Title

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Using Cameras for Measuring Displacements in Model Tests

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ABSTRACT

The use of contact-based sensors (such as linear potentiometers) in model tests for measuring displacements can result in measurement errors due to the interference of sensor movement (vibrations, slippage, and hinging) with the target's response. Advancements in image processing techniques and the availability of reasonably priced high-speed and high-resolution cameras now provide a way to measure displacements without contacting the target surface. This paper describes the first combined use of high-speed cameras and image analysis software to measure the 3D movement of the model in a centrifuge test at the Center for Geotechnical Modeling at UC Davis. It also describes a new relatively cheap non-contact method of measuring settlements of multiple targets in centrifuge tests using only one laser and one camera by performing image analysis of the movement of laser lines projected on the target's surfaces.

Keywords: Displacement sensors, non-contact sensors, image analysis, line lasers, physical modeling

1 INTRODUCTION

Contact-based sensors such as linear potentiometers (LPs) are commonly used to record relative displacements between the sensor's body and the probe attached to a test object in model tests. The benefits of these sensors include long measuring distances, insensitivity to the target material, and a low cost. However, the sensor's finite mass, the limited stiffness and vibrations of the support beam, the clamping mechanism, and the slippage and hinging of the sensor body can severely affect the object's response and lead to measurement errors (Fiegel and Kutter 1994; Kutter and Balakrishnan 1998). Moreover, the requirement for a mounting rack and support beams to hold the sensors often obstructs the view and makes a significant area of the model's surface unavailable for performing other essential investigations. With the availability of reasonably priced high-speed and high-resolution cameras, analysis of recorded images using Digital Image Correlation (IDICS 2018) can be used to obtain displacements without contacting the target's surface.

This paper describes the first combined use of new high-speed cameras and an image analysis software to measure the 3D movement of the model in a centrifuge test at the Center for Geotechnical Modeling (CGM) at the University of California Davis (UC Davis). The paper also describes a new and relatively cheap non-contact method for measuring settlements of multiple targets using only one laser and camera by performing image analysis of laser lines projected on the target's surfaces.

2 MEASURING DISPLACEMENTS USING 3D STEREOPHOTOGRAMMETRY

2.1 Methodology

Snapshots taken from multiple (two or more) cameras viewing the same dynamic event from different angles can be processed to measure the 3D displacements of multiple targets placed on the model. Required steps in the order of implementation include: planning the target locations; preparation of the target surface; designing, producing, and positioning the target markers; mounting and positioning the cameras; providing appropriate lightning; recording and synchronizing the videos; calibrating the cameras for lens distortion; determining the camera location and orientation; and finally using image processing to obtain 3D movements. Sinha et al. (2021a) describe these steps in detail.

2.2 Centrifuge Test Description

Sinha et al. (2021a) used the Photron High-Speed Camera System FASTCAM MH6 (https://photron.com/fastcam-mh6/) and TEMA Classic 3D (https://www.imagesystems.se/tema) image analysis software for measuring 3D movements of the model in a dynamic centrifuge model test (SKS03) [Fig 1.]. The high-speed camera system could record videos up to 10,000 frames per second (fps) with a maximum resolution of up to 1920 x 1440 pixels (only applicable for fps less than 1000). The image analysis software offered a library of tracking algorithms to track multiple targets simultaneously and obtain their 3D movements.

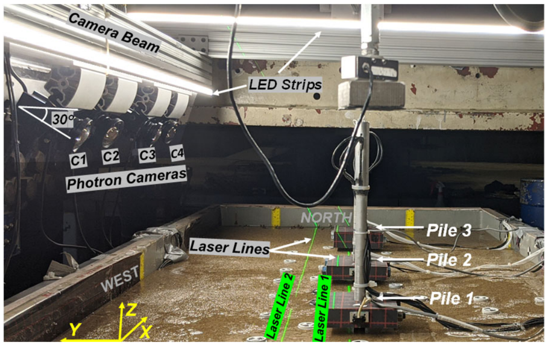

Fig. 1. View of centrifuge model test SKS03 (Sinha et al. 2021c).

The SKS03 centrifuge model studied liquefaction-induced downdrag on axially loaded piles. It consisted of three identical model piles (numbered as pile 1, pile 2, and pile 3) of outer diameter 15.9 mm in an interbedded soil deposit with liquefiable layers. The piles had their tip embedded at the same depth but were loaded differently with a small, medium, and large head load for piles 1, 2, and 3, respectively. The plan view of the model had dimensions of 1651 mm in the shaking (north-south) direction and 787 mm in the transverse (east-west) direction [Fig. 1]. Two pairs of high-speed cameras, identified as North Pair (C1 and C2) and South Pair (C3 and C4), were mounted at an inclination angle of 30 degrees [Fig 1.] to monitor movements in the north (piles 1 and 2) and south (piles 2 and 3) sections of the model [Fig 2.]. The cameras' recording frame rate, resolution, and shutter speed were set to 1600 Hz, 1280 x 800 pixels, and 1/4000 sec, respectively. The camera beam and the camera holder system were designed modularly to mount the camera anywhere over the model and orient it in any direction. The modular design helped adjust and calibrate the camera's position for optimum view angles to the piles. Multiple target markers were placed throughout the model: on the soil surface, the piles' head mass, the model container, and the centrifuge bucket. Figure 2 shows the placed target markers and the view of the model as recorded from the North Camera Pair (C1 and C2). The model was shaken with multiple earthquake motions, and videos were recorded.

2.3 Results

Processing video recordings provided the 3D movement of target markers relative to the cameras. Measurement of the movement of the center section measured independently from the North and South Pair cameras was found identical, verifying the cameras' calibration parameters and the processing of images. The orientation of the model's coordinate system was chosen with the x-axis in the shaking direction, the y-axis in the transverse direction, and the z-axis in the vertical (settlement) direction [Fig. 1 and 2]. Figure 3 shows the 3D movement of pile 2 and a soil marker nearby (S3-3) for the largest shaking event. As expected, the results showed most of the pile settlement during shaking and tiny settlement during reconsolidation. On the other hand, the soil settled mostly during reconsolidation. Measurements show that the soil and pile moved in the shaking (x-) direction and had almost negligible movement in the transverse y-direction. The obtained movements had a precision of 0.15 mm with some noise likely due to the camera beam's vibration, lighting variability, and reflections from moving targets.

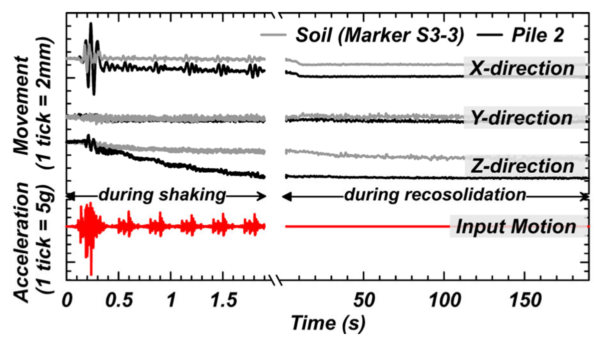

Fig. 3. 3D movement of pile 2 and soil nearby (marker S3-3) during shaking event EQM5.

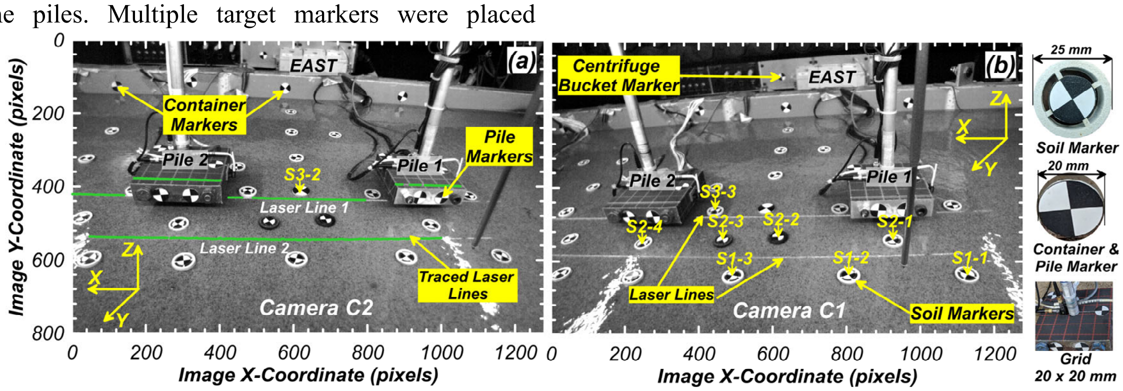

Fig. 2. The north section of the model with placed target markers as viewed from the North Pair camera (a) C1 and (b) C2.

Settlements obtained at target markers provided information on the spatial variability of surface settlement. Figure 4 shows contours of surface settlement for a subsection of the container captured by the cameras for shaking event EQM_5 obtained at t = 200 seconds. The contours show large settlements around the model's center compared to its boundaries. The initial leveled surface of sand layers in the curved g-field of centrifuge resulted in more settlement at the model's center than at the boundaries.

It was also feasible to differentiate the movements obtained from the image analysis to get a reasonable estimate of accelerations of the targets. Figure 5 compares the acceleration of piles obtained from double differentiation of displacement to direct measurements from the accelerometer. Accelerations obtained from image analysis reasonably agreed with measurements from accelerometers. [Fig. 1.]. The camera-based results could likely be improved by reducing the vibration of the camera support camera beams.

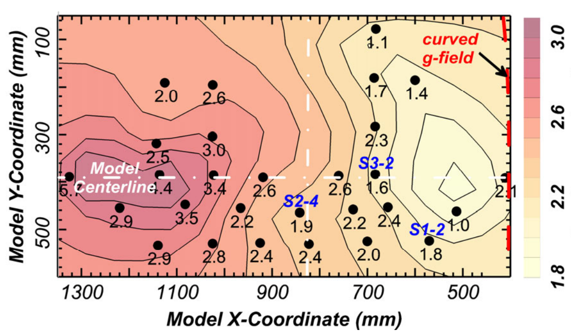

Fig. 4. Contours of surface settlement for shaking event EQM_5 at t = 200 seconds obtained from settlements measured at soil target markers (shown as dots).

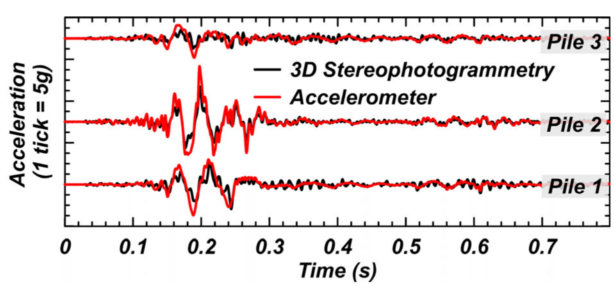

Fig. 5. Comparison of acceleration in piles obtained from 3D stereophotogrammetry with measurements from accelerometers for shaking event EQM_5.

3 MEASURING SETTLEMENT USING A LASER LINE AND A CAMERA

3D stereophotogrammetry is a very effective and state-of-the-art method in obtaining temporal and spatial 3D movements. However, implementation can be expensive in terms of the required number of cameras, expertise, and the processing time to analyze the images and obtain settlements. A new non-contact method was developed using image analysis of laser lines projected on the target surface to obtain temporal and spatial settlement measurements (Sinha et al. 2021b) [Fig. 6]. The new method is cost-efficient, has simpler and faster image processing, and produces temporal and spatial measurements with high accuracy.

3.1 Methodology

The concept behind using cameras and line lasers to measure settlement is shown in Fig. 6. The laser projects a plane of light at an angle (θ) from the horizontal, making a line on the surface. A camera with a light ray angle (ϕ) records the apparent horizontal movement (Δu_c) of the laser line as the surface settles (Δv). The actual horizontal movement (Δu) and the settlement (Δv) of the laser line are estimated as:

$$\Delta u_c = \Delta px / f_{px,mm} \quad (1)$$

$$\Delta u = \Delta u_c \frac{cos\alpha - sin\alpha\ tan\phi}{1 + tan\theta\ tan\phi} \quad (2)$$

$$\Delta v = \Delta u (tan\theta + tan\alpha) \quad (3)$$

where α is the slope of the settled surface and $f_{px,mm}$ is the camera calibration factor representing the number of pixels (px) per unit millimeter of the physical measurement of a real-world object in the image.

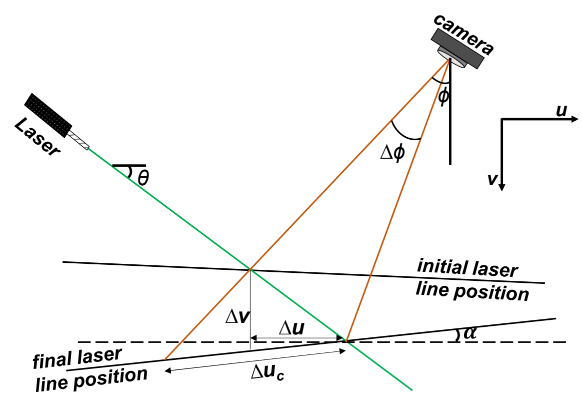

Fig. 6. Schematic diagram showing the movement of laser lines for laser angle θ, camera ray angle ϕ, and settled surface slope α.

3.2 Centrifuge Test Description

The new method was incorporated in the SKS03 centrifuge test [Fig. 2]. The model was instrumented with two lasers (Laser 1 and 2), producing laser lines 1 and 2 on the soil surface and the piles with laser angles 62º and 65º, respectively [Fig. 2, Fig. 3]. The lasers used were 532nm 50mW green light line lasers costing about $60 USD. Laser line 1 was projected close to the model's centerline monitoring the settlement of piles and the soil between them. Laser line 2 monitored soil settlement towards the west side of the model's centerline [Fig. 2, Fig. 3].

3.3 Results

The new method was used to process the recordings of laser lines 1 and 2 from Camera C2 to obtain settlements in soil and piles. The sequence of steps was: lens calibration of camera to remove distortions from recordings and obtain calibration parameter $f_{px,mm}$; the processing of recorded images to track laser lines movement in pixels; obtaining laser angle (θ), camera ray angle (ϕ), and slope angle (α); and finally using equations 1-3 to obtain settlement. Sinha et al. (2021b) describe the procedures in detail. Figure 2(a) shows the traced laser lines in the image coordinate system (in px) on the recorded frame from Camera C2.

Soil and pile settlements obtained from the new method were compared to measurements from 3D stereophotogrammetry. Figure 7 compares the time history of soil (at target marker S3-2) and pile 2 settlement for shaking event EQM_5, obtained from the processing laser line 1 with parameters ($f_{px,mm}$=1.04, θ=62°, ϕ=-54°, and α=0°) and ($f_{px,mm}$=1.15, θ=62°, ϕ=-56°, and α=0°), respectively. Figure 8 compares the soil settlement profile obtained at t = 200 seconds obtained from the processing of laser line 2 with parameters ($f_{px,mm}$=1.2, θ=65°, ϕ=-46°, and α=0°). The temporal and spatial settlements obtained using the new method show a good agreement with the 3D stereophotogrammetry measurements. The variability in the surface settlement [Fig. 4] resulted in some differences in the obtained settlement profile with the measurements at soil markers [Fig. 8]. Table 1 compares the total pile settlement (at the end of centrifuge test) with 3D stereophotogrammetry and hand measurements performed using a depth gage of precision of 0.1 mm. Settlements obtained from image analysis matched quite well with physical measurements.

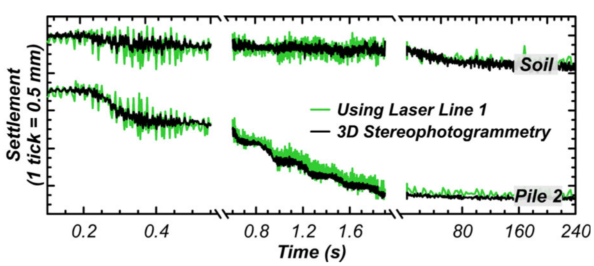

Fig. 7. Comparison of soil (at marker S3-2) and pile 2 settlement obtained from the processing of laser line 1 with measurements from 3D stereophotogrammetry.

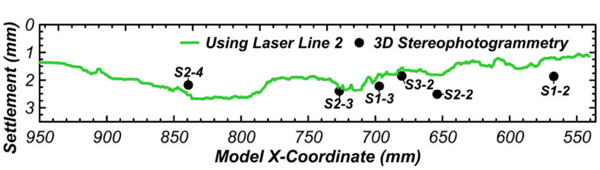

Fig. 8. Comparison of soil settlement profile (at t = 200 seconds during the shaking event EQM_5) along laser line 2 with settlement measured at soil markers from 3D stereophotogrammetry.

Table 1. Comparison of total pile settlement obtained from 3D stereophotogrammetry, laser lines, and depth gage.

Pile	Depth Gage (mm)	3D Stereophotogrammetry (mm)	Using Laser Lines (mm)
Pile 1	7.15	7.13	7.15
Pile 2	7	7.11	7.01
Pile 3	24.25	24.44	24.17

4 SUMMARY AND CONCLUSIONS

This paper described two methods that use cameras for measuring movements in a physical model test. Using cameras offers contactless sensing, diminishes the risk of disturbing the targets, and reduces sensor requirements, making the instrumentation relatively easier, cleaner, cheaper, and leaving more open space for performing other valuable investigations. The first method used 3D stereo-photogrammetry on recordings from multiple high-speed cameras to measure the 3D movement of the model in a dynamic centrifuge test. Results showed that the method effectively obtains displacements and accelerations of targets and spatial variability of movements across the entire model. The second method used a newly developed protocol of tracking projected laser lines to measure settlement. The new method provided spatially and temporally continuous settlements along the laser lines and was validated against 3D stereophotogrammetry. With a single laser and a camera, the new method could be used to measure the settlements of multiple targets, thus reducing the cost and the number of sensors required in the model.

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