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Requirements for the design of geogrid reinforced clay liners of landfills

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ABSTRACT: Liner systems render a significant role in ensuring that waste materials are safely separated from the environment. Despite the advent of modern liner systems, Compacted clay liners are regarded as one of the very significant components of liner system and are being used as a waste containment system in landfills. Compacted clay liners made-up of soil of low permeability characteristics are generally prone to damage: (*i*) for not meeting required material characteristics, (*ii*) due to non-uniform settlements attributed to heterogeneous composition of municipal solid waste and sub-soil and (*iii*) low overburden in the case of capping system. Non-uniform settlements lead to bending and are critical for the behaviour of clay liners. As a result, the clay liner could loose its integrity and sealing efficiency. In such situations, possible alternative is to reinforce the clay liner with a geogrid layer to enhance its deformation behavior and integrity. The main function of the reinforcement layer is to provide necessary tensile resistance at the crack prone region by developing a bond between the soil and geogrid. Based on the centrifuge test results, requirements for the design of geogrid reinforced clay liners are discussed. In this paper, requirements for the design of geogrid reinforced clay liners are presented depending upon (*i*) non-uniform settlements of waste surface, (*ii*) tensile strength-strain characteristics of geogrid layer, and (*iii*) material characteristics of clay liner material, and (*iv*) soil-geogrid interface characteristics.

1 INTRODUCTION

Landfills are the primary disposal method for hazardous and municipal solid wastes. The most important elements in containing pollutants within the landfill are liner systems such as bottom lining systems, side lining systems and capping systems. In all these liner systems, in order to achieve complete encapsulation of waste, it is in practice to have an impermeable layer as one of the components. Several impermeable layers like, compacted clay liners (CCLs), geomembrane layer, geosynthetic clay liners (GCLs), mineral liners, asphalt liners, capillary barriers, etc. are developed and used. Regardless of the advent of modern liners, as a sealing component of liner system CCLs are still largely being used world-wide [Benson et al. (1999)]. The most important requirement of a CCL is to maintain a hydraulic conductivity of 1×10^{-9} m/s or less. One of the predominant causes of the failure of CCLs is due to the occurrence of non-uniform settlements. These non-uniform settlements are ascribed to (i) compressive nature of waste and (ii) on-going bio-decomposition of waste. Mainly, the laboratory and field permeability tests are conducted without taking into account of flexural deformations of CCL caused by non-uniform settlements. The non-uniform settlement of a landfill continues over an extended period of time, with a final settlement spread over large areas that can be as large as 30 - 40 % of the initial height of landfills [Jessberger (1994) and Ling et al. (1998)]. Excessive non-uniform settlements of this nature develop cracks in CCL and these cracks will induce an unexpected increase in surface infiltration and seepage of leachate [Scherbeck and Jessberger, 1993]. Meiβner and Ringelb (1987) reported about observed deformation mechanism of capping system of Floersheim-Weilbach landfill, Germany. During the observation period, formation of wide cracks were noticed and cracks separated with a spacing of approximately 3 m - 5 m. Cracks were observed to occur along the length due to higher strain levels in the clay liner, which ultimately cause environmental contamination. Druschel and Wardwell (1991) reported observation of numerous cracks about 0.1 m wide and two large cracks which are about 0.30 m wide in the soil cover of 28 hectares of municipal solid waste landfill located in Central New England. It was further reported that prior to the construction of a final cover system the acceptance of waste was stopped before 5 - 12 years itself. This suggests the differential movements, which would have continued because of organic decomposition of waste. The occurrence of cracks in the CCL could take place depending upon the plastic behaviour of liner material, consistency, compactive effort, clay content, presence of overburden, etc. The bottom lining system experiences non-uniform settlements due to sub-soil and due to huge amounts of waste surcharge. However, the compressive stress arising out of waste surcharge suppresses the formation of tension cracks in the CCL of the bottom lining system. The potential for clay to crack appears to be greater in landfill capping system due to low surcharge and due to the process of readjustments and on-going bio-degradation of the encompassed municipal solid waste [Daniel and Koerner (1993)] (see Fig. 1 and 2).

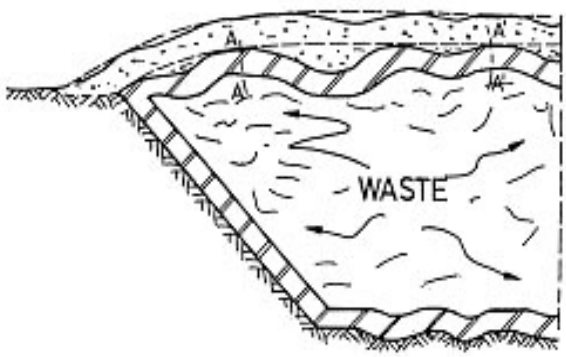

Figure 1 Schematic representation of landfill subjected to non-uniform settlements.

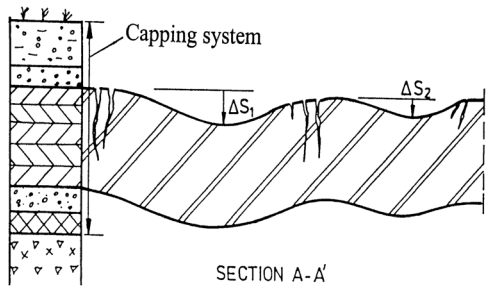

Figure 2. Landfill capping system subjected to non-uniform settlements.

Jessberger and Stone (1991), Scherbeck and Jessberger (1993), Schick and Wunsch (1995), Viswanadham (1996), Edelman and Katzenbach (1996), Craig and Gallagher (1997) have studied the affect of differential settlements on the integrity of clay liner. Investigations have revealed that for the clay liner subjected to low overburden or without any overburden the loss of integrity depends upon the material characteristics and deflection contour with continuous deformations.

Jessberger and Stone (1991) and Scherbeck and Jessberger (1993) have reported about centrifuge test results concerning the response of Kaolin and Bentonite-Sand mixture model clay liners subjected to non-uniform settlements of a landfill. The investigations have proved that the occurrence of cracks in clay liner results in the loss of integrity and consequently clay liner loses its sealing efficiency. The integrity of the liner system is mainly achieved by maintaining the good deformable characteristics of the clay liner throughout different stages of construction. In addition to this, the tensile strength characteristics of clay liner made-up of cohesive soil is very much dependent upon consistency, compactive effort, plasticity, clay content etc. It is also essential to ensure that the clay liner material shall have a consistency in the range of stiff to very stiff in order to possess good tensile strength - strain characteristics.

Due to non-availability of suitable liner material, low overburden stresses and anticipated large non-uniform settlements as in the case of capping systems, the adoption of geogrid reinforced clay liner is an efficient solution to enhance the deformation behaviour of the clay liner (Viswanadham, 1996). In such situations, geosynthetic materials such as biaxial geogrids can be used as a reinforcing element within the clay liner, which can withstand relatively high in-plane tensile strains and stresses induced by non-uniform settlements. The clay liner subjected to non-uniform settlements impose lateral tensile stresses along the soil-reinforcement interface in the tension zone which are resisted by the tension mobilized in the reinforcement in the form of interface bond stresses. Figure 3 presents perspective view of top capping system of landfill along with cover soil, GRCL, gas drainage layer and municipal solid waste. From the field aspect point of view, the introduction of reinforcement inclusion in the form of geogrid layer is relatively easy. For e.g. for a CCL with four lifts, geogrid layer can be placed after completion of three lifts and fourth lift can be placed subsequently. With this method, for the better performance of the reinforced clay liner due care shall be taken to maintain perfect contact between the soil and the geogrid layer. The question arises, in selection of the specific type of reinforcement layer for better performance of geogrid reinforced clay liner.

In this paper, requirements for the design of geogrid reinforced clay liners are presented depending upon (*i*) non-uniform settlements of waste surface, (*ii*) tensile strength-strain characteristics of geogrid layer, and (*iii*) material characteristics of clay liner material, and (*iv*) soil-geogrid interface characteristics. The creep effects of the geogrid material are not covered in the scope of the present work.

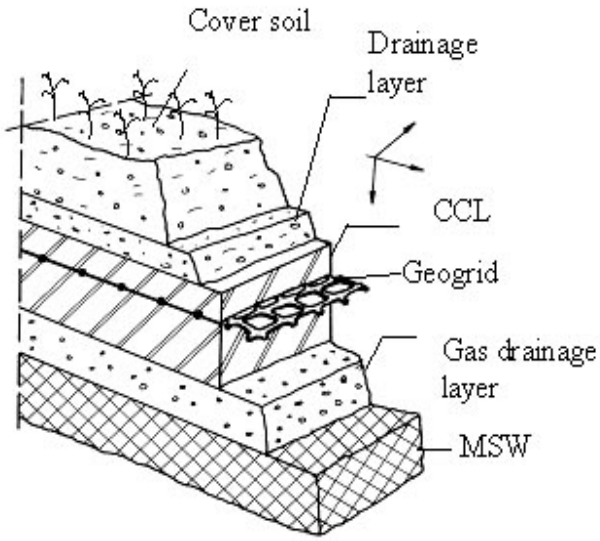

Figure 3. Perspective view of capping system with GRCL.

2 SIGNIFICANCE OF SOIL-GEOGRID COMPATIBILITY IN MAINTAINING INTEGRITY OF CCL

The significance of soil-geogrid compatibility in maintaining integrity of CCL was evaluated through the results of centrifuge model tests carried out in large geotechnical centrifuge facility at Ruhr-University, Bochum, Germany. The centrifuge model tests were performed at 50 gravities (Scale factor N = 50). Details of specifications of large geotechnical centrifuge are presented elsewhere (Jessberger and Güttler, 1988).

The response of kaolin clay liners (extending over a landfill area of approximately 850 square meters) with and without geogrid reinforcement layer was studied. By simulating a trough shaped deformation profile with a maximum central settlement a = 1.25 m (imposed in steps with an increment of 0.25 m) over an influencing length of 20 m [prototype dimensions] respectively. By varying type of model geogrids (MGG1, MGG2 and MGG3), and keeping thickness of clay liner (d =1.25 m) and consistency of clay liner material as constant, centrifuge tests were executed. MGG1 is relatively possessing medium stiffness, MGG2 is having high stiffness and MGG3 is having low stiffness respectively. The modeling considerations, model test package, test procedure, and other details can be found in Viswanadham (1996). The cross-sectional view of deformed geogrid reinforced clay liner (with MGG1 placed within top one-third portion of model kaolin liner) at the end of the centrifuge test (i.e. a = 1.25 m) is presented in Fig. 4. The zone of maximum curvature is shown along with the deformed geogrid layer. Except observation of tiny hair cracks on the surface, the occurrence and development of cracks along the cross-section of the clay liner were not observed during all stages of the test (i.e. before inducing deformations and till the end of completion of deformations).

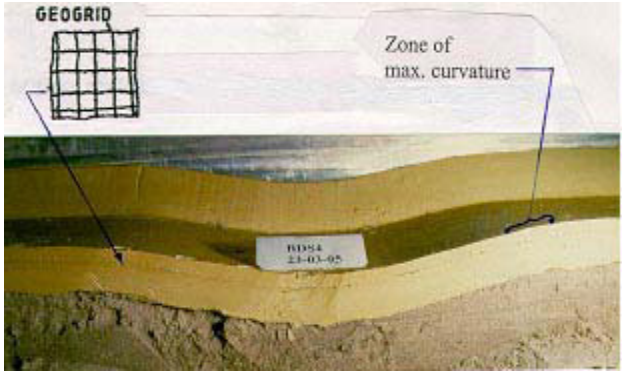

Figure 4. Deformed geogrid reinforced clay liner.

Figure 5a-5e presents comparisons of typical cross-sections of model clay liners at the end of the centrifuge test (a = 1.25 m) with and without reinforcement inclusion. All the typical cross-section portions are taken from the zone of maximum curvature area (as shown in Fig. 4) and without any overburden, except for the case in Fig. 5a. As shown in Fig. 5a - 5e, the occurrence of shearing and cracking mechanism caused by settlement induced deformation in the clay liner. Particularly, the situation depicted in Fig. 5a occurs when the overburden stress suppresses cracking. The minimum height of overburden required to suppress cracking of clay liner is approximately 3 m, which is comfortably available for CCLs in bottom lining systems (Scherbeck and Jessberger, 1993). Uncontrollable rate of increase in leakage was observed for the section of clay liner shown in Fig. 5c. Different pattern of behaviour of reinforced clay liners can be seen from Fig. 5d-5e. In the case of Fig. 5d, the clay liner is reinforced with model geogrid layer MGG3 (relatively having lower stiffness) and observed to develop propagation of cracks of small widths distributed on the surface and piercing upto the level of reinforcement layer. Contrary to this, no cracks were observed to occur during all stages of the test with MGG1 as reinforcement inclusion (Fig. 5e).

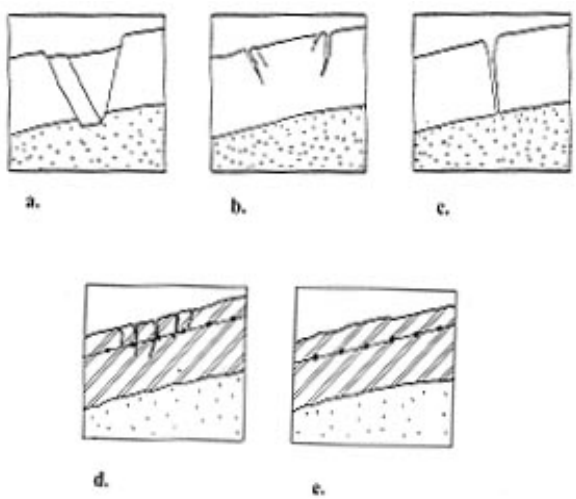

Figure 5. Typical cross-sections of model clay liners with and without reinforcement inclusion.

This is attributed to mobilization of strain distribution in the tension zone due to soil-geogrid interaction. This has been further analyzed by comparing the strain levels in the geogrid layer and in the soil along the soil-geogrid interface. As can bee seen from Fig. 6, the response of geogrid to all settlement levels is indicated that for the magnitude of strain in soil, geogrid tries in mobilize an almost equal amount of strain. Figure 6 shows linear variation of soil strain with geogrid strain for all settlement stages. This also explains model geogrid reinforced clay liner situation at the end of the centrifuge test (see Fig. 4 and Fig. 5e) and depicts significant influence of reinforcement inclusion on the integrity of clay liner. It is very interesting to note about the significance of soil-geogrid compatibility for restraining integrity and sealing efficiency of reinforced clay liner. The correlation relation between strain in geogrid ε_G and the strain in soil along the soil-geogrid interface ε_{SG} is presented in Equation 1 below:

$$\varepsilon_G/\varepsilon_{SG} = 1.2 \qquad (1)$$

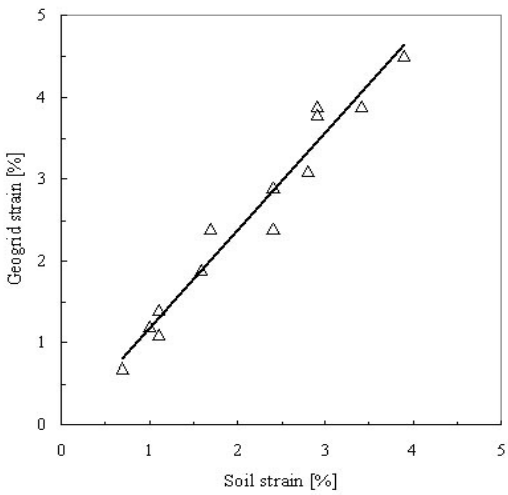

Figure 6. Strains in soil and geogrid.

Figure 7 presents the variation of uplift thrust exerted by different reinforcement inclusions with the central settlement a [at each stage the settlement level is increased by 0.25 m till the maximum central settlement of 1.25 m). An overburden of 8.75 kN/m^2 due to storage of water on the model clay liner is considered in the analysis. The participation of membrane carrying mechanism after attaining large settlement (i.e. a = 1 m) for the clay liner with MGG2 can be noticed in Fig. 7 (hatched portion). This has led to (i) formation of air gap and (ii) loss of contact in the central settlement region. However, by seeing the performance of other reinforced clay liners (i.e. with MGG1 and MGG3), q_G exerted by the geogrid at all settlement stages was found to be well within limits. Several investigators [Bourdeau et al. (1982), Giroud et al. (1990), Espinoza 1994] have considered the influence deformed geosynthetic layer as a tension membrane effect and the geosynthetic material is assumed to provide anchorage resistance by frictional forces away from the settled region.

Based on the geometry of the deformed geogrid layer, the uplift thrust exerted by a geogrid layer can be computed (Espinoza 1994).

$$q_G = J_G \varepsilon_G \kappa \qquad (2)$$

where, q_G = uplift thrust exerted by geogrid [kN/m^2]; J_G = geogrid stiffness [kN/m], ε_G = strain in the geogrid; κ = curvature of geogrid [1/m] = $1/R'$, R' = radius of the deformed geogrid layer. As can be seen from Equation 2, as the geogrid stiffness increases for

the given strain, the uplift thrust exerted by the geogrid will also increase.

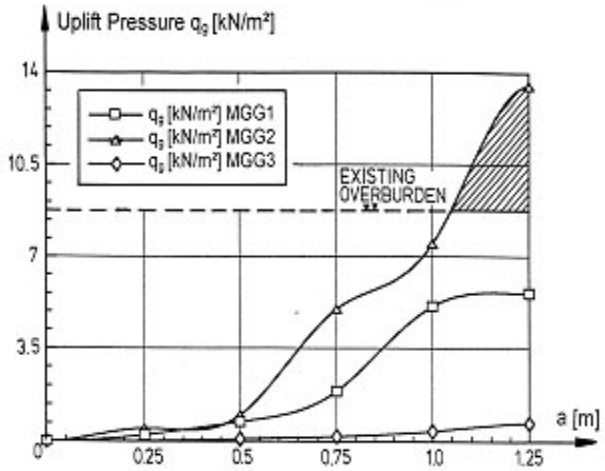

Figure 7. Variation q_G with central settlement a.
[Prototype dimensions]

The results obtained from the analysis were found to be in good agreement with the experimental observations (Viswanadham, 1996). Based on the observations made in the experimental investigations, the influence of geogrid layer on the deformation behaviour of clay liner was observed to have two effects, namely; (i) tension membrane effect and (ii) reinforcement inclusion effect. It was found that the geogrid layer that is placed within the top one-third portion of the model clay liner prevents cracking and enhances the sealing efficiency due to soil-geogrid frictional resistance. The extent of withstanding large tensile deformations depends mainly on the stiffness, geometry of the reinforcement and stiffness of soil.

3 PERFORMANCE OF REINFORCED CLAY LINERS

The outer fibre strain ε_{of} was calculated based on the deformation contours obtained after analyzing the integral displacement of markers fixed in the soil and on to the geogrid. The calculated outer fibre strain includes strain due to change in length and curvature. Figure 8 presents variation of outer fibre strain ε_{of} for a clay liner with minimum curvature radius R for an un-reinforced and reinforced clay liner respectively. In the present investigations, induced non-uniform settlements produce a curvature radii ranging from 77 m to 20 m (i.e. R = 77 m at a = 0.25 m and R = 20 m at a = 1.25 m). Typically, it is considered that if the liner is made-up of soil of medium plasticity and subjected to minimum curvature radius of 200 m then no deformation check is required (LWA - Instructions, 1993). However, as schematically depicted in Fig. 1, over a period of time the capping system is prone to curvature loading of variable nature. Quite often the capping system of a landfill experiences radii of curvature less than 200 m causing high outer fibre strains in the clay liner. Once the outer fibre strain experienced by the clay liner crosses the ultimate tensile strain of liner material, initiation of cracking occurs and propagates further with sub-sequent settlements (see Fig. 2). In the case of reinforced clay liner (with MGG1), it was observed that the occurrence of cracking and the simultaneous increase in hydraulic conductivity has not taken place even after attaining curvature radius of 20m. This is attributed to the frictional efficiency of soil-geogrid-soil system in preventing clay from cracking. In the case of clay liner reinforced with a geogrid layer, tensile stresses along the soil-reinforcement interface are resisted by the tension mobilized in the reinforcement in the form of interface bond stresses.

Contrary to this, an un-reinforced clay liner was observed to experience cracking and subsequent loss of sealing efficiency. As shown in Fig. 8, an un-reinforced clay liner is observed to experience cracking once after attaining a central settlement of a = 0.5 m (i.e. R = 55 m). This leads one to conclude that the reinforcement of clay liner as an alternative solution for maintaining good deformable characteristics during construction and post-closure period of landfills.

A reasonable conclusion is that Geogrid Reinforced Clay Liners (GRCLs) are much superior than CCLs and in order to achieve better performance of clay liner behaviour, a perfect contact between soil and geogrid layer shall be achieved during liner construction as well as post-construction stage. It implies that, it should have (*i*) Soil-geogrid compatibility and (*ii*) Adequate geogrid stiffness. As presented in Fig. 7, if the uplift thrust exerted by a geogrid layer is found to be more than the existing overburden above the geogrid layer, contact in the settled region will be lost and geogrid layer tries to bridge the same. Thus, selection of geogrid layer plays a very significant role for the better performance and deformation behaviour of reinforced clay liners. In the next section, requirements for designing GRCL are discussed in detail.

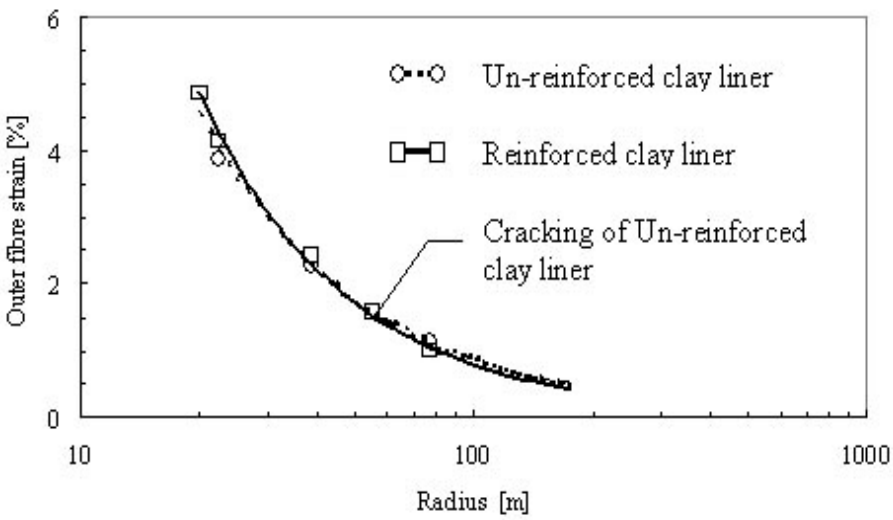

Figure 8. Variation of outer fibre strain with Curvature radius.

4 REQUIREMENTS FOR DESIGNING GRCL

The evaluation of the behaviour of GRCLs without any overburden in centrifuge model tests has shown that the reinforced clay liner tries to retain the integrity even after attaining deformation limit. The extent to which the integrity of clay liner is maintained depends on the soil stiffness, geogrid stiffness and geogrid opening characteristics (for interlocking effect). To design geogrid reinforced clay liner, it is required to know about (*i*) Extent of non-uniform settlements at a particular landfill site, (*ii*) Liner material characteristics- including tensile strength-strain behaviour, (*iii*) Physical and strength characteristics of selected geogrid material, and (*iv*) Soil-geogrid interface characteristics. The following requirements for selecting an ideal geogrid as a reinforcement inclusion for enhancing the deformation behaviour of CCL is suggested based on the performance of reinforced clay liners in a centrifuge test:

Based on the correlation between the strain in geogrid and soil strain along soil-geogrid interface (using Equation 1), the strength condition is evolved. In order to have tiny hair cracks (i.e. ratio of width of crack and spacing of crack less than or equal to 0.005), the selected geogrid shall have tensile strength compatible with tensile strength-strain characteristics of liner material. Equation 3 presents the deduced condition for ascertaining tensile strength characteristics of a geogrid layer.

$$T_G/\lambda q_d \approx \Omega_s \qquad [\text{with } 1 \leq \Omega_s \geq 1.25] \qquad (3)$$

Where, T_G = Tensile strength of geogrid, $\lambda = J_G/E_s$, E_s = tension modulus of soil; q_d = Ultimate tensile strength of soil. By fulfilling the above requirement, desired geogrid with tensile strength characteristics can be selected. In the case of clay liner reinforced with a geogrid of inadequate tensile strength-strain characteristics, as observed in Fig. 5d, clay liner cracks and subsequently sealing efficiency of the liner will be affected. Hence, important part of the design requirement of GRCL depends upon the selection of desired geogrid.

Thereafter, the selected geogrid needed to be checked whether the overburden stress above reinforcement inclusion q_s is adequate to counter tension membrane effect or not. Otherwise, as presented in Fig. 7, it results in loss contact in the central region due to the participation of tension membrane effect. In order to prevent, any such eventuality, it should be seen that the existing overburden q_s is twice the uplift thrust by the geogrid q_G (Equation 4). The uplift thrust q_G can be computed using Equation 2.

$$q_s/q_G \geq \eta_m \qquad [\text{ with } \eta_m = 2] \qquad (4)$$

Finally, selected geogrid shall be checked for adequacy of bond characteristics, so that perfect soil-geogrid-soil interaction can be achieved. The above mentioned design requirements were formulated based on the observed performance of reinforced clay liners in centrifuge tests and subsequent theoretical investigations only.

In the present study, only one layer of the geogrid layer is considered as a reinforcement inclusion within the clay liner. As stated earlier, main purpose of reinforcement inclusion within the clay liner is provide necessary tensile resistance at the crack prone region by developing a bond between the soil and geogrid. Due to interaction along the bottom portion of the clay liner and sand layer, formation of cracks were not observed during centrifuge tests.

From the field perspective, introduction of reinforcement inclusion in the form of geogrid layer is relatively easy. As the clay liner is constructed in lift-wise and an appropriate geogrid layer can be placed at a suitable location. For the better performance of reinforced clay liner, due care shall be taken to maintain perfect contact between soil and geogrid layer.

5 CONCLUSIONS

On the basis of centrifuge model tests on clay liners with and without reinforcement inclusion and subsequent analysis, the following requirements for designing geogrid reinforced clay liners are deduced:

(i) The reinforcement of CCL seems to be very efficient and possible alternative to enhance the deformation behaviour and to retain its integrity.

(ii) The main function of the reinforcement is seen here to provide necessary tensile resistance at the crack prone region by developing a bond between the soil and geogrid layer.

(iii) The compatibility between soil and geogrid layer is very much essential. For the defined strain, the geogrid strength characteristics shall also be compatible with soil tensile strength characteristics.

(iv) In order to counter tension membrane effect, there is a minimum requirement of overburden above the geogrid layer. The overburden shall be greater than or equal to twice the uplift thrust exerted by the deformed geogrid layer. In the present practice, the overburden (in the form of restoration profile and top soil) of about 1.3 - 1.5 m is provided in the case of capping systems and should suffice the aforementioned requirement.

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