Some observations on the use of ‘swap’ elements in staged construction

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Introduction

This paper considers the effects resulting for the use of ‘swap’ elements, i.e. elements that replace soil with another material, e.g. concrete to walls, shafts or tunnels. In particular, the need or otherwise to renumber specific nodes is investigated. It will be shown that where staged construction is used, e.g. in the construction of shafts, the effect of the method of node numbering has a significant influence on resulting stresses/forces and hence in the design requirements.

At the 11th CRISP User Group Meeting the concept was presented of a shaft having no reinforcement in the base, but with the inclusion of steel fibres and constructed from sprayed concrete. Since that time the concept has become a reality, with the shafts being used for ever increasing diameters and depths. The analyses for these shafts have been carried out using SAGE CRISP.

Whilst using the DOS version of CRISP some years ago for the design of tunnels, large equilibrium errors occurred that were traced to the need to renumber the internal nodes to prevent the swapped tunnel lining from inheriting stresses from the soil. Adopting a similar approach with the Windows version of CRISP for staged construction of a shaft (the tunnel lining being inserted over a period of time, but in a complete ring) produces apparently inconsistent results; it is this aspect that is reviewed.

The problem

The shafts, either constructed or being constructed, range from 15m to 18m in diameter and up to 40m in depth. For the purpose of this exercise a shaft of 18m diameter and 40m deep is analysed and is shown below in Figure 1. The lining of the shaft is sprayed concrete to the wall and steel fibre reinforced concrete to the base. The wall thickness is 350mm and the curved base is 500mm thick with an internal radius of 20m.

The analysis is treated as a three-dimensional axisymmetric problem, symmetrical about the axis of the shaft. The finite element mesh is shown in Figure 2.

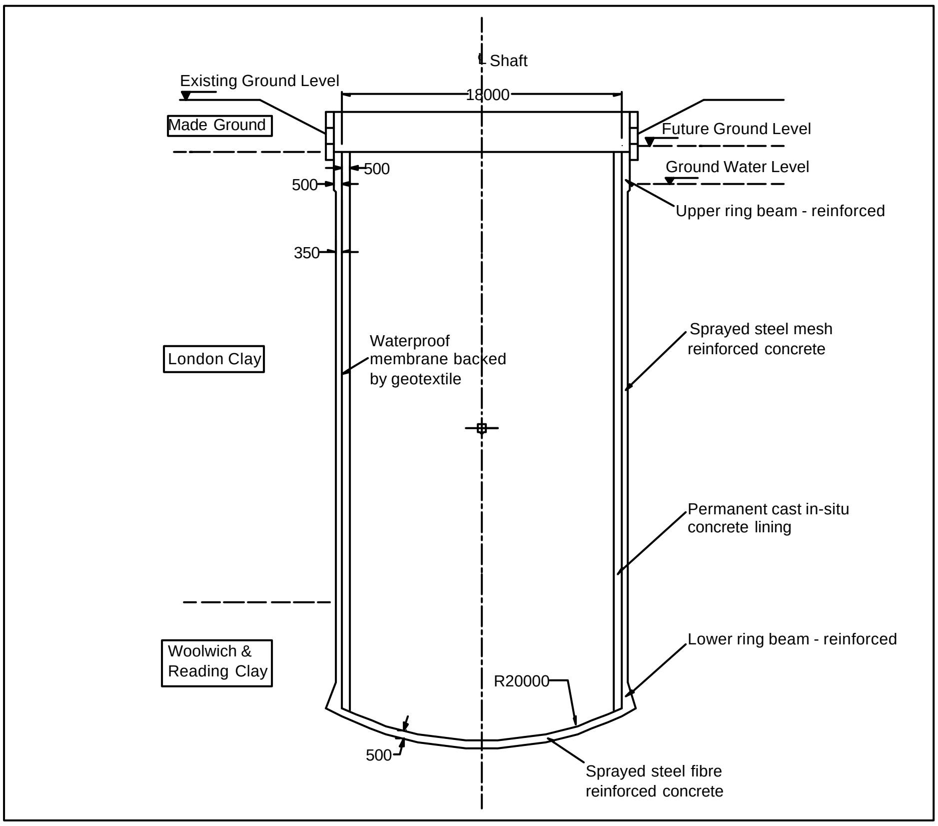

Figure 1. Cross-section through idealised shaft

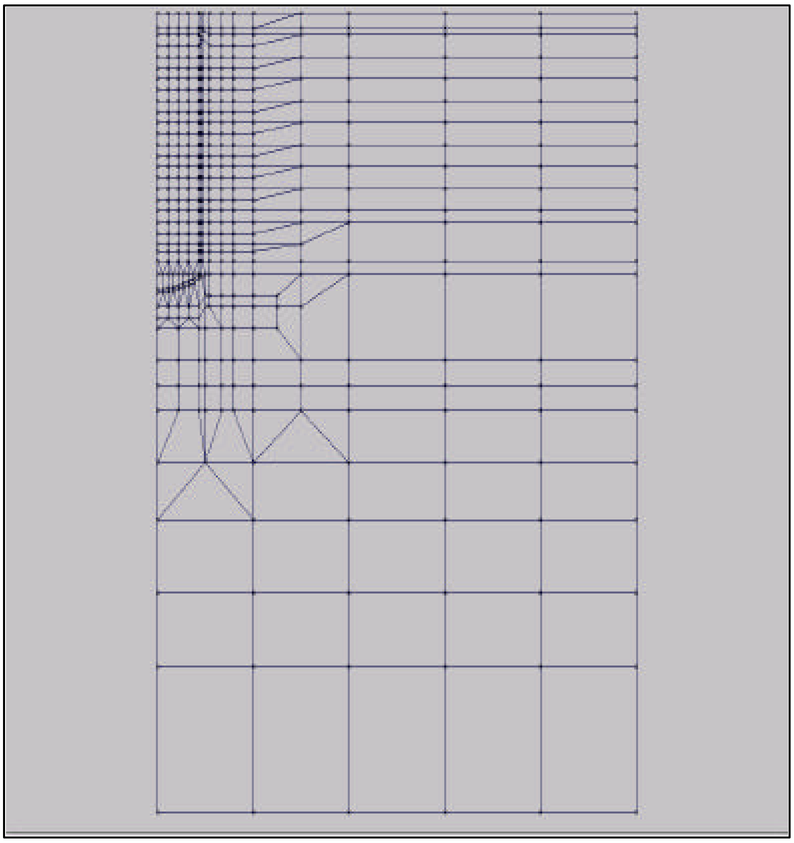

Figure 2. Finite element mesh used in analysis

Soil parameters

The soil parameters used in the analysis are similar to those adopted for the works in the London area, i.e.

Material Type	**g_b** (kN/m^3)	**K_o**	**E´** (kN/m^2)	**u´**	**c_u** (kN/m^2)	**f_u** (°)	**c´** (kN/m^2)	**f´** (°)	**k** (m/s)
Made Ground	20	0.66	9E3	0.2	50	0	0	20	1E-5**
Terrace Deposits	20	0.66	9E3	0.2	50	0	0	20	1E-5**
London Clay	19	1.25 *	240c_u	0.2	30+6z	0	2	25	1E-9**
Woolwich and Reading Beds	20	1.2	72E3	0.2	300	0	0	26	1E-7
Upnor Formation	19	1.0	105E3	0.25	-	-	0	33	3.5E-6(k_v) 1.7E-5(k_h)
Thanet Sands	19	1.0	330E3	0.25	-	-	0	35	3.5E-6(k_v) 1.7E-5(k_h)
Chalk	20	1.0	2500E3	0.25	3000	-	30	48	1E-7**

* - at mid-point of strata
** - assumed

The elastic modulus for the sprayed concrete was 1E7 (35N/mm^2) to take into account the effect of additives used in its production.

The soil is modelled using a fully coupled consolidation analysis with an elastic-perfectly plastic constitutive model with a Mohr-Coulomb yield criterion. The shaft base and walls are modelled as elastic elements.

Finite element analysis results

Bending Moments, Normal forces and Displacements

Consider first the bending moments and normal forces in the curved base for renumbered internal (intrados) nodes compared to no renumbering. Figures 3 and 4 show the bending moments in the base one year after completion of construction (consolidation period of 1 year). The maximum bending moment for renumbered inner nodes is 297.29kNm compared to 293.66kNm where the inner nodes have not been renumbered, a difference of 1%. Now consider the same exercise for normal forces, shown in figures 5 and 6. Here the maximum normal (compressive) force is 1676.61kN for renumbered nodes and 1694.49kN for nodes that have not been renumbered, again a difference of only 1%. So, on this basis it would appear that renumbering has little or no effect. However, when this same comparison is carried out for the shaft wall, quite a different picture is revealed.

Shown in figures 7 and 8 are the bending moments down the shaft wall with and without renumbering respectively. Now comparing the bending moment at the bottom of the wall for each case shows 130.16kNm (with) compared with 255.47kNm (without), a difference of 96%! For the normal forces, figures 9 and 10, the corresponding values are 1243.32kN (with) and 1400.78kN (without), a difference of 13%.

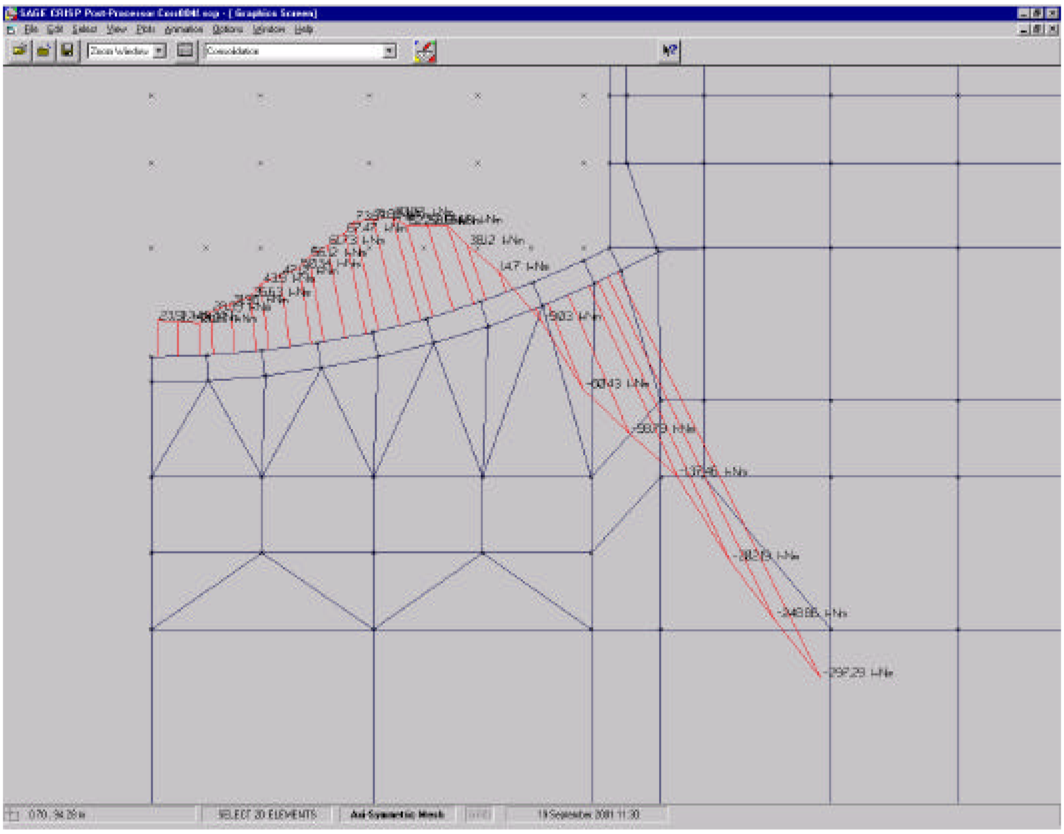

Figure 3. Bending moments in shaft base – renumbered inner nodes

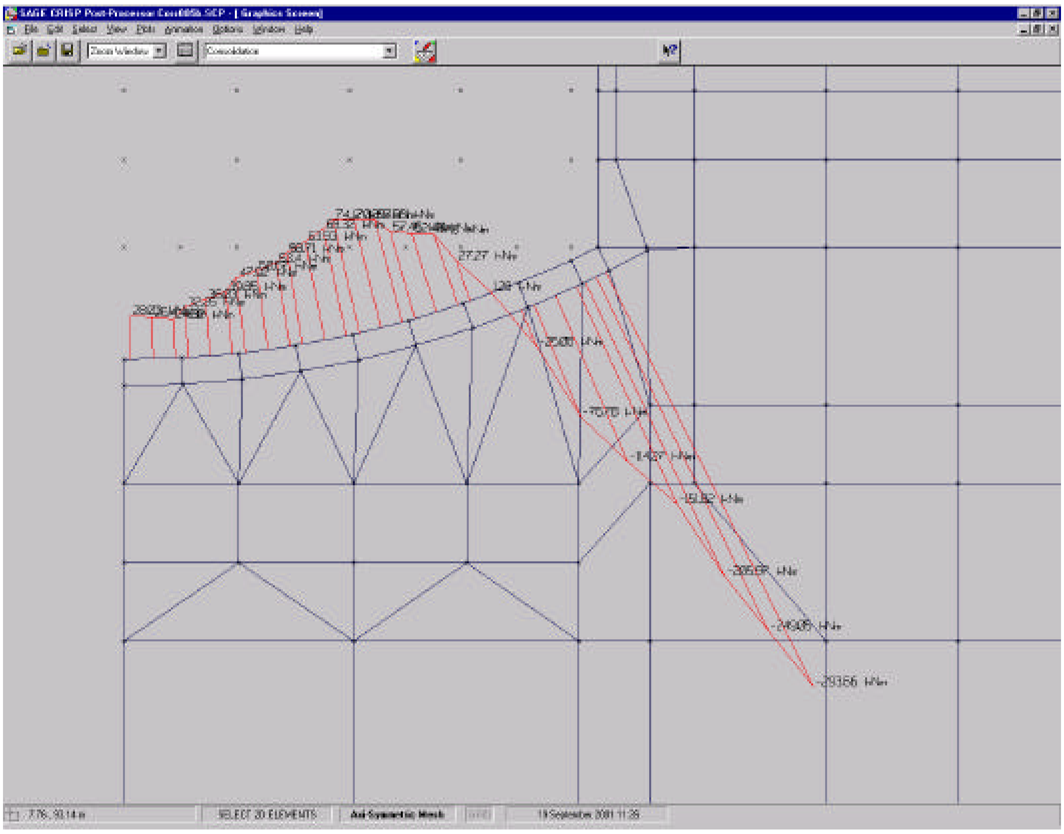

Figure 4. Bending moments in shaft base – inner nodes not renumbered

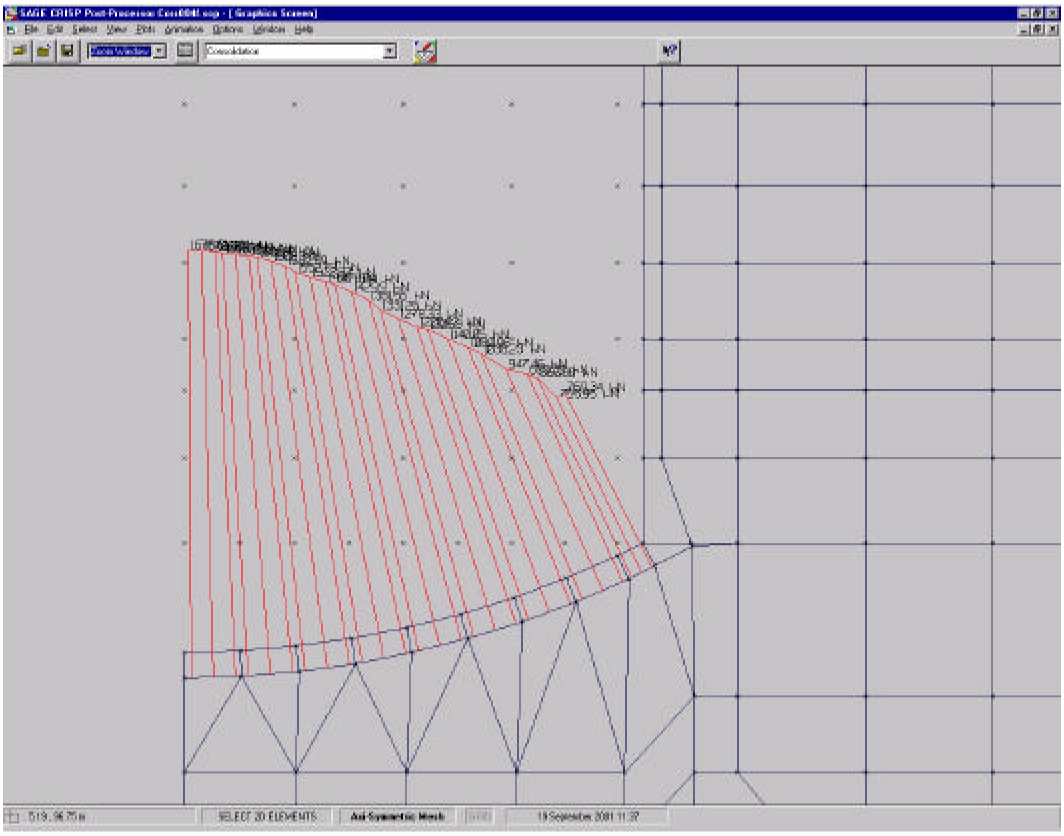

Figure 5. Normal forces in shaft base – renumbered inner nodes

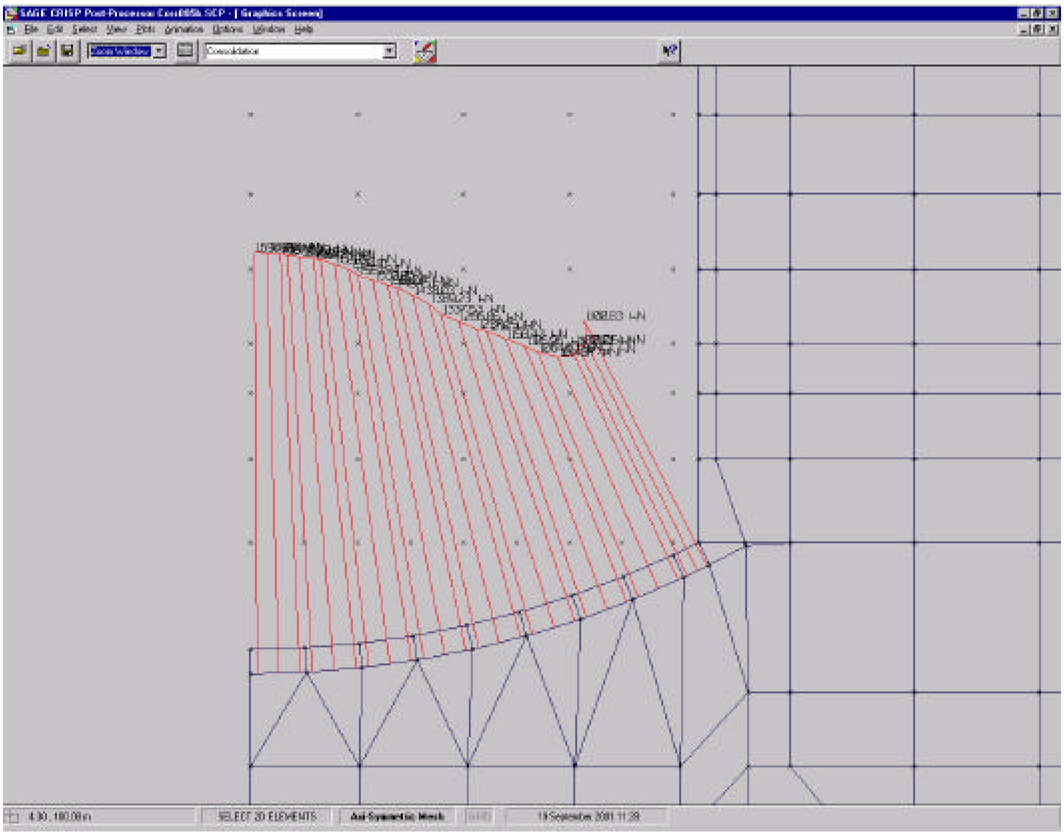

Figure 6. Normal forces in shaft base – inner nodes not renumbered

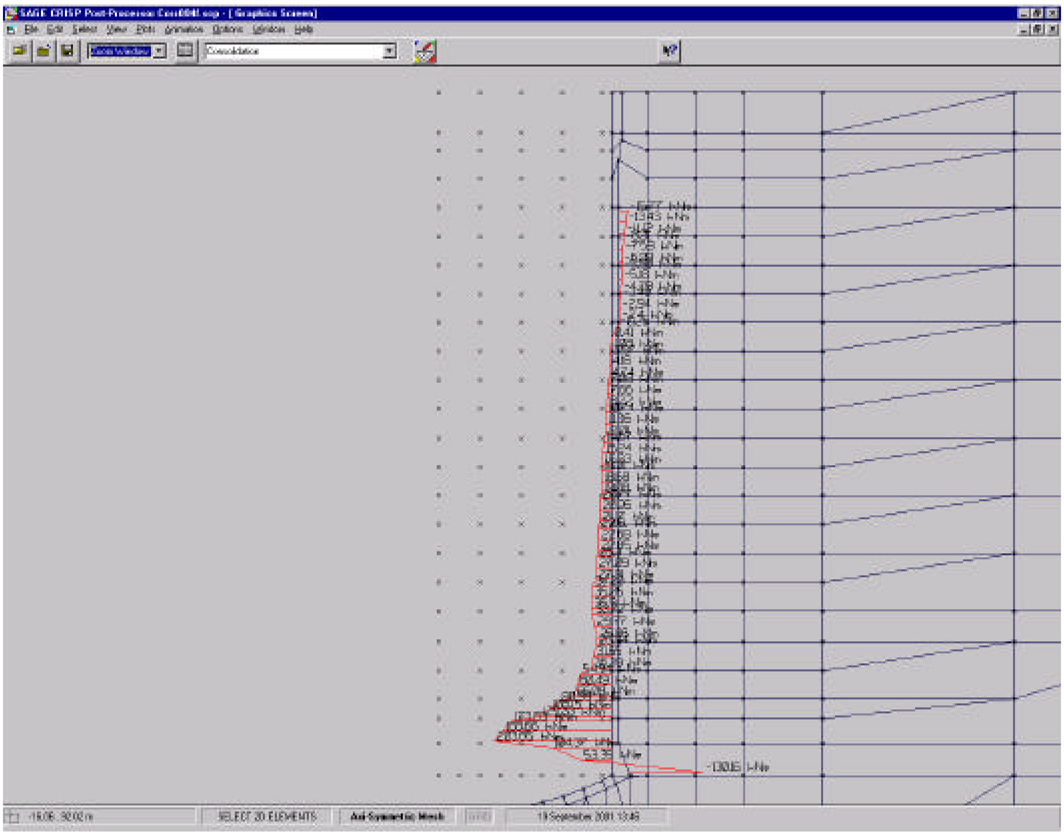

Figure 7. Bending moments in bottom section of the shaft wall – renumbered inner nodes

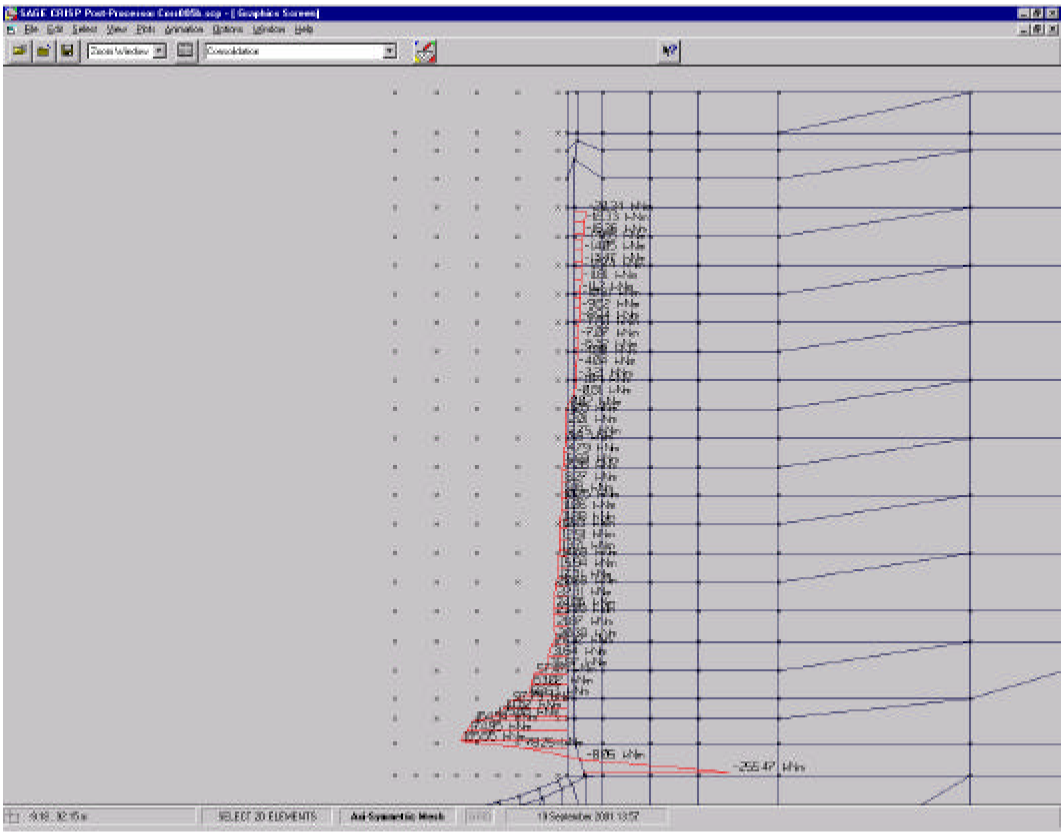

Figure 8. Bending moments in bottom section of the shaft wall – inner nodes not renumbered

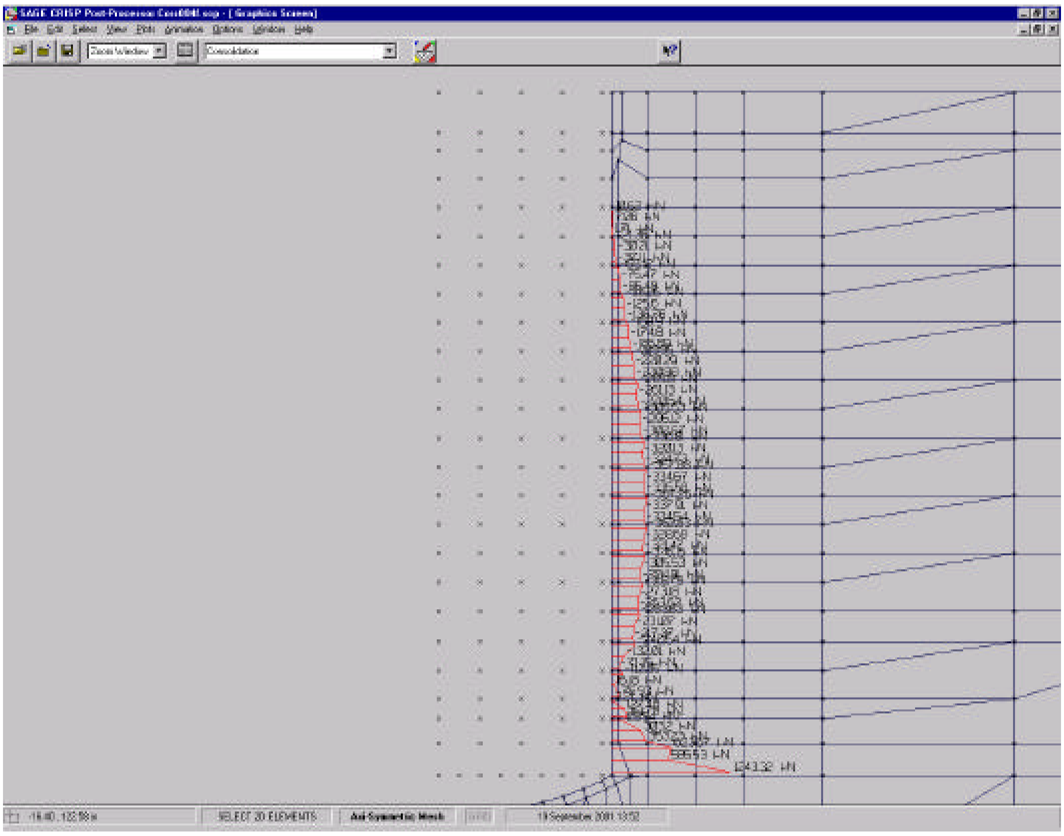

Figure 9. Normal forces in the shaft wall – renumbered inner nodes

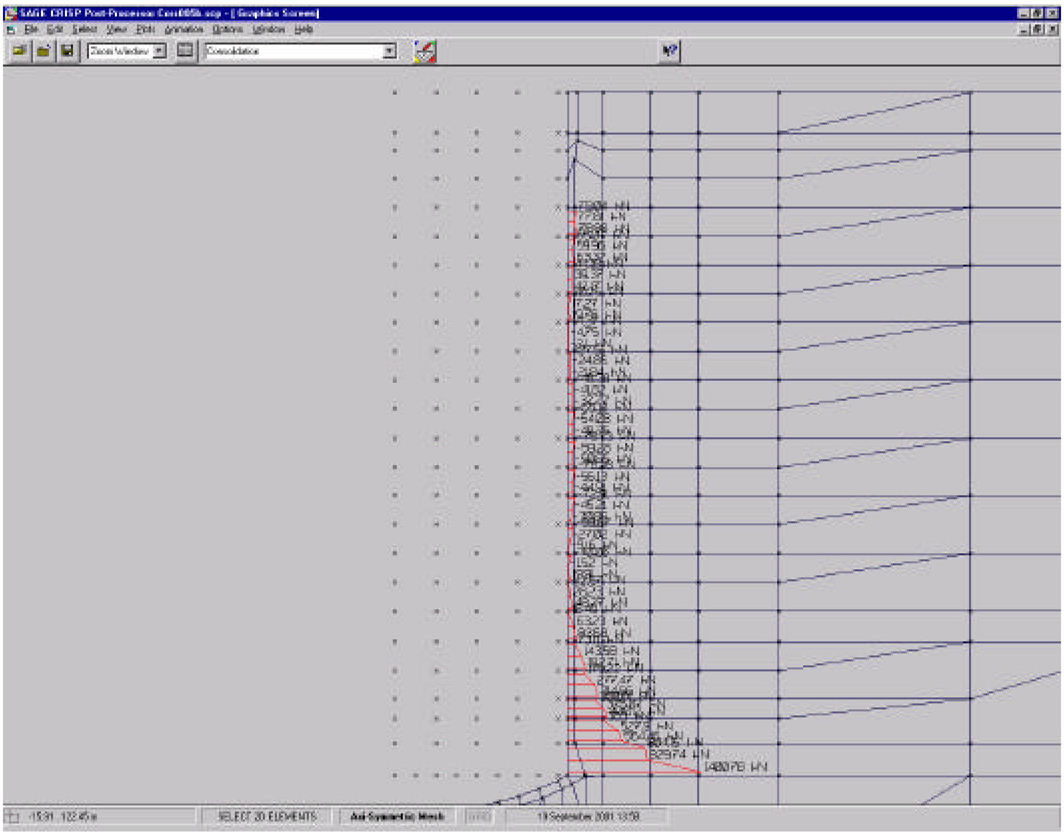

Figure 10. Normal forces in the shaft wall – inner nodes not renumbered

Clearly, such a marked difference in both bending moments and normal forces in the shaft wall will affect the quantity of reinforcement and overall integrity (safety) of the structure. So why the difference between the results fom the base compared with those from the wall? It transpires that there are two main aspects that affect the results; the first is the staged installation of the sprayed concrete, or conventional shaft rings, and the second is the influence of renumbering. In the base the installation of sprayed concrete is completed, analytically, in one operation, albeit over a period of time. Hence there should be no difference in the results to the base; this has been confirmed by Prof. Gunn and Dr. Rahim having reviewed the internal working of CRISP. The small difference identified, i.e.1%, is due to the influence of the wall behaviour in each case, i.e. with and without renumbering. In the wall, however, each 'ring', be it sprayed concrete or conventional rings, is placed sequentially over a period of time for each 'ring'. In addition, and this is the crux of the difference, the renumbering of the inner nodes means there is no connection to the soil element below other than at the extrados to the shaft, figure 11. In effect, the soil below the sprayed concrete in not offering any resistance or uplift (heave). Whereas with no renumbering, there is direct contact between the soil and sprayed concrete, figure 12. This latter approach, therefore, gives support to the recently installed 'ring' and induces uplift, hence a reduction in tensile vertical forces in the wall caused by the weight of the sprayed concrete.

So which approach to adopt? This is where knowledge of the actual construction is important. For both sprayed concrete and conventional rings the soil is over-excavated by some 300mm, i.e. there is a gap below the 'ring'. In this case renumbering would be appropriate. If however, the 'ring' is in direct contact with the soil, then the 'no renumbering' approach would be correct.

An interesting aside to this is in the analysis of tunnels where the ring is generally installed in one increment block. In this particular case it makes no difference whether the inner nodes are renumbered or not. Again, this has been checked by Prof. Gunn and Dr. Rahim.

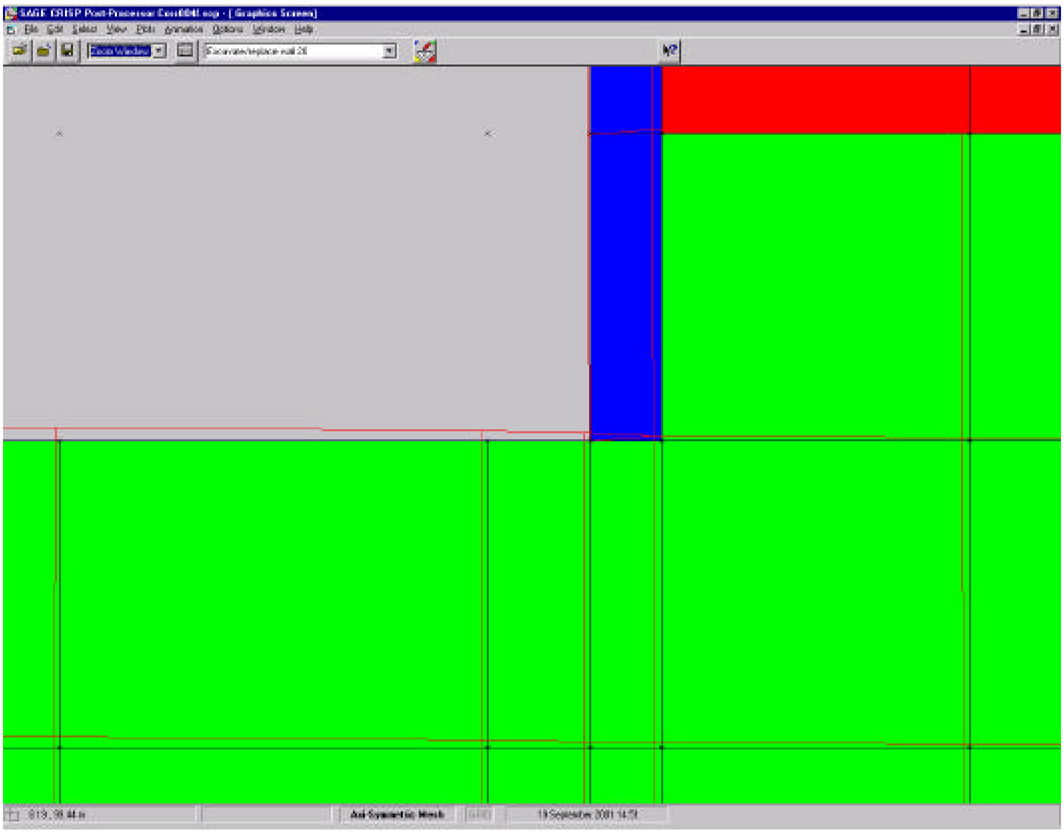

Figure 11. Displacement of the shaft wall – renumbered inner nodes

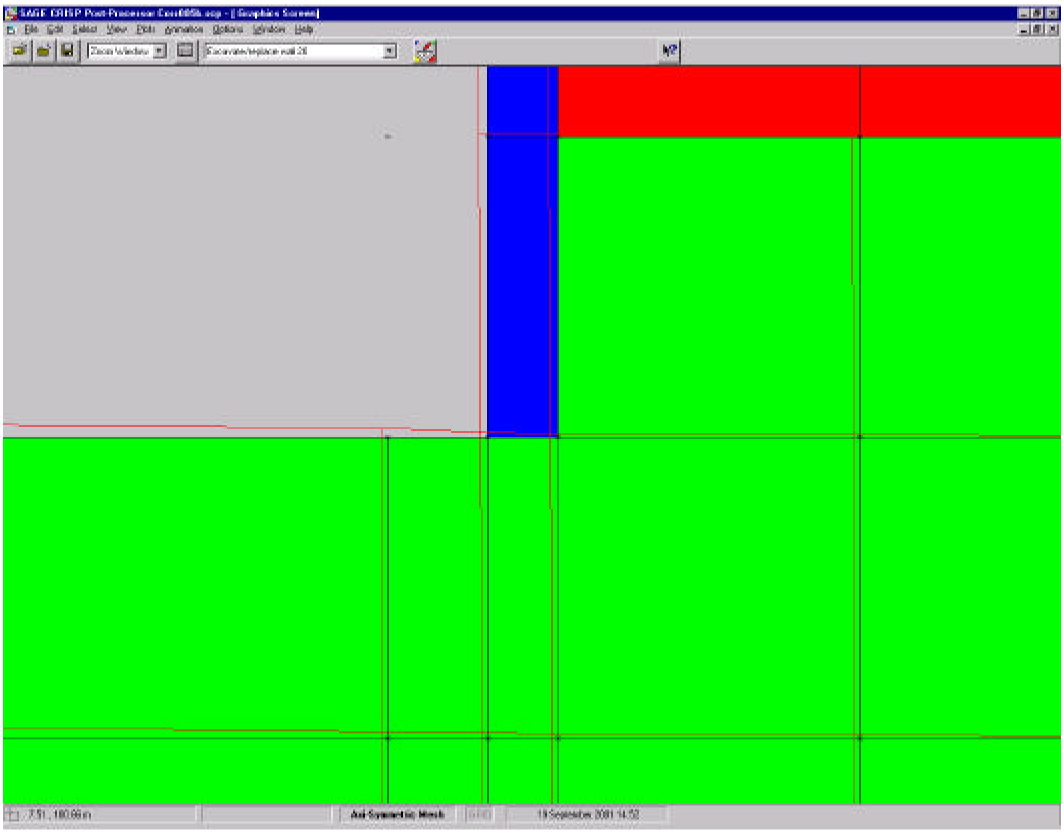

Figure 12. Displacement of the shaft wall – inner nodes not renumbered

Vertical forces in the shaft wall

In figure 9 there are significant tensile forces in the wall a year after completion of shaft construction. What is important for the design is the appreciation that these forces are locked in for the life of the structure. How these tensile forces become locked in is shown in figures 13 and 14 of duration graphs of an integration point (IP) in the wall and an adjacent integration point in the soil.

Consider the behaviour of the vertical stress at an integration point in the wall, i.e. IP #4007. This IP is about a third of the way down the wall. Figure 13 shows how the vertical stress changes as construction proceeds. As can be seen, when the sprayed concrete ring is installed there is no vertical stress. As excavation and installation of the next 'ring' proceeds the vertical stress starts to increase (compression) at the IP, due to the load coming on from the rings above and downdrag soil forces. However, as further excavation and installation of lower 'rings' occurs, the direction of stress changes to induce tension. This is because the ring at the IP is now gripped by the lateral stress from the soil (as shown above in figure 14 for IP 1170, within the soil) due to the dissipation of excess pore pressures (suction), but more 'rings' have been attached lower down the shaft. It is only when the base is completed and an upward vertical stress is applied to the wall through the base, that the vertical stress at the IP again changes direction, but, at least at this IP, never becomes compressive; lower down the wall they do become compressive. The vertical stresses, be they tensile or compressive, are lock in by the lateral soil stresses.

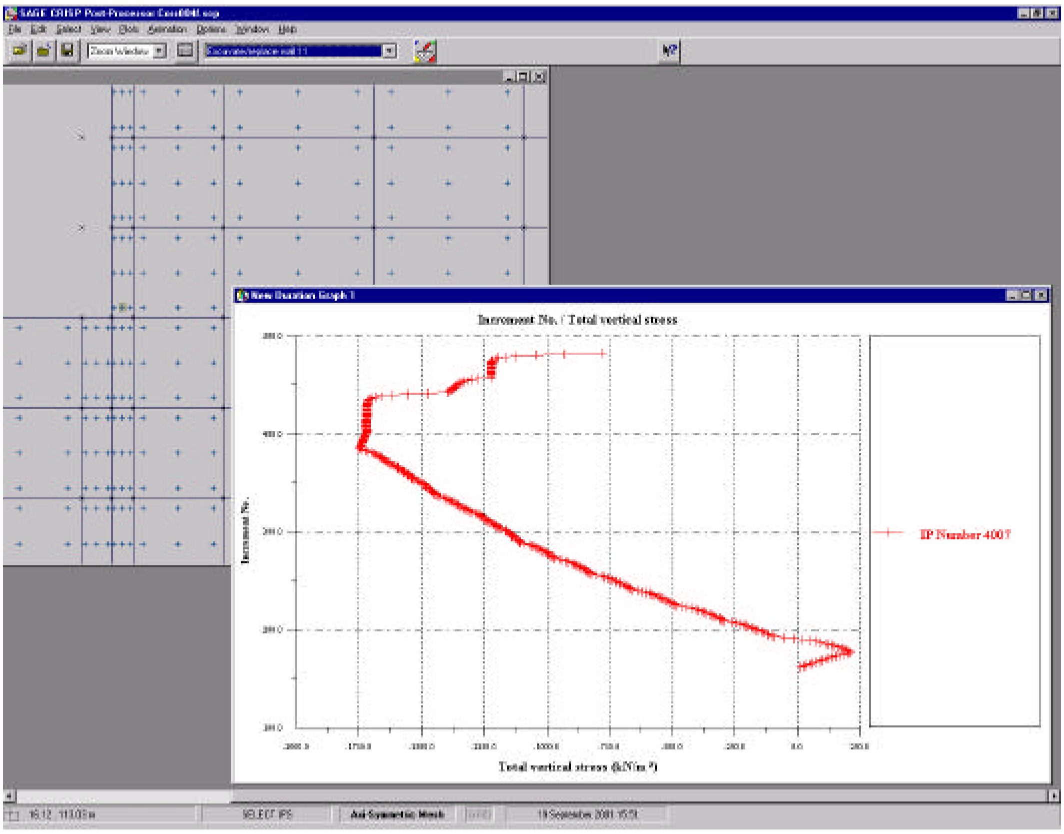
Figure 13. Duration graph of Integration Point #4007 for total vertical stress

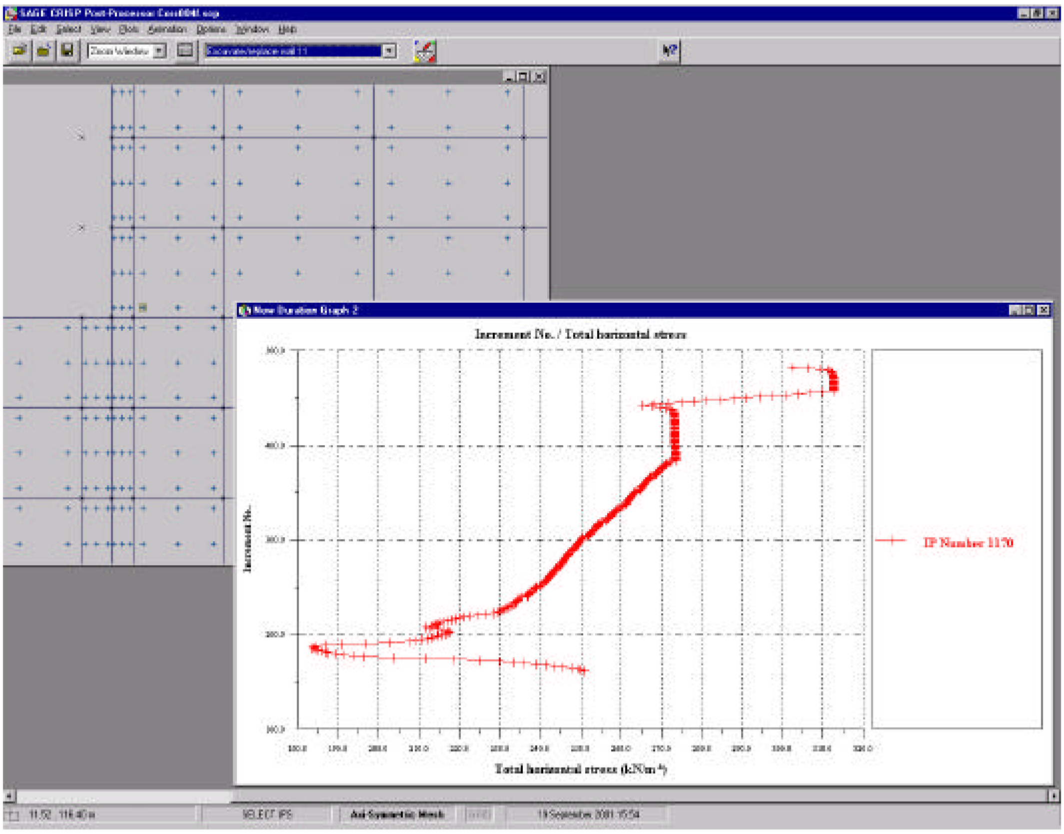
Figure 14. Duration graph of Integration Point #1170 for total horizontal stress

Conclusions

- It is imperative that construction sequence and details are known when modelling staged construction as this will influence the need to renumber, or not, some nodes.

- Significant differences can result for the same problem, with and without node renumbering.

- More than one area of a problem needs to be cross-checked when determining the reliability of a model.