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Phagocytosis-based camera-in-situ method for pile load testing

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ABSTRACT

This paper reports a novel camera-in-situ methodology to calculate pile settlements through nodal displacements, using a biologically inspired mechanism of phagocytosis to correlate successive images. An *x*–*y* grid is placed on the pile-head and high resolution images are captured through a DSLR camera, remotely. Software is also developed and presented herein which automatically interprets the captured-images into nodal pixel indices and subsequently into actual nodal displacements. The software adopts a methodology analogous to that of a monocyte searching for bacteria in its vicinity, to search each node in successive images. Moreover, conventional linear-variable-differential-transformer-based methodology is adopted to validate the results of the presented technique. It is found that the presented approach is in conformance with the guidelines set forth by ASTM standard for static pile load testing, in addition to the advantages of being completely autonomous and free of any embedded instrumentation on the pile.

1. Introduction

Pile load testing is a vital step in finalizing the foundation design [1]. The testing is classified in terms of static or dynamic loading schemes and executed using standardized procedures. ASTM D1143 [2] is used as a guideline to test the piles under axial–compressive loads, within static loading paradigm. Section 7 of D1143 specifies different apparatus to measure the displacements during these tests. Possible approaches for pile load testing include linear variable differential transformers (LVDTs), extensometers and/or dial gages.

This research stems from a need to develop a *reusable*, *non-contact* and *independent* measurement technique that does not require the issues associated with contact type displacement indicators which require special structural considerations during designing, casting and testing phases. Expensive instrumentation is employed to log the displacement data during long hours of the tests if manual reading from the dial gages is to be avoided. Moreover, some of the procedures require embedded instrumentation into the piles like extensometers and inclinometers whereas others require elaborate setup procedures like that of LVDTs.

In this paper, a vision-based approach is designed using off-the-shelf DSLR camera, ensuring that the testing is performed without any *contact* with the pile or its instrumentation and without any *string-attached* during designing and casting of test-piles. The setup can be dismantled and re-employed later on other test sites. The methodology was validated through field test, amidst harsh site-conditions and against conventional LVDT-based technique. Moreover, the results are found to be conforming to the accuracy requirements of ASTM standard (D1143) [2] in recording the displacements. The proposed technique presented herein, therefore, can serve as a cost-effective, third-party confirmatory test.

2. Background

A review of literature indicates that the vision-based techniques to measure displacements in structural and geotechnical domains are few, costly and limited to controlled lab environments. One such technique is particle image velocimetry (PIV) that uses correlation function to relate velocity and displacement between successive images [3]. White et al. [4] used PIV and digital photogrammetry on soil deformation in a calibration chamber to measure planar deformations. They, however, did not take into account the camera resolution, lens specifications and field-of-view sizing in their measurements that may alter the claimed precision. Similar techniques are developed by Zhang et al. [5], Olaszek [6] and Wahbeh et al. [7]. Zhang et al. target the microscopic image analysis for soil particles. Olaszek's approach, on the other hand, demands an offline processing of the acquired data, whereas Wahbeh et al. require a specially manufactured optical setup to conduct the experimentation. The aforementioned techniques consider soil deformation as a primary problem, instead of pile-settlement. The major limitation of using a PIV-based technique to record pile-settlements

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arises from a fact that a typical test is a long procedure [8] in which continuous image-acquisition would be costly. Therefore, snapshots are not taken continuously, making it difficult to correlate nodal displacements in *successive-sparse-images*.

A technique that aims to incorporate the continual image-acquisition is developed by Lee & Shinozuka [9] using a camcorder to measure bridge displacements. A similar approach by Nayyerloo et al. [10] employs line-scan cameras to measure seismic structural displacements. Both of these approaches are limited to dynamic scenarios and the issue of correlating the nodal displacements in sparse images is not addressed. Moreover, the latter technique is not an off-the-shelf option and requires a video-grabber to continuously record the line-scans.

Authors, therefore, have designed a new approach to find respective nodes in successive-sparse images by using the biological inspiration from *chemotaxis* and *phagocytosis* [11,12]. The biological working of amonocyte, searching a bacterium in its vicinity on the basis of secreted/diffused chemoattractants [13], is replicated to correlate sparse images by searching the previous nodes in the vicinity of current nodes. The underlying biological phenomenon is described in the subsequent subsections.

2.1. Chemotaxis

The biological immune system (BIS) can be subdivided into innate and adaptive immunities. The innate part of immune system works as a first line of defense and comprises various cells that recognize and consequently respond to invading pathogens in a generic manner, but does not confer long-lasting immunity. The major function of innate immunity is to call different immune cells to the sites of the infection once a *non-self* is identified, present antigens to the adaptive part of the immune system and remove general pathogens and dead cells [14]. Each of these functions requires a mode of movement called *chemotaxis* [15,16]. Moreover, the bacteria secrete chemicals that diffuse with time. Similarly, the cytokines, released by immune-cells, also add to the combined value of chemoattractants and chemorepellents. Monocytes, a type of immune cells, move randomly but with a bias towards the gradient of combined chemoattractant–chemorepellent presence. The movement is, therefore, termed as a biased random walk [17].

2.2. Phagocytosis

Once a monocyte finds chemoattractant molecules during its biased-random motion, it may move towards the bacterium and engulf it. This phenomenon is called phagocytosis [11]. It should be noted that chemoattractant molecules diffuse in terms of their concentration. The mathematical abstractions from these biological phenomena are detailed in Section 3.2.

The presented methodology is alternatively termed as *C*amera-*i*n-*S*itu *P*ile *L*oad *T*esting (CiSPLoT). The testing of this methodology was done on a mega project in Pakistan, as a third-party confirmatory test. Subsequent sections present the methodology and experimentation details. The acquired results are subsequently discussed along with the conclusions.

3. Methodology

The methodology has two distinct components: one describes the CiSPLoT technique including its algorithm and underlying mathematics whereas the other details a step-by-step procedure to set up the system.

3.1. The algorithm: CiSPLoT technique

It is desired that CiSPLoT technique is designed to accurately track the nodes on a pile-head alongside the time and load data, following the immunological interpretations. Image acquisition and subsequent analysis is at the core of our system. The software, developed in MATLAB, is capable of recording high resolution images along with the time and load stamps. The software then transforms the RGB images to gray-scale data, which is followed by automatic adjustment of image intensity levels through histogram equalization. Nodes on the acquired image are automatically traced through boundary-tracing function. It is followed by centroid calculation for all the nodes. The underlying algorithm is detailed below:

The CiSPLoT Algorithm

Input: ping with load & time stamp

Output: Nodal displacements

- **While** ¬ tF **do**
  - **if** ping | scheduled-snap
    - open camera port
    - capture image with time & load stamp
    - convert from RGB to gray
    - extract region of interest
    - perform adaptive thresholding
    - detect datum
    - First node detection
    - **While** ¬ all nodes **do**
      - detect next node
      - trace boundary
      - calculate nodal center
      - log nodal data
    - **end**
    - augment worksheet
    - map nodal data as chemoattractant molecules
    - plot
  - **else**
    - repeat
  - **end**
  - **if** ∃ previous nodal data
    - diffuse chemoattractants
    - walk a biased phagocyte walk
  - **end**
- **end**

Results

During the development of this approach, some nodes were misclassified and erroneously correlated. This demanded a correlation function but the conventional approach of PIV proved to be computationally heavy for online processing of 12 Mp image size, in addition to the limitations of PIV-based techniques in handling *sparse* images. In order to resolve the issue, the immunity-based mechanism to trace the nodal displacement in successive images was developed. In this approach, the first image, acquired before the loading cycle, is registered as the reference for subsequent images. The nodes in successive images are correlated following a mechanism by which a monocyte searches its environment for bacteria. In this technique, for a two-image sequence the nodes in the first image are tagged as bacteria, whereas the nodes in the second image are declared as monocytes that search through the space of the first image. The distance traveled by each monocyte is registered as the nodal displacement thus eliminating the classification errors. Moreover, each node secretes chemoattractant molecules that diffuse with the passage of time. This establishes a *moving* window