Differential settlement behaviour of coal-ash based barriers: centrifuge study

B.V.S. Viswanadham

i) Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai – 400 076, India.

ABSTRACT

The objective of this paper is to evaluate the performance of coal ash based barriers subjected to continuous differential settlements in a geotechnical centrifuge. Motor based differential settlement simulator was used to induce differential settlements with a distortion level up to 0.125 at 40 gravities in a 4.5 m radius large beam centrifuge facility available at Indian Institute of Technology Bombay, India. A short series of centrifuge model tests were conducted by varying the thickness of coal ash based barriers. All the developed coal ash-based barriers were subjected to an overburden of 25 kN/m$^2$ equivalent to that of in landfill cap covers. All the models were thoroughly instrumented with Linearly Variable Differential Transformers (LVDTs) and Pore Water Pressure Transducers (PPTs) to measure vertical settlements and pore water pressure. Digital Image Cross-correlation (DIC) technique was adopted to arrive at deformation profiles of coal ash-based barriers and strain distribution along the top-most surface of the tested barrier during all settlement stages. The water sealing efficiency was assessed in terms of limiting distortion level and strain at water breakthrough. A 0.6 m thick coal ash based barrier with an overburden of 25 kN/m$^2$ was observed to experience a limiting distortion level of 0.068 and a strain at breakthrough of 0.98%. In comparison, a 1.6 m thick coal ash based barrier has not registered any water breakthrough and noted to sustain large deformations. This centrifuge study demonstrates that coal ash based barriers of an adequate thickness can be used to as impervious barriers of landfill cap covers.

Keywords: coal ash, municipal solid waste, landfills, waste containment systems; cover, model tests, centrifuge modelling.

1 INTRODUCTION

Because of their low hydraulic conductivity and high adsorption capacity, compacted clay soils are traditionally used in landfill waste containment systems. The desirable characteristics, such as low hydraulic conductivity, of a clay based barrier of landfill waste containment systems may change due to on-going bio-decomposition of the municipal solid waste, temperature and moisture fluctuations. Furthermore, clay barrier materials can also be susceptible to chemical attack by permeating contaminants (Kaya and Durukan, 2004). Two predominant causes of failures of clay barriers are: (1) desiccation cracking due to moisture fluctuations; and (2) cracking due to excessive differential settlements. Imperviousness of clay barriers is essential, especially in municipal solid waste landfills and cap covers of low-level radioactive waste containment sites. The problem of cracking of clay barriers of waste containment systems was addressed by several investigators through a variety of research efforts. Morris et al.,1992 and Miller et al.,1998 have reported that the hydraulic conductivity of clay barriers having desiccation cracks has increased considerably. In addition, especially in compacted clayey soils at low overburden, thermally induced moisture changes in the clay barrier can cause a reduction in plastic deformability and desiccation cracks. Differential settlement of clay based cap covers are caused due to MSW stored in landfills undergoing bio-decomposition and the collapse of cavities within the waste or between waste packages or toppling of waste containers (Gourc et al. 2009). Differential settlement and subsidence can result in a catastrophic loss of performance of the landfill cap covers. Excessive differential settlements can result in tension cracks in the zone of sharp curvatures, thereby resulting in loss of integrity of the cap cover system.
Sometimes, it may be difficult to obtain clay barrier materials having the physicochemical characteristics mentioned above to be used as a landfill barrier with low cost. In such situations, the use of coal-ash based barriers in waste containment systems is a viable option. Large quantities of coal ashes are being produced by coal fired thermal power plants all over the world. The need of the day is to have practical engineering applications which involve thesafe disposal of such so considered hazardous materials. Coal ashes have been shown to have beneficial properties such as low specific gravity, lower compressibility, higher rate of consolidation, high strength, high California Bearing Ratio, high volume stability, water insensitiveness to compaction, and pozzolanic reactivity. Coal ash has been used successfully as a structural fill material for constructing highway embankments throughout the world (Faber and Digoia (1976); Toth et al. (1988); Viswanadham (1999) and Chand and Subbarao, 2007). To date, very few studies have been conducted to evaluate the potential engineering applications of coal ash as landfill liners/waste containment systems [Bowders Jr. et al. (1987), Edil et al. (1987), Prashanth et al. (2001), Kaya and Durukan (2004), Cokca and Yilmaz (2004)]. In some cases, hydraulic conductivity values less than $10^{-1} \text{ m/s}$ have been measured in the laboratory on the specimens of coal ash, and stabilized fly ash, with differences in hydraulic conductivity values being attributed to the type and amount of fly ash (ASTM class C or F), admixture, and/or stabilizer, among other factors. Prashanth et al. (2001) studied the potential of a pozzolanic coal ash as a hydraulic barrier in landfill liners. They evaluated the shrinkage, compaction, permeability, consolidation and strength characteristics of three different coal ashes. Kaya and Durukan (2004) studied the utilization of bentonite embedded zeolite (BEZ) as a clay liner. Adsorption characteristics, Cation exchange capacity, volumetric shrinkage; compaction characteristics and hydraulic conductivity of the mixtures were investigated. It was also found that the hydraulic conductivity of BEZ with 10% bentonite is less than $1 \times 10^{-9} \text{ m/s}$. Cokca and Yilmaz (2004) studied the feasibility of utilizing coal ash, rubber and bentonite as a low permeability liner material. Hydraulic conductivity, leachate analysis, unconfined compression, split tensile strength, one dimensional consolidation, swell and freeze/thaw cycle tests were performed. It was found that hydraulic conductivity increases as rubber percent increases and bentonite content decreases. Coal ash with up to 10% rubber and 10% bentonite was found to be suitable for construction of a liner.

Considering the requirement of a new landfill barrier material, a barrier material comprising 80% coal ash blended with 20% bentonite (by dry weight) was formulated. The performance of coal-ash based barriers having two different thicknesses (0.6 m and 1.6 m) subjected to continuous differential settlements was evaluated in a 4.5 m radius large beam centrifuge available at IIT Bombay, India. Motor based differential settlement simulator developed at IIT Bombay was used to induce differential settlements with a distortion level up to 0.125 at 40 gravities. During centrifuge testing, the centripetal acceleration is induced on a small-scale model, thereby increasing the unit weight of the soil, so as to make the identical stress-strain behaviour of the soil in the model and prototype. Thus, the centrifuge modelling technique can be adopted to assess the response of coal-ash barriers to continuous differential settlements simulated in a centrifuge.

2 CENTRIFUGE MODEL TESTS ON COAL-ASH BASED BARRIERS

2.1 Development of coal-ash based barrier

Coal ash

The coal ash used in the present work was collected from an ash pond dam in Kahalgaon thermal power plant in the Bihar state of India and is classified as ASTM Class F coal ash according to (Sridharan et al., 2000). It has an average particle size of 0.09 mm, coefficient of uniformity of 32.5, and coefficient of curvature of 0.931 and is classified as ML according to Unified Soil Classification System. The coefficient of permeability of coal ash was found to be $1.6 \times 10^{-7} \text{ m/s}$.

Bentonite

The sodium based bentonite used in the model tests were obtained from a company in the State of Gujarat of India. The X-Ray diffraction spectra shows that it is predominantly a Montmorrillonite with Maghemite, Hematite, Antase, Calcite and Kaoline traces and chemical composition of bentonite determined by X-ray Fluorescence Spectroscopy, which also confirms the presence of Sodium based Montmorrillonite. The clay content in the Bentonite was found to be 86%, as per the Methylene Test. The Specific Gravity of the bentonite was found to be 2.94. The liquid limit and the plasticity index are 395 and 353 respectively.

Properties of Bentonite blended coal ash

Considering the need for ensuring the permeability less than $1 \times 10^{-7} \text{ m/s}$, several of blends of coal ash and bentonite were tried. Coal Ash content varied from 90% to 80%. The coal ash content signifies the percentage of dry weight of coal ash with respect to total dry weight of combined mixture. In this paper, results of 80% coal ash blended with 20% bentonite...
(by dry weight) were reported. Bentonite blended coal ash was found to have a liquid limit of 81% and plasticity index of 36%. The maximum dry unit and optimum moisture content (according to standard Proctor compaction) are 13.74 kN/m$^3$ and 20.94% respectively and the bentonite blended coal ash is classified as CH according to Unified Soil Classification system. The swell potential of the bentonite blended coal ash was found to be 10% under a normal stress of 25 kPa and the coefficient of permeability determined by performing falling head tests in an oedometer in the laboratory was found to be $1 \times 10^{-9}$ m/s. The falling head permeability test was conducted after subjecting bentonite blended coal ash sample for swelling for about 7 days under a normal stress of 25 kPa and then falling head permeability tests were carried-out over a period of 7 days. This was carried-out considering the presence of bentonite in bentonite blended coal ash and the presence of normal stress in the form of overburden in the cover of the order of 25 kPa.

**Model test package**

A strong box having internal dimensions of 720 mm in length, 450 mm in width and 440 mm in height was used in the present study. A transparent Perspex glass sheet of 50mm thickness placed towards the front side of the container enabled to view the model during flight. The Motor based differential settlement simulator developed at IIT Bombay was used in the present study (Rajesh and Viswanadham, 2010). The MDSS system works on a simple mechanism in which the rotational movement is converted to translational movement. It comprises of a motor, controller, screw jack, central platform, gear trains, connecting shaft and bearings. It has a capability of inducing a maximum central settlement of 25 mm with a distortion level (defined as a central settlement over an influencing length) of 0.125. After placing the MDSS within the strong box, the surface area of the coal ash based barrier is 720 mm in length and 360 mm in breadth and this corresponds to 415 sq. m in the field at 40 gravities. Figure 1 shows the perspective view of the model test package mounted on the swing basket. Details of the model test package are given by Viswanadham(2012). Various accessories like data acquisition system, digital photo camera to view front elevation of the model, illumination arrangement can be noticed. Model preparation commences with the placement of side, rear and central support system within the strong box and provision of non-woven geotextile sheet strips and bentonite paste on all around the sides of the container. A 30 mm thick coarse sand layer followed by 30 mm thick fine sand layer was placed in dry state by raining technique at a relative density of 55%. These layers were introduced to eliminate stress concentration, which may arise due to abrupt discontinuity at hinge locations. These layers are referred herein as sacrificial layers. The sacrificial sand layers are pre-saturated and drained for about 9-10 hours duration in 1g. The coal ash-bentonite mixture was moist-compacted towards wet side its optimum and corresponding dry unit weight. Figure 2 shows the plan view of the various stages of construction of a coal ash-based barrier blended with 20% bentonite. This blend was selected according to Viswanadham (2012). In order to avoid the leakage of water between sides of the container and the coal ash-based barrier, water tight seal made out of a thick bentonite paste was applied all along the sides of the soil barrier (Stage 2 and 4). Markers were placed along the surface of the coal ash barrier to measure integral displacements of these markers during various stages of the test. A 20 mm square grid of markers was placed on the model coal ash barrier surface along the zone of maximum curvature, as shown in Fig. 2e. Five Pore Pressure Transducers (PPT) were placed above the prepared coal ash barrier surface for measuring the water breakthrough at the onset of differential settlements. Further, seven LVDTs were placed above the coal ash barrier surface (or on the sand placed for overburden pressure) to measure the deformation profiles at various stages of central settlement (Stage 5 and 6). One digital camera was placed to view right hand portion of front elevation of the model and one CCD camera was placed to view portion of top surface of the coal ash barrier to monitor the performance during the centrifuge test.
In the present study, thickness of the coal ash-based barrier selected as 0.6m and 1.6m. Since, in the present study, gravity level was fixed as 40g, a 1.6m thick coal ash-based barrier in the prototype scale was modelled as 40mm thick model coal ash-based barrier layer. In majority of landfill sites, thickness of the cover soil and water drainage layer placed above the soil barrier in the cover system ranges from 1m to 1.5m thick. This cover soil can induce an overburden pressure of 25 kPa. In order to observe the effect of overburden on the deformation behaviour of coal-ash based barriers, overburden pressure was maintained as 25 kPa. This was achieved by pluviating dry sand of 27 mm thickness with a dry unit weight of 15 kN/m$^3$ and thereafter it was inundated with water up to 10 mm height above the sand surface. A settlement rate $s_{rm}$ (in model dimensions) of 1 mm/min was maintained for all centrifuge tests performed using MDSS system. The settlement rate may not be realistic when projected to the prototype dimensions, but to some extent represents excessive settlements near the drains in bioreactor landfills, localized depression or collapse of the waste containers, or ground subsidence in waste disposal sites. The projected prototype settlement rates at 40 gravities ($s_{pm}$) is 36mm/day. Figure 3 shows the front elevation of coal ash based barrier during centrifuge test at 40g. When the horizontal distance from centre of the coal ash-based barrier $x$ is zero, the value of settlement is termed as a central settlement $a$ (Fig. 3a) and it is referred herein as maximum central settlement $a_{max}$, if the induced central settlement equals to 25 mm.

The nature of induced deformation in the coal ash-based barrier can be explained using parameters like settlement ratio and distortion level. Settlement ratio, $a/a_{max}$ is defined as the ratio of central settlement $a$ at any stage of deformation to the maximum central settlement $a_{max}$. Distortion level $a/l$, is defined as the ratio of central settlement $a$ to the influence length $l$ within which differential settlements are induced (Fig. 3a). The influence length $l$ is defined herein as a horizontal distance from centre of the soil barrier to a point where induced settlements cease to be negligible. An influence length $l$ equals to 200mm (in model dimensions) from centre of the soil barrier was adopted uniformly in all centrifuge tests. This was fixed based on the measured deformation profiles in number of tests. The MDSS setup can induce a maximum distortion level of 0.125 with a maximum strain value of 5%. Analysis and interpretation of centrifuge model tests are discussed in detail by Viswanadham (2012).

### 2.2 Response of coal ash based barriers to induced distortion

In this paper, an attempt had been made to evaluate the integrity and sealing efficiency of coal-ash based barriers. The settlement ratio and distortion level were evaluated for different gravity levels and overburden pressures. The results showed that the settlement ratio increased with increasing gravity level and overburden pressure, while the distortion level decreased. This indicates that the coal ash-based barriers are effective in preventing excessive settlements and maintaining the integrity of the landfill.
ash based barriers subjected to differential settlements, by varying thickness of Bentonite based Coal-ash based barriers (BCAB). In Model CLG16a1, the thickness of coal ash based barrier is 15 mm (0.6 m at 40g) and it is 40 mm (1.6 m at 40g) for model CLG17. Figures 4a-b show the variation of measured pore water pressure with time after attaining 40g for models CLG16a1 and CLG17. With an increase in thickness from \( d = 0.6 \) m to 1.6 m, a drastic change in variation of pore water pressure with time for model CLG17 can be noted. The presented variation in Fig. 4b indicates that 1.6 m thick BCAB ensures sealing efficiency even after subjecting to distortion level of the order of 0.125 and is not subjected to any leakage with the formation of full-penetration cracking at the zone of maximum curvature.

Figure 5 shows variation of maximum outer fiber strain \( \varepsilon_{o,\text{max}} \) along the top surface of coal ash barriers with \( a/l \) and \( a/a_{\text{max}} \). As can be noted, with an increase in \( a/l \) and \( a/a_{\text{max}} \) an increase in maximum outer fiber strain can be noted. During various stages of central settlements, photographs were captured at 40 gravities through an image acquiring software and were later used for Digital Image Cross-correlation (DIC) to establish deformation profiles of the coal ash-based barriers; and for arriving at strain distribution along the top surface of coal ash barrier (Viswanadham, 2012). The maximum value of strain at the zone of maximum curvature is referred herein as \( \varepsilon_{o,\text{max}} \). Variation of infiltration ratio (IFR) with \( a/l \) and \( a/a_{\text{max}} \) is plotted in Fig. 6.

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Fig. 4 Variation of pore water pressure with time in model dimensions for BCAB.

Fig. 5 Variation of \( \varepsilon_{o,\text{max}} \) with \( a/l \) and \( a/a_{\text{max}} \).

Infiltration ratio, \( IFR \) is defined as the ratio of \( (v_o - v_a) / v_o \); Where, \( v_o \) is volume of water at a particular central settlement and \( v_a \) is the volume of water above the BCAB surface \( a = 0 \) mm at 40g).

Fig. 6 Variation of IFR with \( a/l \) and \( a/a_{\text{max}} \).
Figure 7 shows the status of deformed BCAB at the end of centrifuge tests. As can be noted, with an increase in thickness of BCAB, cracking was observed to extend partially only.

a) d = 0.6 m  
b) d = 1.6 m

Fig. 7 Portion of Top and cross-sectional view of Model BCABs at the end of centrifuge tests.

3 CONCLUSIONS

In this paper, performance of coal ash based barriers subjects to differential settlements in a geocentrifuge. A 0.6 m thick coal ash based barrier with an overburden of 25 kN/m^2 was observed to experience a limiting distortion level of 0.068 and a strain at breakthrough of 0.98%. In comparison, a 1.6 m thick coal ash based barrier was not registered any water breakthrough and noted to sustain large deformations. This centrifuge study demonstrates that coal ash based barriers of an adequate thickness can be used as impervious barriers of landfill cap covers.

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