DEEP EXCAVATIONS IN SOFT GROUND USING TEMPORARY STRUCTURAL STEELWORK

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ABSTRACT

In many city areas, ground anchors and soil nails cannot be used for deep excavation retention in soft ground for various reasons. The solution is often braced excavations involving temporary structural steelwork, serving multiple functions, like strutting, waling, lagging, traffic and construction decking. Based on the author's design and supervision experience on underground metro station, rail, expressway and commercial mall projects, this paper discusses the design, construction and monitoring of steelwork applications in deep excavation environments.

1 INTRODUCTION

Deep excavations in cities are often constrained by physical and statutory limitations which restrict the use of ground anchors and soil nails. Examples include:

a. Deep excavations adjacent to existing structures like basements, foundations, or tunnels;
b. Underground structures having statutory reserves surrounding them, within which works are either forbidden or permitted under rigorous constraints and
c. Land acts, building or environmental statutes forbidding the installation of temporary works under or at the perimeter of adjacent properties, when these cannot be reliably, safely and completely removed later. Where safe removal techniques exist, their cost and program implications may be prohibitive.

Temporary structural steelwork avoids these limitations and fulfils other roles. These include:

a. Traffic decking for bottom-up and top-down construction methods, maintaining traffic flows and facilitating deep excavation approvals;
b. Lagging at gaps in walls for underground services;
c. Utility support frames, avoiding expensive and time-consuming utility diversions;
d. Construction platforms over excavations, expediting construction work and top-down construction;
e. Flexibility in changing traffic decking openings - expediting excavation and concreting;
f. Cost-effectiveness due to steelwork's capacity for multiple reuse, cutting/welding to suit and modifications;
g. Its ductility enabling visual monitoring, forewarning overloading and verification of instrumentation readings and
h. Its flexibility to be locally strengthened on an *ad hoc* basis – critical to handling ground conditions found more severe than at the design stages and if an observational approach is adopted.

2 TYPICAL STRUCTURAL ELEMENTS

Typical steelwork elements are schematically shown in Figure 1:

a. Walls are braced by steel struts and walers. S2 and W2 denote second layer struts and walers respectively;
b. Struts and walers are restrained against buckling by bracing systems involving the vertical H piles or kingposts (KPs) and other steelwork;
c. KPs transmit vertical loads from decking to the ground below formation level;
d. Struts and walers are structural steel beam and column sections (Figure 2), their major axes oriented in the respective principal loading directions;
e. Struts and walers may be single beams (Figure 2), battened double beams (Figure 3) or laced beam girders (Figure 4);
f. Decking may cover any required proportion of the excavation area. Figure 1 shows a half cover, but full cover is possible, with openings at strategic locations to facilitate mucking out and concreting;

g. The vertical load path is: deck → S1→ longitudinal beams → KPs → ground;

h. The transverse load path is: deck → S1→ walls;

i. Struts are often preloaded. Preloading effectively 'pushes' walls into the soil, by axially compressing the struts. It is done at strut installation at each level, when the excavated ground is at strut soffit, to reduce wall deflections and ground movements;

j. Utilities like the 66 kV cable shown are suspended within the excavation and

k. Traffic decking elements (Figure 5) comprise steel beams welded together to increase bending and shear resistances. Their spans govern S1 spacing ('2000 c/c' in Figure 1).

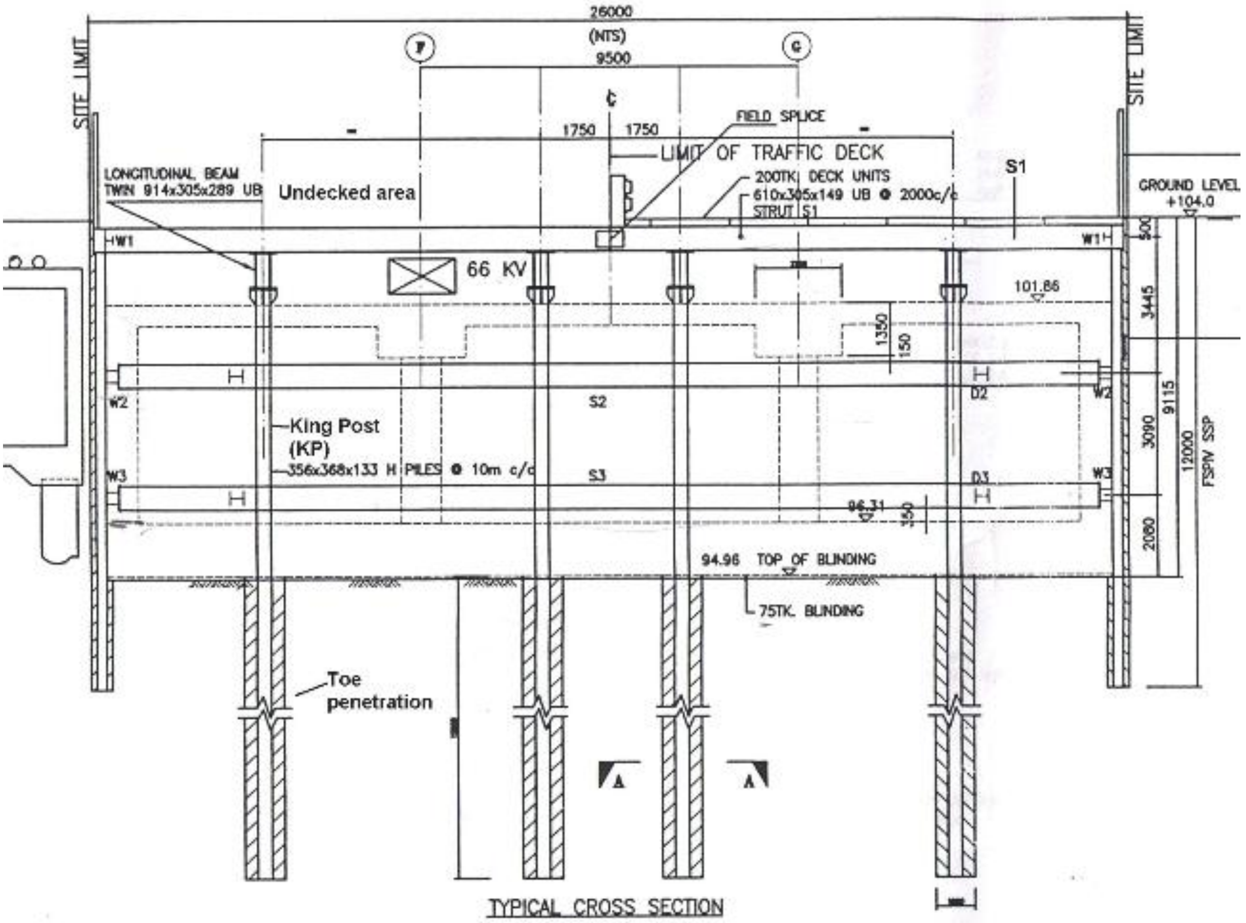


Figure 1: Typical section characteristics.

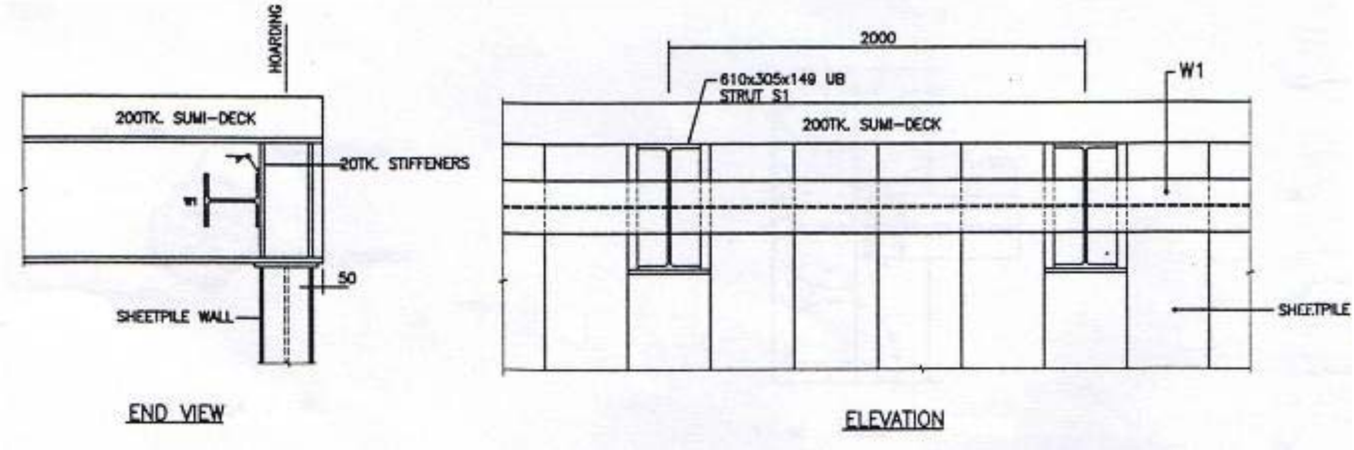


Figure 2: Typical strut/waler sections and orientations.

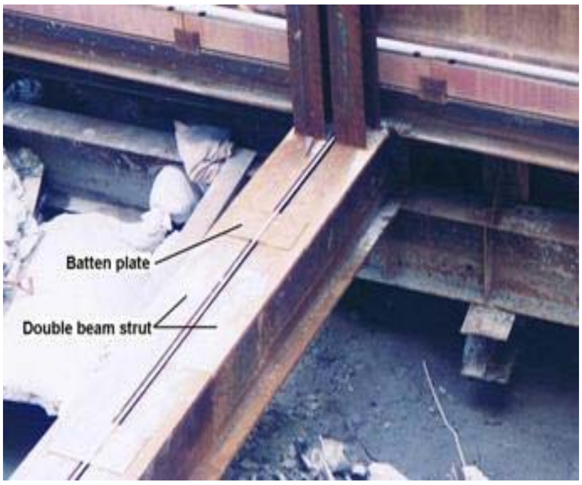


Figure 3: Battened double beams.

Figure 4: Laced beam girder struts.

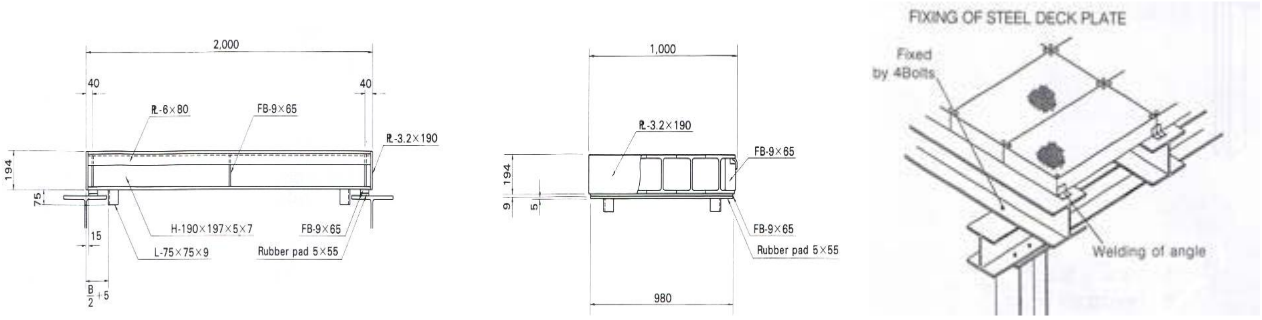


Figure 5: Typical steel decking elevation (L), end view (C) and installed (R) (Hirose, c.1996).

3 CONSTRUCTION ASPECTS

a. Before design, constructors must first plan steelwork areas, extents and timings. Planning starts with land parcel boundary lines, existing feature and utility locations (Figure 6a). The author suggests the principal drivers are minimising utility relocations, phased traffic management and section hand-over dates (to and from clients);

b. Struts, sheet piles and KPs are then initially-positioned (Figure 6b). Positioning is iterative as it affects the loads applied to the steel elements, and element capacities vary according to section size selection;

c. Decking construction is done in sections to limit traffic disturbance. In Figure 1, excavation and steelwork are done for half the section width, which is subsequently opened to traffic. The other half is then worked on (note Undecked Area shown). Figures 7 and 8 clarify;

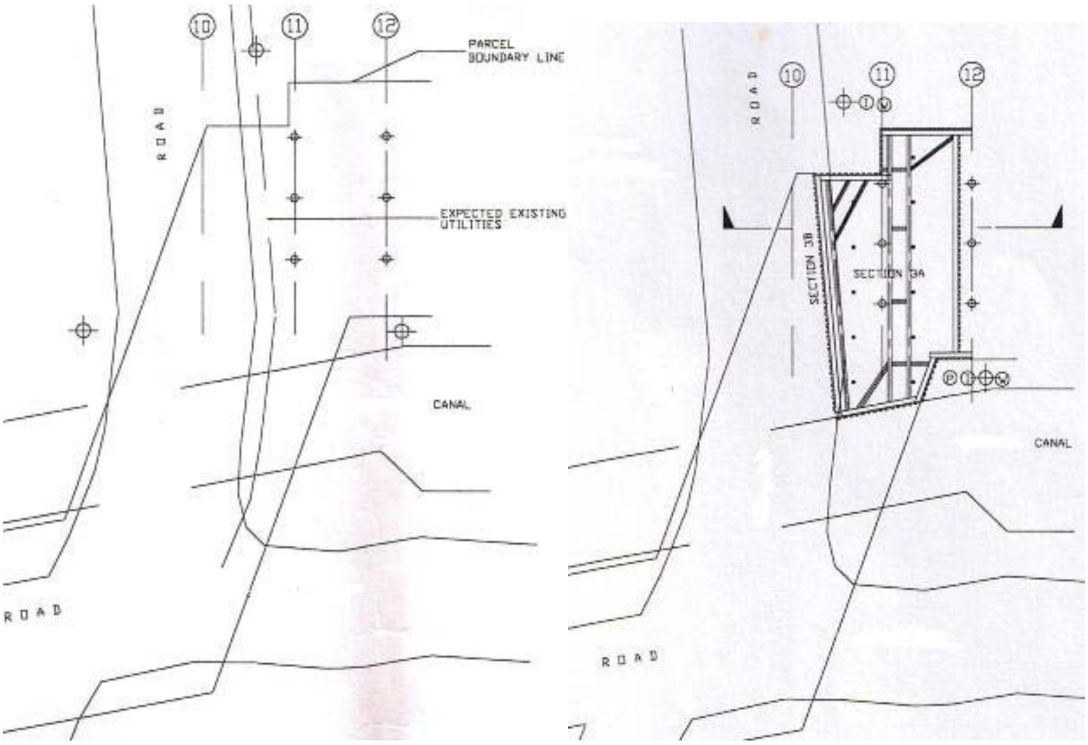
d. For sheet pile hammers, driveability data should exist, often correlated to SPT N values. Reference should be made to geotechnical investigation data, to determine if sheet piling appears feasible to at least 4 m below formation level (author's typical toe penetration initial estimate);

e. To extend to full depth, sheet piles are welded together using full butt or fillet welds with splice plates (Figure 7) via manual electric arc welding. These welds resist earth pressures in shear and bending. Newly-formed welds require cooling times of about 45 minutes and affect driving times;

f. Where sheet piles attain refusal above final formation level, the down-the-hole hammer is effective in breaking up isolated obstructions, if noise pollution is not an issue. Other solutions are partial preboring (Figure 8), and 'berm-and-lag' (author's term – see g). Preboring at intervals enables sheet piles or box sections to attain design penetration below formation level at those intervals. This prebore is grouted with a weak mix to enable sheet piling later. Outside of the prebored locations, sheet piles are driven to refusal;

g. In 'berm-and-lag', excavation proceeds after sheet piling regardless of the high sheet pile toes, leaving an earth berm at the problem location. The berm is then excavated, exposing the pile toes and standing soil faces, in safe stages. The gap is then lagged or shotcreted. Watertightness, lagging, berm slope and soil face stabilities need additional design and supervision work. Program impacts include delayed strutting and staged slab casting;

h. KPs' steel sections are inserted into prebored holes drilled from the surface (Figure 10c) and concreted up to formation level (Figure 1);



(a) (b)

Figure 6: (a) Existing features and land parcel line; (b) planned excavation steelwork (first phase)

Figure 7: Steelwork construction with traffic on the right.

Figure 8: Traffic switched to left after steelwork completion, work proceeds on right.

i. Temporary construction decking is installed in the undecked area of Figure 1 (Figure 11a). It is narrower than traffic decking to maximise open excavation and concreting access areas;

j. For bottom-up construction (Figure 1), the initial excavation is to S1 soffit level, S1 and W1 are installed and S1 preloaded. This is repeated at each level. After the lowest level strut is preloaded, the base slab and wall stumps to strut soffit (dotted) are cast (Figure 11b), then S3/W3 removed. Wall casting proceeds up to S2 soffit, followed by S2/W2 removal. Finally, the roof slab and roof-wall joints are cast (Figure 11c), and backfilling is done close to ground level. Steelwork is removed progressively. Traffic is then switched over to the left, and the same construction sequence proceeds on the right;

k. For top-down construction the permanent walls are installed first, from ground level. Traffic decking, S1/W1 and KP steelworks are installed halfway across, as for bottom-up. The other half is excavated to roof slab soffit level, and the roof is cast. Backfilling and half-road reinstatement may or may not take place above this slab, depending on whether the roof slab is designed to span wall to wall. If it is not, steel KPs may be installed before slab casting, to support the roof during top-down excavation, until the required roof support walls are built bottom-up from lower floor slabs;

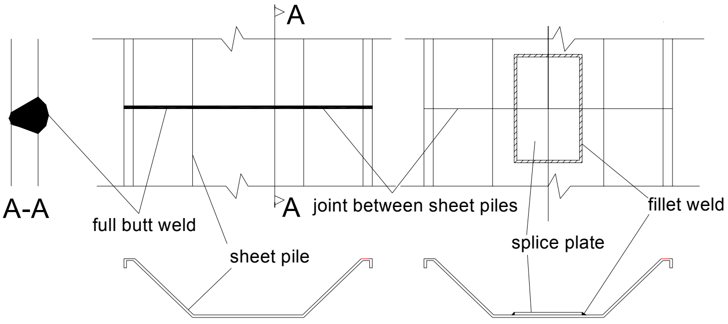
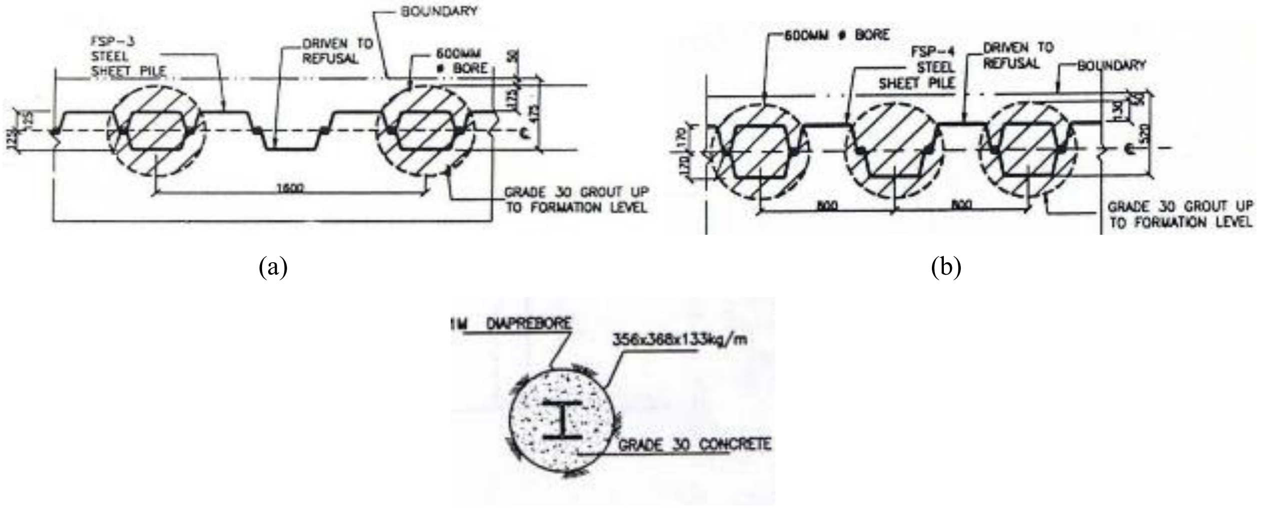


Figure 9: Full-butt weld sheet pile connection and fillet weld joint with splice plate.



(a)

(b)

(c)

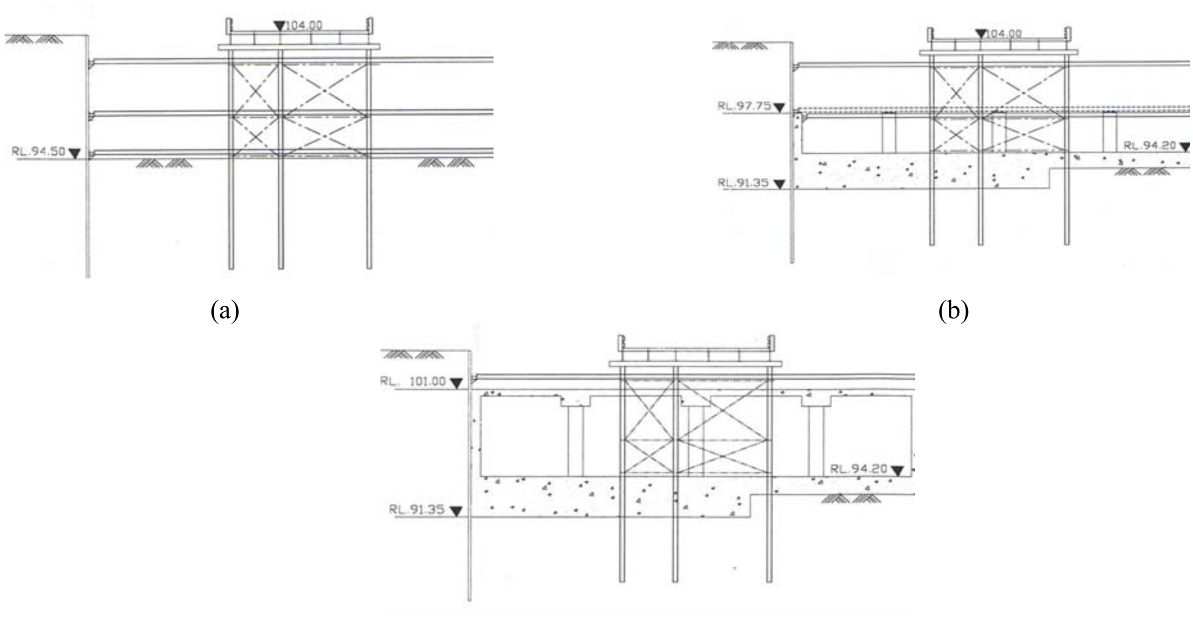
Figure 10: Partial boring solutions – (a) preboring only for 1 in 4 'box' sections, (b) preboring for both alternate piles and 1 in 4 'box' sections, (c) KP toe section.

l. Figures 11 and 12 indicate the extent of transverse and longitudinal vertical cross bracings required for decking stability. There are also horizontal cross bracings not shown. Excavation and RC work methods/sequences need planning as bracings limit plant manoeuvrability and clearances. Usage of mini-excavators and skips is likely;

m. Struts in braced soft soil excavations are preloaded to limit wall deflection and ground movement. Hydraulic jacks are used to preload struts (Figure 13) to the design preload (often 30 to 50% of the design strut load) or design wall preload deflection. Note that preloading using in-strut jacks (as shown) is the more versatile of the two preloading methods generally used. The other uses jacks placed between struts and walers. In both cases, steel elements replace the jacks and enable jack removal after preloading. Preloading significantly increases construction time and strut loads;

n. The effects of temporary structural steelwork on permanent RC works must be considered. As per Figures 1, 11 and 12, steelwork penetrates RC elements during construction, but some elements cannot afford this intrusion for waterproofing or load-bearing reasons. Steelwork must then be positioned accordingly. Constructors should note the cost and program implications of rectification works to the RC elements after steelwork removal and

o. Steelwork and construction sequences affect each other. For example, in Figures 1 and 11, KPs function as piles and strut bracing until permanent roof slabs achieve their required strength. KPs are then cut between the roof soffit and top of base slab (Figure 11), to transfer their vertical loads to the roof slab. Backfilling and road reinstatement proceed after decking is gradually removed and KP lengths above roof slab are cut off. Short lengths of KPs remain within both roof and base slabs, for which rust proofing must be done. KP cutting and removal also affect roof slab waterproofing and structure internal works scheduling.



(a) (b)

(c)

Figure 11: Temporary construction decking and bottom-up sequence stages.

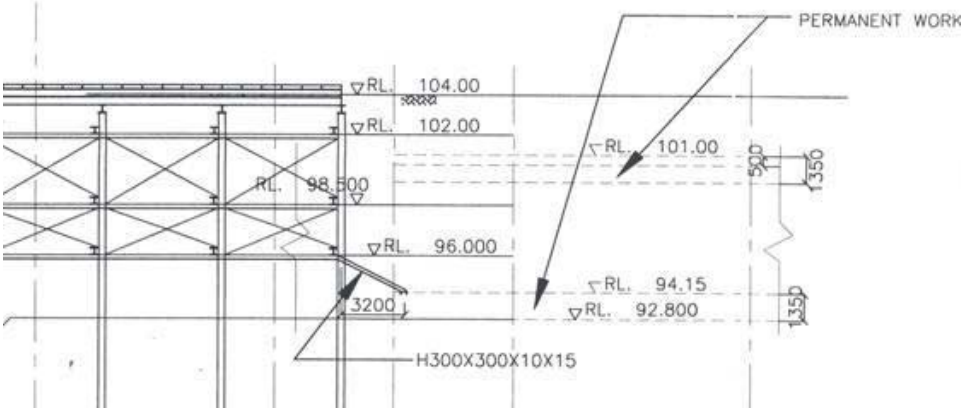


Figure 12: Construction decking longitudinal vertical cross bracing.

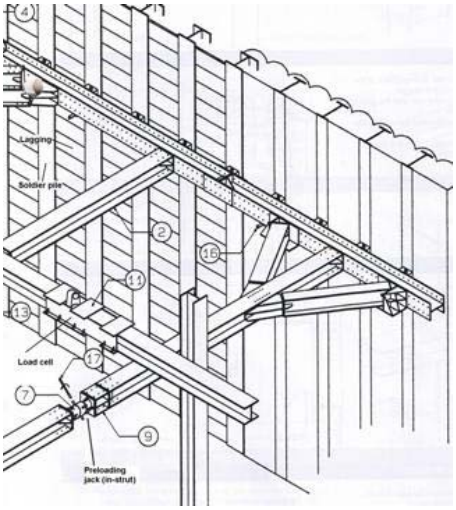


Figure 13: Preloading jack (in-strut), strut load cell (Hirose, c.1996).

4 DESIGN ASPECTS

4.1 LOADING AND SEEPAGE CALCULATIONS

a. Detailed understanding of the geology and groundwater conditions is critical. Design will normally utilise finite-element/finite-difference (FEM/FDM) software, for sensitivity analyses, ground movement, groundwater flow modelling and optimisation of strut spacings and wall type selection;

b. The appropriateness of software soil models and parameters should be understood. Program manuals may suggest non-typical parameter values to prevent ill-conditioning of the stiffness matrix and numerical problems. Examples include 'cohesion' for cohesionless soils, Poisson's ratio and permeabilities (Brinkgreve *et al.,* 2004);

c. The author recommends manual checking using Terzaghi *et al.* (1967), Peck (1969) or Xanthakos (1994) apparent earth pressure diagrams (including surcharge and water pressures). These provide trapezoidal pressure distributions for each brace level, to calculate moments and axial loads in elements. Clough *et al.* (1990), Mana *et al.* (1981) and Bowles (1996) suggest how to estimate ground movements and sheet pile deflections;

d. Similarly, seepage calculations using manual flow net calculations can verify seepage estimates, boiling and piping likelihoods;

e. Unplanned excavation (over-excavation) should be accounted for in the modelling, even if not specified in the appropriate code;

f. If using foreign specialist contractors, their steelwork design approaches must be reconciled with local standards;

g. Appropriate highway codes will supply traffic design loading information. Loads will often be functions of lane numbers and road geometry - hence, the significance of construction aspect 3a and

h. Construction decking load cases should include peak operational track pressures on decking elements and KPs.

4.2 WALLS

a. In wall modelling, the author suggests neglecting KPs due to their typically large spacings in both directions. Lee *et al.* (2003) conclude that, in soft ground, wall deflections would not be accurately predicted by incorporating KPs;

b. Borin (1996) suggests wall deflection reduction is not significant until strut preloading is dramatically increased, at which point the maximum strut loads have also jumped – preloading may not be particularly efficient and

c. The author recommends the highest level strut be placed within 2 m of ground level to limit maximum wall cantilever length and ground movement within tension crack zones.

4.3 STRUTS

a. The principal failure modes are shear, lateral torsional buckling, axial compressive buckling, local web and flange buckling and crushing in bearing;

b. To control lateral torsional buckling in struts, lateral restraints are provided. These need to resist a shear force proportional and transverse to the force in the strut. Lateral restraints are provided by a combination of KPs (vertical and horizontal support) and C-channels (horizontal shear force transmission). In Figure 12, the 'I' struts (projecting out of plane) are restrained at common points by KPs and three tiers of horizontal channels. Horizontally, these transmit restraint forces resulting from transversely restraining each strut;

c. These restraining forces are cumulative and require transmission to adequate anchorage points like walls. The author designed regularly-spaced 'towers' (Figure 14) for this purpose. Towers are completely cross-braced internally and externally, using channels. They collect and transmit restraining reactions from struts and KPs to the walls via cross-bracing. Traction and centrifugal loads from traffic decking are similarly transmitted;

d. With great excavation widths, struts often comprise two columns battened together (Figure 3) to increase axial stiffness and reduce slenderness ratios. Due to self-weight, struts are slightly predisposed to buckle in the vertical direction. Lateral restraint and vertical support are provided by the KPs via brackets (Figure 15);

e. Struts can be simply-supported or continuous beams atop KPs or their brackets, depending on specific location;

f. Note the usage of diagonal struts at corners (Figure 16). They differ from typical transverse struts only in the axial horizontal load component they transmit to walers;

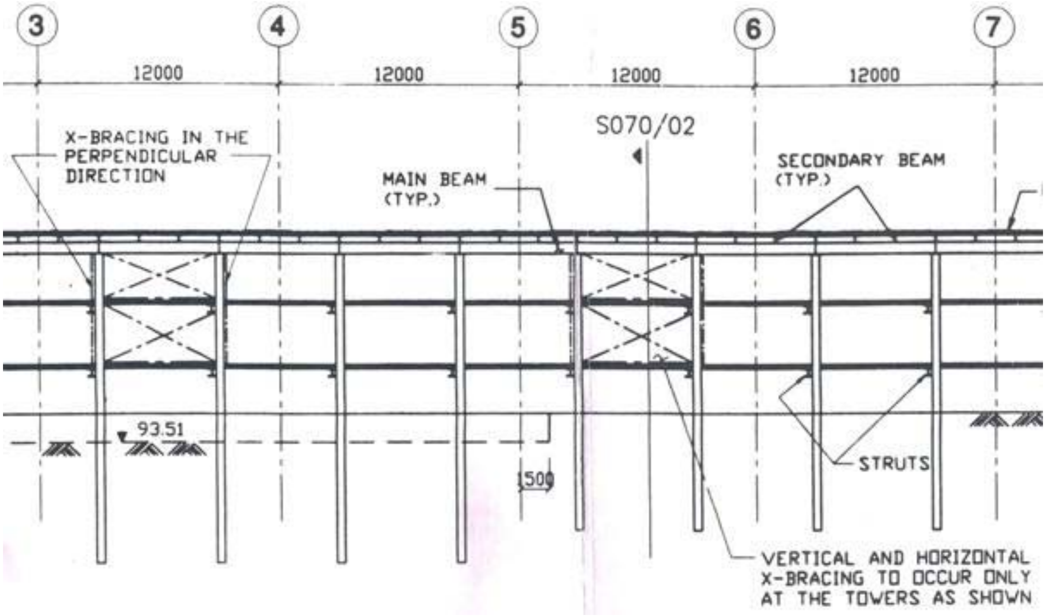


Figure 14: Longitudinal section showing towers to collect and transmit strut/KP restraint forces to walls.

g. Figure 16 displays the detail required at excavation junctions, and the impact of utilities on steelwork. Note the strut (1S3) strengthened with an additional beam and the additional diagonal struts (1DS4) and KP. All these are required to support the water main (Figure 17) and manhole (Figure 18). The cross beams serve three functions - propping the wall, splitting the manhole's load between the KP and the 1S3 and supporting traffic decking;

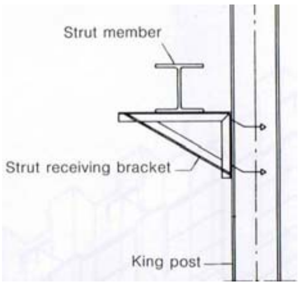


Figure 15: KP bracket (Hirose, c.1996).

h. Many top-down structures have large slab openings for escalators or architectural features. These slabs act as struts later, but these gaps impair this ability during construction. Temporary steel struts 'fill the void' and

i. Element design must include thermal effects. These generate additional strut axial forces and moments at KPs. For example, Ho *et al.* (1994) reported load variations in steel struts due to daily temperature changes of the order of 400 kN in a three-level excavation.

4.4 WALERS

a. Walers generally act only in bending. Effective lengths in buckling often need to be reduced by diagonal strut-waler connections as shown in Figure 13 and

b. Discontinuities in the linearity of the wall (Figure 16) produce axial forces in walers. Waler-wall connection design here should account for this.

4.5 LONGITUDINAL BEAMS

a. For design, primary and secondary longitudinal beams are assumed simply-supported due to varying KP positions. Rows of KPs are generally not straight throughout the excavation – refer to Sections 3a, 3b and 3n.

4.6 KINGPOSTS (KPS)

a. KP layout design is iterative and based on experience and output from Sections 3a, 3b and 3n. Tributary area loads are checked against section axial capacity, considering likely vertical unbraced lengths. The author suggests universal columns of 350 mm depth, 275 MPa steel grade, at 6 m spacings and 3-4 m unbraced length to start and

b. KPs are geotechnically designed as vertically and laterally-loaded piles and structurally as steel columns.

4.7 CONNECTIONS

a. All steelwork connections need rigorous design, with larger safety factors where connection is difficult, for example, overhead welds. Bolting and welding design calculations, particularly for eccentric loads like brackets (Figure 15) are critical.

4.8 UTILITIES AND UTILITY GAPS

a. Utility support loads affect all decking and wall elements. Figures 16 to 18 illustrate this and were discussed earlier;

b. Utility gaps often involve soldier piles to enable safe clearances on both sides of the utility. Soldier piles behave as vertical beams under shear forces from lagging element ends. Soldier pile-lagging wall sections are modelled by averaging the flexural rigidities of the pile and lagging sections, or manually designed as per Section 4c and

c. Lagging is generically represented in Figures 13 and 19. Elements can be sheeting, channels, angles or I-beams, and are designed as simply-supported beams resisting a tributary area of earth and hydrostatic pressures.

4.9 PLANNING CONSTRUCTION SEQUENCES

a. Bottom-up construction requires the progressive casting of wall sections to the soffits of struts, followed by strut removal. The newly-cast wall then behaves as a cantilever. Where slab-wall reinforcement design does not permit this, 'replacement struts' (author's term) are required. These could be typical horizontal struts similar to the ones removed, but their lengths complicate their eventual removal. The author has used inclined replacement struts as shown in Figure 16 to support cantilever walls off base slabs.

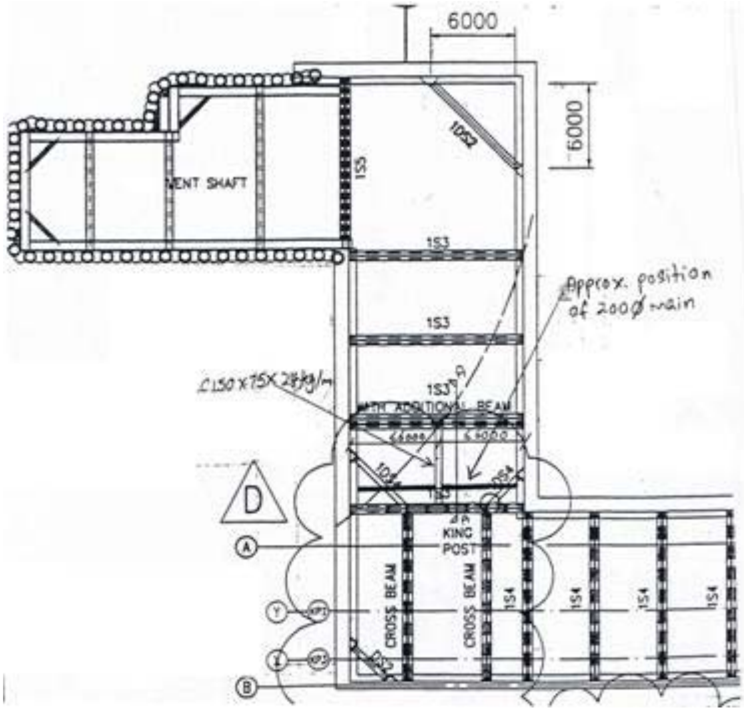


Figure 16: Corner struts, struts/KP supporting water main and manhole.

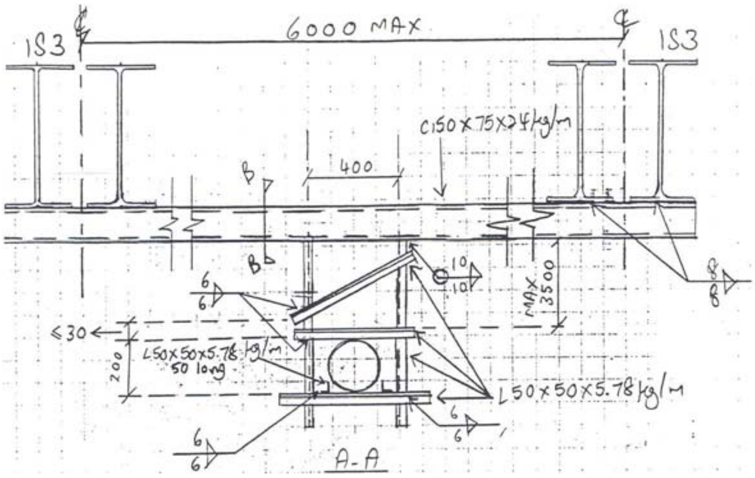


Figure 17: Typical utility support frame and connections.

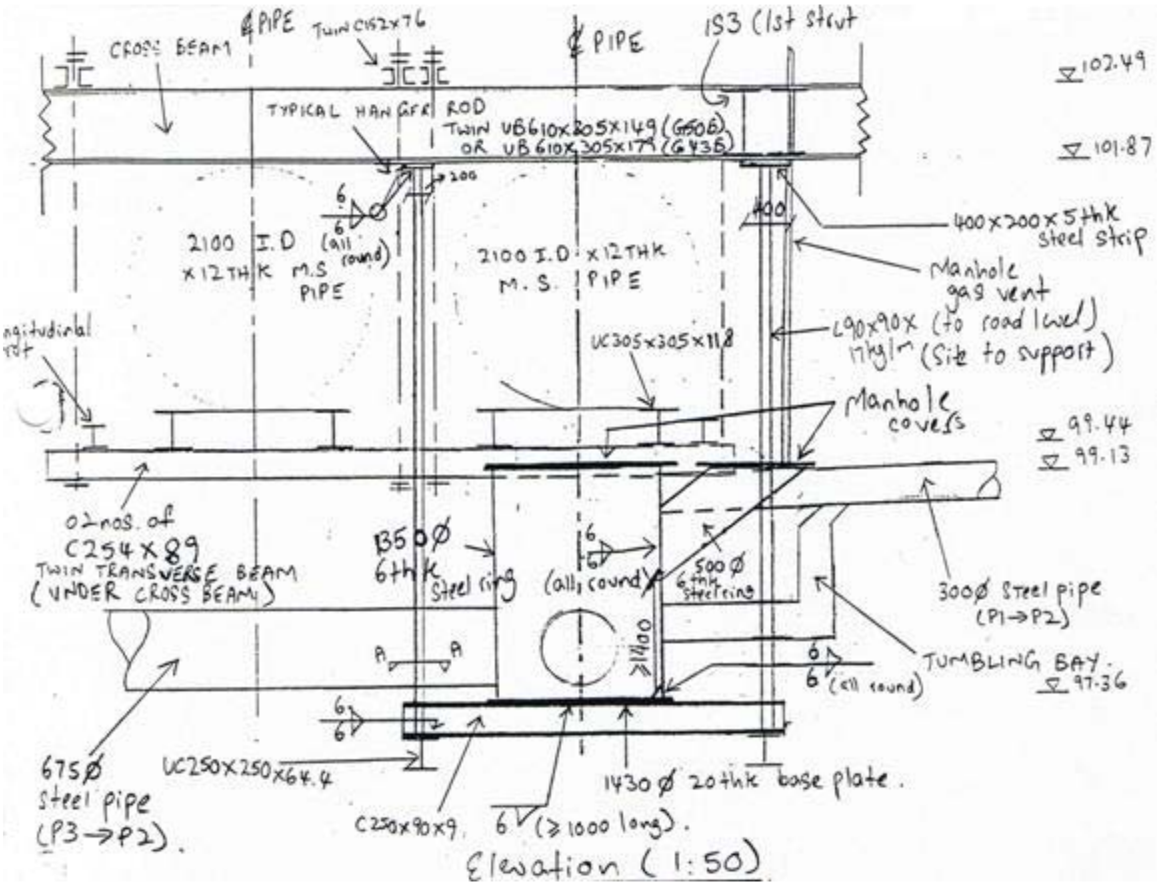


Figure 18: Manhole supported by same strut as water pipe (Figure 17) and cross beam (Figure 16).

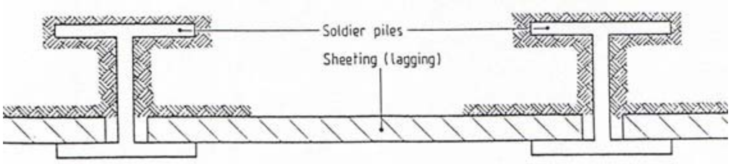


Figure 19: Schematic representation of soldier piles and lagging at utility gaps (BS 8002 : 1994).

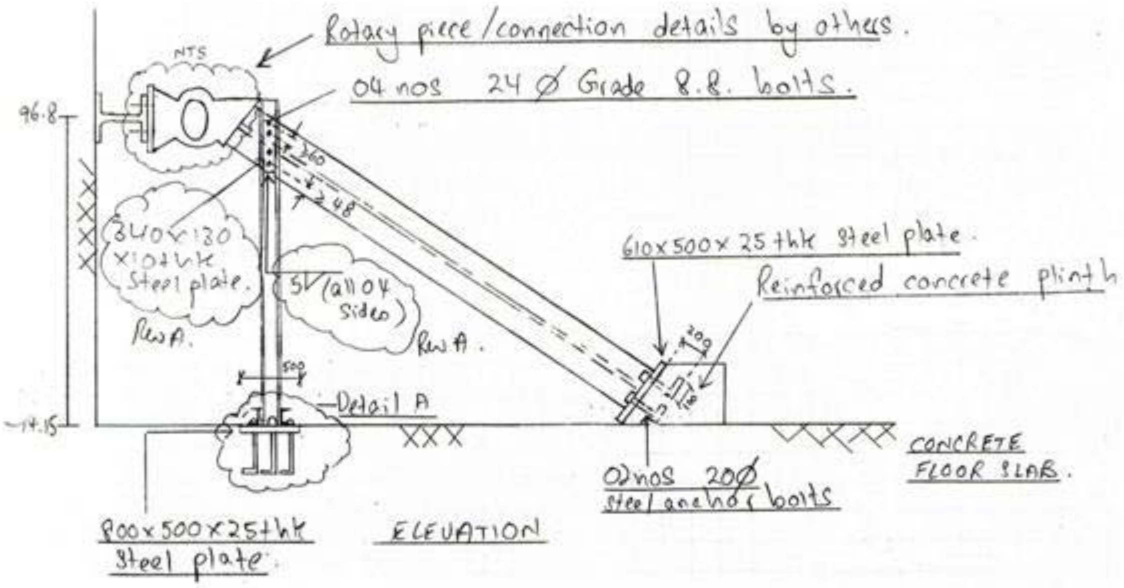


Figure 20: Inclined replacement strut to support RC cantilever walls during bottom-up construction.

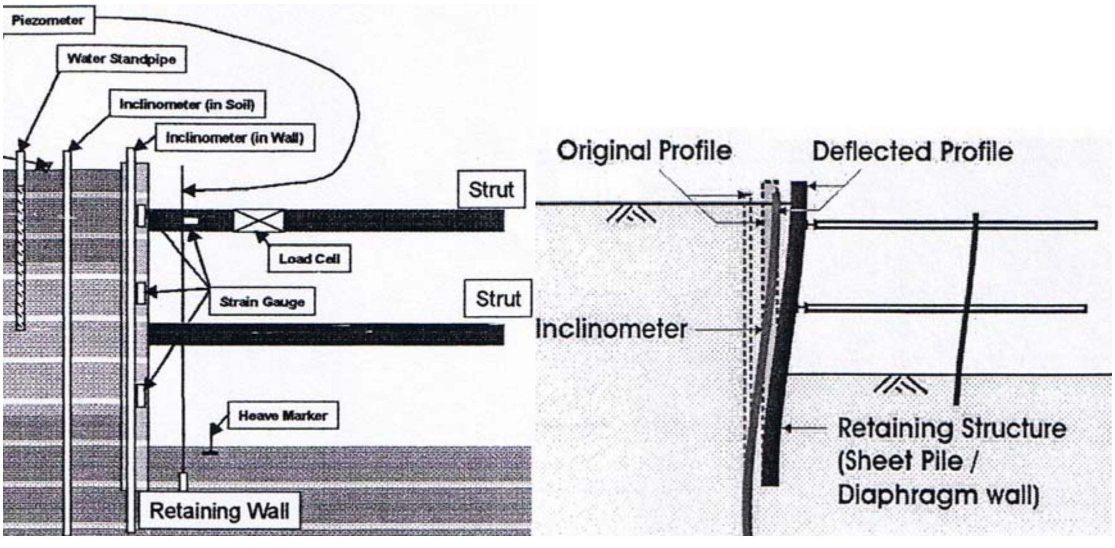
4.10 AUTHOR'S STRUCTURAL STEELWORK DESIGN RECOMMENDATIONS

a. The author suggests maintaining excess capacities of 15% in each ultimate limit state (bending, shear and axial) and overall buckling/combined bending capacity checks. Site steelwork change requests by clients, utility/other authorities and constructors are unavoidable and often overstress lean elements. Strengthening incurs delays and costs and

b. Due to the large loads involved, the author suggests designers start sizing steelwork elements by considering connection requirements. Weld and bolt connection designs require minimum edge distances, parent metal and flange/web thicknesses, thereby often governing section size selection.

5 INSPECTION AND INSTRUMENTATION

The author strongly recommends that regular visual monitoring complements instrumentation monitoring. Designers should also prepare instrumentation arrays for constructors to install on site prior to excavation. These arrays capture ground movements, strut loads and wall deflections, at locations where design predictions exist. The instruments are settlement markers, load cells/strain gauges mounted in/on struts and inclinometers inserted in/behind/on walls respectively (Figure 21).



(a) (b)

Figure 21: Schematics of (a) instrumentation (Orihara, 2003) and (b) inclinometer (Ganeshan, 2003).

5.1 VISUAL INSPECTION CHECKLIST

a. Pre-existing adjacent ground and steelwork defects, to avoid undue alarm later;
b. Sheet pile deflections at the cantilever top and between strut levels, visibly in excess of those predicted;
c. Localised flange, web and lateral torsional buckling of bracing elements;
d. Coloured staining of steelwork inside the shaft signalling soil or groundwater ingresses;
e. Weeping along sheet piles and ponding on walers;
f. Cracking or subsidence in adjacent ground;
g. Surcharge from construction materials and equipment, obviously in excess of design assumptions and
h. Over-excavation (each stage).

5.2 GENERAL CHECKS

a. Steelwork inspections should verify that both sections and steel grades are as designed. Steel mill and heat test certificates should be available and
b. All elements should obviously be oriented (major axis) correctly.

5.3 STRUTS, WALERS, BRACING AND SHEET PILES

a. Visual inspections of struts, bracing and walers ensure buckling is not impending. This includes batten plates, lacing (Figure 3) and splice joints (Figure 9);
b. Baseline readings for strut strain gauges and load cells should be taken before preloading. This enables preload verification and correct axial load monitoring;
c. Connections need close inspection and testing at agreed frequencies and
d. Strut and waler installation should be done promptly.

5.4 STRUCTURAL INSTRUMENTATION (FIGURE 21)

a. Strain gauges enable axial load monitoring of struts – necessary at each stage. Peak loads are expected when excavation has been completed to the next strut level, just before its installation.

5.5 GEOTECHNICAL INSTRUMENTATION (FIGURE 21)

a. Inclinometers enable comparison between actual and predicted sheet pile deflection profiles. Biaxial movements should be indicated and the instrument should extend below formation level to the depth (predicted by design) where deflection is expected to cease and
b. Pneumatic and vibrating-wire piezometer readings indicate GWT variations via inferences from porewater pressure data. Drops in porewater pressure often herald impending settlement.

The author highlights the following pointers gleaned from multiple projects:

a. Attention should focus on trends rather than raw data value variations, because instruments, data processing, readers or other factors occasionally deliver unusual but isolated readings;
b. Current accredited and certified calibration of instruments provided by the equipment suppliers is critical;
c. Baseline readings for all instruments must be taken at the correct time - not always immediately after installation. Examples include recharge well activity masking accurate piezometer readings, or taking baseline inclinometer readings before the casing grout has set;
d. Readings must be taken at the specified frequency and construction stages;
e. Suspect readings in one instrument can be investigated using other instruments' data. For example, an inclinometer profile deflecting unexpectedly should be matched by settlement observed at markers either simultaneously or slightly later. Paper prisms on the same walls act as double-checks on inclinometer movements and
f. Inclinometer readings are often read focusing on the value of the observed deflections compared to the design predicted deflection. However, curvature is inversely proportional to bending moment. The author notes cases where observed deflections were within prescribed limits, but 'sharp bumps' occurred along the vertical deflection profile (Figure 21(b)). The author suggests these bumps reflect high localised wall moments, warranting monitoring, particularly for compliance to crack width requirements in tanked structures.

6 CONCLUSIONS

The author regards temporary structural steelwork as a rational and flexible solution for deep excavations in soft ground especially where conventional earth retention measures utilising ground anchors and soil nails cannot be used. Steelwork support methods also readily accommodate site/authority-requested deviations on utility, manhole, crane platform and other positional changes after steelwork completion via economical *ad hoc* element strengthening.

There are other economies, particularly for structures built bottom-up, due to wall cost savings. These economies depend on labour costs as steelwork is labour-intensive, but this applies equally to all temporarily-braced excavations.

Internal bracing of excavations especially lends itself to situations where traffic staging requires traffic to cross the excavation. The obvious disadvantage of internal excavation support is space restriction for permanent works construction and the management of temporary works elements incorporated into the permanent works.

7 ACKNOWLEDGEMENTS

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