçon de mur de soutènement de 25 km de long pour l'élargissement du secteur nord de l'autoroute périphérique M25 de Londres. Avec une réduction moyenne de l'emploi d'acier de l'ordre de 35 %, alliée à une augmentation de la vitesse d'installation, le système KSP a permis d'atténuer les risques du programme contraignant du marché de construction d'une valeur de 1 milliard de livres sterling, tout en permettant la réalisation d'économies de plus de 10 millions de livres sterling, réparties à parts égales entre le client et l'entreprise. L'augmentation de la productivité, la simplicité de l'installation, mais aussi le contrôle supérieur de l'alignement ont permis de renforcer la constructibilité, en contribuant à une réduction substantielle du bruit et des vibrations, au renforcement de la sécurité, ainsi qu'à une forte diminution de l'empreinte carbone. Les économies et la réduction du bilan carbone vont de pair, ce qui est confirmé par ailleurs par le gouvernement du Royaume-Uni, qui a sélectionné l'emploi de KSP sur l'autoroute M25 comme un des quatre projets exemplaires contenus dans l'Infrastructure Carbon Review, publiée en novembre 2013. Cette communication décrit les principes de base de KSP, ainsi que les avantages de cette technique sur le plan de la constructibilité, de l'environnement et de la durabilité. Le secret du renforcement de la constructibilité est la réduction inhérente de la friction de couple.

1 INTRODUCTION

King Sheet Piling (KSP) is an innovative, radical, yet inherently simple, new form of sheet pile retaining wall. Its first use was on the £1Billion contract to widen 60 km of the northern sector of the M25 London orbital motorway, a high profile and demanding project on which to introduce a new system. KSP saved typically 30% to 35%, and up to 40%, of the steel normally used and yielded practical installation benefits that substantially enhanced constructability and productivity.

Subsequent use of the King Sheet Pile (KSP) system on other projects has confirmed KSP's place as a major technological advance in sheet pile use for retaining wall construction.

The purpose of this paper is to make this invaluable addition to modern engineering practice widely known so the economic, sustainability and environmental benefits can be capitalised on for the benefit of society.

KSP use is discussed first in terms of the M25 DBFO (design, build, finance and operate), where over 25 km of KSP walls is Europe's largest land-based use of sheet piling.

2 M25 DBFO PROJECT

The M25 DBFO project comprised widening 60 km of the M25 London orbital motorway to four lanes, predominately in the Northern sector, refurbishing and upgrading the remainder and operating and maintaining the project roads for 30 years.

The widened sections are Section One (Junctions 16 – 23) and Section Four (Junctions 27 – 30). This busy motorway carries up to 200,000 vehicles per day. The contract stipulated a construction rate twice as fast as achieved on previously widened sections, requiring a peak spend of £1M per day. Programme rather than initial cost was the governing criterion for widening options as liquidated damages and overheads would cost over £200k per day. Safety, sustainability and whole life cost were key.

2.1 Geological Setting

Section One, which contains the majority of the KSP walls, predominantly traverses Upper Chalk, with London Clay and Reading Beds clay east of junction 22. The Upper Chalk is overlain by Glacial Deposits beyond junction 19. East of junction 21, sand and gravel quarries were filled with construction and domestic waste in the 1960s and 1970s. Groundwater is generally encountered in the Upper Chalk some 10-15 metres below finished road level.

The cohesive London Clay, Reading Beds and Glacial Clay are generally firm to stiff. The Upper Chalk is Grade IV to V in the upper 2 – 3 metres and Grade III below this depth.

Cutting slopes were generally 1V:3H in London Clay and Reading Beds, 1V:2H in Glacial Clay and Grade IV Chalk and 1V:1.5H in Grade III Chalk. Maximum cutting depth was 15.2 metres but generally in the range of 5 to 8 metres.

Embankments were typically formed of material from adjacent cuttings, generally at 1V:3H slopes where formed of London Clay and Reading Beds and 1V:2H where formed of Chalk and Glacial Deposits. Maximum embankment height was 10.6 metres but generally in the range 3 to 6 metres.

KSP walls in Section Four are predominantly in embankments constructed of London Clay, typically with 1V:3H slopes.

2.2 Tender Design

The contract required all widening to be carried out within the original boundaries of the motorway, leaving most structures un-widened and incorporating a reduced hard shoulder width.

During the tender design in 2007, the construction joint venture undertook extensive value engineering to identify the most cost-effective and programme-efficient means of widening. Retaining walls were used only where mandated by space and environmental constraints. Where embedded retaining walls were required, the most economical form was either an L shaped reinforced concrete wall founded on bored piles or a sheet pile wall, the latter proving quicker to construct.

2.3 Development of the KSP system

Reviewing the tender design, the author was struck by the realisation that sheet pile walls are often highly inefficient, with much surplus structural capacity. This arises because many walls use sections sized to allow them to be driven to the required depth without damaging the piles. Post tender, the author conceived a more efficient sheet pile wall concept. Termed King Sheet Piling or KSP®, the system harnesses the surplus structural capacity in the wall, typically by selecting alternate pairs of normal length sheet piles to serve as "kings" with lighter, shorter sheet piles, termed "intermediates", spanning horizontally between them (Figure 1). Typically this saves 30% to 35% of the steel normally used, and often up to 40% or more, as well as yielding substantial productivity, environmental and sustainability benefits. Although fundamentally simple, the KSP concept represents a major change in 120 years of sheet piling practice and has been patented (GB2463079, others granted or pending).

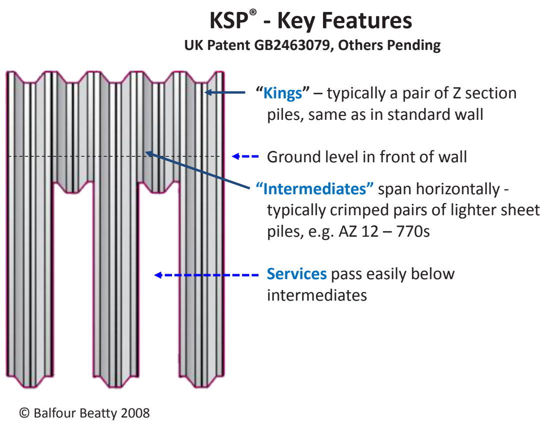


Figure 1. Elevation of KSP wall

KSP is similar in principle to a king post wall, which typically consists of H sections concreted in bored piles with planks between them to retain the soil on the active side. Bored piles are needed to mobilise sufficient width in the passive zone for overall stability. Sheet piles are efficient as kings as they are wide, strong sections that can be installed using simple pile driving plant in one operation.

Whilst the concept and the patent allows for other members as intermediate sections, installing sheet piles as intermediates greatly simplifies the construction of the wall and speeds completion. Similarly, whilst the concept and patent allows use of any type of sheet pile in any long/short grouping, the system would normally only be used with Z profile piles unless there are over-riding reasons to use U profile piles, e.g. using up existing stock. Use of U profile piles in a KSP wall is inherently inefficient, as discussed later.

Key to KSP development was:

- Recognition that all Larssen sheet pile sizes have identical clutches, allowing interconnection of light and heavy sections.
- Researching clutch shear capacity to determine the safe load transferrable to the kings by intermediate sections.
- Understanding how a sheet pile wall performs structurally and why Z not U profile piles should be used.
- Investigating the practical aspects of installation, including potential drag-down of intermediates during driving.

2.4 Detailed Design of KSP walls

Detailed design focussed on optimising the tender design to suit the construction programme, which commenced in June 2009. All structural widening solutions were assessed in terms of both cost and construction time.

The approach used to select sheet pile section size for driving (Williams & Waite 1993) was reviewed with sheet pile contractors to establish optimum sections for driving. AZ 19 and AZ 25 sections were selected for cohesive and chalk widening solutions respectively.

Initially, the KSP walls were designed as pairs of full-length AZ piles alternated with pairs of crimped AZ 17 piles embedded a nominal 1.0 metre below final ground level. AZ 17s were selected to keep a common section width so if a king refused short on flints, another could replace the next intermediate. The kings resist the active load on the wall and the function of the intermediates is confined to retaining the small arc of material between the kings by spanning horizontally onto them. Complex analysis of intermediate performance was not considered necessary and a simple empirical approach was adopted, drawing on combined ("combi") wall experience.

To minimise whole life cost, the sheet pile walls are un-painted, eliminating periodic maintenance, traffic restrictions and associated hazards. Sacrificial corrosion loss over the 120-year design life was determined in accordance with Eurocode 3 part 5 (BS EN 1993-5 2007), A simple U or L shaped steel channel and linked safety fence completed the walls, avoiding multiple operations for reinforced concrete capping beams, reducing working at height and further speeding construction.

KSP's faster installation speed meant that the solution was adopted in further phases instead of reinforced soil and soil nailing solutions. KSP also proved less susceptible to delays due to periods of wet weather. Services also fitted easily beneath the intermediate piles. KSP's advantages of offsite manufacture and simple mechanised installation, using one set of equipment, minimised the people/plant interface, and increased safety.

By early 2010, newly developed 700 mm wide pile sections replaced the original 600 mm wide sections. With wider AZ 12-770 intermediates, these provided increased steel savings and productivity with no detrimental effect on installation.

East of Junction 21, the worked-out Glacial Gravel pits predominantly backfilled with construction and domestic waste in the 1960s and 1970s, required thicker steel sections to deal with higher potential corrosion. Here, the M25 runs in false cutting with retained height typically 1.5 to 2.5 metres. Walls were generally designed as AZ 28-700 or AZ 37-700 kings with AZ 28-700 intermediates.

Over 22 km of sheet pile wall was installed on Section 1, 19% of which was in embankment, with the remainder in cutting. Added to KSP walls in embankment on Section 4, where steel savings up to 40% were not uncommon, a total of over 25 km of KSP wall was installed on the M25 widening.

2.5 Construction

Construction commenced in the west, where both cuts and embankments were predominantly of chalk. Sheet piles were installed by the pitch and drive technique using vibratory pile drivers ('vibro-drivers") mounted on leader rigs, with the provision for percussive driving to full depth if necessary. Initially, pronounced bands of large flints in the Upper Chalk in cuttings caused concern. To mitigate risk of delay, a pre-augering contingency protocol was agreed in advance with the designer.

In practice, the KSP kings were easily vibro-driven to full depth, with percussive driving only being required on very rare occasions. Pre-augering proved unnecessary. After seeing the size of flints exposed in cuttings, a technical expert from the steel supplier commented that he would not normally advise use of conventional sheet pile walls in such ground. The primary reason for the success of KSP in these conditions is the lack of any significant clutch friction either side of the kings. Normally, slight manufacturing deviations, within normal tolerances, and slight deviations of piles during driving can lead to a substantial build up of friction in the clutches. Without this effect, the kings could be vibro-driven much deeper, including through the flint bands, without the need for percussive driving.

The ease of driving kings and speed of inserting intermediates meant 60 linear metres per rig day was routinely achieved in the chalk, four times the original planned rate of 15 m per rig day. The works were accelerated and the sheet piling resources reduced. As the ground became more cohesive the installation rate slowed, with more need for percussive driving, but was still about twice as fast as for a normal sheet pile wall.

With the wider AZ 12-770 intermediates, percussive driving was reduced to 47.6% of any length requiring it. Furthermore, without the clutch friction, the kings could be vibro-driven deeper before percussive driving became necessary. Hence noise due to percussive driving was more than halved, as was the energy required to install the wall.

To maximise the KSP savings, the length of kings and intermediates was varied continuously along each wall as retained height varied. This put considerable pressure on logistics planning as the steel for each wall was cut to length at the mill, shipped, stored and transported to each wall site on a just-in-time basis

Initially, sheet piles longer than 8m were ordered in un-crimped pairs so that, if pairs refused early, they could be driven further as singles. Early experience of installing a rare length of continuous sheet pile wall was that the piles rattled substantially in the clutches, creating excessive noise and consuming driving energy. The clutches on remaining stock were tack-welded and all further piles were ordered in crimped pairs.

As the shallow cut slopes in London Clay on Section Four made slip-formed smooth-faced retaining walls feasible, the majority of the KSP walls were on Section One and those on Section Four were confined to embankments On Section Four, the subcontractor elected to stick to its standard practice of panel-driving, even for KSP walls.

2.6 Constructability benefits of KSP

The marked increase in linear installation speed and substantially reduced need for percussive driving are only two of the constructability benefits.

An important spin-off of KSP is the effect on installation methods. Panel driving is normally the preferred sheet pile installation method to ensure alignment control, particularly where hard driving is required. The disadvantages, however, are it requires setting up the piles in a frame, working at height to clutch the piles and continuous rig movements as pairs of piles are driven sequentially, ensuring no pair leads others by more than about two metres. The process is slow. The alternative is the pitch and drive method in which each pair is driven to full depth before the process is repeated with the next pair. This approach is less risky for operatives, and produces less down-time in windy conditions. Whilst quick and simple, the penalty is that it is much more difficult to control wall alignment. As each pair is constrained by being clutched to the previous pair it develops a forward lean as it is driven. This is cumulative and attempts to correct this are required regularly as the wall advances. Specially fabricated piles are sometimes required to correct the alignment.

With KSP, it was quickly apparent that this problem with pitch and drive disappears. The lack of clutch friction meant it was easy to maintain the alignment of each king. This was a considerable contribution to speeding the installation rate. It also contributed substantially to safety by minimising the need for working at height.

Operatives were impressed by KSP's ease of installation and speed. Other notable benefits are the reduced lay-down area required and ease of handling of the short piles.

2.7 Environmental and sustainability benefits

Sheet pile walls produce less excavation, material import and waste export than alternatives such as a reinforced concrete wall on bored piles. KSP extends these advantages substantially. The typical steel savings of 30% to 40% over a conventional sheet pile wall reduce embodied carbon in steel used and transported and in installation energy.

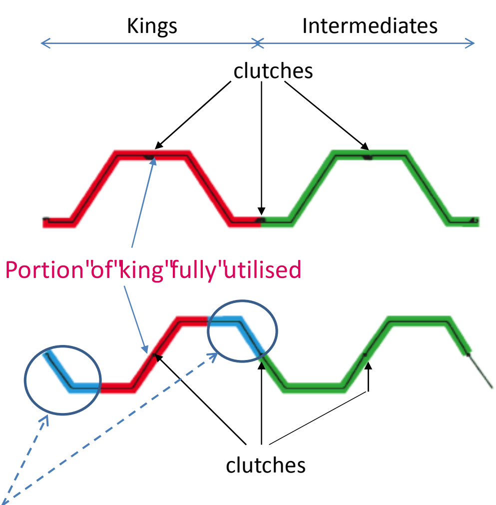
The short intermediates and negligible clutch friction more than halve both the energy required to install a KSP wall and the noise and vibration from percussive impact driving. Faster installation means less disruption to other operations and to the public. All these benefit both residents and the environment.

With minimal clutch friction, KSP sheet piles are much more easily extracted for re-use or recycling in the future.

2.8 Staggered Piles and Sheet Pile Profile Selection

Staggered pile walls, which are sometimes confused with KSP, are walls in which the toe level of alternate piles or pairs is varied or staggered. As distinct to KSP, the staggering is towards the pile toe where the bending moment has reduced sufficiently for the longer piles to function structurally on their own. In contrast to KSP, the piles above any stagger are designed to all bend in the vertical axis in the same manner as in a normal sheet pile wall. Guidance on this design approach is available in German practice (EAU 2006) and BS 6349-2:2010.

KSP walls best suit Z, not U, profile sections. In simplistic terms, a pair of U piles requires adjacent piles in a continuous wall to mobilise its full bending capacity. In isolation, the pair is only 50% efficient, as more bending would potentially overstress the web (Figure 2), as well as doubling the stresses causing slippage in the central clutch. If U piles are used in a KSP wall, for example to utilise existing stock, the section modulus of the end half of each U pile king assemblage is ignored. Other design issues are concerns over clutch slippage and oblique bending, (Steel Piling Group 2008) neither of which applies to Z piles deployed in pairs.



Circled portions of U piles normally bend around adjacent piles, which are absent. They are ignored for design.

Figure 2. Comparison of Z (top) & U profile piles in KSP walls

Whilst U piles may function acceptably in a wall with a limited stagger length, they are inefficient, if not unsuitable, in longer staggers or KSP walls.

3 KSP USE ON OTHER PROJECTS

On the A421 M1 to Bedford dual carriageway project completed in 2010, a large pumping station was on the critical path. It sat at the base of a 7m cut in stiff and very stiff Oxford Clay with Kellaways Sand, a dense and very dense silty sand at about the base of the pumping station, 4 m below cut level. KSP walls replaced a contiguous piled wall serving both a temporary and permanent function.

Use of KSP in the re-designed pumping station, saved £880,000 and avoided a 10-week programme over-run. The client saved £2.7M and embedded carbon was reduced by 90%, saving 905 tonnes of CO_2 equivalent.

On the M4/M5 Managed Motorway project completed in 2013, 1 m to 3 m retained height KSP walls in Lower Lias replaced gabion walls for overhead sign gantries and emergency refuge lay-bys.

Construction was confined to the hard shoulder, a very narrow working environment where controlling the people/plant interface was vital to minimise risk. Sheet pile walls were preferred to gabions for their low construction footprint, increased safety and reduced loss of existing vegetation barriers screening nearby communities. They also avoided considerable logistical difficulties to maintain traffic flow, supply and stockpile gabion materials and remove spoil.

Initially, it was considered impracticable to drive sheet pile walls into the fractured very weak to moderately strong mudstone. Early in the design phase, site trials demonstrated that AZ 25 KSP walls could be installed with pre-augering. Concern over this causing unacceptable deflections did not apply because of the rocklike nature of the ground. Crucially, the short intermediates and minimal clutch friction made KSP feasible in the hard ground. This simplified construction, increased safety, maximised vegetation barrier retention and saved on programme.

4 SUMMARY

The King Sheet Piling (KSP) retaining wall system transforms 120 years of sheet piling practice, typically saving 30% to 40% of the steel required whilst simplifying and speeding installation. On the M25 DBFO London orbital motorway widening, 25 km of KSP walls provided substantial economic, constructability, environmental and sustainability benefits and de-risked the challenging programme through KSP's installation speed advantages. KSP use on the A421 and M4/M5 projects has demonstrated the markedly enhanced driveability of KSP walls due to much reduced clutch friction. With particular advantages where programme is critical, noise is a concern or water pressure equalisation is desirable, KSP has proven a valuable addition to sheet piling technology.

The patented KSP system is available to all under a simple license agreement (Balfour Beatty 2015).

ACKNOWLEDGEMENT

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