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Estimation of earth pressures in the design of a deepened quay wall formed of an existing relieving platform

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Introduction

A programme of modernisation and deepening of the existing berths at Limehouse Wharf, Rochester was envisaged for the bulk handling of newsprint.

Most of the existing wharf structure consisted of a relieving platform with a section as shown in Fig.1. The front wall consisted of sheet piling 15.5 m in

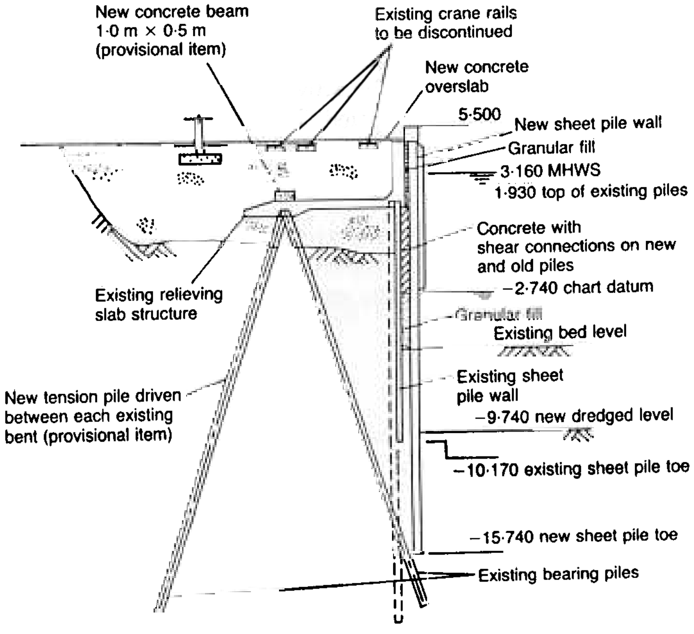

Fig. 1: Typical cross-section of existing and proposed new works

height, attached to an R.C. relieving platform 8 m wide at a depth of 3.5 m below wharf level supported on pile bents. Each bent was believed to consist of three BSP cased piles, two driven to landward and one to seaward, raked at 1 in 2.75. The bents were placed at 4 m centres. From the ground succession and the driving characteristics of BSP cased piles, these piles were estimated to be about 13 m long.

The use of a relieving platform introduces several benefits, particularly in circumstances where the ground conditions limit the efficacy of anchor piles in tension while capacity in compression is good. More particularly since the platform slab carries all the load above to a level at or below dredge, it substantially reduces the height of retained soil. It also provides vertical surcharge to the sheet piles to assist against pull-out forces and to improve passive resistance to the embedded section.

The effectiveness of the relieving platform is a function of both the geometry and the soil-structure interaction. Three empirical hypotheses have been postulated to facilitate analyses of these structures

(*a*) *Fully screened* — The fully screened hypothesis assumes that the concrete slab transfers all the load above to the toe level of the sheet pile wall and raking piles, which are remote and below dredge level. Thus the active pressure diagram against the wall consists of two independent diagrams for pressure above and pressure below slab.
(*b*) *No screening* — The no screened hypothesis assumes that the slab does not carry vertical load and thus the active pressure diagram against the wall is the same as if no slab existed. The wall is in effect a propped cantilever, the prop force provided by the anchor effect of the pile bent supporting the slab.
(*c*) *Partially screened* — The partially screened hypothesis assumes that only part of the self weight above the slab is transferred to toe level of the sheet piles and the platform piles. Thus the earth pressure diagram acting on the sheet piles is larger than in the fully screened hypothesis but less than the no screen case.

Soil conditions

The soil conditions vary somewhat along the length of the wharf but in generalised terms can be described thus

(a) 3.5 m made ground
(b) 3 m silt
(c) 6 m silty sand
(d) 5 m gravel
(e) chalk.

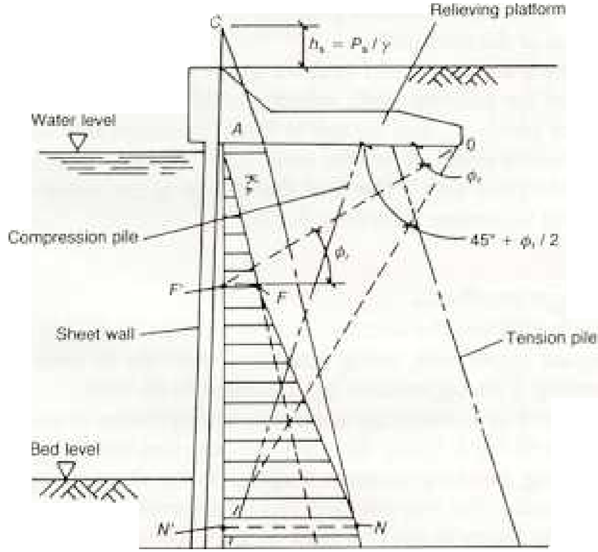

Fig. 2: Theoretical pressure distribution on rear of wall. BS 8349

The Made Ground consisted of loose to medium dense black sandy gravel, ash, with fragments ot brick and concrete overlying older soft to firm clay with flints, chalk, glass fragments, shells, timber, ash, etc with Standard Penetration Tests in the range 3 to 19.

Soft peaty clay was sometimes present beneath the made ground.

The Silt was described as soft grey clayey silt with Standard Penetration Tests in the range 8-10.

The Silty Sand was generally loose to medium dense, dark grey or black, often malodorous and slightly organic. Standard Penetration Test values varied from 10-28.

The Gravel was loose to dense sandy and fine to coarse with Standard Penetration Test values generally in the range 25 to 54 and appearing to become more sandy with depth.

The Chalk was Grade V for about 1.5 m increasing to Grade II and then Grade I within 1 to 2.5 m.

Proposed solution

It was proposed to dredge the bed to approximately 15.5 m below cope level, i.e. about the same level as the toes of the existing sheet pile wall, to accommodate larger vessels without grounding and thus allow vessel movements at all states of the tide.

To achieve this it was proposed to drive a new sheet pile wall to greater depth in front of the existing wall, which would also be attached to the existing relieving platform, also shown in Fig.1. To design this required an estimate of the earth pressure on the new wall, the new loadings in the relieving platform piles and a check of the ability of the members in the relieving platform to assume their new duties.

Existing design methods

BS 6349 Part 2: 1988 and the German Code of Practice EAU 1985 adopt the partially screened hypothesis, using empirical methods to determine the extent of screening. Two approaches are described in BS 6349.

The first approach is to define the earth pressure by means of an empirical method as shown in Fig.2. Using this pressure diagram the factor of safety against overturning, bending moment diagram in the sheet piling and the anchor force applied to the rear pile bent can be determined.

The effect of the forces in the pile bent on the sheet pile wall is ignored. "Average" soil parameters are assumed, the method cannot deal directly with stratified soil conditions.

The second approach uses the Culmann Wedge method (Fig.3) to determine the effects of the forces in the raking piles on the sheet pile wall. The disadvantage of this method is its inability to deal with stratified ground. It also does not generate an earth pressure distribution and one is therefore

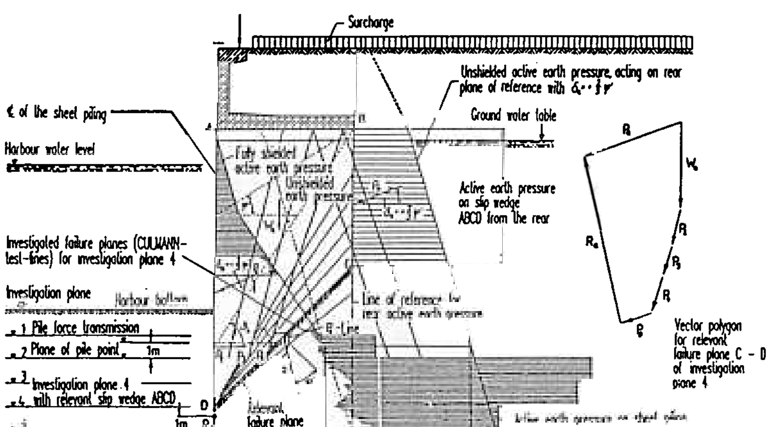

Fig.3. Culmann Trial Wedges

unable to obtain an estimate of bending moment in the sheet piles.

While extensive site investigations were conducted to obtain representative soil parameters for design, it remained central to the proposal to analyze the existing wall structure in order to test the soil parameters we were proposing to use and thereby assess the ability of the existing relieving platform to cope with the forces and moments generated by the deepening of the wharf.

The first of these tasks immediately presented a problem. Even by assuming the most optimistic interpretation of the site investigation it was difficult to justify the existing design using either of the empirical analytical methods. It was essential to resolve this problem before proceeding to the analysis of the proposed new works. The fallacy lay in the empiricism rather than in the soil parameters. It was therefore decided to examine these methods critically in an attempt to improve on them.

Methods adopted

Since each method possesses some merits of its own, it was decided to attempt to combine the principles behind each and to compare the end result with a non-linear plane strain finite element analysis.

Earth pressure distribution method

The procedure for carrying out the analysis based upon earth pressure distribution, but adapted to cater for stratified soil and incorporating the effects of the thrust in the pile bent was as follows

(*a*) The "average" c' and ϕ' of the soil behind the wall was estimated.
(*b*) Based on the "average" ϕ' value the transition line between the "fully shielded" and "unshielded" earth pressure was found.
(c) The unshielded earth pressure line for the actual stratified soil was then superimposed on the diagram. The transition line representing the stratified soil was assumed to be given by applying the ratio of the transition line intercept obtained in (*b*) to its unshielded intercept as a "shielding factor" to the stratified unshielded line.
(*d*) Using this diagram the depth of penetration of the sheet piles for a required factor of safety can be determined together with the bending moment diagram for the sheet piles and the anchor force pulling on the rear pile bent. This set of results was called Result Set No.1.
(*e*) It was then assumed that the load above the concrete platform is carried by the platform which is simply supported by the sheet piling and anchor pile bent. Hence, by simple statics the vertical load component in the pile bent can be obtained.
(*f*) Combining the horizontal pull from (*d*) with the vertical force from (*e*)

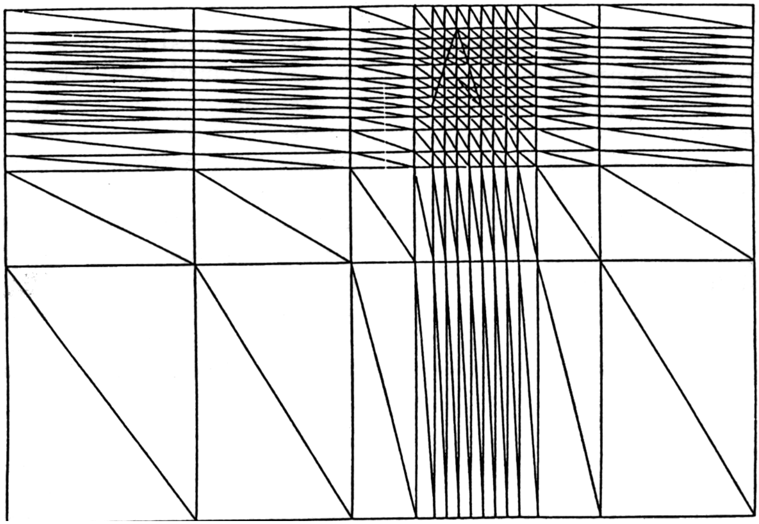

Fig.4. Finite element mesh

the force equilibrium at the top of the pile bent gives the load in each raking pile.
(*g*) Assuming each raking pile transfers all its load from the head to the toe, and that at toe level this force is applied to the soil as an inclined uniform line load, the surcharge on the rear of the sheet piles due to the raking piles can be found using Melans formula.
(*h*) When this additional surcharge is introduced into the re-calculation of the stability of the wall this yielded a new anchor force.
(*i*) Introducing this new anchor force steps (*f*) to (*h*) were repeated.
(*j*) Steps (*f*) to (*i*) were repeated several times until the difference in anchor force became insignificant, i.e. a short manual iteration process. Although this process sounds laborious, convergence is actually quite quickly achieved. The anchor force, factor of safety etc resulting from this process was called Result Set No.2.

A corresponding result was obtained using the wedge analysis based upon average c' and ϕ', with the forces indicated in Fig.3 together with the effects of the surcharge due to the raking piles from analysis of earth pressures. This was termed Result Set No.3.

The finite element approach
The finite element analysis was carried out using CRISP-90 which is able

Table 1.Summary of analysis of old dredge level

	Analysis by Earth Pressure		Analysis by Wedge	Analysis by Finite Element
Result Set No	2	2	3	
FOS	1.2	1.16	1.04	1.86
Active thrust (kN)	383	392	427	495
Prop force (kN)	136	133	N/A	190

to combine two dimensional elements, beam elements, bar elements and interface elements together. In our analysis plane strain conditions are assumed with the concrete slab and sheet piles represented by the beam elements, the raking piles by bar elements and an interface element used beneath the slab and on both faces of the sheet pile. The mesh used is shown in Fig.4. In order to maintain a state of equilibrium at the start of this analysis, the elastic continuum representing the soil initially has a level surface with internal stresses in equilibrium with external constraints. Staged excavation is then carried out in front of the wall, eventually to the old dredge level. The sheet pile is then extended to the new level and further staged excavation carried out down to the new proposed dredge level.

Summary of results

A summary of the results obtained, compared with those from the Finite Element method are shown in Tables 1 (existing dredge level) and 2 (proposed new dredge level).

From these comparisons it appears that the factor of safety obtained by the methods used by BSI and EAU, when extended to allow for stratified soil as proposed, are conservative compared with the Finite Element Analysis,

Table 2. Summary of analysis of proposed dredge level

	Analysis by Earth Pressure		Analysis by Wedge	Analysis by Finite Element
Result Set No.	1	2	3	
FOS	1.48	1.32	1.21	1.98
Active thrust (kN)	771	860	987	1208
Prop force (kN)	291	293	N/A	291

Table 3. Summary of the effect of raking pile

	Old Dredge Level		New Dredge Level	
	Surcharge (kN)	% Increase in Active Thrust	Surcharge (kN)	% Increasein Active Thrust
Wedge analysis	44	11.5%	112	14.5%
Finite Element Analysis	216	56.4%	437	56.7%

although the anchor forces are in reasonable agreement.

When the berth is deep or when the penetration characteristics of the anchor piles is limited (either by the system, or by the density of the soil) the compression piles may be founded above dredge level. The accepted convention is that if the piles are founded more than 1m above dredge, the surcharge effect of the pile load should be included in the analysis of the sheet pile wall. From the results the authors have attempted to assess these effects on the design of the sheet piles. The effect of taking the forces in the raking piles into account was assumed to be the difference between the results from the wedge analysis and Results Set No.1 and the difference between the Finite Element Analysis and Result Set No.2.

From Table 1, using the modified earth pressure method the factor of safety in the existing section drops from 1.2 to 1.104 with the inclusion of the effects of the raking pilea by Wedge Analysis.

In the case of the proposed new dredge level the corresponding factor of safety drops from 1.48 to 1.21.

The corresponding factors of safety obtained from the finite element analysis are 1.86 and 1.98.

Conclusions

A method has been postulated, combining the Earth Pressure Distribution and Wedge approaches embodied in BS 6349 to investigate the pressures on a sheet pile relieving platform in stratified soil, in which the pile bents impose load on the rear of the wall. The results of this method have been compared with those obtained from finite element models of the same cases.

The most striking result of this comparison is that whereas using BS 6349 methods the adequacy of the existing wall appears, on paper, to be very marginal (yielding factors of safety ranging between 1.04 and 1.2), the factor of safety against passive failure, from the finite element analysis is 1.86, which would seem unnecessarily high. Needless to say, the existing wall has behaved entirely satisfactorily for some years.

Similarly, when the deepened wall is designed by BS 6349 to provide an acceptable factor of safety against active failure (factors of safety ranging from 1.21 to 1.48) the finite element analysis yields a factor of safety of 1.98.

Prop forces, deduced from the finite element analysis are equal or up to 40% greater in the finite element analysis than from the earth pressure method in which active thrusts are also higher, by 30-57%.

The wide disparity between the results is a matter of some concern, since the conventional methods are yielding a design which falls short of the accepted minimum standards while the finite element approach suggests that the designs are somewhat conservative. In part at least, the difference lies in the inclusion of friction between soil and wall in the latter case.

It seems that the empirical methods currently being used, although apparently performing satisfactorily, are achieving their objective fortuitously rather than definitively.

Since all the methods rely to a greater or lesser extent on empiricism or theory, many more results from model tests and field monitoring are needed before improved methods of analysis can be verified.

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