The outline design of earth retaining walls

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The outline design of earth retaining walls involves the choice of wall, while the detailed design concerns the numerical calculations necessary to ensure the safety of the chosen wall. The outline design is less understood and documented by geotechnical engineers than detailed design. However, wall selection forms a crucial part of the overall design process and hence should be given much greater attention. This paper focuses on the outline design by proposing a practical design procedure and targets the factors which dominate the choice of wall through the examination of a number of case studies. The suggested practical design procedure should lead to economies of selection as a more informed comparison of alternative retaining wall types can be made.

Introduction

Earth retaining walls are commonly used to support soils and structures to maintain a difference in elevation of the ground surface. This difference in elevation can be produced through excavation below existing ground level or by earthworking above existing ground level. There is a large variety of retaining walls to choose from and a number of factors govern the selection. Retaining walls will normally be grouped into gravity walls or embedded walls. Gravity walls are the most common when construction is above ground level and provide retention by their weight alone which can consist of concrete, masonry or selected stone, or by a combination of this material and the soil resting on the heel of the wall. Embedded walls, on the other hand, rely on the resistance of the soil in front of the wall of stability. The stability can be enhanced through the use of external support systems such as props.

The overall design of retaining walls will involve outline and detailed design stages. The outline design is primarily concerned with the choice between types of retaining wall, while the detailed design concerns the numerical calculations carried out to ensure the safety of the selected wall. The selection of an appropriate retaining wall is particularly difficult if the quality of some of the crucial information is doubtful. Choice between wall types will be affected by the soil and groundwater conditions, the site conditions, construction requirements, environmental factors, the nature and size of project, and will often have considerable cost implications. The prioritising of these factors will reflect the nature of the work, the defined design criteria, and how the designer or contractor approaches the design. For an informed choice of wall, the engineer would need to exercise considerable judgement and expertise.

The outline design of retaining walls is less understood and documented by geotechnical engineers than detailed design. However, the choice of wall is a crucial part of the overall design process and should be given greater emphasis. This paper concentrates on the outline design by proposing a design procedure and targeting the factors which dominate the choice of wall types through the examination of a number of case studies. Advice is given on the application of the main types of retaining wall and their preliminary stability analysis. A brief discussion is also included on work currently taking place to improve the approach to wall design through the development of a knowledge-based system.

General design philosophy

The overall design of earth retaining walls is a somewhat complex process, normally incorporating some degree of analysis but more importantly involving the choice of the wall. Knowledge will be required of the many different types of wall available and this will form the conceptual design stage. The number and diversity of potential solutions will be related to the defined design criteria. Recent developments in wall construction techniques such as reinforced soil, bored piles and diaphragm walls, and the use of new materials such as geotextiles, should form an important part of the catalogue of options. Of the large number of alternatives postulated at this initial stage, many will be eliminated, perhaps without explicitly being considered when evaluated against the defined design criteria. The breadth of this range of alternatives precludes the use of detailed and complex analyses but would include knowledge of the project and site as obtained from the desk study and site survey. Any sort of ground investigation information at this stage would rarely be required. In the early conceptual phase of design, the engineer would certainly benefit from being able to recall examples of existing successful designs and listing points that should be considered at a later stage.

Preliminary design follows the conceptual design stage and would normally be carried out in two steps. Step one involves eliminating the least feasible wall types from the catalogue of wall types produced earlier. This selection process will not be straightforward; it will require considerable judgement and expertise on the part of the engineer. In evaluating the alternatives, the engineer's decision will be influenced by factors such as:

- ground, groundwater and tidal conditions
- proposed height and ground topography
- availability of materials (eg backfill) and specialist equipment
- construction space available
- ground movements (susceptibility of adjacent structures) and external loads
- design life and maintenance requirements
- underground obstructions
- appearance
- confidence in design and construction.

The final decision will not normally be influenced by a single factor but be based more on a number of the factors given above. It would be inappropriate at this step to assess the stability of the wall types from preliminary calculations covering the main limit states. At the end of step one a list of feasible wall types would be produced for final consideration at the second step. The second step narrows the
list down further to a preferred solution based on environmental considerations and on a relative cost comparison. During the preliminary design stage the engineer would tend to rely on information obtained primarily at the preliminary ground investigation stage.

The conceptual and preliminary design stages represent the outline design of the retaining wall which forms a critical part of the overall design process. The flow of information between these two stages is two way, reflecting the iterative nature of design where checks and refinements will take place.

The retaining wall selection process (preliminary design) is less understood and documented by geotechnical engineers than the detailed design of which analysis forms an important part. For example, a review of BS8002 (Anon') shows that the bulk of the content is concerned with detailed procedures of design and the control of safety through design calculations, but it pays little attention to the selection process ('/ page in a document over 100 pages long). However, it does outline the main limit states associated with common wall types and their potential application. Similarly, EC7 (Anon') is confined entirely to aspects relating to design calculations in minimising the occurrence of limit states.

The final stage in the design procedure mainly concerns the numerical calculations carried out to ensure the geotechnical and, when necessary, structural safety of the selected wall. Tools of increasing technical sophistication can be employed for this. The information required for a full design would be obtained from the main or detailed ground investigation.

**Outline design: Proposed design procedure**

Based on the general design philosophy outlined above, a procedure for the outline design of earth retaining walls is proposed in Figure 1.

For the purposes of identifying the particular requirements of the conceptual and preliminary design stages, it will often be convenient to carry out the desk and site surveys before the conceptual design stage, and the preliminary ground investigation stage after the conceptual design but before the preliminary design. The continuity of these information gathering stages will depend on the nature, size and type of project. For example, in projects where the retaining wall forms part of a larger project, then the stages will often be carried out together, and in relatively small projects the preliminary ground investigation may not be required. In most cases, however, the two stages would be consecutive.

The use of Tables 1(a) and 1(b) provides a useful reference (initial catalogue) during the conceptual design stage. Table 1 classifies the main types of earth retaining wall in terms of gravity walls where construction tends to be above ground level, and embedded walls where construction tends to be below ground level. The wide range of wall types makes selection difficult and hence guidance is given on their main application or usage.

The table has been compiled on the bases of the experience of the author and on the information obtained from the following sources: BS8002 (Anon'), Hambly', and Fleming et al.

The catalogue of alternative retaining wall types established during conceptual design will be reviewed and then refined on the basis of the selection criteria and a preliminary assessment of stability (STEP 1) and the final choice of wall will be based on environmental considerations and a relative cost study (STEP 2). The selection criteria relate to the factors mentioned previously which affect the choice of retaining wall.

The choice will not always be obvious nor straightforward, but will depend on a number of factors. The engineer in this case would rely on experiences on other retaining wall projects to evaluate the other solutions to determine the most appropriate. In the next section, four case studies are presented which highlight the importance of this early evaluation, the main factors affecting the final choice of retaining wall and the selection process.

The preliminary assessment of wall stability will involve simple
Embedded walls are generally convenient for construction from ground level down, when their high cost is compensated for by the speed of construction and lack of temporary work. They usually require some form of facing after excavation. Their selection depends very much on whether or not they are required to retain water, it is expensive to choose a water tight type of wall when it is not required.

Cantilever walls are suitable for moderate retained heights. For flexible steel sheet piles, up to 5m is acceptable, while for stiffer reinforced concrete sections, up to 12m is acceptable. However, deflections should always be checked especially at the head of the wall. Cantilever not suitable if services or foundation occurs in the active zone. To reduce penetration length, deflections, and bending moments one or more levels of anchors or props can be installed. For information on ground anchorage’s see BS8081: 1989. The choice of using ties or props is complicated, but they are essential where hard stratum occurs at such a depth that the penetration of a cantilevered wall is either impracticable or excessively expensive.

Steel sheet piling has generally been associated with temporary works and used to construct quay walls and to support and protect river banks. However, it is now used to advantage for permanent works with protection/additional thickness provided against corrosion, and has been used successfully on bridge abutment, pumping station, basement, underground car park and motorway widening projects. Economy is evident when sheet piles are needed in any case for a temporary cofferdam. For further information on the design and construction of steel sheet cofferdams see CIRIA SP#6. Finally it is important not to use too small a section which cannot be driven into the ground.

Soldier/king piles have been used to support deep, narrow, shallow or wide excavations in clays and sands. Excavation in water bearing ground may require special attention. Method is unsuitable for the exclusion of water.

Contiguous bored piles are often the more economic for small or isolated works. Best in cohesive soils, but may be unsuitable when water level is high on retained side of wall. Piles can be ‘secant’ for better water sealing providing the tolerances of positioning and vertical alignment are sufficient to prevent any gaps.

Diaphragm walling may be economic for large or repetitive works. They can be constructed using heavy rope operated grabs to depths of about 50m, though the difficulties of extracting very deep stop ends are considerable.

Soil nailing is a relatively recent construction method of reinforcing the ground in situ. The method should be given serious consideration in the permanent support of excavations. Guidance is given in BS8006: 1995.
methods of analysis such as limit equilibrium techniques, stress field methods or limit analysis approaches (Potts'). These methods will be appropriate in obtaining first estimates of stability in relation to the geotechnical limit states given in Table 2. The choice of whether or not to assume undrained or drained behaviour would have to be considered. Preliminary calculations can be shortened by a prudent choice of the initial wall geometry, where simple changes in shape can improve stability as easily as an increase in weight. Common proportions for various types of gravity wall are given in Figure 2, while Figure 3 shows initial dimensions for the stability evaluation of cantilever and single propped embedded walls. BS8006 (Anon') provides initial dimensions for reinforced soil walls and abutments (Table 19 and Figures 19 and 20).

The use of preliminary design charts can simplify the analysis. Oliphant and Corney have produced a series of preliminary design charts for mass gravity retaining walls. A typical chart is shown in Figure 4 where a minimum base width can be established to satisfy both the overturning and sliding limit states. Other charts have been produced to cover other loading conditions and a range of backfill and foundation material types. The charts are simple to use and provide a rapid means of establishing the main wall dimensions for the subsequent cost study.

British Steel' has produced preliminary design tables for steel sheet piles in cohesionless and cohesive soils. For cohesionless soils, recommendations are given on pile sections and lengths for various retained heights of both cantilever and anchored walls. For cohesive soils assuming undrained conditions, recommendations are also given on pile sections and lengths for various retained heights, but for cantilevers only.

Bica and Clayton' have produced preliminary design charts for cantilever embedded walls in granular soils based directly on experimental data. These charts can be used to evaluate the depth of embedment and maximum bending moment for selected values of plane strain angle of shearing resistance and factor of safety.

### Factors affecting selection: Case Study 1

Howard et al' examined a number of types of retaining wall for the marine esplanade in Liverpool. A wall was required to form a permanent barrier between the River Mersey and the International Garden Festival Site. The main design criteria included a two year contract limit, a budget limit of £1.5m, a 100 year design life, and a 500m section of wall at a site with difficult tidal conditions.

A feasibility study was carried out on a number of retaining wall types, each evaluated against the design criteria, and the results are shown in Table 3. It was only through a detailed cost study that the post tensioned precast concrete wall was found to be too expensive. The authors stressed the importance of considering the ease of construction of each wall option, and not being preconditioned by tradition in always opting for the reinforced concrete cantilever retaining wall.

### Case Study 2

Yoonan² has reported on the widening of the M3 motorway from the existing three lanes of carriageway to four lanes. A number of retaining walls were considered as the most effective solution for the motorway widening. The chosen wall had to satisfy two main design criteria. First it had to be environmentally acceptable in terms of landscaping and noise pollution, and secondly a fast and effective construction method was needed to minimise traffic congestion and disturbance.

The preliminary design considered the economies of construction and environmental impact of gabion, reinforced concrete, sheet pile and reinforced soil retaining walls. Table 4 shows the relative cost comparison for the wall options based on a particular set of parameters. Costings were done for walls constructed to a batter of one horizontal to two vertical and a retained height of 2m. The reinforced soil wall was priced for both geogrids and polymer strips as the reinforcement. Also included in Table 4 is the cost effectiveness ratio (CER) for the reinforced soil wall with polymer strips over the wall options. The CER is defined as the ratio of the cost of the reinforced soil wall with polymer strips to the cost of the alternatives and, hence, the greater the CER the greater the
saving.

The retaining wall with reinforced soil with polymer strips was finally selected as it imposed minimum environmental impact by restoring the natural appearance of the motorway slopes and allowing vegetation growth on the wall, and had the added benefit of reducing noise pollution.

**Case Study 3**

The design and construction of the deep basement for the new headquarters of the United Estates Overseas Bank in Singapore has been described by the authors. The site is underlain by soft marl and the water level is near ground surface. The excavation was carried out to 12m deep or 16m in places. The chosen permanent support to the sides of the excavation would have to act as a deep groundwater cut off and minimise adjacent ground movements. Diaphragm walls were selected as they satisfied these two criteria and there were several contractors in Singapore who had gained considerable experience of diaphragm walling during construction of the Singapore Mass Rapid Transport System.

Steel sheet piles were considered unsuitable due to the large ground movements associated with their use, although no attempt was made to estimate these movements at the preliminary design stage. Contiguous bored piles were found to be too expensive as they were not sufficiently watertight. Secant bored piles were not considered beyond the conceptual design stage as there were no contractors in Singapore who specialised in this technique.

**Case Study 4**

This case study involved the steepening of a natural slope in a rural setting during realignment of the A7 Edinburgh-Carlisle trunk road at Colterscleuch, south of Hawick. An ancient monument was located at the top of the natural slope. Two conditions were placed on the chosen retention system. First, the ancient monument was located close to the crest of the slope and had to be protected throughout construction. Secondly, the steepened slope had to blend in with the natural surroundings. Soil nailing was the only method considered to satisfy these conditions and the one solution to be proposed at the preliminary design stage. The soil nailing construction afforded minimal ground disturbance and the need for a grouted system was reduced. The cost effectiveness ratio was found to be the most cost effective and visually attractive.

**Discussion of case studies**

The case studies have shown that the selection of earth retaining walls is influenced by many factors involving design, construction, environmental and economical considerations. Table 5 summaries the factors considered explicitly at the preliminary design stage which influenced the final selection for each case study.

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**Table 3: Evaluation of a number of wall types for the marine esplanade, Liverpool**

<table>
<thead>
<tr>
<th>Wall type</th>
<th>Applicability/feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel sheet piling</td>
<td>Not considered feasible. Difficult to drive sheet piling and guarantee durability of steel for 100 years in such a hostile environment. Difficult to achieve successful toe anchorage in sandstone of varying degree of weathering. Costly to tie back head of pile to reduce bending moments.</td>
</tr>
<tr>
<td>In-situ concrete reinforced</td>
<td>Considered feasible but impractical. Costly and time consuming to provide watertight caissons and a delay in reclaiming and landscaping the garden site. Concerned with the corrosion of the reinforcement in the marine environment.</td>
</tr>
<tr>
<td>Pre-cast reinforced concrete</td>
<td>Considered feasible but impractical. Any problems with demolding, lining and fixing the pre-cast sections in position.</td>
</tr>
<tr>
<td>Post tensioned pre-cast concrete</td>
<td>Considered feasible but impractical. Feasible to construct and provide a durable and attractive solution. Found to be too expensive.</td>
</tr>
<tr>
<td>Mass concrete</td>
<td>Considered feasible and practical. Found to be the most cost effective, durable and visually attractive.</td>
</tr>
</tbody>
</table>

**Table 5: Summary of factors influencing wall selection for case studies.**

<table>
<thead>
<tr>
<th>Selection factor</th>
<th>Case study I</th>
<th>Case study II</th>
<th>Case study III</th>
<th>Case study IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction time</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capability of contractor</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Wall geometry</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Ground and ground water conditions</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Site accessibility</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Movements during construction</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Environmentally acceptable during construction</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Preliminary stability analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmentally acceptable in intended location</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4: Relative costs for retaining walls (Yuan)**

<table>
<thead>
<tr>
<th>Wall Option</th>
<th>Cost (CER+)</th>
<th>(£/m run)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabion</td>
<td>400</td>
<td>1:1:0</td>
</tr>
<tr>
<td>Reinforced concrete</td>
<td>600</td>
<td>1:1:5</td>
</tr>
<tr>
<td>Sheet pile</td>
<td>1200</td>
<td>1:3:0</td>
</tr>
<tr>
<td>Reinforced soil</td>
<td>500</td>
<td>1:1:25</td>
</tr>
<tr>
<td>Geogrid</td>
<td>400</td>
<td>1:1:25</td>
</tr>
<tr>
<td>Polymer strips</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Cost effectiveness ratio</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Case Study 1 demonstrated that a simple mass concrete wall can be cost effective, durable and visually attractive. It also shows that simplicity in construction especially under difficult conditions is generally considered to be cost effective. The outline design process followed that of Figure 1 where the conceptual and preliminary design stages were performed with a detailed cost study carried out on two of the wall options.

Case Study 2 placed emphasis on the cost of construction and environmental assessment, normally considered later in the outline design process. A clear advantage of using the relatively innovative reinforced soil technique was found compared to the more conventional retaining walls. The cost effectiveness ratio for the chosen wall is 1:1.5 compared with the reinforced concrete cantilever wall, 1:3.0 compared with the sheet pile wall, and 1:1.25 compared with the reinforced soil wall with geogrids.

The evaluation of the retaining walls in Case Study 3 was carried out at the preliminary design stage without resorting to any cost or environmental study. The factors affecting selection related more to the two main design criteria as well as to the lack of contractors with experience in a specialist construction technique.

The decision to use soil nailing in the fourth case study was based entirely on the nature of the site and type of project and no explicit consideration was given to alternatives at the preliminary design stage. The case studies have shown that the extent of the outline design varies considerably and appears to be related to the type of project and the importance placed on environmental considerations. Clearly, when referring to Figure 1, the engineer has the option to omit any of the design stages but this would only be done with a good knowledge of the site and the proposed project.

**General discussion & conclusions**

The suggested procedure for the outline design of earth retaining walls (Figure 1) should lead to improved understanding of the variety of wall types available, the range of factors affecting the choice of wall, the methods available for preliminary design and the structured approach to the design process.

This should result in a more informed comparison of alternatives (eg reinforced soil wall versus reinforced concrete cantilever wall) in order to make economies. The development of a computer-based decision support system encapsulating the above features of the design process would greatly benefit the engineer. This is the current focus of research by the author in developing a knowledge based system for the design of earth retaining walls. There are two main objectives to this research work. First, to develop methodologies for eliciting and analysing expert opinion on the wall selection process. This expertise will come primarily from a wide range of contractors in the UK. Second, to provide a more rigorous and structured approach to the outline design of
Open and closed case
Report of a meeting entitled "Services under streets: a debate on trenches versus trenchless technology" held by East Midlands Geotechnical Group at Loughborough University on 19 May, by Richard Bennett of Nottingham University.

Meeting chairman Dr David Chapman of Nottingham University started the debate by running through the perceived advantages and disadvantages of trenchless technology. He suggested that trenchless techniques offered reduced surface disruption and potentially lower overall costs than conventional open cut service installation. Disadvantages of a trenchless approach were a higher degree of risk and a need for specialist equipment, which created high initial direct costs.

Alwyn Morgan of Midlands Electricity (MEB) speaking in favour of trenchless technology said his organisation installed 1,000km of cabling and services a year, at a cost of £16M to £18M. Approximately 50% of the cables are installed in unmade ground, the remaining 50% in made ground, mostly under urban footpaths.

MEB, said Morgan, has a declared policy of using trenchless technology wherever socially or economically justified, the long term mission being the concept of "zero dig". The company employs four directional drilling machines and several hundred impact moles. Contractors are used in addition to the direct labour force.

Morgan covered the development of trenchless techniques at MEB, commencing with no dig trials with Grundomat and Pierce Arrow soil displacement tools. These proved to be very cost effective for cable road crossings and service replacements in domestic properties. In 1991 MEB purchased a Ditch Witch 420 Jet-Track. This was used for river, road, railway and canal crossings and was an economic success, paying for itself within three months of operation.

The experiments continued with the use of moles and jet-tracks along footpaths where the exact location of utilities were known. These tests were successful but it became apparent that lack of knowledge about the exact location of services was hindering progress. Ground probing radar (GPR) was used in subsequent trials and found to be effective for the detection of pipes and voids, but did not provide a complete answer.

Morgan stated that buried services present a unique problem. Not only are they hidden from view but they constitute a three dimensional maze of pipes and cables. When considering laying new underground services, particularly in urban sites, it is imperative to determine the exact location of services.

Morgan went on to describe an innovative system of three dimensional mapping currently under development by MEB. Existing two dimensional records are first studied to determine the extent of possible site congestion, followed by an electromagnetic locator survey to pinpoint services by plan and depth. EML is used to detect services with a metallic content, and a signal emitting sonde for non-metallic pipes or ducts. The data is collated into a three dimensional database which can be interrogated for cross-sections wherever desired.

Selective cross-sections can also be taken by GPR to find plastic pipes, mass concrete or rock horizons. EML and GPR surveys can be compared to identify anomalies, and in this way the location technique can be optimised, but overall costs of efficiency on site and overall costs. Tests have compared three dimensional mapping cross-sections with trial pits, with considerable success. Development has progressed to the stage where installation crews are now using the system to direct cable installation. The ultimate goal of three dimensional mapping would be to allow the system to directly steer the rig.

Morgan emphasised that the true benefits of a three dimensional database are realised as a planning tool. Service routes can be effectively planned and decisions made on the optimum cable installation technique to be employed: no dig, open cut, narrow trenching or a combination of all three.

He went on to describe the potential financial savings associated with trenchless technology used in conjunction with three dimensional mapping. The example given was a three year linear rate cable installation contract, finalised by MEB in 1995. Figure 1 shows the typical annual high and low voltage cable installation rates, and the comparison of open cut to no dig contractor prices. The difference between these rates offered the opportunity to introduce three dimensional mapping (and so reduce risk by gaining a better knowledge of the ground), and still reduce overall costs.

A number of projects have now been undertaken in urban areas of the West Midlands using the system, and are showing savings of 20% over projected costs with open cut. Without the benefit of three dimensional mapping, ground uncertainty in all of these projects would lead to the use of trenching, with the associated disruption and social costs.

Current developments associated with the three dimensional mapping system include a research project being undertaken with David Chapman at Nottingham University to investigate the forces exerted on existing services by impact moles and directional drills. This will allow the development of an understanding of the effects of using no dig techniques in ground congested with services. A possible goal of this work is to produce guidelines for recommended safe distance between existing and new trenchless services in various types of ground.

Morgan concluded by reiterating the cost savings created by combining impact moiling and directional drilling with a three dimensional mapping technique. He emphasised MEB's commitment to developing this approach and specifying it as a standard cable installation method for both its direct labour and contract installation crews.

Debating the case for trenches, John Banyard of Severn Trent Water argued against trenchless technology on the basis that cost overruns in trenchless projects were higher than for conventional projects. He started on the premise that engineers were often unsuccessful in estimating the costs of construction projects, particularly those involving work in the ground.

As an example, Banyard pointed out that the Channel Tunnel, had cost nearly two and half times the original estimate of £4bn, and is viewed by investors as an unmitigated disaster. Huge cost overruns occurred on the project, even with the balance sheet being restructured on several occasions.