The Design and Construction of a Reinforced Embankment on Soft Compressible Soil

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ABSTRACT

The paper centres on the design and construction of a leachate lagoon at a landfill site located in Essex, United Kingdom (UK). The lagoon is to be used for the storage of between 150,000m^3 and 200,000m^3 of leachate generated by the adjacent landfill site as part of its treatment process. The location of the lagoon is on the southern boundary of the site, and is bounded to the north by the landfill itself, to the east by an existing leachate treatment lagoon and to the south and west by a flood defence bund for an adjacent creek and the Thames estuary beyond. Due to the proposed capacity and size of the lagoon, it qualifies in the UK as a reservoir under the 1975 Reservoirs Act and the design and construction is therefore constrained by this legislation. The area proposed for the lagoon is generally level, but with groundwater levels close to, or at, the ground surface. Waste dating from the 1950's underlies the site and this overlies a generally soft stratum of alluvial clays and sands. A similar, but earlier, lagoon encountered significant difficulties during construction associated with the high groundwater levels and the trafficability of the waste and the soft alluvial materials.

A discussion of the geotechnical and environmental issues considered during the design process is presented and the need for responsive design during the construction phase of a project is highlighted. The benefits of value engineering in civil engineering are also discussed in the context of design and construction projects. By their very nature, civil engineering projects such as this require imaginative and innovative design solutions, coupled with the use of non-traditional geomaterials. A discussion of the geosynthetics employed at this site is provided, in the context of their primary and secondary applications.

INTRODUCTION

This paper describes the approach to the design of a leachate lagoon on a soft soil with poor geotechnical characteristics, particularly in terms of deformability and permeability. The main issues that impact on this design are also presented, emphasising the importance of value engineering and the observational method as part of the design process.
The paper centres on the design and construction of a new leachate lagoon at Cleanaway's Pitsea landfill site, and is located to the south of Basildon, Essex (United Kingdom), as shown in Fig. 1. The construction period ran from the summer 2002 to early 2003. The lagoon is to be used for the storage of between 150,000m^3 and 200,000m^3 of leachate generated by the adjacent landfill site as part of its treatment process. The location of the lagoon is on the southern boundary of the site, and is bounded to the north by the landfill itself, to the east by an existing leachate treatment lagoon and to the south and west by a flood defence bund for the East Haven Creek and the Thames estuary beyond. Due to the proposed capacity and size of the lagoon, it qualifies as a reservoir under the 1975 Reservoirs Act (ICE, 2000) and is therefore subject to this legislation.

The area proposed for the lagoon is relatively even but with groundwater levels close to, or at, the ground surface. Waste dating from the 1950's underlies the site in a layer between 1m and 7m thick and this overlies a generally soft stratum of alluvial clays and sands. A similar, but earlier, lagoon encountered significant difficulties during construction associated with the high groundwater levels, and the trafficability of the waste and the soft alluvial material.

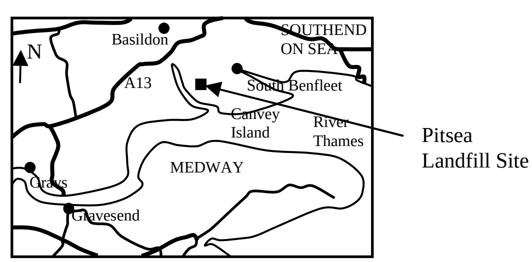


Fig. 1. Landfill site location

A number of constraints on the proposed structure were identified and include a minimum leachate capacity of

150,000 m^3 and a maximum design and build cost of £1.3 Million.

The principal objectives of any proposed design are to:

- Minimise imported fill material by adopting steeper slopes accepting that such steepened slopes would require geosynthetic reinforcing elements;
- Ensure the stability of the perimeter embankment during construction and during the operational life of the facility;
- Maximise the area of the lagoon, which reduces the required height of the perimeter embankment, by taking less area for the perimeter embankment;
- Reduce, or eliminate the need for excavation of the waste within the footprint of the lagoon;
- Satisfy all the requirements of the Reservoirs Act, including certification of the design by a qualified civil engineer approved by the Secretary of State.

SITE CONDITIONS

The area of the proposed lagoon is generally flat lying within a floodplain, with a typical elevation of around 3.0 to 3.5m above ordnance datum (AOD); there is a small raised area in the north-east corner of the proposed lagoon which reaches an elevation of just over 4.0mAOD. The elevation of the base of the lagoon increases northwards from the general 3.5mAOD level to about 4.0mAOD as the existing waste level increases.

The site lies adjacent to East Haven Creek (a tributary to the River Thames estuary), and is located on existing waste overlying marine and estuarine alluvium comprised of:clays, silty clays, silts, thin peats and silty sands. A ground investigation for the lagoon area was carried out which comprised ten cable percussive boreholes to a maximum depth of 25m, two continuous flight auger boreholes to a depth of 7m, five trial pits and a suite of laboratory testing. This confirmed the sequence of strata beneath the site and provided geotechnical parameters for design purposes.

In summary, the ground conditions encountered in the area of the lagoon comprised 0.9m to 3.0m of old domestic refuse which it is understood dates from the 1950s, overlying soft clay and loose sand alluvial deposits. The ground conditions below the northern section of the proposed lagoon comprises up to 7.5m of more recent waste overlying the alluvium.

DESIGN PHILOSOPHY

Instead of excavating into the waste, the design sought to form the base of the lagoon at the current ground level. In order to achieve the required lagoon capacity, this would require significantly steeper embankment slopes. The final proposed design consists of the following elements (Fig. 2):

- A reinforced soil perimeter embankment, typically 5.5m high, with external side slopes of 1V:2H and internal side slopes of 1V:1H founded on a 20m wide by 1m thick reinforced platform constructed at the existing ground level;
- A lagoon with a base area of approximately 32,000m^2 lined with a composite lining system of a 2mm thick Linear Low Density Polyethylene (LLDPE) sheet and a geosynthetic clay liner (GCL);
- An underdrainage geocomposite drainage layer to limit hydraulic pressures from the leachate and gas;
- Lining of the perimeter embankment with 2mm thick LLDPE geomembrane underlain by a geocomposite drainage layer connected to a piped drainage system;
- A series of inclined risers to allow monitoring and active extraction of groundwater from beneath the lining system when the lagoon level is drawn down.

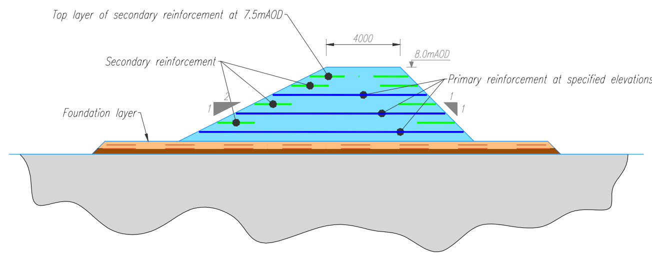


Fig.2. Typical cross section through perimeter embankment

In order to achieve the target lagoon capacity without lowering the base levels by excavating into the waste, it was necessary to have relatively steep perimeter embankments. The material available for the construction of the embankments was variable and comprised a stockpile of inter-mixed cohesive soils.

To construct the embankments with the available material and with the steep slopes it was necessary to reinforce the embankments with geosynthetic layers. Geotextile reinforcement was chosen in preference to traditional geogrids due to the ability of the geotextile to aid in the lateral dissipation of construction pore pressures within what was anticipated to be mainly cohesive embankment fill material. The embankment contained a primary geotextile reinforcing layer placed at specified elevations and persistent through the entire width of the embankment, and a secondary geogrid reinforcement layer which extended to a depth of 2m in to the embankment, in order to increase face stability, as shown in Figs. 2 and 3.

The final elevation of the top of the perimeter embankments was designed to be 7.5m AOD, however due to the significant amount of consolidation related compression anticipated within the alluvium beneath the embankments (estimated to be in the order of 300 to 500mm) it was proposed to construct the embankment to an elevation of 8.0mAOD. This would allow a further 0.5m for an extreme overflow event with a maximum design leachate level of 7.0mAOD. Additionally, the embankments have a crest width of 4m.

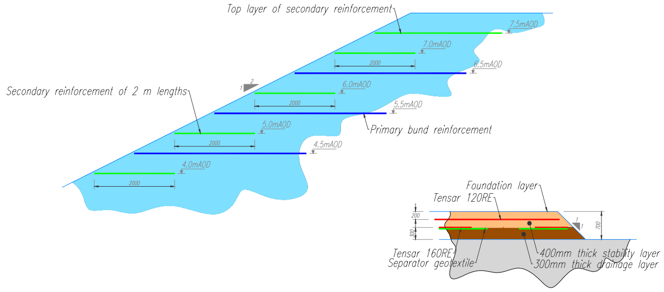


Fig. 3. Embankment and foundation layer reinforcement details

As the initial time available for the design was limited, a number of conservative parameters were adopted. Consequently, optimisation of the design and construction sequences was implemented immediately prior to and during construction, in order to achieve further cost savings without compromising the geotechnical design. A series of field trials of parts of the design was proposed to verify that the Contractor could achieve the design assumptions.

A key factor in the design of the perimeter embankments is their stability, in particular, the destabilising effect of increased pore pressures in the alluvium due to the construction of the embankments. Stability analyses were carried out to investigate the influence of these construction pore pressures, together with the tidal effects of the adjacent creek, and the results indicate that the rate of build up and dissipation was critical to stability.

There are a number of factors that influence pore pressures, not all of which can be allowed for during design without an over-conservative approach. It was considered essential for piezometers to be installed to monitor the development of pore pressures on site. Where pressures are greater than those predicted, or do not dissipate as quickly as expected, then additional berms could be placed at the toe of the perimeter embankments to aid short-term stability until pore pressures dissipate.

To facilitate the construction of toe berms, should they become necessary, a 700mm thick reinforced granular layer (embankment foundation layer) was installed beneath the perimeter embankment, extending 4m beyond the edge of the embankment. The foundation layer comprises crushed concrete with geogrid reinforcement placed at heights of 300mm and 500mm above the base of the layer, as shown in Fig. 2 and Fig. 3.

In order to establish and retain vegetation on the outer face of the embankments, a soil retention geocomposite was specified. This geocomposite was placed over soil forming material and a prescribed seed mix to protect against erosion prior to natural regeneration from the adjacent vegetation.

The design proposed gives a total leachate capacity of around 180,000m^3 from the existing ground level to a leachate level of 7mAOD.

Some site preparatory work was necessary in order to form a relatively flat surface suitable to install a lining system. The majority of the grass and vegetation that covered the area was track compacted, flattened and left in place. Any hummocky areas were re-profiled by the removal of high areas and low areas backfilled with suitable granular material. The elevated ground in the north-east corner of the site was excavated to produce a smooth final profile at around 3.5mAOD.

Basal engineering works were undertaken in order to facilitate construction of the lining system and low pressure tracked dozers were used to form the base of the lagoon. The basal engineering works comprised of the lining system placed on top of the prepared formation. However, in particularly soft areas the prepared formation was not suitable as a running surface for the dozers, in which case the basal engineering works were modified as follows:

- Lining system;
- 300mm sandy gravel;
- Separator geotextile;
- Prepared formation.

Field trials were successfully carried out to assess these options prior to the start of the main construction works.

DESIGN ISSUES

Geotechnical design considerations

Internal stability assessment. The main elements of the geotechnical design for the lagoon can be considered under two headings; internal and external stability. As part of the internal stability of the perimeter embankment, the following issues were considered and addressed using the commercially available slope stability software, Slope/W (GeoSlope, 2000):

- Inside face (short-term using undrained shear strength, intermediate-term using effective stress strength parameters with no leachate impoundment, and long-term using effective stress strength parameters with leachate impoundment and dissipation of excess pore pressures within the alluvium.)
- Outside face (short-term using undrained shear strength, intermediate-term using effective stress strength parameters with leachate impoundment, and long-term using effective stress strength parameters with leachate impoundment and dissipation of excess pore pressures within the alluvium.)
- Inside face, northern embankment (short-term using undrained shear strength, intermediate-term using effective stress strength parameters with no leachate

impoundment, and long-term using effective stress strength parameters with leachate impoundment and dissipation of excess pore pressures within the alluvium.)

An assessment of the likely pore pressure build-up in the alluvium due to the construction of the perimeter embankment was also conducted, with calculations processed for two locations; beneath the mid-point of the slope and beneath the toe of the slope. Parameters used for design purposes are presented in Table 1, with additional properties for the alluvium taken from the ground investigation results. The pore water pressures in the soils beneath the northern section of the embankment were assumed to be lower as the ground level was significantly higher in this area therefore, groundwater levels were much lower than the ground surface. In other areas, the groundwater level was much higher. Factors of safety against failure of the embankment slope ranged from 1.3 to 2.1, indicating satisfactory stability. It was considered that the factors of safety should increase during the operational phase of the lagoon, due to dissipation of the construction pore pressures and the lateral support given to the internal slopes by the leachate.

Table 1. Soil properties

	c' (kPa)	ϕ' (deg)	r_u	Additional information
Fill	0	24	0.1	-
Foundation layer	0	30	0.1	-
Old waste	0	25	0.5	main slope
Old waste	0	25	0.3	northern embankment
Alluvium	0	25	0.2 to 0.8	$m_v = 0.2m^2/MN$ $k = 1 \times 10^{-8}m/s$

External stability assessment. As part of the consideration of external stability of the perimeter embankment, issues such as basal sliding, bearing capacity and settlement were considered. The adoption of a 20m wide foundation layer resulted in bearing capacity failure not being an over-riding concern with this project. However, settlement of the underlying soil layers was thought to be a significant design issue. The maximum embankment height was constrained by planning conditions and yet the design had to ensure a minimum lagoon capacity of between 150,000m^3 to 200,000m^3. Therefore a minimum leachate level would be required (or a maximum operating level), which, coupled with a minimum required freeboard to account for flood rise and wave run-up, meant that settlement had to be considered.

Using approaches proposed by Poulos & Davis (1974) and based on consolidation parameters determined from the ground investigation, a total settlement of approximately 400mm was predicted, beneath the embankment, and 350mm beneath the lagoon area.

Groundwater. As part of the internal stability assessment, assumptions were made regarding the groundwater conditions, in particular the pore water pressures generated by the additional loading. An assessment was made of the likely excess pore water pressure developed in the alluvium.

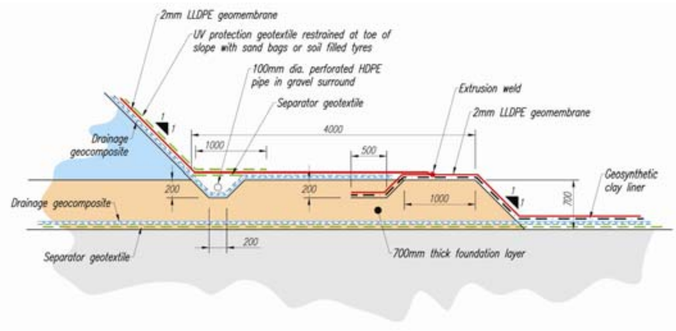
Although the analyses indicated that an increasing pore pressure ratio would be detrimental to the stability of the embankment, factors of safety against failure were satisfactory. Notwithstanding this, through the use of geotextile reinforcement in the embankment rather than geogrids, excess pore water pressures would not develop during construction of the embankment. Similarly, excess pore water pressure in the underlying alluvium materials would be allowed to dissipate by the use of a geocomposite layer beneath the lagoon and the perimeter embankment, combined with the drainage layer within the foundation layer, comprising 75mm crushed concrete. From a construction point of view, it was decided that phased construction of the embankment would be advisable; in this case, 0.5m per week of fill was considered appropriate. Furthermore, piezometers were installed around the perimeter embankment in order to monitor the development of pore pressures in the alluvium and should these pressures have exceed the values assumed in the analyses, then further measures would have been undertaken, such as the cessation of construction works or the use of additional soil berms located at the toe of the embankment.

Environmental design considerations

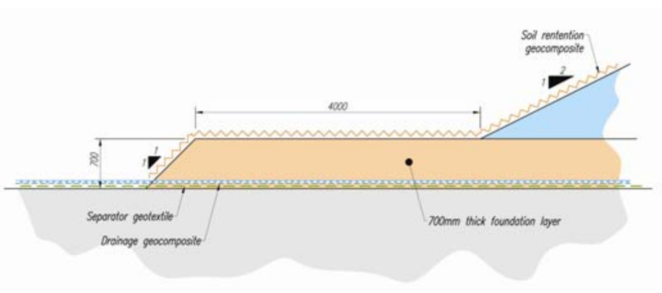
The main function of the leachate lagoon is the storage and containment of leachate generated by the process of waste degradation taking place in the adjacent landfill. As a consequence, there were a number of design issues that had environmental drivers. These are discussed briefly in the following sections.

Leachate containment. The purpose of the lining system is to contain the leachate within the lagoon and to minimise leakage. A composite geomembrane/geosynthetic clay liner system was adopted for the base of the lagoon. The geomembrane component of the composite lining system must be able to withstand the total and differential settlement expected during the lifetime of the lagoon, and be chemically resistant to the proposed leachate. A 2mm thick Linear Low Density Polyethylene (LLDPE) geomembrane sheet was therefore chosen instead of High Density Polyethylene due to its superior multi-axial properties.

In the upper sections of the perimeter slopes a single LLDPE geomembrane was used as the potential for damaging the geomembrane was considered to be lower. This LLDPE geomembrane was protected from ultra violet light with a suitable protection material, in this case, a non-woven polypropylene geotextile with a minimum carbon black content of 10%. In addition, the geotextile has been securely anchored to prevent uplift due to wind loading. The geotextile solutions will also afford a certain amount of protection to the geomembrane from accidental damage. The lining details are presented in Fig. 4.



(a) Inside face



(b) Outside face

Fig. 4. Lining details

Underdrainage system. A full under-drainage system was required to remove excess gases that might be generated through the continued degradation of the waste material directly beneath the lagoon as well as any vegetation left during the site preparation works, and the underlying peat deposits. A full under-drainage system was also required to remove excess liquid and dissipate the pore pressures in the alluvium beneath the lagoon. The main drainage comprises a 12mm thick geocomposite layer placed below the lagoon construction. Additional perforated pipes have been installed along the edges of the haul roads and in any particularly wet areas encountered during the construction works. A sub-liner drainage geocomposite was also placed directly beneath the geomembrane on the perimeter slopes to intercept any leakage from the liner and transmit it to a perforated pipe at the toe of the embankment.

CONSTRUCTION ISSUES

Groundwater

Groundwater monitoring has been established at a number of locations around the perimeter embankment with the intention of recording pore pressures within the alluvium beneath the embankment. Ongoing monitoring allows pore pressure ratios to be determined and compared with those assumed during the analyses. If excessive pore pressures are induced, then measures can be taken in order to reduce them to acceptable levels.

To this end, nine drive-in vibrating wire piezometers were installed at three locations around the perimeter of the embankment together with fourteen standpipe piezometers to confirm the water pressures beneath the embankment. The locations of the piezometers relative to the embankment are shown in Fig. 5.

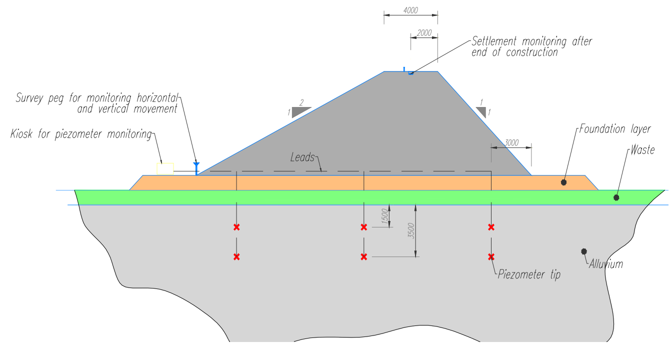


Fig. 5. Groundwater and settlement monitoring locations

Fig. 6 indicates the ongoing monitoring results as a graph of pore water pressure (mAOD) against time since the end of construction. The graph illustrates that the pore water pressure is significantly lower than that assumed within the stability analyses. The upper solid line in this figure indicates the impounded leachate level in the lagoon. Within the stability assessments a pore water pressure value (r_u), which is the pore water pressure expressed in terms of the overburden pressure, of between 0.2 to 0.8 was assumed with increasing depth in the alluvium.

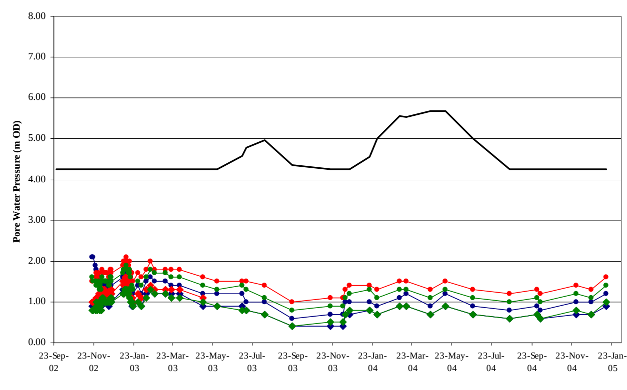


Fig. 6.Pore water pressure in the alluvium beneath the perimeter embankment

The monitored pore pressures (Fig, 6) correspond to values towards the lower end of this range. Fig. 7 shows the pore water pressure ratio at different locations around the perimeter of the embankment and at different elevations beneath the embankment. The curves show that the calculated r_u (from measured pore water pressure values) ranges from approximately 0.1 to just in excess of 0.3.

Construction Quality Assurance

Although most geomembrane sheets are nearly impermeable (fluid transfer occurs through diffusion), their performance is controlled by the number of defects in the geomembrane during its working life. These defects can occur in the geomembrane sheet or at welded joints and can be caused by mechanical damage, tearing or overstressing. Independent third party construction quality assurance (CQA) was carried out on both the geomembrane and the GCL thus minimising the possibility of defects in the liner prior to the placement of leachate in the lagoon. Should any defects develop in the geomembrane during its working life, the use of a geosynthetic clay liner beneath the geomembrane will limit the lateral spread of any leakage. This composite effect will thus substantially increase the performance of the lining system.

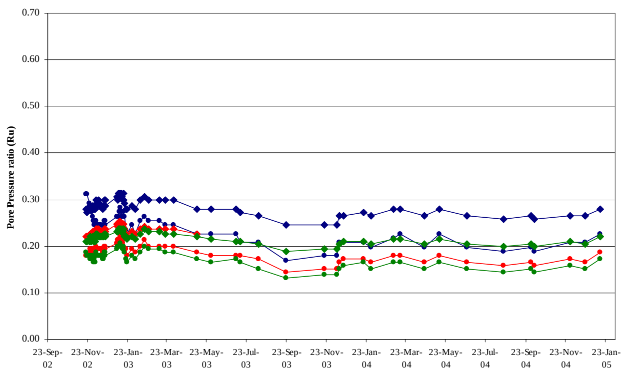


Fig. 7. Pore water pressure ratios calculated in the alluvium beneath the embankment

Settlement

Temporary survey stations were installed for horizontal and vertical displacement monitoring at the toe of the embankment at each of the instrumented sections and at four other intermediate locations. These temporary stations were monitored on a daily basis using electronic survey equipment to a high standard of accuracy during the construction phase of the works. The frequency of monitoring was subsequently reduced in light of results and the dissipation of pore pressures as discussed previously.

To monitor total settlement after construction a series of permanent monitoring stations were installed on the foundation layer and crest of the embankment, the locations shown on Fig. 5. The stations were surveyed initially on a weekly basis and then the frequency decreased to monthly and then quarterly as the rate of settlement decreased. A plot of settlement against time is presented in Fig. 8. The upper set of curves indicate that the elevation of the top of the bund has reduced from an initial as-built elevation of 8.0mAOD to round 7.7m, indicating that the actual settlement is towards the lower limit of the predicted settlement of between 300 and 500mm. The lower set of curves show the elevation of the foundation layer for the bund.

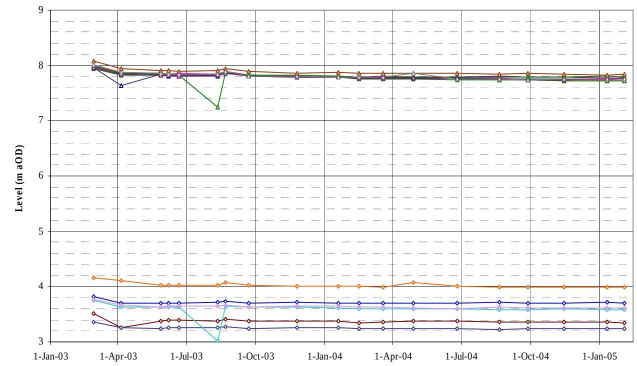


Fig. 8. Settlement monitoring results for the perimeter embankment

CONCLUSIONS

A critical review of the design issues relating to the construction of a leachate storage lagoon has been presented. In this case history, the geotechnical and geoenvironmental applications of geosynthetics have been explored in order to ensure the short and long term stability of the perimeter embankment of the lagoon and to ensure containment of the leachate.

The geotechnical complexities relating to the construction of the leachate lagoon have been documented, and relate primarily to the poor ground conditions, the high groundwater levels and the specification of recycled materials in the construction of the bund. The proposed site for the new lagoon was an old tip area, comprised of waste material from the 1950's overlying soft, compressible alluvial deposits. The compressibility characteristics of these strata presented a significant design challenge. Additionally, the groundwater levels in this material were near to, and in some areas, at the ground surface, and so it was envisaged that excess pore water pressures could develop in the materials during construction of the embankment. Finally, by specifying the use of on-site, recycled soil materials of varying engineering quality for the bund construction, the short and long term stability of the perimeter embankment would require careful analysis and monitoring.

In summary, these issues were addressed primarily during the design stage by specifying a range of geosynthetics with a range of engineering functions, from drainage through to reinforcement, and in many cases, the geosynthetcis were specified to perform more than one function at any one location. During the construction stage, these issues were also considered by applying a combination of observational methods and responsive design. The details of the construction aspects of this project will be the subject of a subsequent paper.

The geosynthetics used in this project can be summarised as:

Geosynthetic Material	Function
Geotextile	Reinforcement and Drainage
Geotextile	UV protection
Geocomposite	Drainage
Geogrid	Reinforcement
Geopipes	Drainage
Geomembrane	Primary component of composite liner
Geosynthetic Clay Liner	Secondary component of composite liner

Clearly, each of these elements require some degree of engineering design in order to ensure fitness for purpose, and the design process has been documented in this paper. As part of the design and construction processes, value engineering, the observational method and responsive design play an important role; this has been discussed in the context of this case study.

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