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A design study for a road tunnel: The effects of construction detail

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ABSTRACT: This paper reviews a design study for a cut and cover tunnel. Although this was a comparatively simple structure it is a useful illustration of the need to accurately model the construction sequence and details such as connections between structural components. These details dictate how the structure, and the ground around it, will behave and have implications for design.

1 INTRODUCTION

As part of a major trunk road improvement scheme in the London area, an underpass or road tunnel is to be constructed beneath a major intersection. During the tendering process a number of finite element analyses were undertaken in order to design the retaining structures and to assess the long term effects of the method of construction on the carriageway. To assess the global behaviour of the structure there is a need to understand how structures are likely to be built and how elements of the structure interact.

Even though this was a comparatively simple structure (see Figure 1) this study showed the need to model structures such as this in some detail.

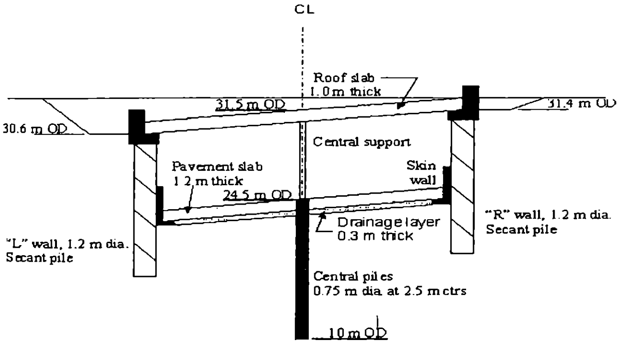

Figure 1. Schematic cross section

Without using finite element analysis the effects of construction sequence (in this case "bottom up" and "top down"), sway, long term heave and even connection details could not have been realistically predicted (Potts (1993)). All these factors had implications for the design.

This paper describes the results of the analyses and uses them to illustrate the importance of realistic modelling. These results can be used as a control allowing the relevance of other forms of analysis to be assessed.

2 GROUND CONDITIONS

Before any contracts were let an investigation was undertaken to obtain parameters for the design and to define ground conditions. These were broadly 2m of Made Ground above Boyn Hill Gravel which was 3 to 4m deep, over London Clay. There was a layer of weathered London Clay about 2m in depth above unweathered material. Boreholes were not sufficiently deep to prove the base of the London Clay but these borings did extend to more than 30m below current ground level.

3 SOIL PROPERTIES

Subsequently a supplementary investigation was commissioned by the Promoter's agents. This included self boring pressuremeter tests from which it was intended that in-situ stresses could be deduced. However, these tests were also used to derive non-linear elastic parameters for use in the analysis using the procedure described by Jardine (1992).

To represent the soil behaviour, non-linear elastic models of the form described by Jardine et al (1986) were used in conjunction with a Mohr-Coulomb yield criteria. One aspect of the design was the long term behaviour of the structure and the carriageway; an option for the carriageway was a flexible foundation in which case the clay beneath it would be free to swell in an unrestrained manner.

Figure 2 shows a comparison between some high quality swelling tests on London Clay (Hight and Higgins (1994)) and a simulated test using the adopted model for the London clay. There is very good agreement between the laboratory tests and the simulation which shows that the model used should reasonably reproduce the long term behaviour of the clay and structure.

4 THE STRUCTURE AND ANALYSES

Figure 1 shows a cross section through the structure which is about 28m wide and has a roof slab 6m above the level of the carriageway. There are two secant pile walls which retain the ground. Individual piles are connected by capping beams which, in the long term, support a continuous roof slab. The roof slab is also supported by a central wall which in turn is supported by a series of piles below the level of the pavement. Two options were considered for the pavement; a 1.2m thick slab and a flexible foundation, both with a drainage layer beneath.

To model the structure and behaviour of the ground a series of finite element analyses were undertaken using the computer program ICFEP. During construction the clays were assumed to be undrained but in the longer term they were allowed to drain. At the time the analyses were undertaken the programme for construction had not been finalised.

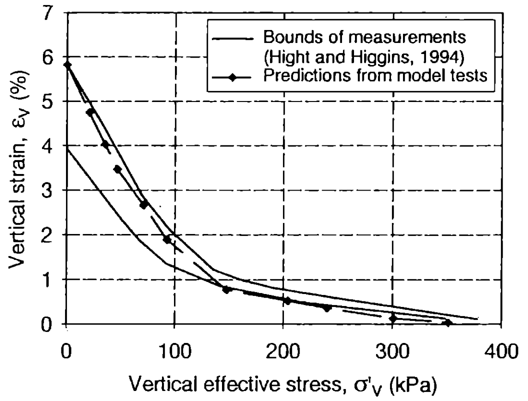

Figure 2: Swelling data for the London Clay

5 CONSTRUCTION SEQUENCE

Two methods of construction were considered, "top down" and "bottom up".

For "top down" construction the roof slab was constructed after a preliminary excavation for a piling platform and installation of the secant pile walls and the central piles. Ground was excavated beneath the roof slab down to formation level and then the pavement was constructed. Throughout construction the roof slab was supported on the central piles.

For "bottom up" construction a temporary prop was to be installed after pile installation but there was no central support at this stage. Excavation to formation level followed and a base slab was constructed. A central support was then built on top of a pile cap and the permanent slab cast as the temporary prop was removed.

After the road tunnel had been completed backfill was to be placed above the structure to existing ground level and then an embankment was to be constructed above it applying a uniform surcharge to the structure.

6 SYSTEM STIFFNESS

For "bottom up" construction a series of analyses were run in which the stiffness of the temporary prop was varied. Prop stiffnesses (K = EA/L) ranged from 10 MN/m/m up to 1000 MN/m/m, a variation of 100 times. Figures 3 and 4 summarise the results of the analyses showing, respectively, the variation of temporary prop force and the variation in maximum bending moments in the two secant pile walls with changing prop stiffness. On these figures results have been normalised against those obtained from the analysis in which the temporary prop stiffness was 100 MN/m/m. Therefore, on Figure 3, which shows

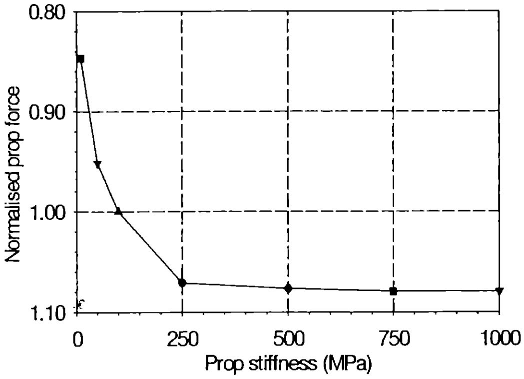

Figure 3. Variation of prop force with prop stiffness

the variation in temporary prop force with changing prop stiffness, the normalised prop force is 1.0 when K = 100 MN/m/m. Likewise on Figure 4 the normalised maximum bending moments are 1.0 when K = 100 MN/m/m.

The results of the analyses are consistent with those of Clough et al (1989) and Potts and Day (1990). As the system stiffness increased, by virtue of an increase in the prop stiffness, the effect on the temporary prop force and the maximum bending moments in the wall became less pronounced; beyond a stiffness of 100 MN/m/m there was little advantage to increasing the prop stiffness either by reducing the spacing of the props of by increasing the size of the section.

7 METHOD OF CONSTRUCTION

When constructing the tunnel by the "top down" method the permanent prop was in place but, based on a Young's modulus of 28 GPa, and with no allowance for construction joints, thermal effects etc, the stiffness of the slab (K) was about 100 MN/m/m and yet maximum bending moments in the wall were about 10% lower than for bottom up construction. The difference was simply due to subtleties between the two methods of construction (e.g. the support to the roof slab etc).

For "bottom up" construction there was no support for the temporary prop during construction but for "top down" construction the roof slab was supported by the central piles. It was therefore important that shear stresses on the sides of the piles were not overestimated and so interface elements were used to represent the pile-soil interface. Such an approach was also necessary in order that in the long term the piles did not artificially restrain the clay as it swelled.

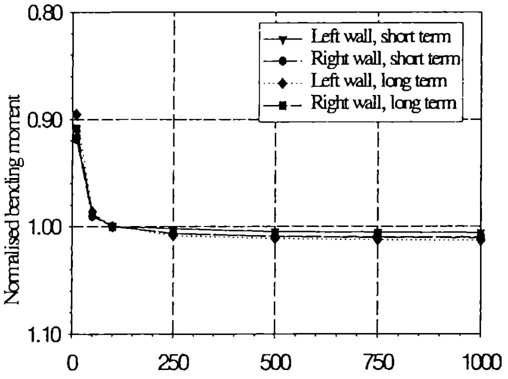

Figure 4. Variation of bending moment with prop stiffness

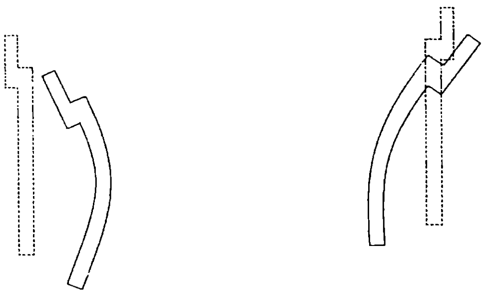

Figure 5. Displaced shape, "bottom-up" construction

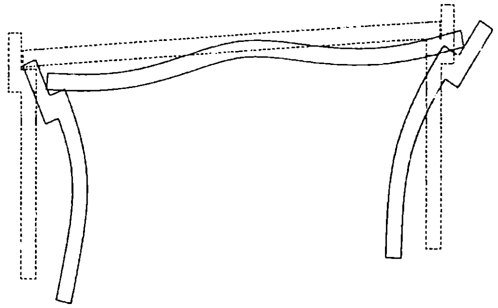

Figure 6. Displaced shape, "top-down" construction, pinned connections

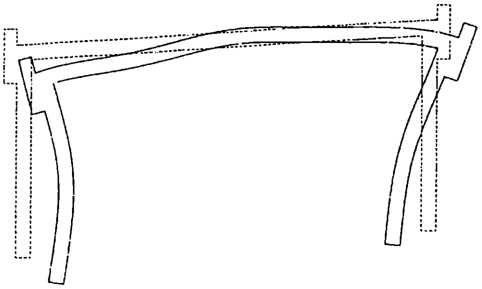

Figure 7. Displaced shape, "top-down" construction, full moment connections

8 SWAY

Figure 5 shows the displaced shape of the roof slab and pile walls for "bottom up" construction. Similarly Figures 6 and 7 show the displaced shapes of the roof slab and the retaining wall for analyses that modelled "top down" construction, with pinned and full moment connections between the roof slab and the retaining walls respectively.

The deformed shape is the solid line whereas the dotted line is the profile "as constructed". These diagrams are plotted to the same scales.

In all three cases the structure appears to sway, one wall is pushed back into the soil whereas the other wall moves in to the excavation

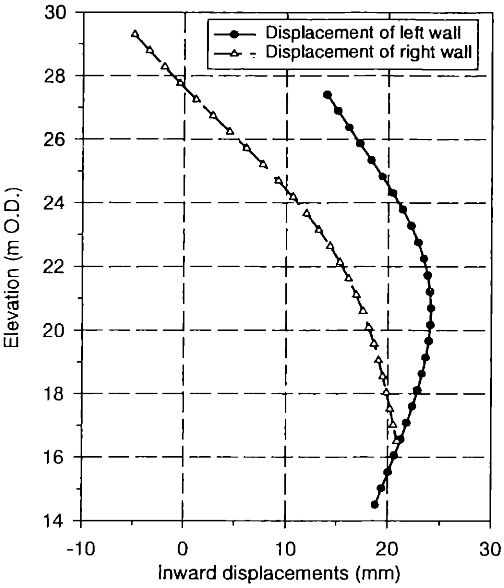

Figure 8. Displacements of left and right walls

Movement of the left wall is resisted by passive pressures built up in front of it and behind the other wall. The flexibility of the roof slab and the method of supporting it also influenced the overall behaviour of the structure. Figure 8 shows wall displacements for the two walls for "top down" construction with full moment connections between the roof slab and walls (positive displacements relate to movements into the excavation).

Sway of the structure will not only influence the forces and bending moments in it but this will also have an obvious impact on the behaviour of the ground surrounding it and of remote structures. This has implications for the assessment of building damage.

An analysis that had assumed symmetry, either because this was implicit in the method of analysis or because of assumptions made, would not have correctly predicted how the structure might behave.

In an analysis that assumed symmetry the same bending moment distribution would have been predicted for both walls. From inspection of the displaced shapes of the walls it is apparent that this was not the case (refer to Figures 5 and 6). This has obvious implications for the designer of such a structure not only in terms of ground movement but also in terms of the structural detailing.

9 CONNECTION DETAIL

The detailing of connections between structural components influences how forces are distributed between them and has to be an important consideration in any design. Even so this is often a point of much debate between structural engineers and those undertaking an analysis of this form. In the outline of a scheme these details, or the implications of these details, are rarely well defined. To understand the influence of the detailing of connections it is necessary to look closely at how the roof slab and the top of the walls behave; there are marked differences between the analyses with pinned (Figure 6) and full moment connections (Figure 7).

Figure 9 shows the bending moment distributions for the left wall (refer to Figure 1) for the analyses with pinned and full moment connections (refer to Figures 6 and 7) in the short term.

The maximum bending moment for the left wall (refer to Figure 1) in the analysis with the full moment connection was approximately 1079 kNm/m, as opposed to 1625 kNm/m with the pinned connection, a 50% increase. For the other wall, bending moments of 1351 kNm/m and 1779 kNm/m are predicted, a 30% increase in bending moment due to the difference in connection detail. Different modes of deformation result in differing bending moment distributions.

Although national codes of practice may allow the designer to take account of moment re-distribution when detailing reinforcement, there are obvious implications for the designer. This example shows how careful the analyst must be to fully understand how the structure "works" and to ensure that details such as connections between structural elements are modelled realistically.

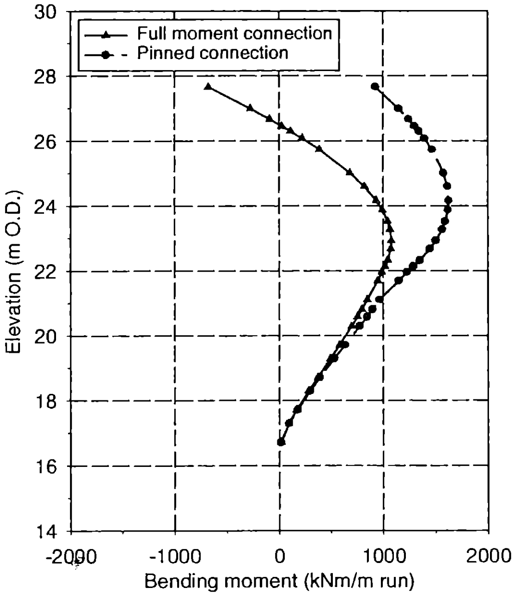

Figure 9. Bending moments in left wall for pinned and full moment connections

Table 1: Soil Properties

Strata	Density (kN/m^3)	K_o	c' (kN/m^2)	ϕ' (°)	Dilation	
					Short term	Long term
Made Ground	19	0.5	0	25	$\phi'/2$	0
Boyn Hill Gravel	20		0	35	$\phi'/2$	$\phi'/2$
Weathered London Clay	20	Top 5m varies from 0.5 to 2.0, elsewhere 2.0	10	21	$\phi'/2$	0
Unweathered London Clay	20		15	23	$\phi'/2$	0

10 CONCLUDING REMARKS

Influences that became apparent during the design of this comparatively simple structure were the system stiffness, the method of construction, the movement of the structure and the detailing of connections between structural components.

The effects of system stiffness have been reasonably well known for some time and it could be anticipated that the construction sequence chosen might influence the behaviour of the structure and the design of it. However, the detailing of connections between structural components needs careful consideration and in this case detailing of connections between the roof slab and the walls has had a marked effect on the bending moment distribution that has to be accommodated. Differences in bending moments due to different connection details changed the maximum bending moments in the walls by 30 to 50%.

In this case potential damage to adjacent structures was not an issue, however the sway of the structure would have had implications if it had been. Although excavation proceeded evenly across the tunnel, once the piling platform had been formed, such a mode of deformation would not have been predicted by an analysis (of whatever form) that assumed symmetry. Movements on one side of the structure would have been greater than an analysis which assumed symmetry would have predicted whereas movements on the other side of it would have been less than predicted by such an analysis. Even so, methods and software packages that do assume symmetry are still used in practice for design.

Any analysis obviously has to be realistic if it is to be used for design. This simple design study has provided a useful illustration of some of the factors that need to be considered in the design of structures of this form and the need to model them in sufficient detail. Even with high quality soil data and sophisticated constitutive models for the soil, without an appreciation of how structural components interact, how the structure is likely to behave and how the structure is likely to be built, it is apparent that realistic analyses cannot be performed.

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