EVALUATION OF DEFORMATION BEHAVIOUR OF SOIL BARRIER SUBJECTED TO DIFFERENTIAL SETTLEMENTS THROUGH DIGITAL IMAGE ANALYSIS

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ABSTRACT: Landfills are the primary disposal method for hazardous and municipal solid wastes. Soil barrier is being used as an impervious barrier in base and cover systems to safeguard the environment from contamination. One of the predominant failures of soil barrier is cracking due to the occurrence of differential settlement resulting from the decomposition of waste and/or subgrade over which the containment system is laid. The paper deals with the use of a digital image analysis technique for evaluating the deformation behaviour of soil barrier of cover system subjected to differential settlements. In this paper, an attempt has been made to adopt image analysis technique to trace the movement of discrete markers placed on the soil barrier and to arrive at the deformation profiles of the soil barrier at various stages of differential settlements. A digital camera placed on the front side of the model was used to acquire the series of pictures while inducing differential settlement in the high gravity environment. A detailed procedure of image acquisition, image selection, image processing, digitisation, and data generation is presented. In addition, methodology adopted for computing deformation profiles for various settlement stages and strain distribution along the length of the soil barrier was demonstrated using a centrifuge study carried out at IIT Bombay.

1. INTRODUCTION

The development in the area of digital imaging has been rapid during recent years. Due to the advent of digital cameras, CCD (charge couple device) camera, higher pixel size, comfort in the image processing, greater memory capacities of the personnel computer; the need of digital image analysis has arise irrespective of research division starting from medicine to engineering in which geotechnical engineering is no exception. Several researchers successfully used digital image analysis for determining the particle size distribution, deformation characteristics, failure pattern, shear band location, pore structure of geotextile and micro-structural response of soils etc. To assess the actual behaviour of the soil from any physical model tests either through full scale or reduced scale models, the accurate measurements of deformation and strain are essentials. Deformations can be determined from the displacement transducers, however, major limitation of these transducers is, it can sense the displacement only at the point of location hence in order to know the actual deformation, more number of contact type and/or non-contact type transducers have to be used which in most of the cases not feasible. Limitation of this can be overcome using the digital image analysis (DIA) where the deformations are measured using the series of images taken during any physical modelling event at required intervals of time. In order to study the geotechnical event, various researchers used marker based DIA (Viswanadham & Rajesh, 2009) or Particle Image Velocimetry (White et al., 2003). The present study focuses on the marker based DIA. The detailed procedure of image acquisition, image selection, image processing, digitisation and data generation along with methodology adopted for computing deformation profiles and strain distribution of the soil barrier was demonstrated using a centrifuge study carried out at IIT Bombay.

2. MODELLING DIFFERENTIAL SETTLEMENT IN A GEOCENTRIFUGE

The centrifuge modelling technique can be used to study the response of a soil barrier subjected to continuous differential settlements created artificially in the centrifuge because the deformation and the cracking of the clay barrier is highly influenced by the presence of prototype stress conditions. When the centrifuge model is subjected to an inertial acceleration field of \( N \) times of the earth’s gravity, the vertical stress at any depth \( h_m \) will be identical to that in the corresponding prototype at depth \( h_p \) where \( h_p = N h_m \) (where \( N \) is the scale factor or gravity level). Thus, the stress
similarity is achieved at homologous points by accelerating a model of scale $1/N$ to $N$ times the earth’s gravity. The clay barrier is prepared with a mixture of Kaolin and Sand having 4:1 ratio (dry weight) compacted at OMC + 5% and corresponding dry unit weight (14.2 kN/m$^3$). The thickness of the clay barrier chosen for the present study is 1.2 m, with water as an overburden. A custom designed and calibrated Motor based differential settlement simulator (MDSS) setup is used to induce differential settlement in flight. Various sensors used in the present study are the LVDTs and PPTs. Marker based DIA is used to assess the deformation behaviour of the clay barrier subjected to differential settlement. Figure 1 shows the details of the test setup, various soil layers, position of permanent and discrete markers, camera and illuminating arrangement. The details of the test setup and model preparation are extensively described by Rajesh & Viswanadham (2009).

2.1 Centrifuge Facility

The 4.5 m radius beam centrifuge at Indian Institute of Technology Bombay (IIT Bombay) is being used for studying number of problems of importance in geotechnical and geo-environmental engineering. The centrifuge capacity is 250 g-ton with a maximum payload of 2.5 t at 100g and at higher acceleration of 200g the allowable payload is 0.625t. The detailed specifications are discussed in Viswanadham & Rajesh (2009). In the present study, $N$ is chosen as 40.

3. DIGITAL IMAGE ANALYSIS

Often the term image processing and image analysis are used interchangeably. However each has distinct processes. Image processing is a sequence of several operations on a single image or a series of images, leading to a new set of images. In other words, images are manipulated to suppress the unwanted information, extract necessary elements, and improve the quality or readability of the image. Image processing can be done using light and chemical processes in a dark room for images taken on film, on the other hand through computers and appropriate software for the images taken by digital camera (Graham, 2005). Image analysis is a process of image data transformation, leading to some actions, decisions or conclusions. Obviously, any image which needs to be analysed precisely should be appropriately prepared using image processing. An image is a mosaic of very small areas, called pixels, filled with a single grey level or digitally defined colour. Thousands of pixels, touching each other and placed with in a grid provides a realistic, smooth image. The basic principle of DIA is sequential storage and transformation of the pixel nature of computerized images to the matrices of numbers (Wojnar, 1999).

Figure 2 shows a schematic diagram of the image acquisition system and DIA process that is used in National Geotechnical Centrifuge Facility available at Indian Institute of Technology Bombay, India. One digital camera and one CCD camera was mounted on the centrifuge swinging platform to monitor the model during experiments, as shown in Figure 1.

3.1 Image Acquisition

Images are captured from the cameras through on-board PC, via a USB (Universal Serial Bus). The on-board PC fixed at the centre of the beam centrifuge has the camera operating software which holds the complete control on the camera operations. The on-board PC is then linked to a control room PC by Ethernet link via a slip ring stack. The Ethernet link allows transfer rates of up to 100 Megabits per second, which is fast enough for the image acquisition. Digital camera used
in the present study for taking the front elevation of the model during flight is Canon Powershot A400. It has 3.2 megapixel with $2.2 \times$ optical / $3.2 \times$ digital / $7 \times$ combined zoom. It has an extraordinarily fast shutter release with the quick shot function. The camera is mounted on specially designed mounting stand which has been proof tested up to 100 g. A uniform illumination is provide using two 18 W Philips lamp in front of the model and one lamp on top of the model as shown in Figure 1.

3.2 Image Selection and Enhancement

The images are captured using the image acquisition software during centrifuge testing at various central settlement stages from 0 to 1 m in the interval of 0.2 m. Figure 3 shows the typical front elevation of the soil barrier before inducing differential settlement at 40 g. Since the differential settlements are induced symmetrically, only the left side of the model is used for DIA and hence permanent markers (positions are pre-determined) are positioned as boundary of zone of interest. Camera zooming was set in such a way that the four permanent markers are visible in the frame. Since the digital image is a matrix of numbers, with the help of mathematical functions basic image enhancements such as contrast and brightness control, color balance and corrections, image blur and anti-aliasing, dust and scratches removal can be performed. In the present study, all the images are enhanced using Microsoft office picture manager.

3.3 Digitization of Markers

Enhanced images are digitized using a module map edit of GRAM++ software (GRAM++, 2004). The coordinates (global) of the pre-determined permanent markers are used to standardize the image to be digitized. The error involved in digitizing the permanent markers i.e., standardizing the image can be obtained from the GRAM++ software. The snapshot of the error involved for the image is shown in Figure 4. Once the error is within the tolerable limit, digitization of the discrete markers is carried out. The coordinates of the discrete markers are obtained with reference to the global coordinates. The above mentioned process of assigning global coordinates and obtained local coordinates are performed for all the images used for determining the deformation profiles and the strain distribution.

4. ANALYSIS AND TRACKING OF MARKERS

Figure 5 shows the movement of the discrete markers at maximum central settlement of 25 mm (1 m in prototype). The measured co-ordinates of discrete markers in all settlement stages are approximated with an exponential equation of the normal distribution to get the deformation at various stages and strain computations along the longitudinal axis of the soil barrier (Viswanadh & Rajesh, 2009). Figure 6 shows the deformation profile of the soil barrier under various stages of central settlement using LVDTs and DIA. It can be observed that deformation profiles obtained from both the methods are in good agreement.
The computation of the strain along the top fibre of the soil barrier can be arrived using combined bending and elongation method (Viswanadham & Rajesh, 2009). Let \( w(x) \) is the function of deformation profile of the deformed soil barrier; where \( w(x) \) gives the settlement of the deformed barrier at any horizontal distance \( x \). Consider an element of length \( dx \) in the original undeformed state of the barrier. Let the element is subjected to a differential settlement of \( du \) in the vertical direction. Then increase in length due to the settlement difference can be written as,

\[
\Delta x = \sqrt{dx^2 + (du/dx)dx^2} - dx
\]

(Equation 1)

**Elongation strain:** The elongation strain in the deformed soil barrier is due to change in length and it can be computed from \( \Delta x / dx \). By simplifying the Equation [1], the elongation strain or the strain due to change in length \( \varepsilon_t \) can be computed as follows:

\[
\varepsilon_t = \sqrt{1 + \left(w'(x)^2\right)} - 1
\]

(Equation 2)

**Curvature strain:** Curvature strain or bending strain \( \varepsilon_c \) along the top surface of the barrier can be obtained from theory of pure bending as,

\[
\varepsilon_c = R_{of} \kappa(x) d
\]

(Equation 3)

where \( d \) is the thickness of soil barrier

\( \kappa(x) = \text{Curvature at any horizontal distance } X \). It can be obtained by differentiating the settlement contour function \( w(x) \) twice,

\[
\kappa(x) = \frac{w''(x)}{(1 + w'(x)^2)^{\frac{3}{2}}}
\]

with \( w'(x) = 0 \) then \( k(x) = w''(x) \) [4]

\( R_{of} \) = Neutral axis factor (assumed as 0.67)

**Outer fibre strain:** Outer fibre strain along the top surface of the barrier \( \varepsilon_{of} \) is the algebraic summation of elongation strain and curvature strain. It is given by,

\[
\varepsilon_{of} = \varepsilon_t \pm \varepsilon_c
\]

(Equation 5)

Figures 7 to 9 shows the variation of elongation, curvature and outer fiber strain along the horizontal distance from the mid-span of the 1.2 m thick soil barrier respectively for various central settlements. It can be observed that as the central settlement increases, all the strain levels increases and the maximum strain were observed to be occurred near the zone of maximum curvature.

5. CONCLUSIONS

In the present study, the use of marker based digital image analysis has been demonstrated by performing a centrifuge test at 40 gravities. Moreover, the methodology adopted to perform marker based DIA were presented in detail. A 1.2 m
thick clay barrier is subjected to the differential settlement using a custom designed MDSS system with central settlement ranging from 0 to 1m in the interval of 0.2 m. The deformation profile and the strain distributions were plotted using the coordinates of the discrete markers at various central settlements; which are obtained by tracking the markers embedded with in the soil barrier. It was found that deformation profile obtained from the DIA and LVDT were found to be in good agreement. From the strain distribution plots, it can be concluded that as the central settlement increases the strain values also increases. The maximum outer fiber strains for all central settlement were obtained at the zone of maximum curvature.

REFERENCES