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ABSTRACT

Snapshots recorded from multiple cameras viewing the same dynamic event from different angles can be processed and used for the dynamic tracking of 3D displacements of multiple targets placed on the model. This report describes the first combined use of new high-speed Photron cameras and the TEMA Classic 3D software at the Center for Geotechnical Modeling (CGM) at University of California, Davis (UCD). The cameras and their mounting, as well as the target markers, lighting, camera calibration, and camera triggering are described, followed by a discussion on the software options selected for the analysis of videos recorded for a centrifuge model test conducted on the 9 m-radius centrifuge. The results presented show that this method is effective and reliable in obtaining the positions, displacements, velocities, and accelerations of the targets. Recommendations are made for improvements in future applications.

Obtaining the 3D displacements of targets requires multiple cameras to take snapshots (images) of the target from different view angles and a software to perform the image analysis. The Photron High Speed Camera system available at CGM UCD is equipped with six MH6 monochromatic cameras that can record videos up to 10,000 frame per second and with a maximum resolution up to 1920 $\times$ 1400 pixels (only applicable for frame rates less than 1000 fps). Multiple trigger methods are available to trigger the cameras to start recording. The ResDAQ software at the CGM was modified to synchronize the Photron's image acquisition system synchronized with the DAQ system. Triggers (CAMERA$^{\text{Trigger}}$ and SNAPSHOT$^{\text{Trigger}}$) were deployed within the shaker controller to ensure the image acquisition and DAQ coincided with the dynamic shaking experiment. The CAMERA$^{\text{Trigger}}$ triggers the Photron image acquisition system to start saving recordings at the beginning of the shaking, i.e., when the motion file is sent to the shaker to control the shaking of the servo-hydraulic shaking table. The SNAPSHOT$^{\text{Trigger}}$ system enables taking snapshots at a variable rate which is especially useful in a dynamic test when images are needed to be taken at a fast rate during shaking, and slower rate during reconsolidation. The TEMA CLASSIC 3D software offers a library of tracking algorithms (correlation, quadrant, virtual points, center of gravity, etc.) that can be used to process images and track multiple targets simultaneously to obtain their 3D position. Depending upon the plane of motion and number of cameras used, it can obtain the 2D as well as the 3D motion of the object.

Using cameras and image analysis to obtain 3D movements of the model comprises several steps. These steps in order of implementation include: planning the marker locations, preparation of model surface, designing and producing the markers, positioning the markers, mounting the cameras, providing appropriate lightning, recording, and synchronizing videos, calibrating the cameras for lens distortion, determining the camera location and orientation, and finally using image processing to obtain 3D movements. Placing well-designed camera target markers at key locations makes it easier for TEMA to track them in the recorded images. A larger size target marker should be used for distant objects (away from the camera). Target markers should be placed on moving parts of the model (such as soil, pile, model container, and the centrifuge bucket) to enable calculation of their relative motion. The material used to fabricate the markers should not produce glare in the videos taken. Having proper lighting is key, especially at high frame rates. Sufficient light, uniform light, and no reflections are desired. At least two camera views must

overlap for each target of interest such that the recorded images can be later processed to obtain its 3D position. The camera pairs should be mounted on a stiff beam, properly positioned, and focused to monitor the important parts of the model surveyed with target markers. When displacements are important in the direction of the view angle of the camera, the cameras should be moved apart to increase the stereo angle. It is further advised to take practice videos using the actual lighting, frame rate, and shutter speed to confirm the image quality and the field of view. This report outlines and describes all the steps in detail through an example implementation on a centrifuge model test featuring a layered liquefiable deposit with three embedded piles (SKS03). Two pairs of high-speed Photron cameras were placed in the model to monitor movements in the north and south section of model. The camera beam, light beams, and camera holder system were designed to be modular to make it easy to position and orient the cameras in any direction within the model. Three strips of LED lights (1000 lumens/foot) produced sufficient lighting to run the cameras at 1600 fps and a 4000 Hz shutter speed. Quadrant target markers and square grid markers were designed and placed throughout the model (on the soil surface, the piles, the container, and the centrifuge bucket). The model was shaken with multiple earthquake motions and videos of the model with target markers were recorded.

The snapshots recorded during and post shaking were processed in TEMA to obtain the 3D dynamic position of target markers. Soil and pile movements were obtained relative to the container by subtracting the average movement of the container top ring from their absolute movements. Movements obtained in the center section of the model independently from the north pair and the south pair cameras were identical. The obtained movements had a precision of 0.15 mm with smaller noise likely due to beam vibration, lighting variability, reflections from reflection from moving targets. Pile settlements obtained from the image analyses matched with the hand measurements taken using a depth gage. It was also possible to differentiate the marker positions obtained from the image analysis to obtain a reasonable estimate of the accelerations of the objects. The natural frequency of the camera beam (60 Hz) was found to be smaller than the applied shaking (in the order of 100 Hz). The vibration of the camera beam introduced noise in the obtained movements and as such installing the cameras on a stiffer beam would have reduced these vibrations. Results obtained on soil and pile movement showed that this method is effective and reliable in obtaining positions, displacements, velocities, and accelerations of the targets, and thus promising for use in future applications.

The use of cameras makes the model instrumentation relatively easier, cleaner (i.e., no LVDT racks and cables running across the model) and provides more model space for performing other important investigations. It offers contactless sensing, which reduces the potential disturbance of the model. At the same time, the video recordings offer an immense amount of data which can be processed to get 3D displacements at any point within the model. The high-speed Photron cameras and TEMA software are found to be a great addition to the Center for Geotechnical Modeling at the University of California, Davis, towards simplifying the model instrumentation while advancing the sensing capabilities in centrifuge tests, and they overall make an important step towards the future of contactless model instrumentation and monitoring.

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1. INTRODUCTION

Advancements in camera technology, tracking and image processing techniques have offered applications in a wide range of industries (such as automobile, bioengineering, computer vision, remote sensing, etc.) and too at wide scales from micro measuring strains and deformations to large structures measuring their movements. The application of interest in this report is to use cameras for obtaining 3D movements of targets placed on the model during an experiment. Having no physical contact eliminates the concern of changing targets' response and helps in exposing the model surface for performing other important investigations. Obtaining 3D movements require multiple cameras to take snapshots (images) of the targets from different view angles and a software to perform the image analysis. IDICS (2018) 'A Good Practices Guide for Digital Image Correlation' is a good reference for understating basic concepts of Digital Image Correlation (DIC) and photography techniques. This report describes (1) the use of high-speed Photron cameras to enable tracking targets during dynamic centrifuge tests, and (2) the use of the TEMA Classic 3D software for processing recordings to obtain 3D displacements.

2. PHOTRON HIGH SPEED CAMERAS

Photron specializes in providing high-speed digital imaging camera systems. The model available at CGM (at the time of writing the report) was the "FASTCAM MH6" camera system. It included six camera heads and a main unit as shown in Figure 2.1. The cameras were connected with special cables to the main unit and could be operated over a network. The main unit is like a central processing unit (CPU) of the camera system which communicates with all the cameras, triggers the image acquisition, and stores the recordings. Section 2.1 describes the specifications of the camera head and the main unit. Photron also provided one user interface application, the Photron FASTCAM Viewer (PFV), to interact with the cameras and the main unit as well as a metadata reader application, the Photron IRIG Viewer, to read the camera configuration and image properties from the recorded videos. Sections 2.2, Section 2.3, and Section 2.4 discuss their applications in the presented centrifuge test.

2.1 Camera Head and Main Unit

Camera Head

The MH6 cameras are monochromatic cameras which can record videos up to 10,000 frames per second (fps). The maximum resolution offered is 1920 × 1400 pixels, but this resolution was only available below 1,000 fps. The physical pixel size of the CMOS image sensor was 6.6 square microns. The lens attached to the camera was model LM6HC (https://lenses.kowa-usa.com/hcseries/417-lm6hc.html) with a focal length of 6 mm. Being a monochromatic camera, the color depth was 8-bit per pixel. The camera holder mechanism (Figure 2.2) enabled adjusting the vertical angle of the camera between -12.7° to 16.1° and the twist angle between -7.35° to 7.35°.

Main Unit

The main unit is the CPU of the camera system which communicates with all the cameras, allocates memory, and stores the recordings. The main unit had 24 GB of high-speed memory (i.e., RAM) and 512 GB of hard disk (solid-state drive SSD). The recordings took place in RAM and all the cameras shared the memory. Thus, when all six cameras are connected, only 4 GB of memory per camera head was available for recording by each camera. If only one camera is connected, all 24 GB of memory was available for recording. Recording stops automatically when the memory reaches 24 GB. Once the recording is complete, it gets copied from the RAM and is saved in the hard disk. More details (drawings and product specifications) on the camera and main unit can be found in the FASTCAM MH6 Manual. The link to the manual is given below.

- FASTCAM MH6 Manual: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/file/777914324533
- Camera Head Drawings: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/folder/131962535542

Note: Since the recording memory is limited (24 GB when one camera is connected or 4GB/camera when six cameras are connected) and the recording automatically stops when the memory is full, the frame rate, resolution, and duration of recording should be carefully optimized beforehand.

2.2 Photron FASTCAM Viewer

The Photron FASTCAM Viewer (PFV) is the application that provides an interface to communicate and control the functioning of the main unit. The application shows the live view of all the cameras connected and provides options to control the resolution, frames per second, shutter speed, trigger mode, and light settings of the recording. It also has built-in capability to perform lens distortion correction and apply it while saving the recordings. More details on the application and system controls can be found in the corresponding manual. The installation files for the software can be requested from the CGM. The link to the manual is given below:

- PFV4 Manual: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/file/777916346262

Recording an Event

Once all the camera recording options have been selected, the record button (see Figure 2.3) can be pressed to make the system enter the recording ready state. Once the camera is ready the button changes its color from grey to green and reads “Ready” (see Figure 2.3). At this point, the camera is ready to start recording once a trigger signal is made (either through an external trigger or manually by pressing the ready button). When recording begins, the button color changes to orange and reads "Now recording...".

The PFV application offers multiple internal trigger modes to initiate the recordings. Some of the important ones are listed below while more details on the triggers can be found in the PFV manual:

- *Start:* recording starts at the time of trigger input.
- *Center:* records equal number of images right before and after the trigger input is recorded.
- *End:* records images right before the trigger input is recorded.
- *Manual:* the trigger point can be specified manually. Thus, it can take unequal number of snapshots before and after the trigger input is recorded.
- *Random:* the trigger can be activated randomly at any number of times. It only records a given number of images after the trigger has been activated.

The Photron camera system also supports communication by external hardware using the Trigger Input Signal (TTL). This enables the recordings to be triggered externally by the Data Acquisition System (DAQ) and hence to be synchronized with other sensor data collected by the DAQ. This can be particularly useful in centrifuge dynamic model testing where one specimen can have multiple different sensors. The link to the tutorial on external triggers in Photron system is shown below.

- Photron Trigger Tutorial: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/file/777913369134

2.3 External Trigger Modes Used for Dynamic Shaking Experiments at the CGM

Dr. Dan Wilson modified the ResDAQ software at the UC Davis CGM to provide TTL signals to trigger Photron's image acquisition system synchronized with the DAQ system. The triggers were deployed within the shaker controller to ensure the image acquisition and DAQ coincide with the dynamic shaking experiment. There are two external trigger modes available in the modified ResDAQ software. In the remainder of this report, the two external trigger modes are named CAMERA$^{\text{Trigger}}$ and SNAPSHOT$^{\text{Trigger}}$.

CAMERA$^{\text{Trigger}}$

The CAMERA$^{\text{Trigger}}$ triggers the Photron image acquisition system to start saving recordings. It is triggered at the beginning of the shaking, i.e., when the motion file is sent to the shaker to control the shaking of the servo-hydraulic shaking table. The external CAMERA$^{\text{Trigger}}$ mode can be used with any of the "Start", "Center", "End", and "Manual" internal trigger modes available in the PFV software (see Section 2.2). The researcher can use any of the trigger modes depending upon when they want to start saving the recording. To start saving data at the beginning of shaking a start trigger can be used. If the researcher is interested in recording data before the beginning of the shaking, the center trigger or the manual trigger can be used. Figure 2.5 shows the

CAMERA$^{\text{Trigger}}$ being triggered at the beginning of the shaking. To use this external trigger, the instructions below must be followed:

- Open PFV and connect the software to the cameras over internet.
- Set up the recording and trigger options in PFV software. This includes selecting the frame rate, duration, internal trigger modes, etc.
- Press the "Record" button
- When the button changes to "Ready", the CGM staff may initiate the servo-controller shaking sequence as usual.

SNAPSHOT$^{\text{Trigger}}$

The SNAPSHOT$^{\text{Trigger}}$ system allows saving images at a variable rate. This provides researcher a control on the timing when the snapshots are taken and optimizing it to gather image data over a large time during an event while keeping the memory requirements within 24 GB. One application of SNAPSHOT$^{\text{Trigger}}$ is to record images at a fast rate during shaking, and slower rate during reconsolidation.

When triggered, the SNAPSHOT$^{\text{Trigger}}$ generates a specified number of signals to the Photron image acquisition system at fast and slow frames per second (fps) (see Figure 2.4 (a) and Figure 2.5). It can be triggered either internally when CAMERA$^{\text{Trigger}}$ sends a signal to the Photron image acquisition system or externally by manually pressing the "Ready" button in PFV software. The ability of the SNAPSHOT$^{\text{Trigger}}$ to generate multiple trigger signals to the Photron image acquisition system, makes it extremely useful to be used in combination with the internal "Random" trigger mode available in the PFV software to take snapshots by all the connected cameras every time a trigger is sent. Since in the "Random" trigger mode, the timing of the trigger is not known in advance, the *IRIG time stamp* should be enabled to get the exact timing of the individual snapshots. When the *IRIG time stamp* is enabled, the exact timing of the snapshots is stored in the metadata (*.chix XML) file. Once recording is complete, the IRIG time stamp data can be retrieved from the metadata *.chix XML file using the Photron IRIG viewer (see Section 2.4). The SNAPSHOT$^{\text{Trigger}}$ can also be used with any of the other internal modes ("Start", "End", "Manual", and "End") available in the PFV software. However, these trigger modes ("Start", "End", "Manual", and "End") require only the first trigger signal to start saving data.

A LabVIEW program "cameratiming.exe" was developed by Dr. Dan Wilson providing an interface to the options for the external SNAPSHOT$^{\text{Trigger}}$ option. The program is accessible on the CGM student server. The input parameters of the program are shown in Figure 2.4 (a). The fast and slow rate (Hz) defines the frequency of the trigger signals to be generated. The number of slow and fast frames defines the number of trigger signals to be generated at slow or fast frequencies, respectively. Once the input parameters are set and the *OK* button is selected, the program asks the user for whether to use an internal or external trigger (see Figure 2.4 (b)). Selecting the "Trigger" option enables it to get triggered when the CAMERA$^{\text{Trigger}}$ sends a signal to the Photron image acquisition system to start saving recordings. When "No Trigger" is selected, it will get triggered when the user manually presses the "Ready" button in PFV software. It must be noted that to use the "Trigger" option for triggering the SNAPSHOT^{Trigger} signals, the CAMERA^{Trigger} must be also set up.

To use this mode, the instructions below must be followed:

- Open the PFV and connect the software to the cameras over internet.
- Set up the recording and trigger options in PFV software. This includes selecting the frame rate, duration, internal trigger modes, etc.
- Select the internal trigger mode in the PFV software ("Start", "End", "Manual", "End" or "Random").
- Enable IRIG time stamp (Menu → Configuration → I/O → IRIG time stamp). Required especially for the "Random" trigger mode to get exact timing for snapshots. Since for ("Start", "End", "Manual", and "End") trigger modes, the recording FPS is fixed, this step can be skipped.
- Press the "Record" button and wait until it gets "Ready".
- Open the "cameratiming.exe" LabVIEW program. It is accessible on the CGM student server.
    - Fill out the fast rate, number of fast frames, slow rate, and number of slow frames. Press OK. (see Figure 2.4(a))
    - A new dialog box will open with two options: "Trigger" and "No Trigger".
        - Click the "No Trigger" option to trigger the SNAPSHOT^{Trigger} sequence manually by pressing the "Ready" button in the PFV software.
        - Click the "Trigger" option to trigger the SNAPSHOT^{Trigger} automatically when the CAMERATrigger sends a signal to the Photron image acquisition system to start saving recordings.
- Once the trigger option is selected, the cameratiming.exe program continues to run until the "Ready" button is pressed either manually (in "No Trigger" mode) or internally at the beginning of the shaking (in "Trigger" mode).

For the project used to illustrate the procedure in this report, the SNAPSHOT^{Trigger} with the "Trigger" option was used. The internal trigger was set to "Random" in the PFV software. This was done to record high frequency snapshots during shaking and slow frequency snapshots post-shaking. Figure 2.5 shows the SNAPSHOT^{trigger} signals generated from the beginning of the shaking when the CAMERA^{Trigger} sent a signal to the Photron image acquisition system to start saving the images. It should be noted that while ResDAQ starts saving sensor data at time t = 0 s when the servo controller sequence starts (as shown in Figure 2.5), the images start being saved when the Shaking Command Motion File is sent to the servo controller (at time about 4.9 s in Figure 2.5). Images are saved every time the camera controller receives a SNAPSHOT^{Trigger}. The IRIG time stamp data as well as the SNAPSHOT^{Trigger} signal can also be used to obtain the time of each recorded snapshot.

Note: To use either of the above external triggers (CAMERA^{Trigger} or SNAPSHOT^{Trigger}), the TTL cable should connect the external hardware to the main unit. Researchers need to consult Dan Wilson or Anatoliy Ganchenko at CGM on how to make appropriate connections. When using the

SNAPSHOT^{Trigger} mode, the recording frame rate in the PFV software should be set to be higher than the fast frame rate.

2.4 Photron IRIG Viewer

Photron IRIG Viewer (https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/file/777897630823*)* is an application that reads the IRIG time stamp data of the snapshots in the recordings. When the IRIG time stamp is enabled (Menu → Configuration → I/O → IRIG time stamp*)*, the exact timing of each snapshot taken (in microseconds) is recorded. At the end of recording, a **.chix* XML file is produced which stores information about all camera heads, the recording options, and IRIG time stamps. The Photron IRIG Viewer can read the metadata and extract the exact timing when the snapshots were taken. Saving IRIG time stamp data is especially useful to have when the internal trigger mode is set to "Random" or "Random manual" through the PFV software while recording.

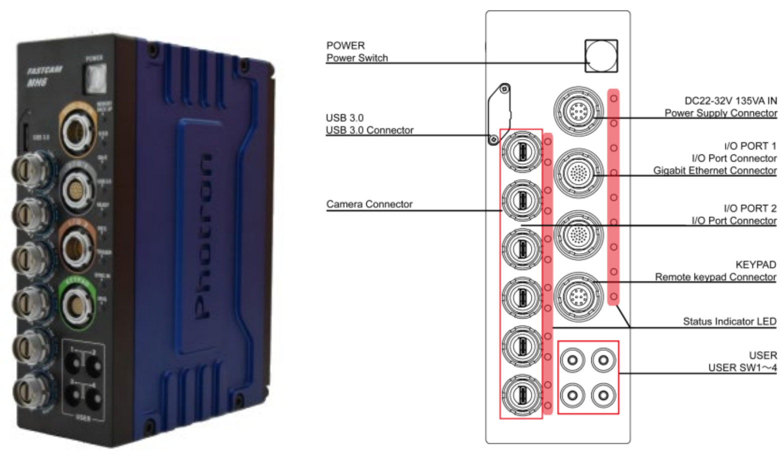
The installation of the software is straightforward. After extracting the zipped file, the software is installed by running the setup.exe file. Using default options, the program will be installed at "C:\Program Files (x86)\CIHX_IRIG". To read IRIG data stamps from recordings, the steps below must be followed (also illustrated in Figure 2.6):

- Open the CHIX_IRIG.exe
- Load the *.*chix* XML produced in the recording. The program will automatically start extracting data.
- Once all data is extracted, the export option will get enabled.
- Click on the export option to save the data in a csv file.

2.5 Technical Support

Technical support on the use of the software can be reached at image@photron.com.

Camera Head



Main UNIT

Figure 2.1. FASTCAM MH6 camera system.

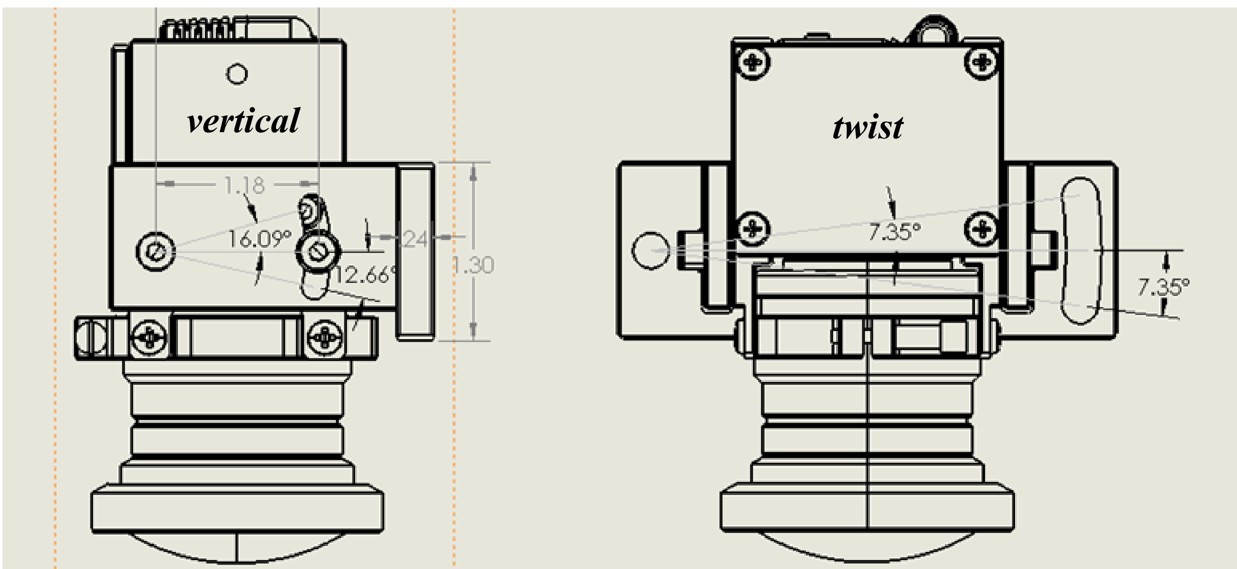
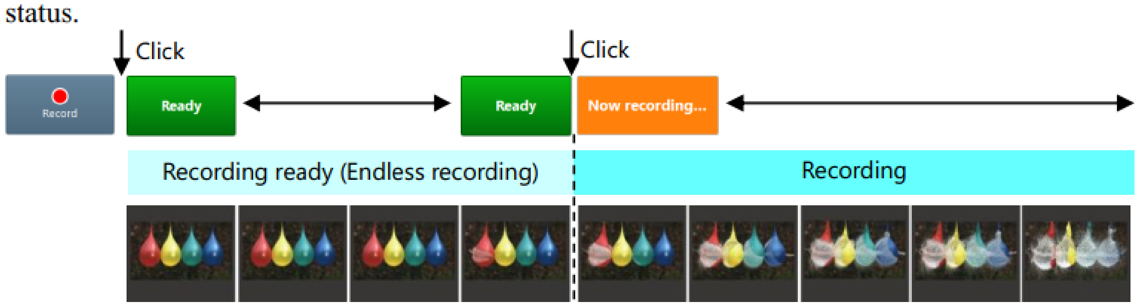
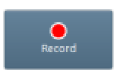
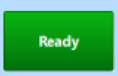
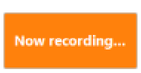


Figure 2.2. Adjustable camera angles using the available camera holder.

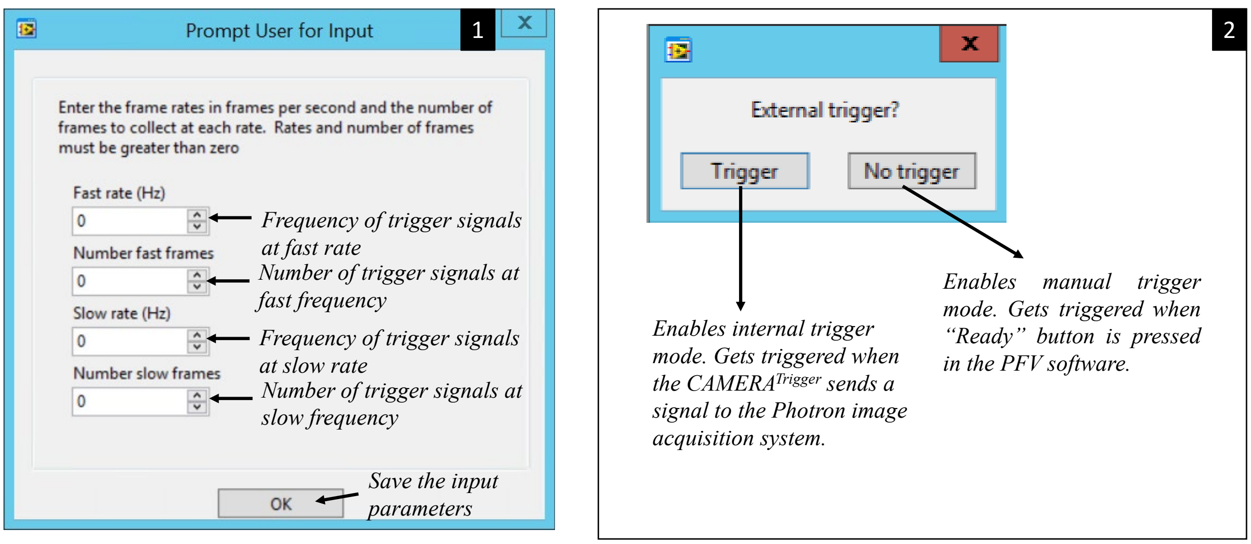
Use the [Record] button on the recording/playback panel to start recording.
The [Record] button name and color change according to the status. The button name indicates the curr status.



Button Used	Description
	Clicking this makes the system enter the recording ready state. (For the trigger mode to make an endless recording, the endless recording is started.)
	Clicking this inputs a trigger. Recording in the specified trigger mode starts at the time when the trigger is input. Trigger is input in the order of IP address when multiple cameras are connected.
	Indicates the recording state after the trigger is input. In this state, nothing happens even if it is clicked.

* In the start mode, random mode, and random reset mode, a trigger signal is input in the [Wait for trigger input]; therefore, the [Endless recording] button is not used.

Figure 2.3. Buttons used for recording (after PFV4 Manual).



(a) Enter the fast and slow frame rates. (b) Choose between "Trigger" and "No Trigger".

Figure 2.4. Steps for using the SNAPSHOT^{Trigger} mode using the "cameratiming.exe" LabVIEW program.

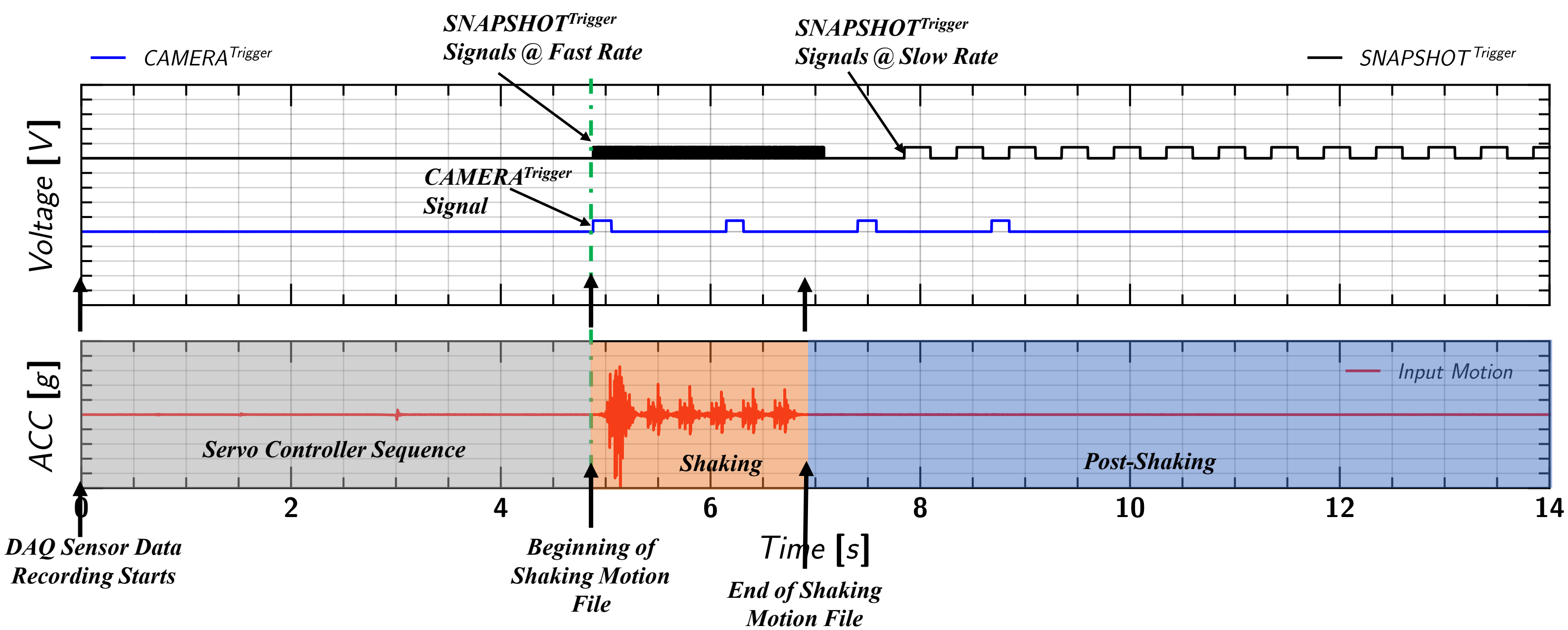
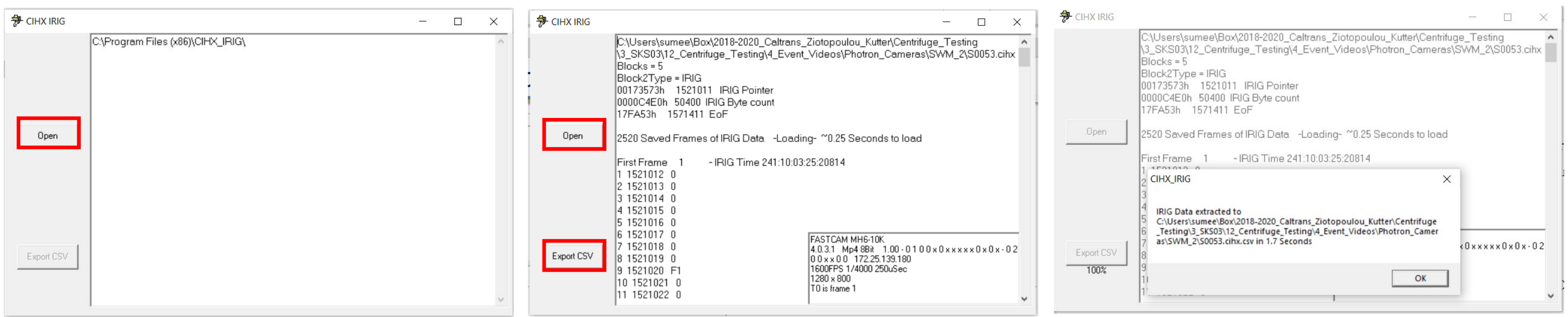


Figure 2.5. Illustration of external trigger modes (CAMERA$^{\text{Trigger}}$ and SNAPSHOT$^{\text{Trigger}}$) used in the centrifuge model test SKS03.



Open CHIX_IRGIG.exe — Load the *.chix* XML file — Export IRIG time stamps to a .csv file

Figure 2.6. Steps for reading the IRIG time stamps from a saved recording.

3. TEMA CLASSIC 3D

TEMA Classic 3D is the software to determine position of markers from the video images recorded. It has a library of tracking algorithms (correlation, quadrant, virtual points, center of gravity, etc.). The software can compute 2D as well as 3D displacement fields depending upon the plane of motion and number of cameras used. If two or more cameras are viewing the object from different view angles, 3D movements of the object can be obtained. If the plane of motion remains constant, a single camera can be used to obtain the 2D motion of the object.

The software used for this project was TEMA CLASSIC 3D. The download link and installation instructions are outlined below. TEMA comes with a dongle, which acts as a license key to the software, and it is required for both the installation and use of TEMA.

3.1 Software and Manual Downloads

At the time of this work, TEMA CLASSIC 3D Version 2020C was used and it can be downloaded for free. Contact the CGM to obtain the latest available links. The link to the manuals is given below:

- TEMA 2020c Manual: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/file/777915607874
- TEMA DIC User's Guide: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/file/777913783383
- TEMA 2020c Release Notes: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/file/777915561495
- TEMA CRASH Tutorial: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/file/777914497072

3.2 Installation Instructions

- Get the dongle from the CGM.
- Plug the dongle into the computer you wish to perform the installation on
- Run the installer for TEMA T2020c-64 (or the latest version of the software)
- When prompted for a configuration code, please enter the 32-digit alphanumeric code obtained from the CGM.
- At some point during the installation, the user is prompted to remove the dongle. At this stage, the dongle should be removed to proceed with the installation process.
- When the installation is complete, insert the dongle back into the computer or laptop, and open TEMA.

3.3 Configuring TEMA

This section describes how to configure TEMA to set the precision and units of measured quantities and autosave rate. Before any analysis is carried out, it is recommended to review the settings below and make appropriate changes:

- To set the units and precision of the measured quantities, select "Tools → Preferences → Precisions and Units". For the present project, standard SI units (m/s^2 for acceleration, m/s for velocity, millimeters for settlements) were used as the default units with 5 as the significant digits set for the precision.
- The autosave interval should be changed to a value smaller than the default. An Autosave interval of 30 seconds was used for the present study. This enabled frequent autosaving of the analysis and thus only 30 seconds of analysis was lost if TEMA crashed. To change the autosave interval select "Tools → Preferences → General" and scroll down to the "Archive" section at the bottom as shown in Figure 3.2.

In the case a crash occurs while preforming an analysis, use the backup file (**.ted.back)* to reopen the analysis file and continue from the last autosave state. Please note that the analysis files in TEMA have a **.ted* extension.

3.4 Technical Support

Technical support on the use of the software can be reached at support@imagesystems.se They are very helpful and willing to help train users of the software.

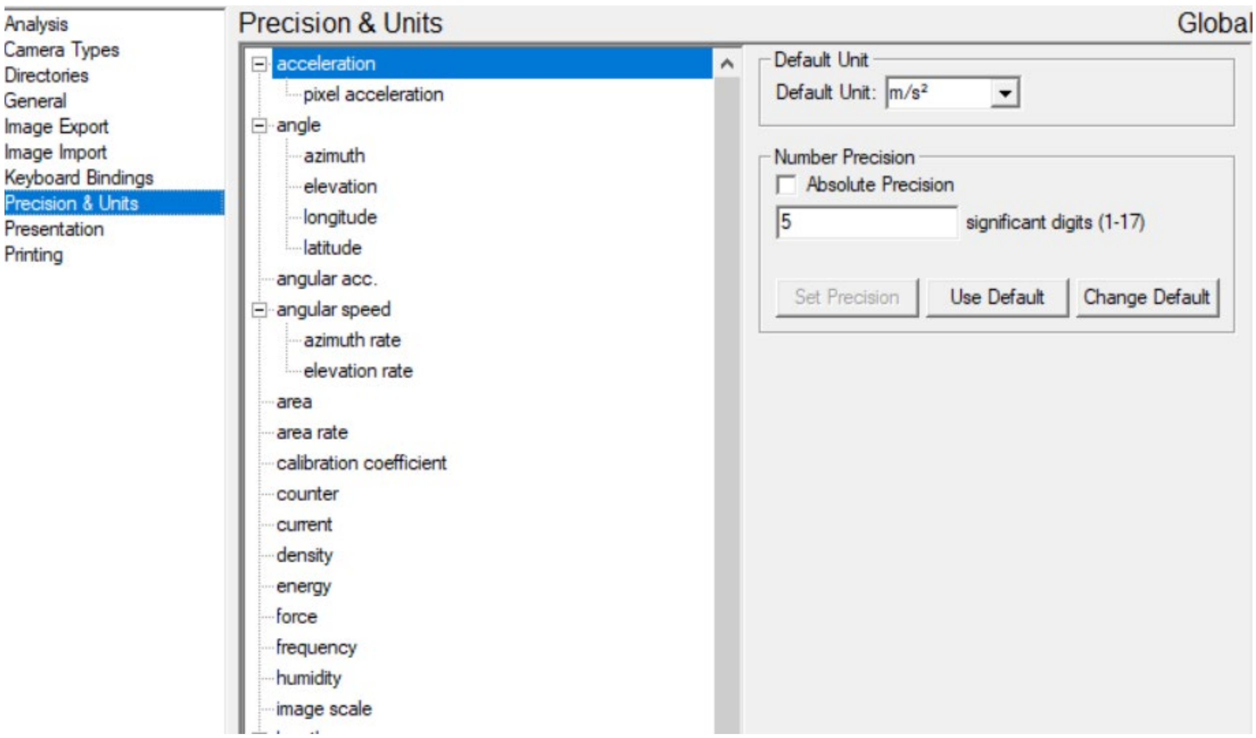


Figure 3.1 View of the TEMA settings window for setting up the units and precision of measurements while performing the image analysis.

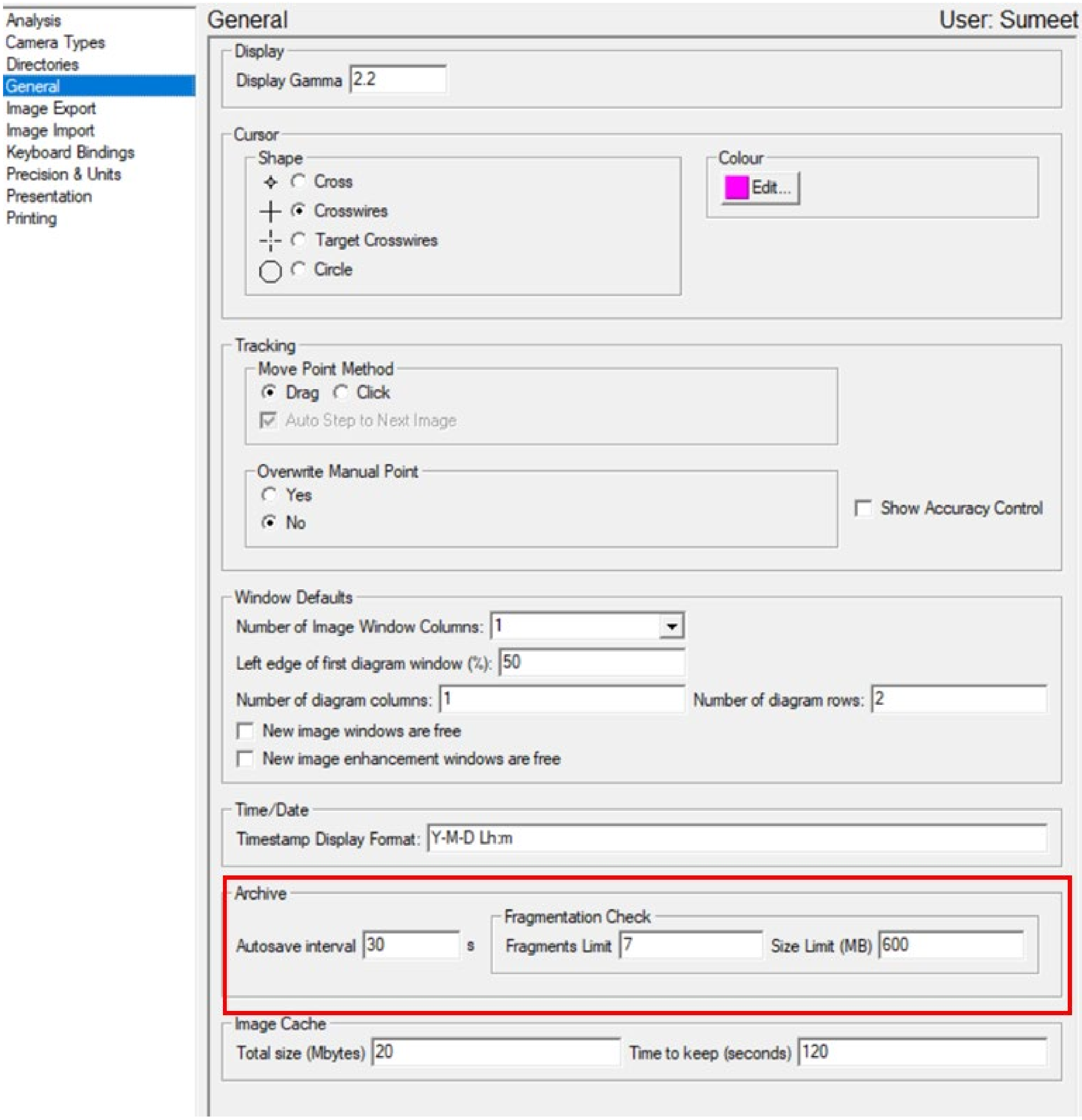


Figure 3.2. View of the TEMA settings window for setting up the autosave rate.

4. USING CAMERAS IN CENTRIFUGE TESTS

Using the Photron cameras and TEMA software for obtaining 3D movements of targets requires numerous steps such as

- preparation of model surface,
- planning the marker locations,
- designing and producing the markers,
- installing markers,
- mounting cameras,
- providing appropriate lightning,
- recording and synchronizing videos,
- calibration of the cameras for lens distortion,
- determining the camera location and orientation, and
- finally using image processing to obtain 3D movements of the model.

The steps implemented for a centrifuge model test featuring a layered liquefiable deposit with three embedded piles (SKS03) are described herein, along with some suggestions for improvements that could be used in future implementations.

The SKS03 centrifuge model test (Sinha et al. 2021) was conducted on the large 9 m-radius centrifuge at the Center for Geotechnical Modeling at the University of California, Davis. The test was performed to study the liquefaction-induced downdrag on axially loaded piles. The test included three identical piles: Pile 1, Pile 2, and Pile 3 installed in the soil. The model was shaken with multiple earthquake motions and the response of the model was recorded. Movements of soil and pile during and post shaking were recorded with four high-speed Photron cameras. Figure 4.1 and Figure 4.2 show the plan and cross-section view of the centrifuge model. The experiment was conducted at a centrifugal acceleration of 40 g. The recorded camera images were analyzed in TEMA to obtain 3D movements of the soil surface and the piles. Section 5 describes the image analysis in TEMA.

4.1 Model Instrumentation

Four high speed Photron cameras were used in the SKS03 test. Figure 4.1 shows the plan view of the model with the four cameras. Camera 1 and Camera 2 were oriented to view Pile 1 and Pile 2, whereas Camera 3 and Camera 4 were oriented to view Pile 2 and Pile 3. Accelerometers were installed on each of the pile masses (see Figure 4.2) to measure horizontal accelerations, vertical accelerations, and rotation. The coordinate system (X, Y, and Z) of the model is shown in green color in Figure 4.1 and Figure 4.2. The origin was located at the bottom of the north-west corner of the container (see Figure 4.2).

Mounting Cameras

The cameras were attached on a T-20/80 2040 2″ x 4″ beam running from the north-south direction of the model. For the sake of convenience, in the rest of the report the corresponding beam is referred to as the Camera Beam and it is shown in Figure 4.3. The Camera Beam rested on two T-20/80 2040 2″ x 4″ East-West Beam 1 and East-West Beam 2 as shown in Figure 4.3 and Figure 4.6. A vertical accelerometer ($\text{CAMERA}^{\text{ACC V}}$) and a horizontal accelerometer ($\text{CAMERA}^{\text{ACC H}}$) were attached to the Camera Beam to measure its vibrations during the test and facilitate later corrections. Figure 4.2 shows the position of the accelerometers placed on the Camera Beam. The modular connection of the Camera Beam to the East-West Beams enabled its easier movement along the Y-direction and thus helped in adjusting and calibrating its position for optimum view angles to the piles. Figure 4.4, Figure 4.5, and Figure 4.6 show the SolidWorks 3D model of the centrifuge bucket showing the configuration of the beams and their location, camera position, and the camera mounting system. The Camera Beam was placed on the east side of the bucket whereas the East-West Beam 1 and East-West Beam 2 were placed on the north and south sides of the centrifuge bucket, respectively. The coordinates of the beams are summarized in Table 4.1.

Note: The 3D SolidWork files of the camera holder mechanisms, Camera Beam and 30-, 45- and 60-degree T-20/80 beams connecting the Photron cameras can be viewed and download from the link accessible at https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/folder/131962803257.

Table 4.1− Coordinates of the Camera Beam and the East-West Beams used in the centrifuge test SKS03.

End	***X (cm)***	***Y (cm)***	***Z (cm)***	***Beam Description***
North End	*-23*	*81.04*	*93.96*	*Camera Beam*
South End	*154.8*	*81.04*	*93.96*	
East End	*1.74*	*81.04*	*104.01*	*East-West Beam 1*
West End	*1.74*	*-63.59*	*104.01*	
East End	*143.2*	*81.04*	*104.01*	*East-West Beam 2*
West End	*143.2*	*-63.59*	*104.01*	

The modular section of the camera mounting system enabled it to slide, rotate, and twist the cameras until the optimal configuration was achieved. The following factors should be considered while positioning the cameras in the model:

- *The cameras should be placed neither too far nor too close to the target of interest.* A camera placed too far from the target leads to reduced resolution (pixels/mm). On the other hand, placing the camera too close reduces the field of view. The cameras should be placed at an appropriate distance such that pairs of cameras include images of targets that need to be tracked while still obtaining the required resolution. The resolution obtained in the present study was 3.5 px/mm near the pile and 1.25 px/mm on the west side of the centrifuge bucket. As explained later, it is feasible to resolve marker positions with subpixel resolution.

- *At least two camera views must overlap for each target of interest such that the recorded images can be later processed to obtain its 3D position.* In the present application, two pairs of cameras were defined; the North Pair which included Camera 1 and Camera 2 and the South Pair which included Camera 3 and Camera 4 (see Figure 4.3 and Figure 4.9). The North pair was responsible for monitoring the North portion of the model container as well as Pile 1 and Pile 2. The South Pair monitored much of the south side of the container as well as Pile 2 and Pile 3. As illustrated in Figure 4.8, it is useful to track markers on the soil surface, on the model container, and on the centrifuge bucket so that soil and pile movements can be computed relative to the model container. When placing cameras and target markers, attention is required to minimize obstructions blocking the views of markers. Anticipated deformations of the model components and instrumentation/cables should also be considered to anticipate movement of obstructions.
- *The camera pairs should be positioned far enough apart to give a significantly different perspective.* According to TEMA, the best results are obtained when the two cameras and the center of the target forms an equilateral triangle (i.e., the stereo angle measures 60 degrees). For a given pair of cameras, the stereo angle will vary depending on the distance of the target from the cameras. Smaller stereo angles lead to better in-plane displacement accuracy, at the cost of increased out-of-plane uncertainty whereas larger stereo angles lead to better out-of-plane displacement accuracy, at the cost of increased in-plane uncertainty. Two important things to be tracked are the motion during shaking which was primarily in the X-direction and the settlement which was in Z-direction. In the test, for the South Pair cameras the stereo angle difference as indicated in Figure 4.6 was about 18 degrees for targets on the pile caps and 7 degrees for the centrifuge bucket markers. Computation of displacements along the viewing direction of the cameras (~ Y-direction) can be improved by increasing the stereo angle by placing the cameras further apart.
- *The focus of the camera should be adjusted such that the important markers are sharply in focus*. Sufficient lighting allows the use of a small aperture and a larger depth of field.
- *Important features of the model should be avoided at the corners of the image*. Skewness and lens distortion can introduce larger errors in the computed measurements, depending on the quality of the lens and the lens calibration/correction.
- *The camera(s) should be mounted to a stiff beam*. Movement/vibrations of the cameras during recording will produce errors in the computed movements. Ideally the cameras would be rigidly clamped to the rigid beams and the beams would in turn be rigidly clamped to the bucket. When the cameras are used during dynamic shaking events, the natural frequencies of the mounting system should be large relative to the predominant frequencies of the dynamic experiment. In the present study, the ground motions were of the order of 100 Hz. The apparent movement of the centrifuge bucket wall markers (see

Figure 4.8) can be monitored to provide an estimate of the error due to the flexibility of the mounting beams and camera brackets. The computed movement of the centrifuge bucket markers is an indication of deformations of the camera mounting. For cameras rigidly mounted to the bucket, the movement of the centrifuge bucket wall relative to the cameras would be zero.

- *The location (X, Y, Z coordinates) and the orientation (roll, pitch, and yaw) of the cameras should also be recorded.* The measured location and orientation of the cameras can be used later to check the orientation and relative position of the cameras computed by the TEMA software during the camera orientation calibration process (see Section 5.1). Table 4.2 summarizes the location and the orientation of the cameras used in this study.

Table 4.2− Position and orientation of the Photron cameras used in the centrifuge test SKS03.

Name	***X (cm)***	***Y (cm)***	***Z (cm)***	***Orientation***
CAMERA 1	*58*	*78.5*	*78.94*	*~33^o clockwise in Z-X plane, Twist (~5^o)*
CAMERA 2	*73*	*78.5*	*79.44*	*~33^o clockwise in Z-X plane, Twist (-~5^o)*
CAMERA 3	*97.5*	*78.5*	*79.2*	*~33^o clockwise in Z-X plane, Twist (~5^o)*
CAMERA 4	*114.6*	*78.5*	*79.24*	*~33^o clockwise in Z-X plane, Twist (-~5^o)*

Lighting

Proper lighting is particularly important at high frame rates. As shutter speed increases, the amount of light entering the camera decreases. Lowering the aperture size to increase the sharpness and the focal depth of field also decreases the amount of light entering the camera. The following factors should be considered while designing the lighting:

- *Too low as well as too high intensity of lighting should be avoided*. Low lighting makes it difficult to distinguish between the model features whereas too much lighting introduces overexposure (white patches) in the recorded images. If the images are too bright, the shutter speed may be increased, and the aperture may be reduced.
- *The shutter speed can be increased to reduce overexposure.* A fast shutter speed has the added benefit of reducing motion blur.
- *The light source and direct reflections of the light source should not be visible in the camera images.* The light source should produce uniform lighting in the areas of interest. Painting shiny metal surfaces flat black is useful to minimize reflections. Water reflections can be minimized by placing the light source near the cameras and not looking straight down. Light sources near the camera lenses will also minimize shadows produced by the test objects.
- *A constant intensity light source should be used.* Some LED light power supplies produce significant flicker that will introduce error in computed displacements and will be distracting when the movies are viewed in slow motion.

- *Practice videos should be taken using the actual lighting, frame rate, and shutter speed to confirm the image quality and the field of view.* Note that reflections can be affected by changes in water level during the experiment and water waves caused by wind and shaking in the experiment.

With the above points in mind, three LED strips were placed, one on the Camera Beam and one on each of the East-West Beams (1 and 2) aiming towards the model. This provided sufficient lighting during the recording. The mounting of the lights and cameras both on the east side of the container, avoided much of the reflections that could have arisen from the water surface. Still, a nonuniformity of light is apparent in Figure 4.8. Figure 4.3 shows the location of the LED light placed in the model. The materials used for placing the LED light sources are summarized below.

- LED track: https://www.superbrightleds.com/moreinfo/aluminum-channels/micro-alu-led-strip-channel-universal/2039/
- Brackets to hold the track: *https://www.superbrightleds.com/moreinfo/housing-accessories/pds-stn-mounting-bracket/897/*
- LED lights (4000K-Natural White, 24V DC): *https://www.flexfireleds.com/industrial-ultra-bright-led-strip-light-bright-white-reel/*

Camera Setup in PFV Software

Figure 4.9 shows the live view of the four cameras as seen from the PFV software. It also shows the recording setup options. The recording frame rate was set to 1600 Hz and the resolution of the camera was set to 1280 px x 800 px. Using the PFV exposure assistance, the shutter speed was adjusted to 4000 Hz which produced minimum glare and sufficient lighting for the cameras. The trigger mode was set to "Random" to achieve longer recording by using the SNAPSHOT$^{\text{Trigger}}$ signals. A high frame rate was used to record movements during shaking and a lower frame rate for movements post-shaking (i.e., reconsolidation). The IRIG time stamp was also enabled to get the exact timing for each snapshot taken during the recording.

4.2 Camera Target Markers

Placing well-designed camera target markers at key locations makes it easier for TEMA to track them in the recorded images. The camera target markers offer two purposes. First, they enable tracking of key locations in the model and second, their initial measured (X, Y, Z) coordinates can be used to calibrate the position and respective orientation between the cameras. Section 5.1 and Section 5.2 describe the use of target markers for camera calibration and analysis in TEMA. Although the TEMA software can track almost any distinct feature in images, a quadrant type target marker is recommended for application in the centrifuge. The following factors should be kept in mind while deciding target markers:

- *The size of the target markers appearing in the recorded image should be large enough.* Although there is no fixed rule on the size of the target marker, a width of 8 pixels in the image has been found to work well. To decide on the marker size, it is advisable to run the TEMA software on them and check if the size is appropriate for tracking the target. It is recommended to use larger quadrant type markers on objects that are further away from the camera.

- *The marker should not have glare while recording the images.* The material of the markers and the direction of their illumination should be appropriately chosen to avoid glare and reflections while recording. For the present study, the markers were printed on a non-glossy sticker paper. TEMA recommends markers from Accurate Tape & Label Co, Inc[1]. These recommended target markers are especially designed to work best for TEMA. Since these target markers are not listed on the seller's website and they have to be ordered over phone.

```
Accurate Tape & Label Co, Inc.
14500 Jib Street, Plymouth, MI 48170
Business Hours: Monday – Friday 8:00 AM – 6:00 PM
Phone: 734-451-7500, Fax: 734-451-1204
```

- *The marker should be properly glued to the target's surface.* When using some of these camera target markers for camera orientation calibration method, the following points should be considered:
    - *The target points for camera orientation calibration process should be placed throughout the camera view spanning across the X, Y, and Z directions.* The orientation calibration target points should not be located on a plane. At least four reference markers (calibration points) are required to perform a static camera orientation calibration in TEMA. The coordinates (X, Y, Z) of the target points can be measured and used in the camera orientation calibration process to determine the camera coordinates and orientation in the model coordinate system.
    - *Even if the positions of the markers are not accurately measured, it is still possible to proceed using a process called "relative camera orientation".* When using relative camera orientation, the software assumes one of the cameras is at (0, 0, 0) (reference camera) and the positions of the other cameras and the target markers are calculated relative to the reference camera. This requires viewing of at least six non-coplanar common markers by the cameras. However, relative camera orientation is less convenient because it will also require subsequent transformation of coordinates to the model (X, Y, Z) coordinate system.

In the present study several camera target markers were placed on the soil, pile, model container and the centrifuge bucket as shown in Figure 4.8 and Figure 4.10. The target markers were created using Adobe Illustrator and then printed on a non-glare waterproof paper. Quadrant markers of size 15 mm (see Appendix A) and 20 mm (see Appendix B) were placed on the soil and pile, respectively. The mass of the piles was covered with a 20 mm × 20 mm square grid (Appendix C). Figure 4.9 shows the camera view with markers placed in the model. The coordinates (X, Y, Z) of the placed camera target markers were also recorded and used later for camera calibration. The design of quadrant markers and square grid markers can be downloaded from the links below.

- Quadrant Markers: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/folder/131963316211

- Square Grid Markers: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/folder/131962659657

Soil Target Markers

In the presented experiment, soil target markers were prepared by gluing a quadrant marker of 15 mm (see Appendix A) at the center of the 3D printed LEAP (Liquefaction Experiments and Analysis Projects) soil surface markers (Kutter B.L. et al. 2020) as shown in Figure 4.11. A gap of 5 mm between the quadrant target marker and the LEAP surface marker was left to allow drainage for dissipation of the excess pore pressures. These markers worked quite well in tracking the soil surface movement. However, the following improvements could be undertaken in the future applications:

- The thickness of the tube can be reduced from 2.5 mm to 0.5 mm. This would decrease the weight of the marker by about 40%.
- The surface marker can be painted with anti-glare black color to increase image contrast near the edge of the quadrant marker.
- The soil inside the surface marker can be colored black to further increase the image contrast near the edges.
- The sides of the tube could be perforated to provide radial drainage for dissipation of the excess pore pressures. This would further decrease the weight of the markers.

The 3D SolidWorks model of the soil surface markers can be downloaded from the following link: https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm/folder/131963325644.

4.3 Recording and Saving Data

Trigger System

In the test, the SNAPSHOT$^{\text{Trigger}}$ mode was used to record frames at 1600 FPS during the shaking and at 2 to 4 FPS post-shaking. This was done in conjunction with the "Random' trigger mode available in the PFV software. Table 4.3 shows the RESDAQ configuration required for setting up the CAMERA$^{\text{Trigger}}$ and the SNAPSHOT$^{\text{Trigger}}$. The TTL cable was connected between the external hardware to the Photron main unit. The IRIG time stamp was also turned on. The system was tested using the LabVIEW program "cameratiming.exe" with "No-Trigger" and "Trigger" modes (Section 2.3) at 1 g before the test to make sure all the connections worked well.

Table 4.3− RESDAQ configuration for the CAMERA$^{\text{Trigger}}$ and the SNAPSHOT$^{\text{Trigger}}$.

Name	***Sensitivity***	***Sensitivity Units***	***Bridge Type***	***Terminal Configuration***	***DAQ Range***	***DAQ Units***	***Excitation Source***
CAMERA$^{\text{Trigger}}$	*1000*	*mv/Volt*	*N/A*	*DIFF*	*10*	*Volts*	*External*
SNAPSHOT$^{\text{Trigger}}$	*1000*	*mv/Volt*	*N/A*	*DIFF*	*10*	*Volts*	*External*

Saving Data

Before spinning up the centrifuge, the PFV software was started, and all the cameras were connected to the internet. All the recording options shown in Figure 4.9 were set. During the dynamic shaking event, the following steps were performed to record the data:

- When the model was ready to be shaken, the “Record” button in the PFV software was pressed to enter in the recording mode.
- When the button in PFV software turned to “Ready”, the LabVIEW program “cameratiming,exe” was opened (on the CGM student server), and the slow and fast frame rates and numbers of frames were set up. Since 4 four cameras were attached to the main unit, 6 GB of memory per camera head was available for each camera. Thus, to maximize the recording duration in the limited memory, the parameters of the SNAPSHOT^{Trigger} were accordingly calculated.
- Table 4.4 shows the trigger parameters used for different shaking events. The number of frames varies due to the varying duration of the shaking events. The table also shows the total memory requirement for saving the snapshots. The number of frames during and post shaking was accordingly chosen to keep the total memory requirement per camera head below the 6 GB limit.
- Following that, the “Trigger” option was selected in the “cameratiming,exe” LabVIEW program. The program started to run waiting for the beginning of shaking event to trigger CAMERA^{Trigger} which would trigger the SNAPSHOT^{Trigger} signal.
- The CGM staff in charge of running the centrifuge was then asked to initiate the shaking sequence.
- When loaded to the shaker, the beginning of the motion file triggered the CAMERA^{Trigger}, which triggered the Photron image acquisition system, which in turn triggered the SNAPSHOT^{Trigger} signals as shown in Figure 2.5. At this state, the button on the PFV software changed to “Recording…”. For each of the SNAPSHOT^{Trigger} signal, a snapshot was recorded.
- When recording was finished, the PFV software automatically moved the recording from the RAM to the hard disk.
- The recordings were then downloaded over the internet and saved to the local storage.

Table 4.4− SNAPSHOT$^{\text{Trigger}}$ parameters used for different shaking events in the centrifuge test SKS03 (Sinha et al. 2021).

Shaking Events	***During Shaking***			***Post Shaking***			***Total Memory Requirement (GB)***
	Fast Frame Rate	***Total Frames***	***Recording Time (s)***	***Slow Frame Rate***	***Total Frames***	***Recording Time (min)***	
EQM_2	*1600*	*2560*	*1.6*	*4*	*3600*	*15*	*5.87*
EQM_3	*1600*	*2560*	*1.6*	*4*	*3600*	*15*	*5.87*
EQM_4	*1600*	*3250*	*2.031*	*2*	*2412*	*20.1*	*5.40*
EQM_5	*1600*	*3250*	*2.031*	*2*	*2412*	*20.1*	*5.40*

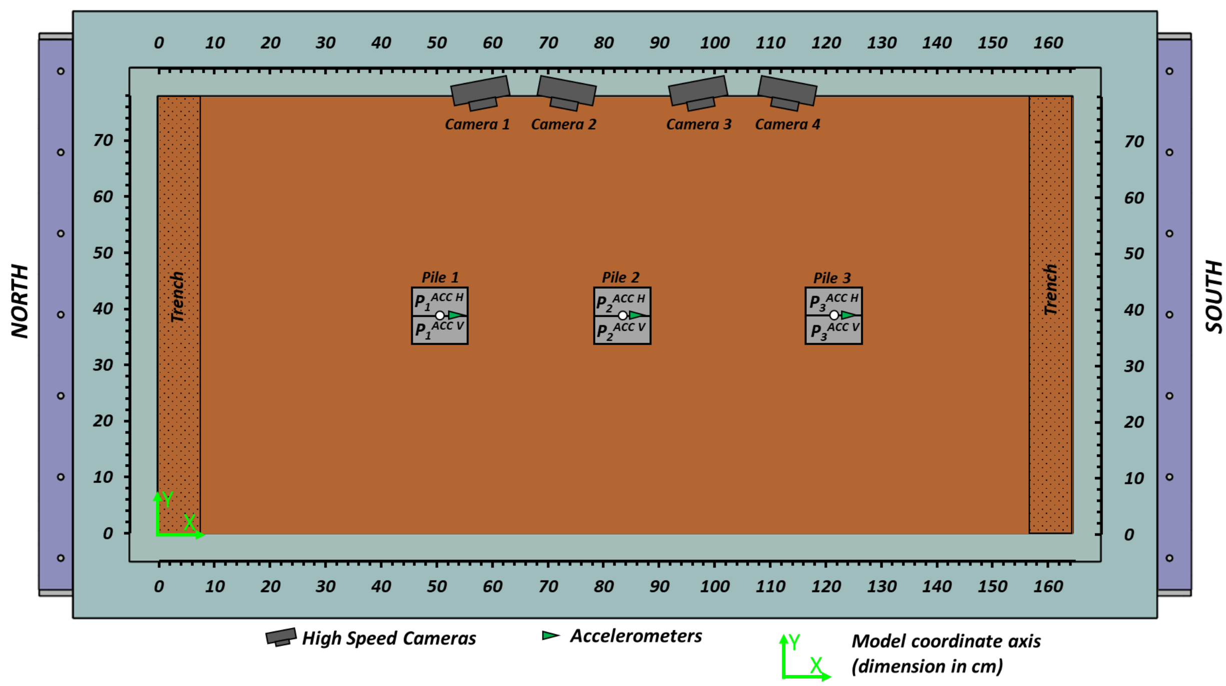


Figure 4.1. Centrifuge model test SKS03: Model plan view (dimensions in cm).

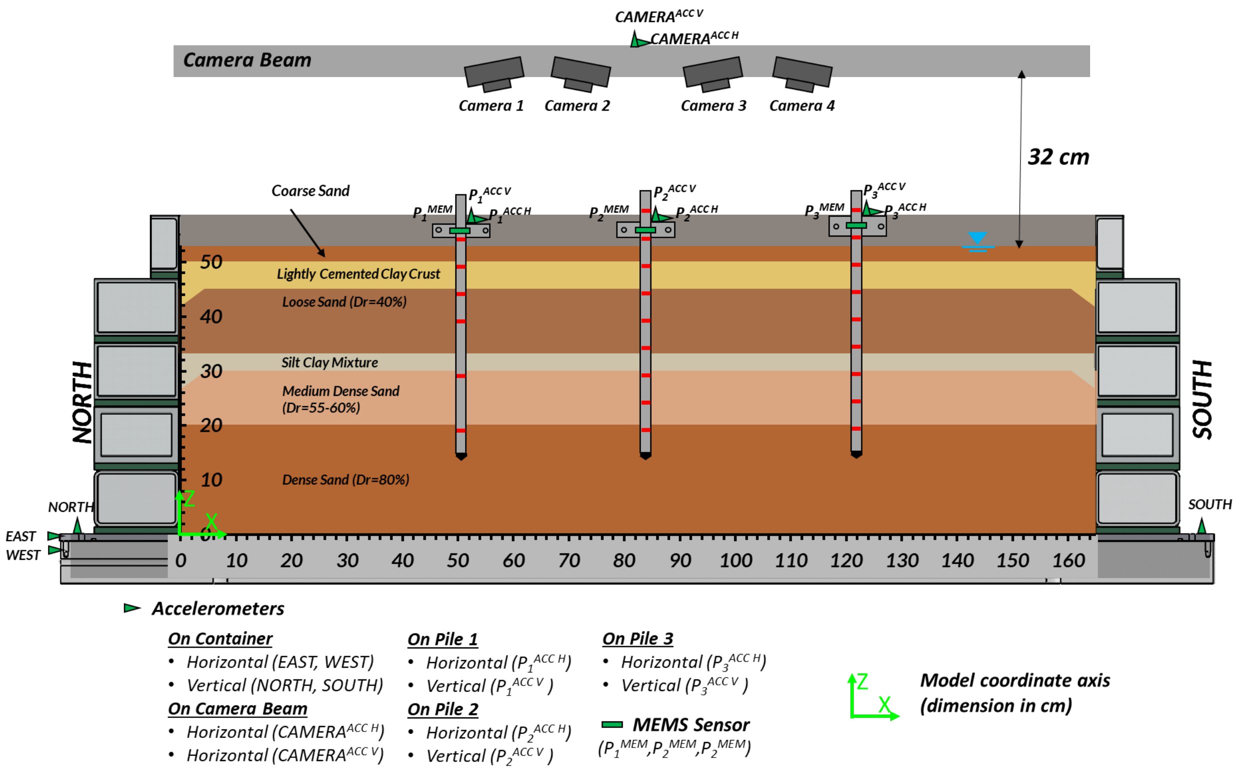


Figure 4.2. Centrifuge model test SKS03: Model cross-section view (dimensions in cm).

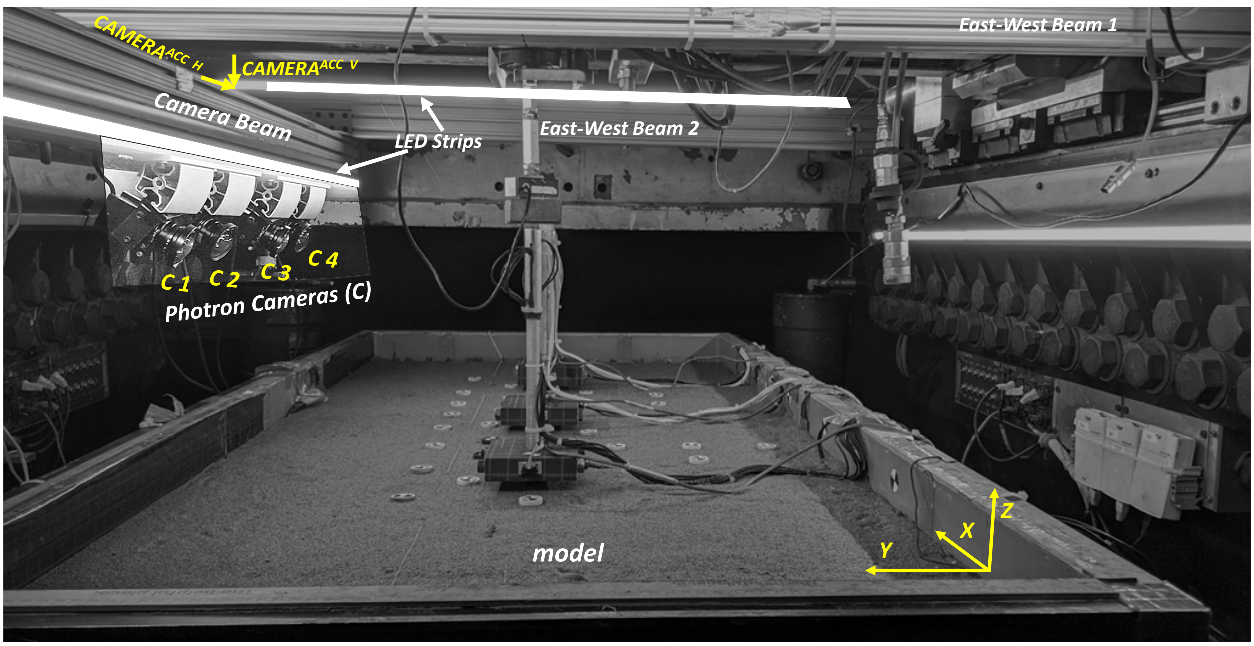


Figure 4.3. View of the completed model from North showing the four Photron cameras mounted on the camera beam.

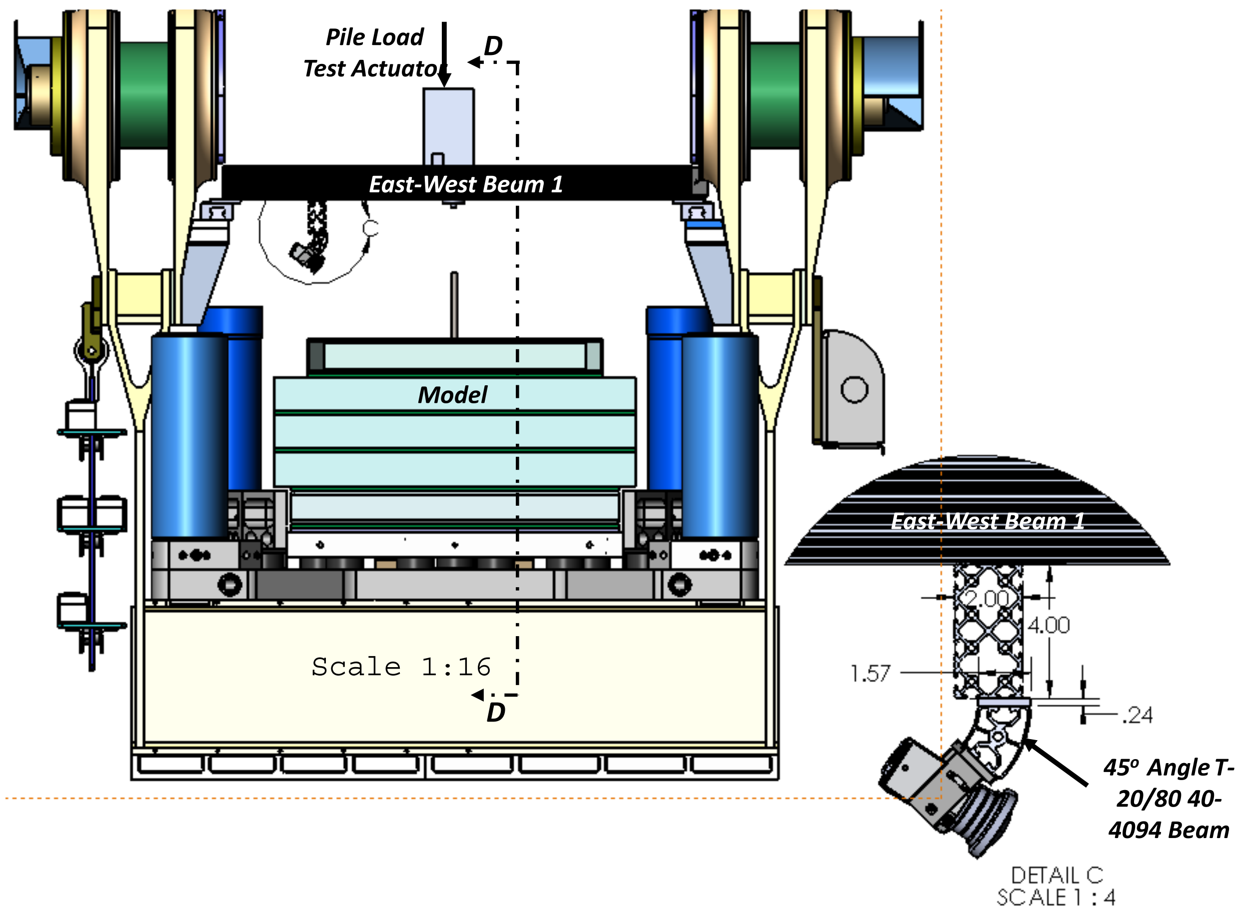


Figure 4.4. SolidWorks drawing showing the camera position and the camera mounting system (dimensions in inches).

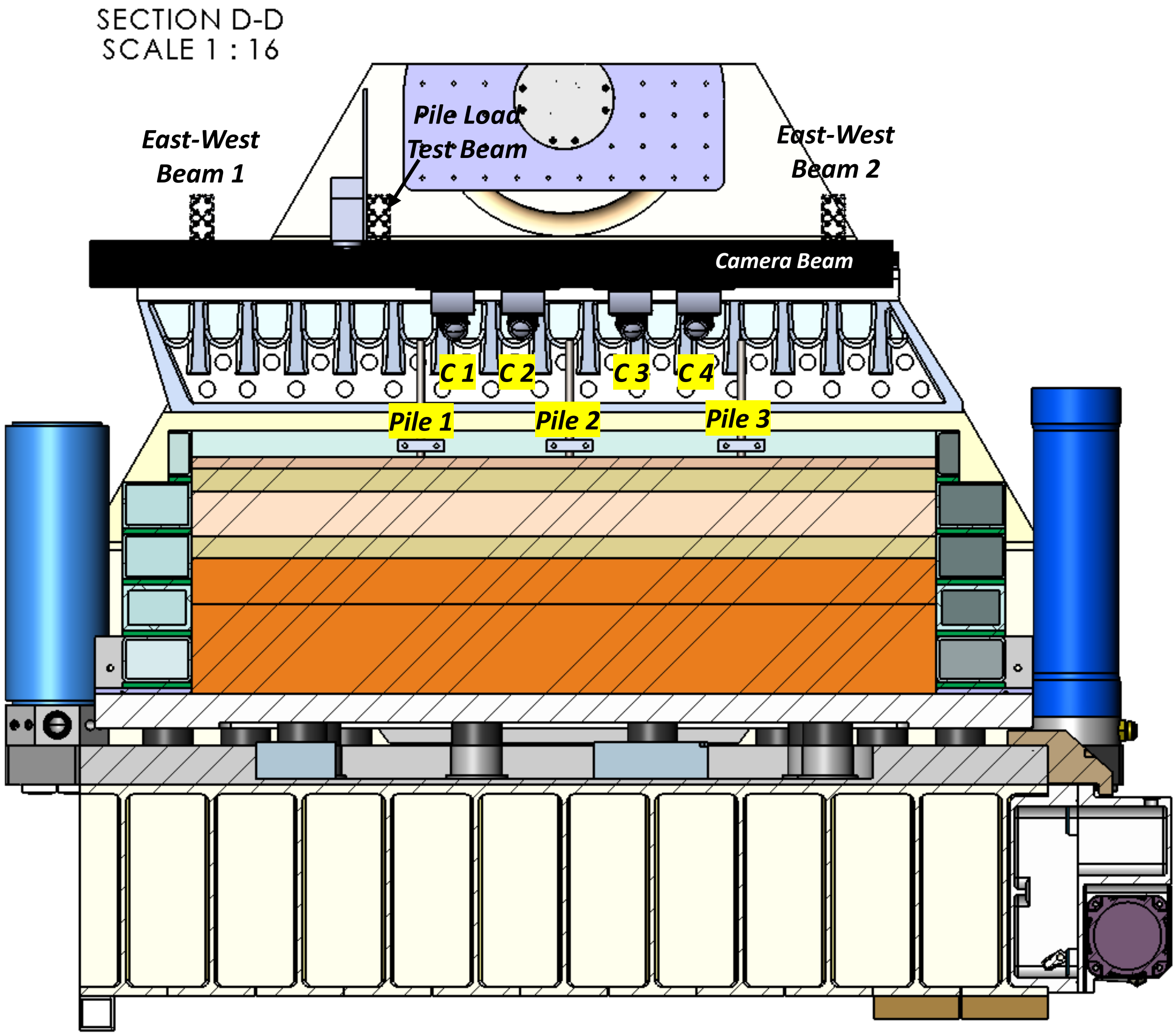


Figure 4.5. Cross-section view (at Section D-D in Figure 4.4) of the model container placed on the centrifuge bucket.

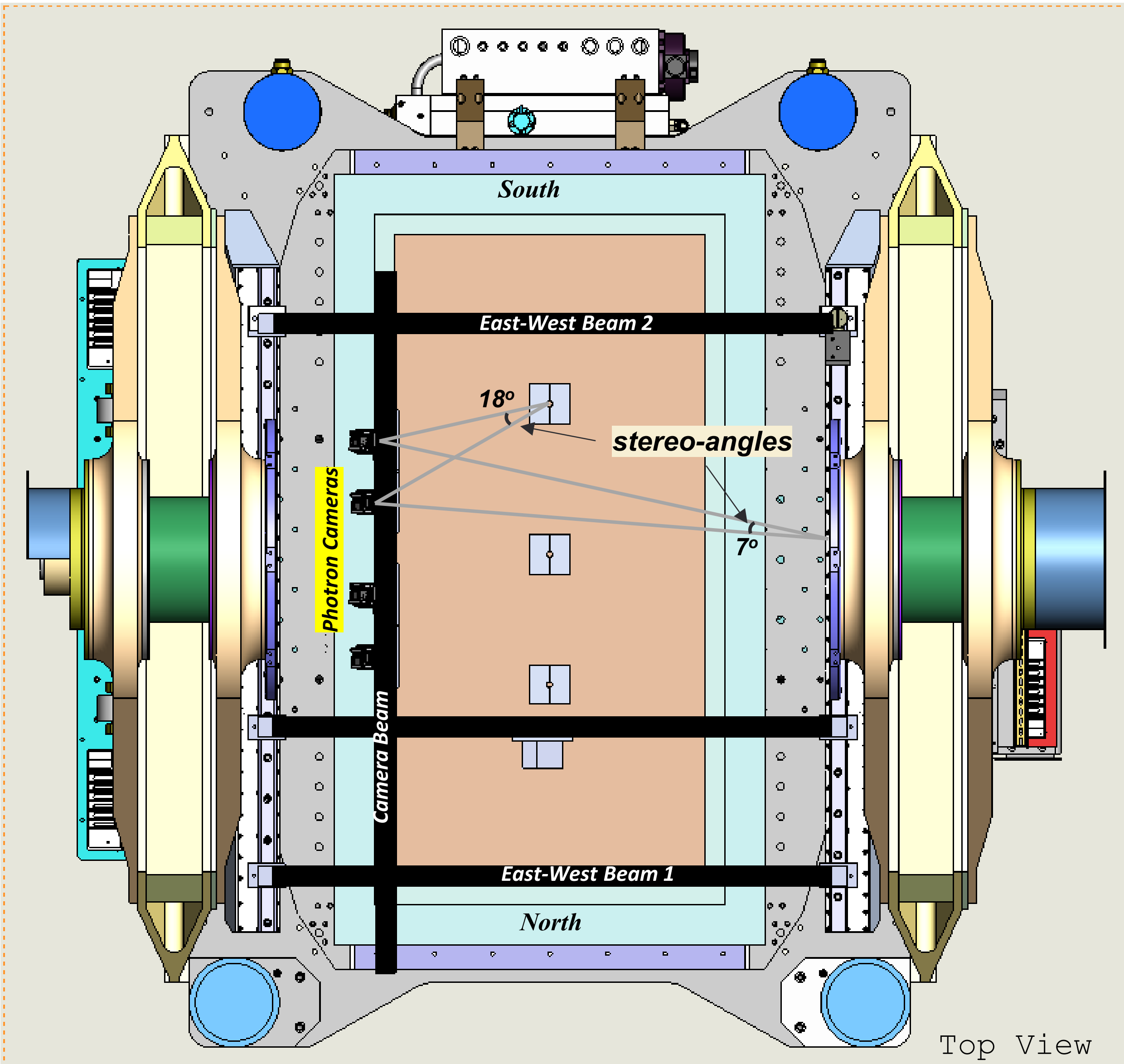


Figure 4.6. Plan view of the model container with the centrifuge bucket showing the locations of the Camera Beam, the East-West Beams, and the Photron cameras.

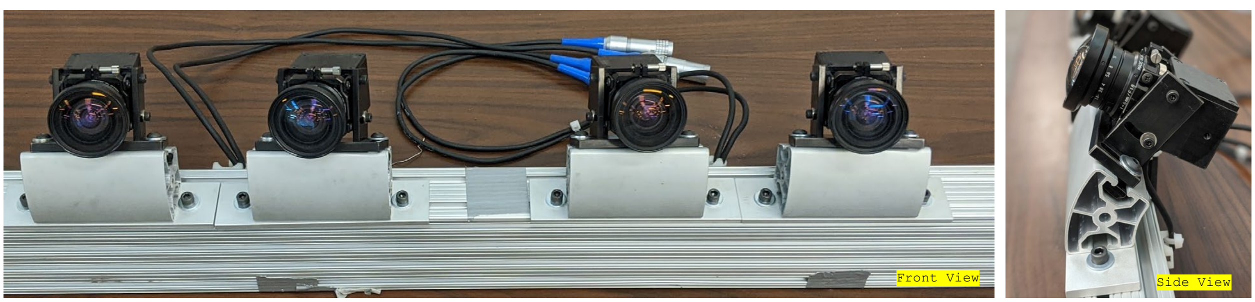


Figure 4.7. Front and side view of the four Photron cameras connected on the Camera Beam.

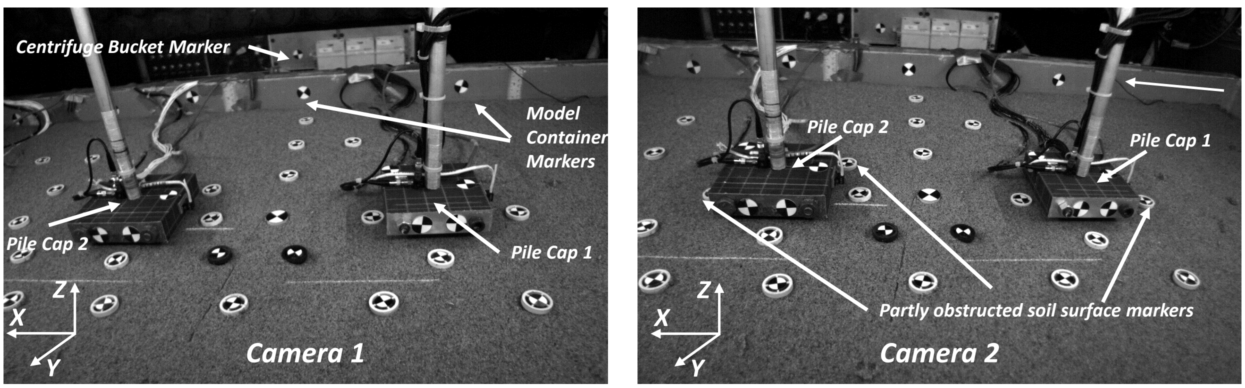


Figure 4.8. A view of the model from the North Pair Cameras (Camera 1 and Camera 2). The X- and Y- direction is in the plane of the soil surface whereas Z-direction is out of the plane.

Figure 4.9. Live view of the model from the four Photron camera heads as viewed in the Photron FASTCAM Viewer.

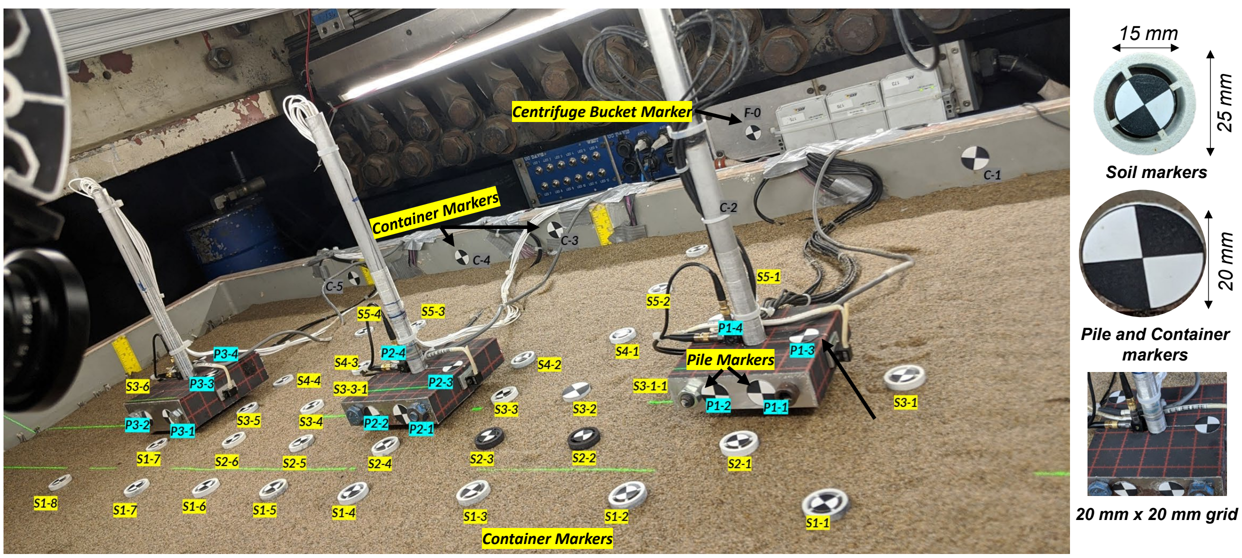


Figure 4.10. Camera target markers placed on the soil, on piles, and on the model container.

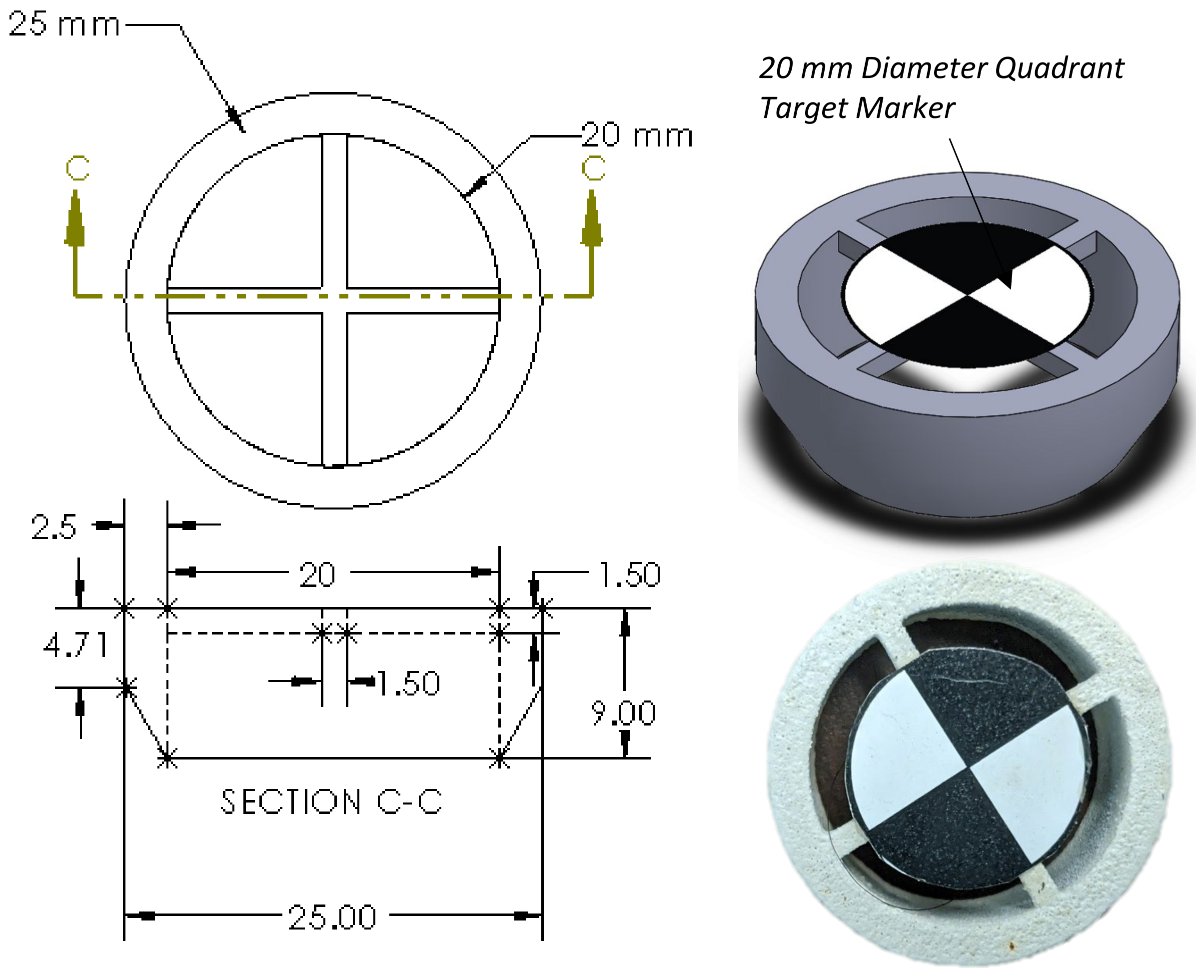


Figure 4.11. Drawings of the LEAP (Kutter B.L. et al. 2020) soil surface marker with a 15 mm diameter quadrant marker glued on its top (dimensions in millimeters).

5. IMAGE ANALYSIS IN TEMA

The recordings (or series of snapshots) from the Photron cameras were processed in TEMA (Image Systems Motion Analysis 2020) to obtain 3D movements of the soil surface, the piles, and the container. The camera target markers placed on soil, pile, and container (see Figure 4.10) are summarized below.

Piles

- *Pile 1*: P1-1, P1-2, P1-3, and P1-4
- *Pile 2*: P2-1, P2-2, P2-3, and P2-4
- *Pile 3*: P3-1, P3-2, P3-3, and P3-4

Soil

- *Row 1*: S1-1, S1-2, S1-3, S1-4, S1-5, S1-6, S1-7
- *Row 2*: S2-1, S2-2, S2-3, S2-4, S2-5, S2-6, S2-7
- *Row 3*: S3-1, S3-2, S3-3, S3-4, S3-5, S3-6, S3-7
- *Row 4*: S4-1, S4-2, S4-3, S4-4, S4-5, S4-6, S4-7
- *Row 5*: S5-1, S5-2, S5-3, S5-4, S5-5, S5-6, S5-7

Container

- *Top Ring*: C-1, C-2, C-3, C-4, C-5

Centrifuge Bucket

- *West Side:* F-0

The first step towards the image analysis is the camera orientation calibration and application of lens distortion correction to the images. The next step then is to identify target marker points in the images, track their position in the image, and then process the pixel coordinates to obtain 3D positions. Section 5.1 describes the camera calibration process in TEMA. Section 5.2 describes the method for tracking for target markers in TEMA. If two or more camera views overlap a target, the 3D position of the target point can be obtained.

5.1 Camera Calibration

Camera calibration is the method to obtain extrinsic and intrinsic properties of the camera optics. The extrinsic properties refer to the 6D position of the camera i.e., the physical coordinates (X, Y, Z) and orientation (roll, yaw, and pitch) of the camera sensor. The intrinsic properties of the camera refer to the lens distortion and skewness parameters, the focal length, the optical center of the image, the number and spacing of pixels of the camera sensor. Figure 5.1 shows the camera calibration parameters obtained after calibrating Camera 1. The sub sections below describe the camera orientation and lens calibration process in TEMA.

Camera Orientation

TEMA offers static camera orientation calibration as well as relative camera orientation calibration. For the static camera orientation calibration process, at least four target reference points with known 3D coordinates are used. For the relative camera calibration process, at least six target reference points with known distance between the points are required. In the present study, a static camera calibration was performed to obtain the orientation and position of the camera in model coordinate system. Three-dimensional measurements (at the center) of the camera target markers taken during the model instrumentation process were used in the process. The following points should be considered while running the camera orientation calibration:

- *For a static camera calibration, the images used to calibrate the camera orientation should be taken concurrently to the coordinates of the target reference points.* For relative camera calibration, the images used to calibrate the camera orientation should be taken concurrently with noting the relative coordinates of the target reference points.
- *If the position of the camera remains fixed, a static camera orientation calibration will suffice.* However, if the position of the camera changes during recording, a dynamic camera orientation calibration must be performed.
- *The target reference points used in the calibration should span in all X, Y, and Z directions*. Having reference target points close to one plane reduces the accuracy of the calibration process. A smaller value of the root mean square (RMS) residual in the order of millimeters ensures higher accuracy.

Table 5.1 compares the measured position and orientation of the cameras with the obtained position and camera orientation from the camera calibration process. This comparison was useful to check whether the camera calibration did a good job in estimating the 6D position of the cameras. A static camera orientation (Camera→Camera Orientation→Static Camera Orientation) was performed which produced an accuracy (RMS residual error) of 1.08 mm. All the cameras were calibrated, and their obtained orientations and coordinates were saved in their respective XML files.

Table 5.1− Comparison of the camera position coordinates and their orientation measured manually versus obtained numerically from the camera calibration process in TEMA.

<table>
<tr><th rowspan="2">Cameras</th><th colspan="5">Hand Measurements</th><th colspan="6">Obtained from Camera Calibration (roll, pitch, and yaw as defined in TEMA)</th></tr>
<tr><th>X (mm)</th><th>Y (mm)</th><th>Z (mm)</th><th>Orientation</th><th>Twist</th><th>X (mm)</th><th>Y (mm)</th><th>Z (mm)</th><th>Roll</th><th>Pitch</th><th>Yaw</th></tr>
<tr><td>Camera 1</td><td>580</td><td>785</td><td>789.4</td><td rowspan="4">33 degrees clockwise angle from the Z-X plane</td><td>5^o</td><td>579.3</td><td>801.6</td><td>794.3</td><td>5.14</td><td>-29.3</td><td>-83.0</td></tr>
<tr><td>Camera 2</td><td>730</td><td>785</td><td>794.4</td><td>-5^o</td><td>735.1</td><td>807.9</td><td>797.9</td><td>-5.49</td><td>-31.9</td><td>-97.8</td></tr>
<tr><td>Camera 3</td><td>975</td><td>785</td><td>791.9</td><td>5^o</td><td>972.3</td><td>798.3</td><td>791.8</td><td>5.3</td><td>-28.4</td><td>-81.9</td></tr>
<tr><td>Camera 4</td><td>1146</td><td>785</td><td>792.4</td><td>-5^o</td><td>1124</td><td>805.8</td><td>798.5</td><td>-5.9</td><td>-28.9</td><td>-97.9</td></tr>
</table>

Lens Calibration

The next step was to perform the lens calibration to find the lens distortion parameters. There are many lens distortions models available in TEMA. Figure 5.1 shows four lens distortion models ("Image System", "Radial", "Bouguet", and "Polynomial") available in TEMA. In the present study, the "Image System" distortion model was used using the Lens Calibration wizard module. TEMA recommended that a calibration board (see Appendix D) be used for this purpose. The calibration board image was printed and glued to an aluminum plate and may be available for re-use at the CGM. The manual for TEMA describes the details of the calibration process. After lens calibration was performed on all their cameras, the distortion model parameters obtained were saved in their respective XML files. The calibration parameters obtained for Camera 1, Camera 2, Camera 3, and Camera 4 are shown in Appendix E, Appendix F, Appendix G, and Appendix H, respectively. One point that was not very clear in the manual was the importance of calibrating the cameras all the way to the edges of the field of view. At the end of the Lens Calibration wizard in the TEMA software, the parts of the image which are satisfactorily calibrated for lens distortion are turned to green while the parts which require improvement are shown in red. Figure 5.2 shows the results of the calibration process by summarizing the mean and maximum residuals of the calibration points. A green color overlay in all the 16 segments of the image shows that the calibration has been performed satisfactorily throughout the image.

5.2 Obtaining 3D Displacement Field

The TEMA software was used to track the target markers and obtain their 3D movements during the test. The recordings from Camera 1 and Camera 2 were processed together to obtain the 3D movements of the soil, piles (Pile 1 and Pile 2), and the container on the north side of the model. The recordings from Camera 3 and Camera 4 were processed together to obtain the 3D movements of the soil, piles (Pile 2 and Pile 3), and the container on the south part of the model. Figure 5.3 shows the view of analysis performed in TEMA on Camera 3 and Camera 4 for shaking event EQM_5.

In order to track the center of the target markers in TEMA, a quadrant symmetry Digital Image Correlation (DIC) tracker algorithm was used. For the cases where the target markers were not clearly visible (due to an obstruction from the wires, investigation test probes or from the movement of the parts of the model itself) a "correlation" and "correlation+" tracker algorithms were used. Figure 5.4 shows all the available tracker algorithms in TEMA. The quadrant symmetry tracker was found to be faster, precise, and achieved high accuracy in tracing the targets. The correlation and correlation+ trackers on the other hand also performed a decent job in tracking the targets. Since these trackers search for cross-correlation in the search area to identify the target, it is slower and produces larger noise in the obtained movement than the quadrant symmetry trackers. Also, since these trackers look for correlation within the target image from previous time steps, they often drift from their targeted position.

Based on the use of these trackers in TEMA, below are some points are listed which should be considered while deciding the DIC algorithms and their properties for processing images in TEMA:

- *The search area (represented by the yellow box, see Figure 5.4) should be larger than the movement of target points within the successive frames.*
- *When using the Quadrant algorithm, the purple box (also referred as object size, see Figure 5.4) should be smaller than the target object, to avoid noise from the outer edges.*
- *The tracker tolerance can be made higher to increase the accuracy of predicted movement.* However, because of the 'noise' level in the images, a too strict of a criterion can cause multiple rejections. The default tolerance of 50% was found to have a good balance between accuracy and precision.
- *The quadrant symmetry tracker is recommended because it provides easier and faster tracing, produces accurate results and is more reliable*. However, it requires the presence of quadrant type markers to be placed and visible by at least two cameras.
- *The correlation and correlation+ trackers perform a decent job in tracing any type (shape or size) of feature in the model*. This is particularly useful to trace model features at locations where target markers have not been initially placed. The *correlation+* tracker algorithm works best when the background inside the object area remains constant. The *correlation* tracker works even when the background inside the object area changes.

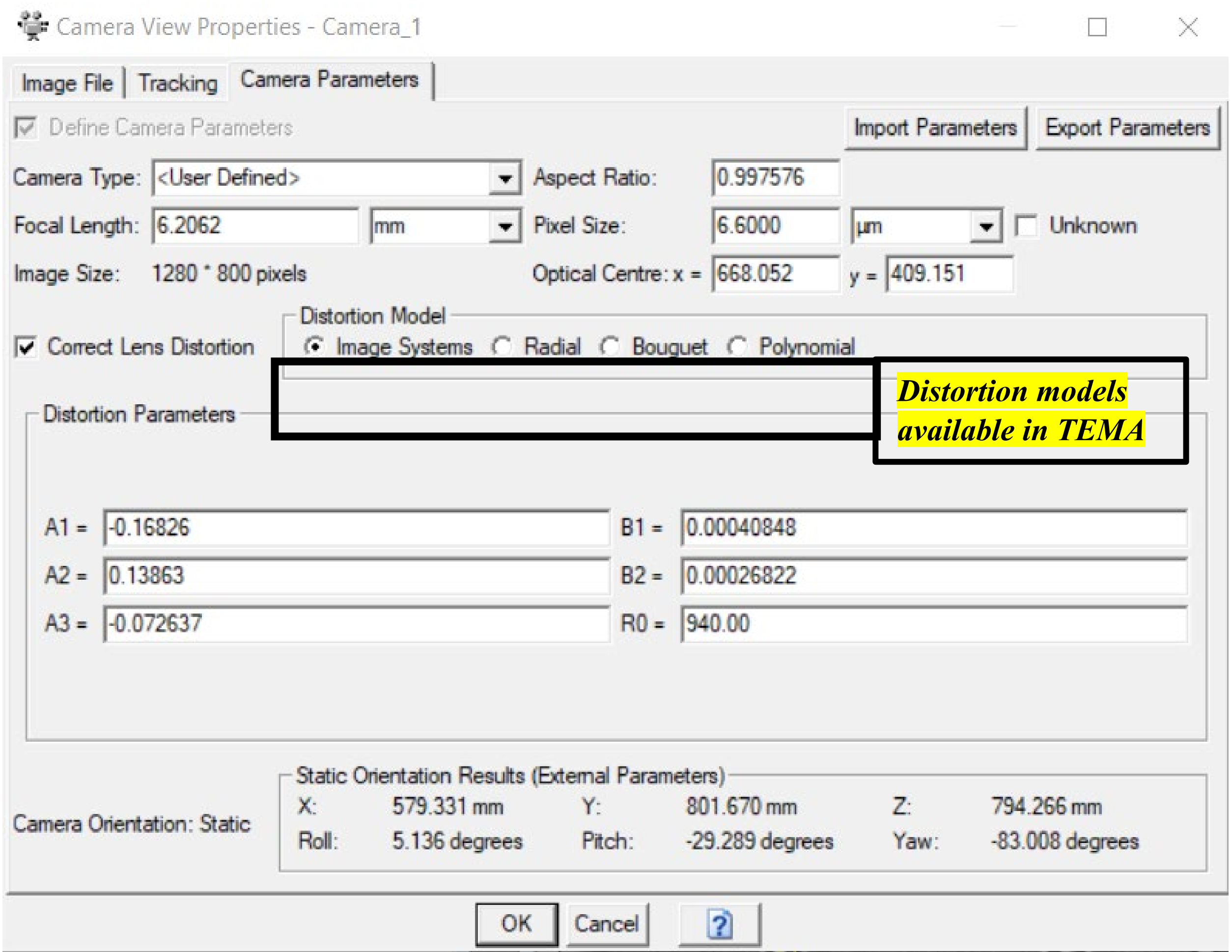


Figure 5.1. Obtained camera calibration parameters for Camera 1 in the centrifuge test SKS03.

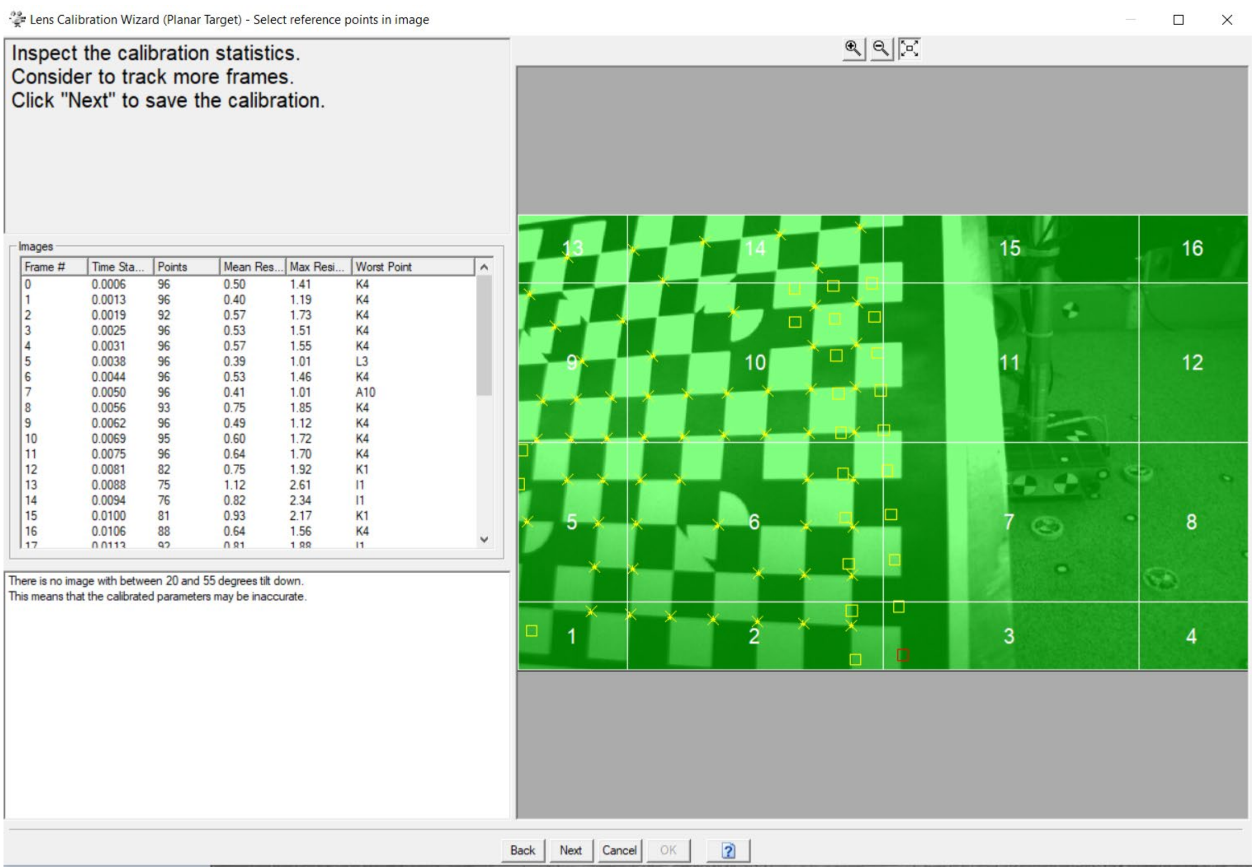


Figure 5.2. Reviewing the results of the lens calibration process in TEMA.

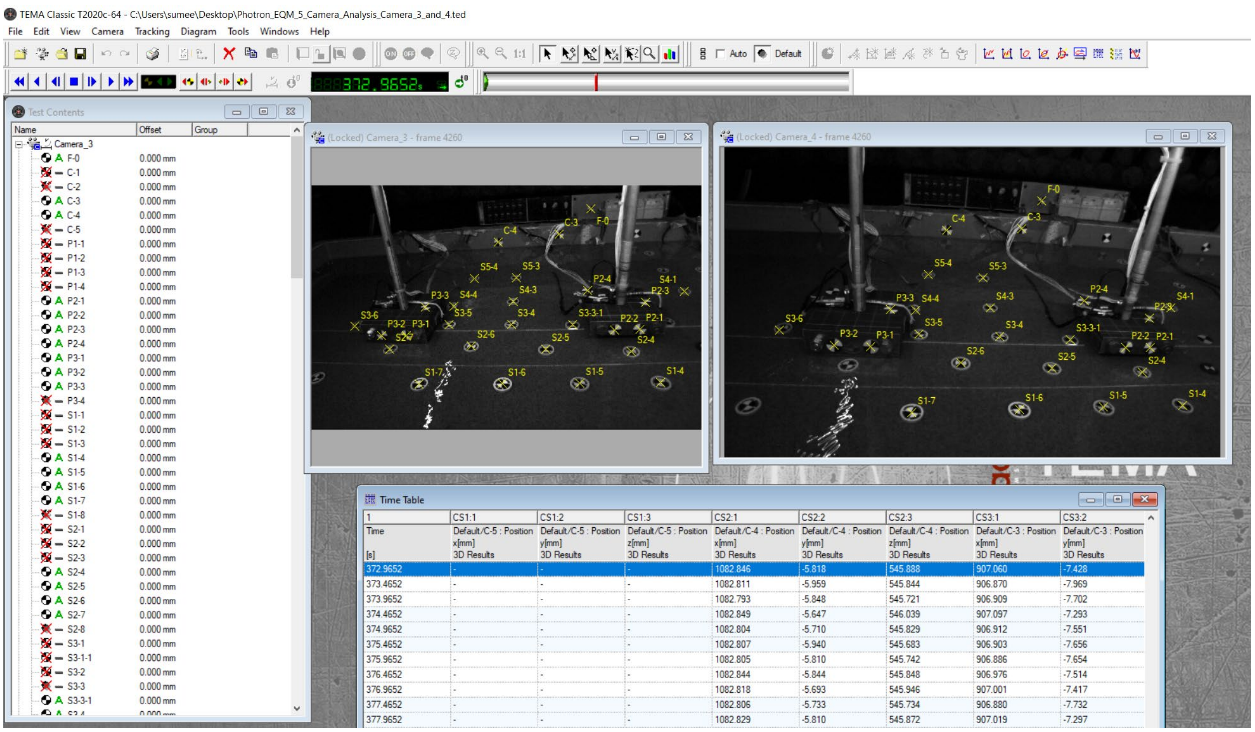


Figure 5.3. View of the image analysis performed in TEMA using Camera 3 and Camera 4 for shaking event EQM5.

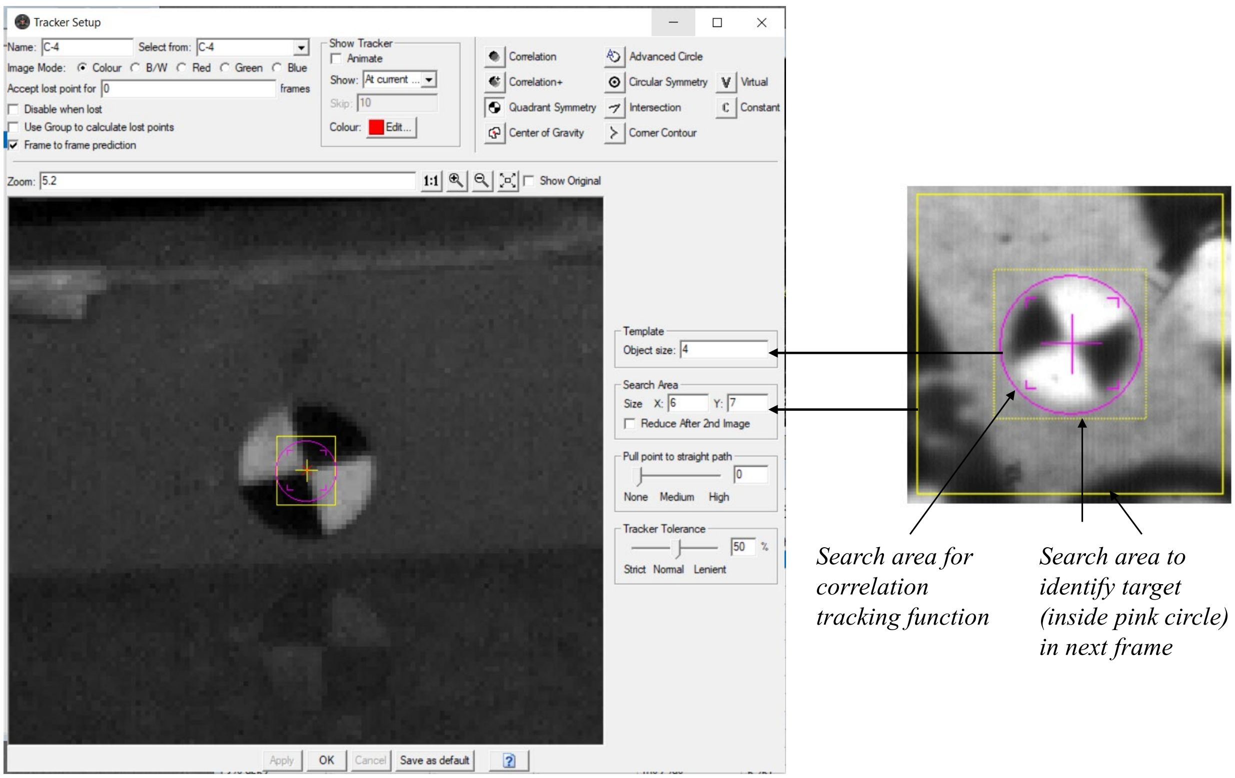


Figure 5.4. Target tracker setup in TEMA.

6. RESULTS

The series of snapshots recorded from the Photron Cameras were used to perform image analysis in TEMA. Although the snapshots were taken at different frame rates during and after shaking, TEMA was able to automatically extract the timings for each image from the (*.chix)* metadata file. Figure 6.1 shows the 3D movement of pile 2 marker P2-2 obtained from two separate analyses: one from the North Pair (Camera 1 and Camera 2) and the other one from the South Pair (Camera 3 and Camera 4). The plots show a good agreement between the 3D movements obtained. The X-component of the displacement corresponds to the shaking direction of the actuators. The Z-component of the displacement corresponds to the settlement of the pile during shaking. The discrepancy between measurements from the North Pair and South Pair is an indication of the error in the measurements. Some of the possible reasons include errors arising from camera movement, image noise or narrow stereo angles. The computed movement in the Y-direction (Figure 6.1), which is the out-of-plane movement is noisy likely because of the small stereo angle and image noise. The computed movements in X and Z direction, being the in-plane movement have comparatively smaller noise.

6.1 Evaluation of the Stiffness of the Mounting System

The vibration of the mounting system was monitored by two accelerometers on the camera beams. One horizontal ($\mathrm{CAMERA}^{\mathrm{ACC\ H}}$) and one vertical ($\mathrm{CAMERA}^{\mathrm{ACC\ V}}$) accelerometer were installed (see Figure 4.3) on the Camera Beam to monitor accelerations in the in the X- and Z-directions, respectively. Figure 6.2 shows the response of the Camera Beam during the first 0.8 seconds of shaking. These vibrations of the beam in X- and Z- direction can introduce noise in the captured images as well as in the computed 3D movements. Figure 6.3 shows the Fourier amplitude spectrum computed from the camera accelerations and the applied shaking motion. The natural frequency of the Camera Beam was found to be about 80 Hz. Since the applied shaking is of the order of 100 Hz, installing the camera on a stiffer beam will reduce these vibrations. Figure 6.2 also shows the displacements in the Camera Beam by integrating the accelerations. The plot indicates that the maximum amplitude of the camera beam vibration before the shaking is about 0.02 mm in both X- and Z-directions. During the shaking, the maximum amplitude of vibration is about 0.3 mm in the X-direction and about 0.15 mm in the Z-direction.

Figure 6.4 shows the displacement of the centrifuge bucket target marker in X-, Y- and Z-directions with respect to the camera during the first 0.8 seconds of shaking event EQM_5. If the cameras were rigidly fixed to the bucket, and there would be no noise in the computed displacements, the apparent movement of the bucket relative to the cameras would be zero. Some of the oscillations in Figure 6.4 may be the result of image noise and some may be due to ambient vibration of the camera beam prior to triggering the shaker. The background vibration and image noise are indicated by the computed displacement before shaking starts. The peak-to-peak noise is about 0.1 mm, 1 mm, and 0.3 mm in the X-, Y-, and Z-directions respectively in the data apparent in the first 0.1 s of the record. As may be expected, being out of plane direction, the Y-component of the displacement is especially noisy due to the narrow stereo angle (~7° , see Figure 4.6) between the camera views. Since all the cameras were inclined by about 30 degrees in the Y-Z plane (Figure 4.4), the effect of vibrations in the Camera Beam produces smaller noise in the computed displacements in the in-plane X- and Z- direction. A possible reason for comparatively higher noise in Z-component of the movement compared to X-component could be from the inclination of the camera or that the beam was vibrating more in the vertical direction than in the horizontal direction.

Figure 6.5 shows the Fast Fourier Transform (FFT) of the computed displacements from the camera. It can be observed from the plots that the major frequency contribution to the beam is at 60, 80 and 140 Hz, consistent with frequencies observed by the accelerometers. Comparing the X-displacements in Figure 6.3 and Figure 6.4 reveals that the cameras and accelerometers computed similar amplitudes of displacements (about 0.2 to 0.3 mm). The Z-components of displacement of the bucket from the cameras is much noisier than the Z-component of displacement from the beam accelerometers. Camera vibration noise can be amplified due to variability of vertical displacements along the length of the beam and rotations of the cameras clamping mechanisms. The Y and Z components are exaggerated due to low stereo angle and differences in vibrations of the two cameras. The X-component of the vibration along the length of the beam may be more uniform resulting in comparatively lower noise in the computed movements.

6.2 Effect of Shaker Hydraulics on Movements before and after Shaking

In the present application, the cameras were mounted to the bucket and the servo-hydraulic shaker shook the model container relative to the bucket. The soil model in turn, vibrates relative to the model container. So, the camera system measured the displacement of the model relative to the bucket. However, the displacements of the model, relative to the model container are of more direct importance to the researcher. By measuring the displacements of the container, it is possible to compute relative displacement as described in Section 6.4.

Some seemingly erroneous results were obtained in the initial data processing that are explained by some basic knowledge about how the servo-hydraulic shaker works. Before triggering the shaking, large valves that increase the oil pressure are opened that allow the actuators to come under servo control. When they come under control, the actuators center themselves very accurately. Once the actuator is under control, the shaker command file is sent to the actuators, and the shaking event occurs. Then after shaking, the valves are closed and the container drifts away from its accurate center.

Figure 6.6 shows the X-component of movement of the top ring of the container. The response during the shaking event is as expected. However, between 2 and 9 seconds, the drifting of the container away from the accurate center is apparent. The drifting occurs relatively slowly and smoothly over these 7 seconds so it should not be affecting the behavior of the experiment. The drift is easily eliminated by subtracting container displacements from all the computed model displacements.

Finally, it should be noted that when using a flexible shear beam container (FSB) like FSB2, the top part of the container is not rigidly connected to the base of the container. The relative movement of the top ring and the container base could also be accounted for by integration of difference between accelerations of the top ring and the base of the container.

In summary, displacements are always measured relative to something. The researcher should always consciously assess the desired displacement reference and make sure that sufficient data is collected to achieve this.

6.3 Container Movement in Y- and Z- Direction

Figure 6.7 and Figure 6.8 show the movement of the container in the Y- and Z- directions, respectively. It can be seen from the plots that overall; the container does not move significantly in the Z-direction. However, a small drift can be seen in the container movement in the Y-direction (see Figure 6.7) between 2 to 9 seconds. Target markers C-1 and C-2 were located on the north side of the model whereas C-2 and C-3 were located on the south side of the model. While equal and opposite movements in the C-2 and C-3 markers indicate twisting of the container, the small movement in the far end-located target markers on the north and south side of the container is inconsistent with rigid body rotation of the container. Another possible reason for this drift could be the result of the image noise produced between 2 and 9 seconds while the container drifted from the servo-controlled center. Since the Y-direction corresponds mostly to out-of- plane motion and the target markers on the container were located very far off the camera, producing a small stereo angle, the image noise produced from movement of the container in X-direction could have severely affected the computed displacements. While all the reasonings listed above could be a possibility, the exact cause of the apparent Y- movement is not completely understood.

6.4 Soil and Pile Movement

To obtain the relative movements of the soil and pile with respect to the container, the average movement recorded in the target markers located on the top ring of the container was subtracted from the movement of the target markers computed in TEMA (see Figure 6.6, Figure 6.7, and Figure 6.8). Figure 6.9 and Figure 6.10 show the movement of the piles and the soil nearby in X-, and Z- directions respectively with respect to the container for shaking event EQM5. The movement of the pile mass was computed by taking the average movements of target markers (P1-1,P1-2) for Pile 1, (P2-1,P2-2) for pile 2, and (P3-1 , P3-2) for Pile 3. The soil target markers selected nearby the piles were S2-1, S2-4, and S2-7 for Pile 1, Pile 2, and Pile 3, respectively. Figure 6.6 shows a drift in X-direction post-shaking (after 9 seconds). This might have resulted from the tilt in the bucket causing lateral movement of the soil during the reconsolidation process. It can be seen from the plots that the drift is positive showing that the soil is moving towards the south side of the centrifuge bucket.

Table 6.1 compares the pile settlement obtained from the image analysis performed in TEMA with the hand measurements performed using a depth gage. The physical measurements were taken using the depth gage, with a precision of 0.1 mm. The results from the image analysis had a precision of 0.15 mm. The obtained measurements from image analysis match quite well with the physical measurements. The differences are within the precision of the measurement method. For pile 1, the hand measurements from day 1 are about 0.4 mm higher than the ones obtained from image analysis. This difference could have been from the bumping the marker or operator error.

Table 6.1− Comparison of pile settlements obtained from the image analysis in TEMA with the physical measurements using a depth gage.

Pile Target Markers	***Settlements from Shakings on Day 1 (mm)***		***Settlements from Shakings on Day 2 (mm)***	
	Depth Gage	***Image Analysis***	***Depth Gage***	***Image Analysis***
P1-3	*1.6*	*1.25*	7.15	7.13
P2-3	*0*	*0.05*	7	7.11
P3-3	*0.5*	*0.28*	24.25	24.44

6.5 Pile Acceleration

This section compares the absolute horizontal acceleration measured from TEMA with the accelerations measured from the sensors placed on the pile mass (see Figure 4.2). To obtain absolute horizontal accelerations, the absolute horizontal displacements of the pile mass were computed by subtracting the movement of centrifuge bucket (marker F-0) from the movements obtained from image analysis. The obtained absolute displacements were then double differentiated to obtain absolute accelerations. Figure 6.11 compares the absolute acceleration in piles computed from TEMA with the one obtained from accelerometer sensors. The results obtained from TEMA are in reasonably good agreement with the accelerometers. However, TEMA shows a relatively higher noise, which could have arisen from the image noise or from the vibrations of the Camera Beam.

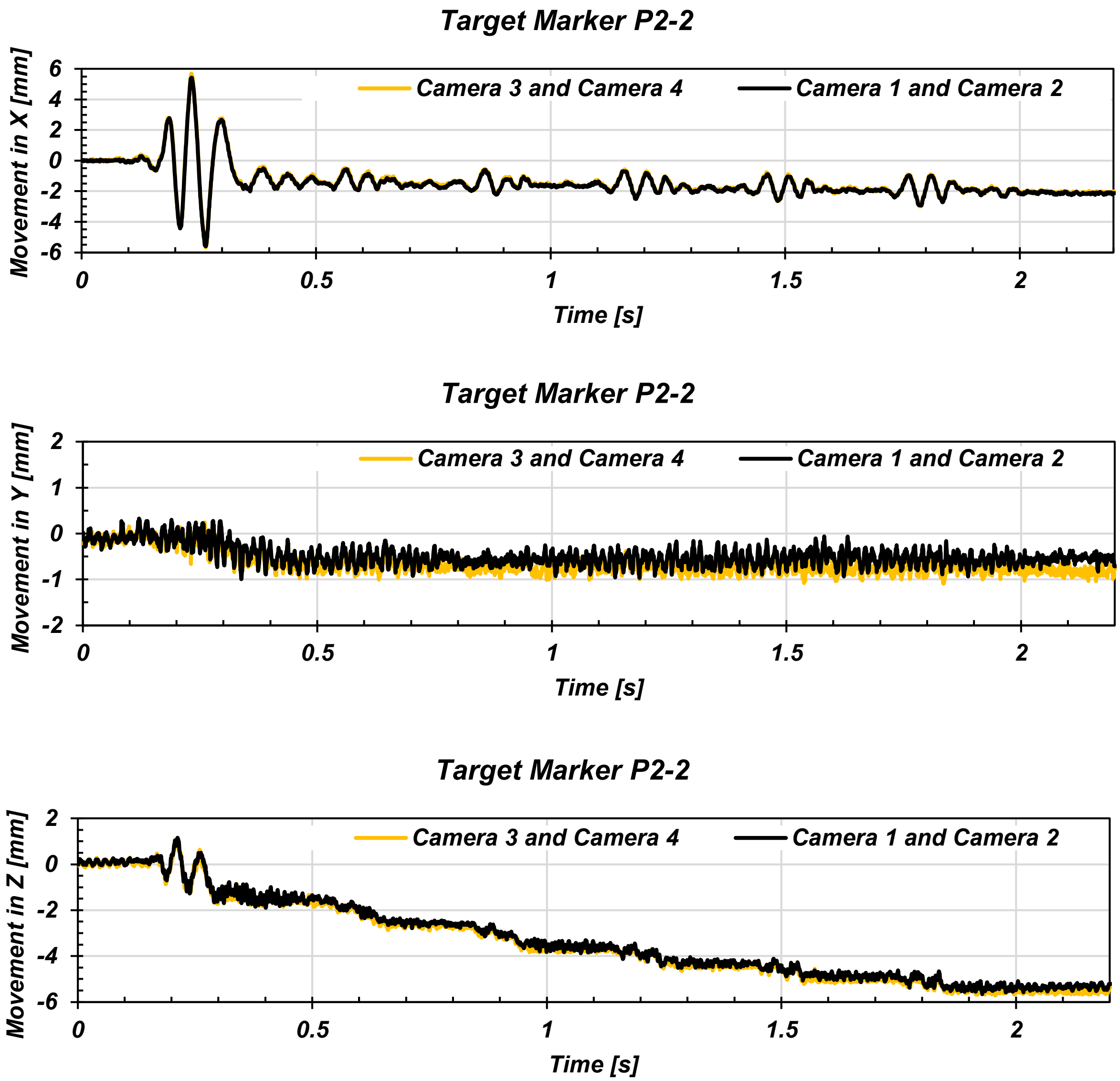


Figure 6.1. Measured 3D movement (relative to the camera) of pile 2 target marker P2-2 obtained from two separate TEMA analyses: one using the Camera 1 and the Camera 2 pair and the other using the Camera 3 and the Camera 4 pair.

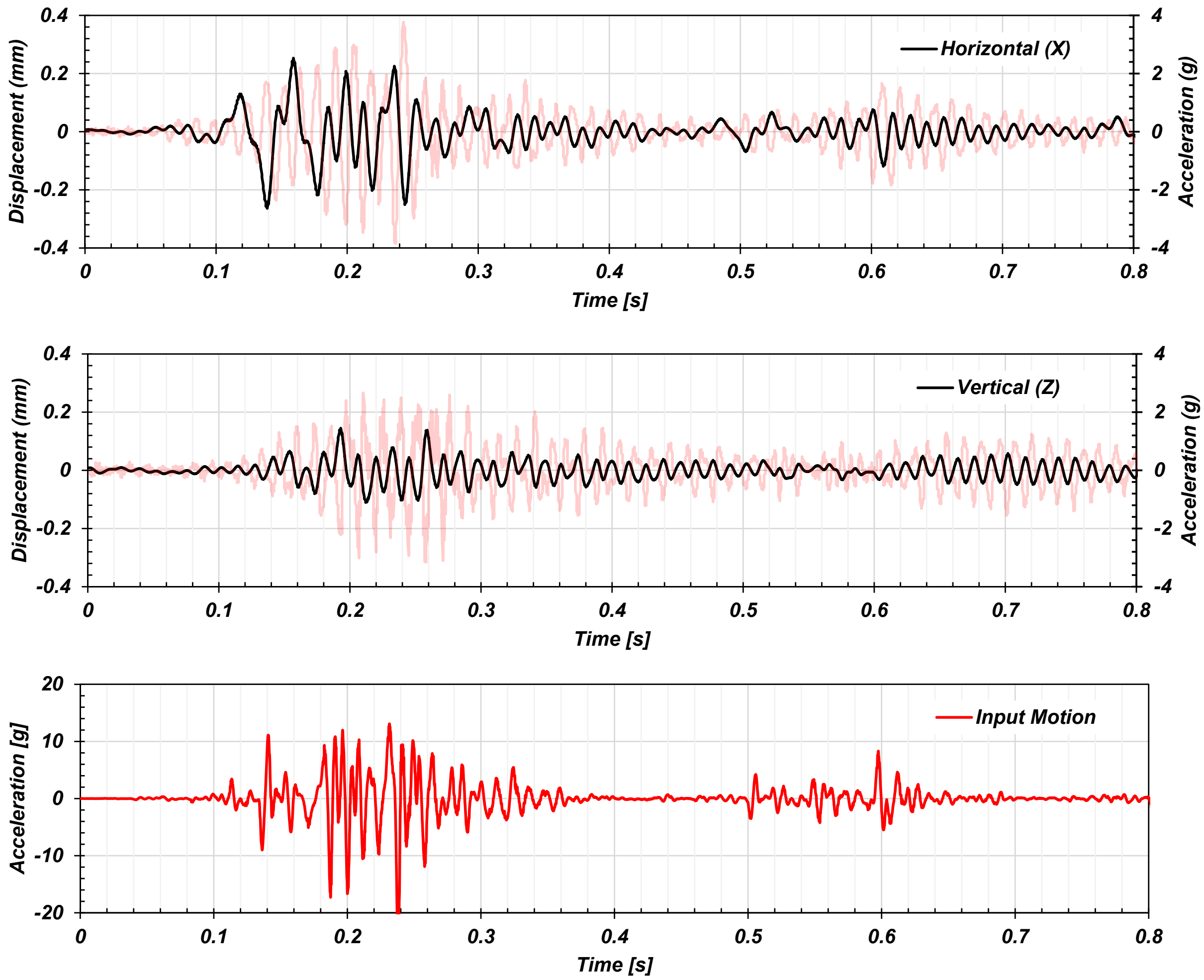


Figure 6.2. Computed horizontal (X) and vertical (Z) displacements (in black) of the Camera Beam obtained from the integration of the recorded horizontal and vertical accelerations (in red) by the accelerometers (CAMERA$^{ACC\ H}$ and CAMERA$^{ACC\ V}$) placed on the Camera Beam.

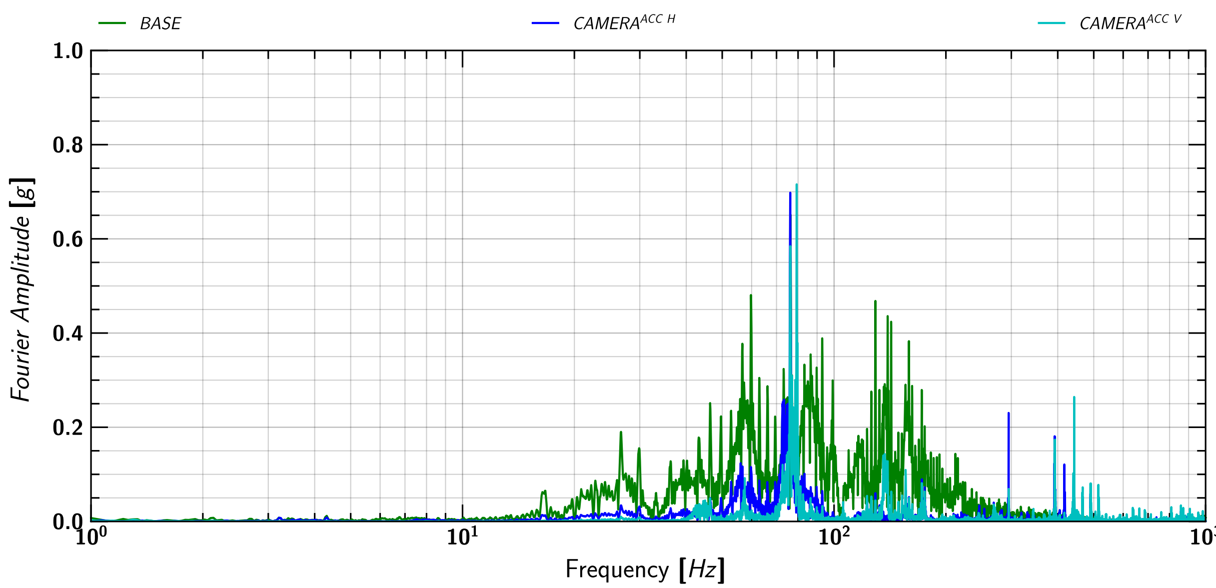


Figure 6.3. Fourier amplitude spectrum of the horizontal (CAMERA$^{ACC\ H}$) and vertical (CAMERA$^{ACC\ V}$) accelerations measured at the center of the Camera Beam compared to the input motion (BASE) accelerations measured at the base of the centrifuge container.

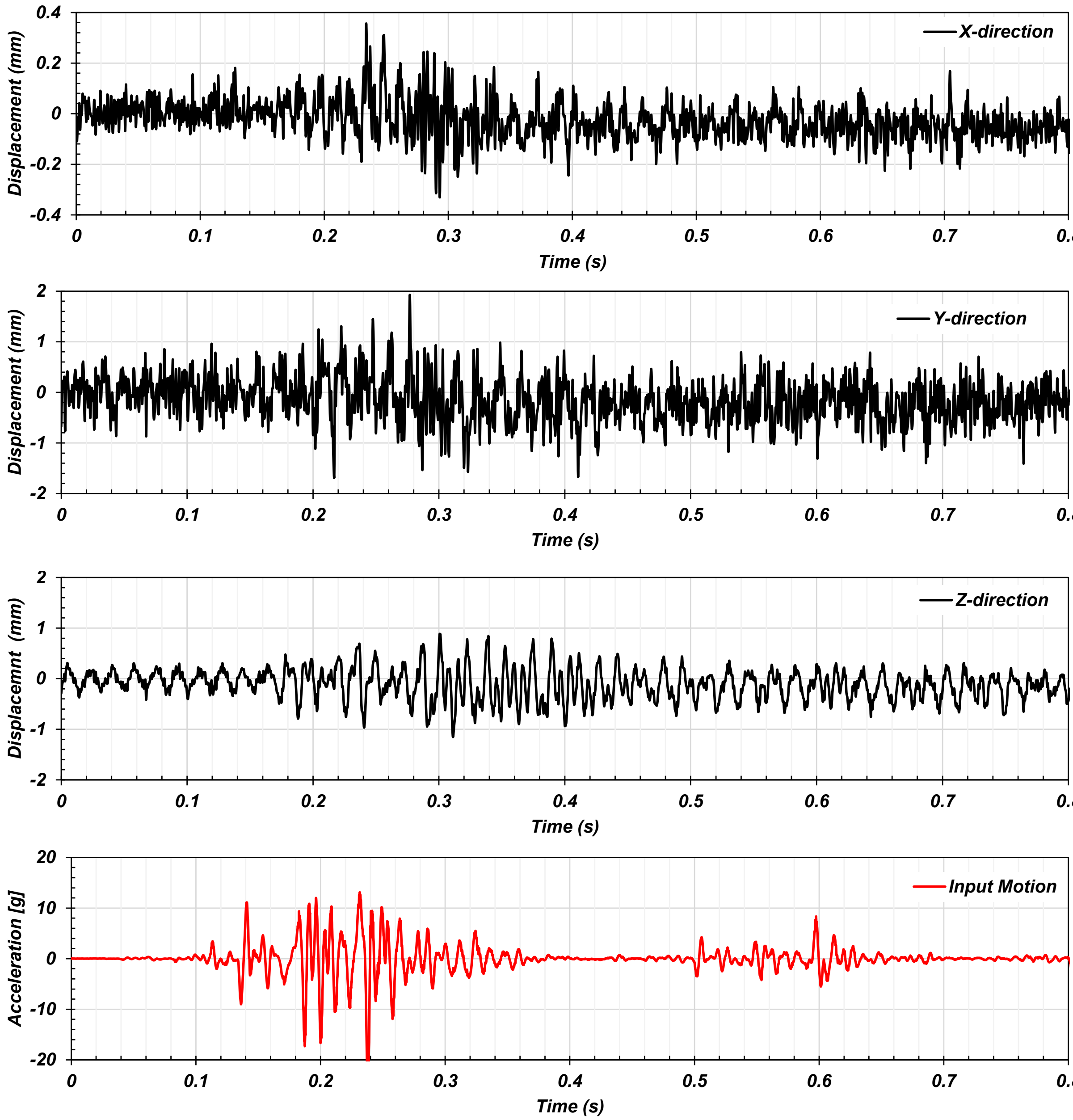


Figure 6.4. Movement of the centrifuge bucket with respect to the cameras in X-, Y-, and Z-directions during the first 0.8 seconds of shaking event EQM_5.

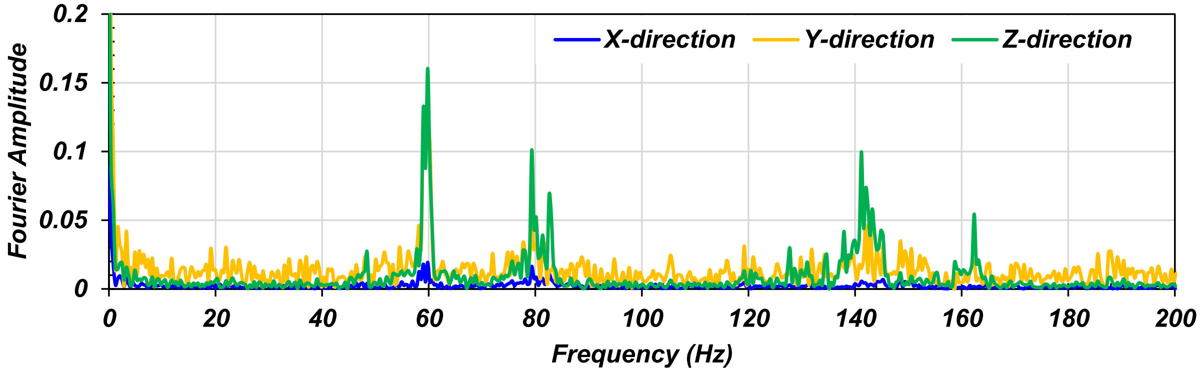


Figure 6.5. Fourier Amplitude of the displacements time-history in X-, Y-, and Z-direction of the centrifuge bucket marker F-0.

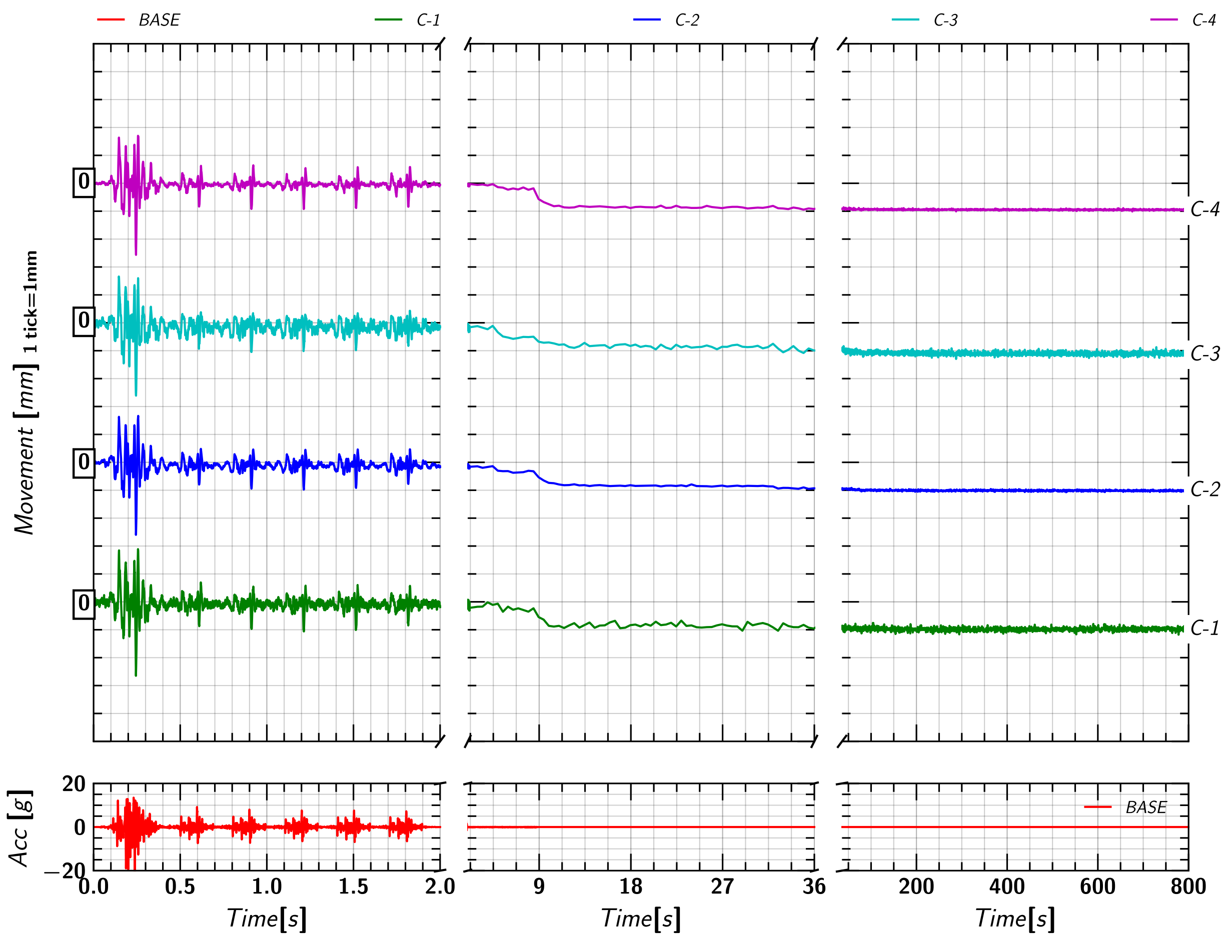


Figure 6.6. Movement of the container target markers in X-direction for shaking event EQM5.

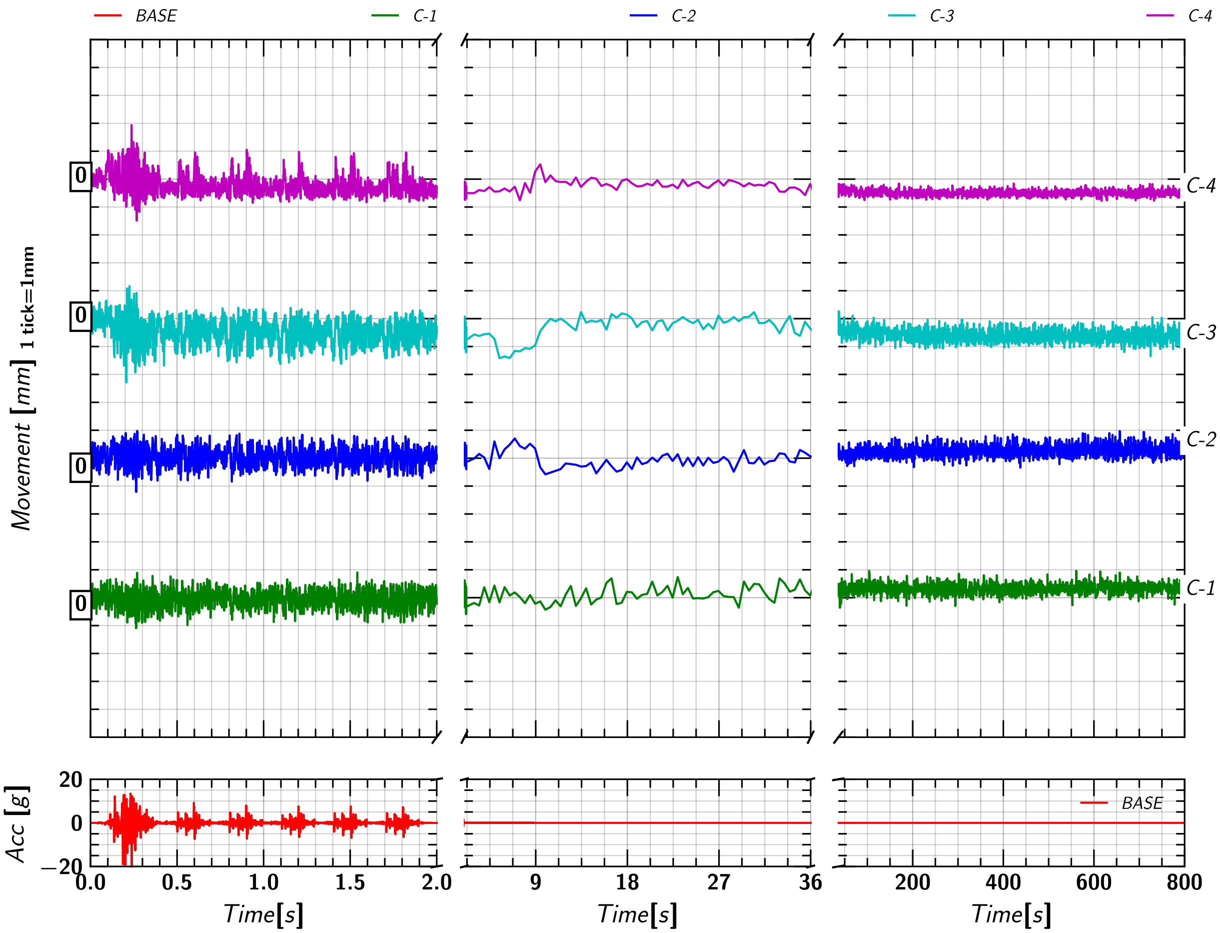


Figure 6.7. Movement of the container target markers in Y-direction for shaking event EQM5.

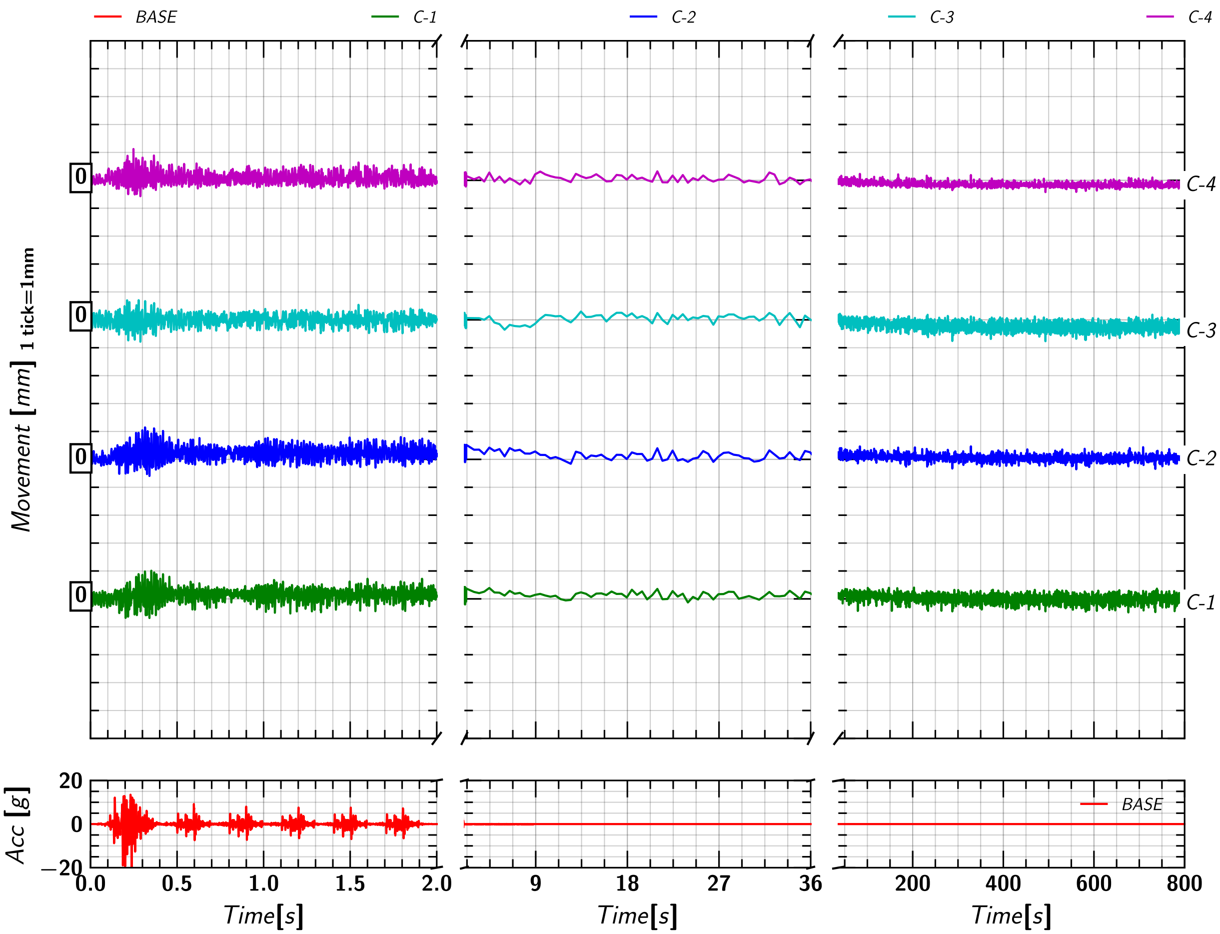


Figure 6.8. Movement of the container target markers in Z-direction for shaking event EQM5.

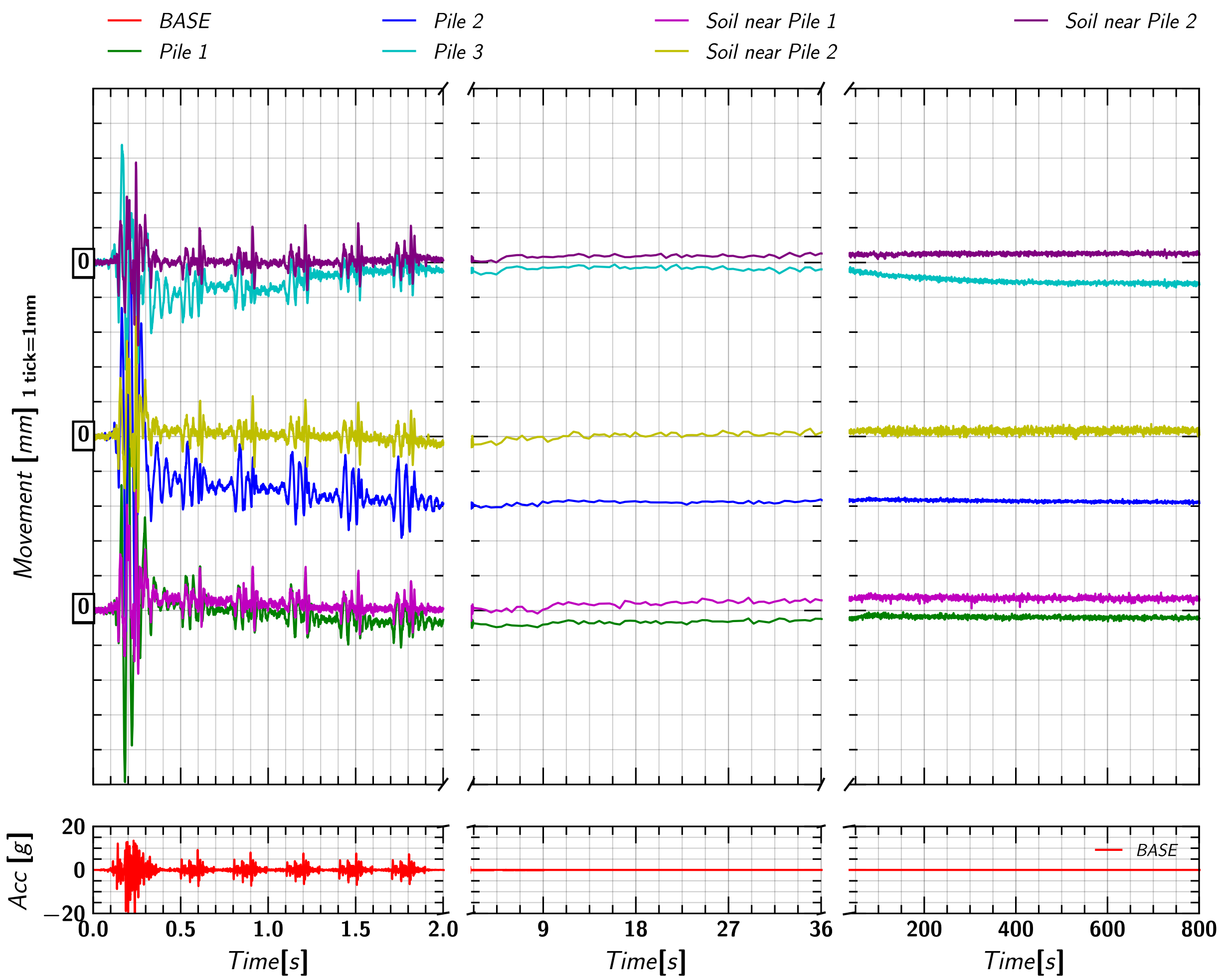


Figure 6.9. Movement in pile head mass and the soil nearby with respect to the container in X-direction for shaking event EQM5.

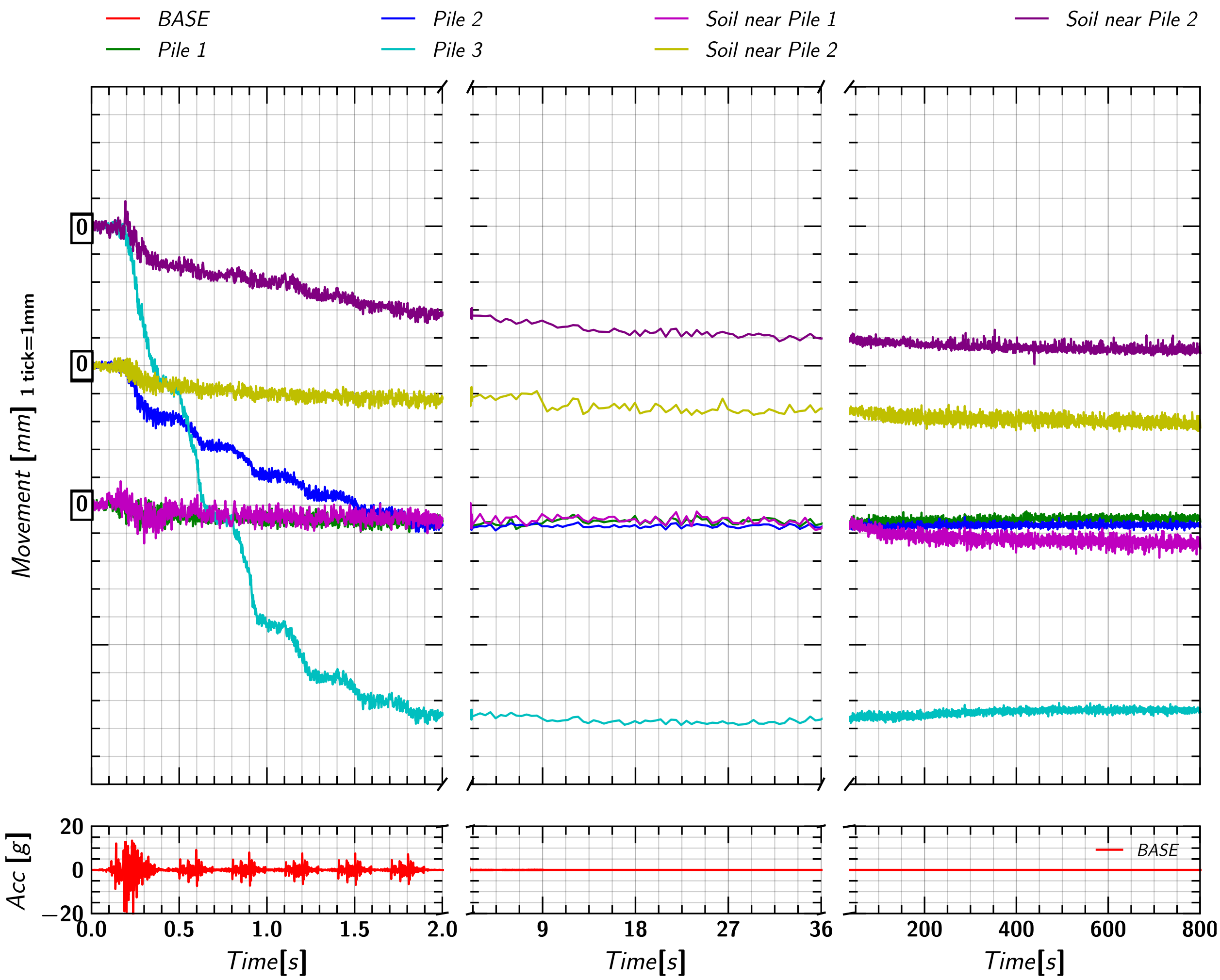


Figure 6.10. Settlement of the piles and the soil nearby for shaking event EQM5.

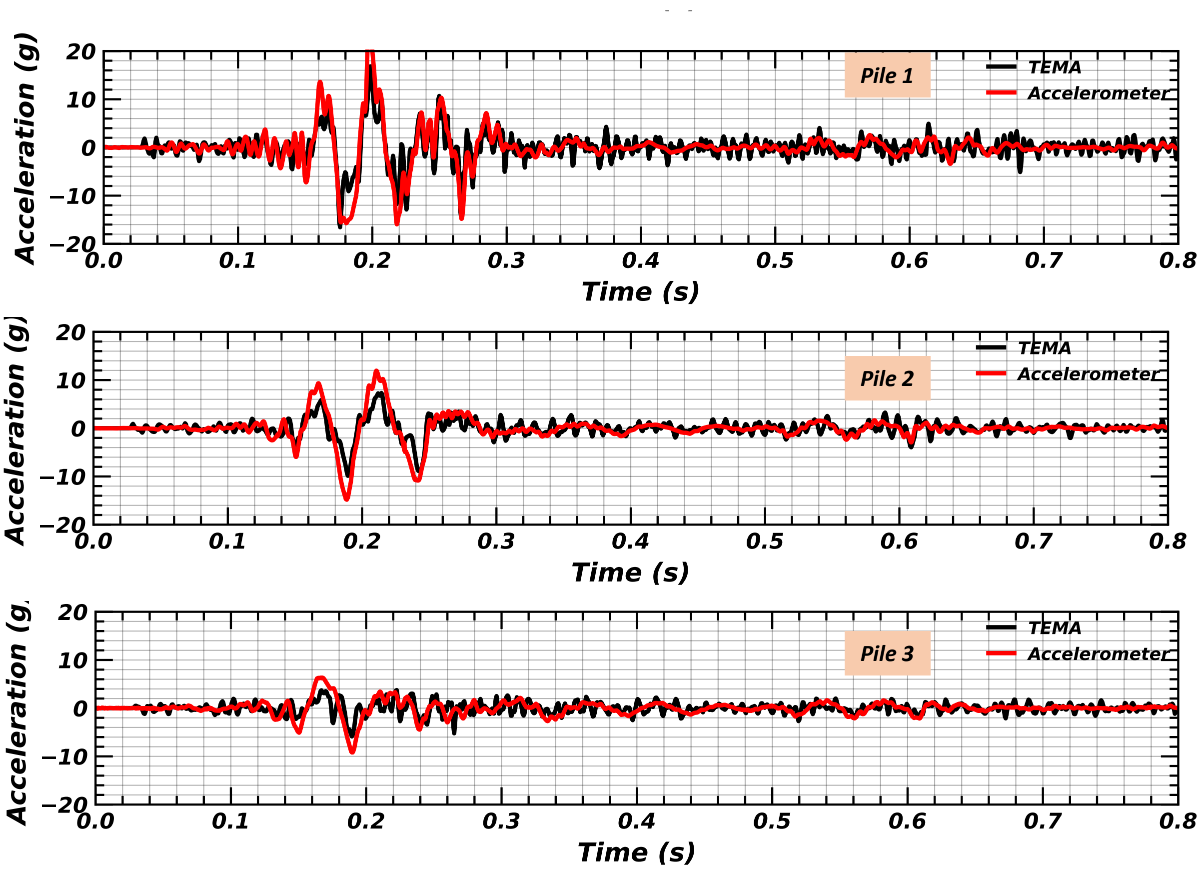


Figure 6.11. Comparison of horizontal accelerations measured from accelerometers placed on the pile head mass with the computed accelerations from displacement time-history measured from image analysis in TEMA for shaking event EQM_5.

7. CONCLUSIONS

New high-speed Photron cameras and TEMA Classic 3D software were used together in a large dynamic centrifuge test for the first time at the Center for Geotechnical Modeling at the University of California, Davis. This report described the important parts of the software, model instrumentation process, image analysis, and interpretation of results. Discussions are made on the cameras, camera mounting, target markers, lighting, camera calibration, camera triggering, and software options selected for the analysis and recommendations are provided for improvements for future applications. Results presented showed that this method is effective and reliable in obtaining positions, displacements, velocities, and accelerations of the targets, and thus promising for use in future applications.

The use of cameras instead of linear transducers to measure displacements, makes the model instrumentation relatively easier, cleaner, and provides more model space for performing other important investigations. It also leaves more sensor channels unoccupied that can be used to connect other sensors. It also offers contactless sensing, which reduces potential disturbance of the model. At the same time, the camera recordings offer an immense amount of data which can be processed to get 3D displacements at any point within the model. The high-speed Photron cameras and TEMA software are a great addition to the CGM towards simplifying the model instrumentation and advancing the sensing capabilities in centrifuge tests. It is a progressive step towards the future of contactless model testing. As a supplement to this report, "A Good Practices Guide for Digital Image Correlation" by International Digital Image Correlation Society (2018) is a very good reference for understating basic concepts of Digital Image Correlation (DIC) and photography techniques.

Outlined below are some important conclusions and considerations for using the cameras and image analysis for obtaining 3-D movements:

- The modular design of the Camera Beam, light beams and camera holder system made it easier to position and orient the cameras in any direction within the model. Using cameras instead of Linear Potentiometers made the model look pretty. They simplified the model instrumentation process by eliminating the need of model racks which also resulted in larger model surface available for other important investigations.
- Uniform and sufficient lighting is critical; three strips of LED lights were used in the present study, totaling 1000 lumens per foot. This produced sufficient lighting to run the cameras at 1600 fps and 4000 Hz shutter speed on the Photron cameras.
- Since centrifuge model tests are comprised by multiple moving components at very high accelerations, it is important to put sufficient markers on the model container to allow for computing the movements of soil markers relative to the container. Markers should also be placed along the centrifuge bucket to estimate vibrations of the cameras. In the presented study, target markers were placed on the top ring of the flexible shear beam (FSB) container and on the centrifuge bucket.
- Quadrant markers worked well for tracking in the TEMA image analysis software. Markers of different sizes should be used depending on the distance from the target to the camera.

- Quadrant target markers should be placed (if possible) at all important parts of the model that need to be precisely tracked.
- The camera(s) should be directed towards the plane of most important measurements. In the current study, the cameras were directed towards the X-Z plane to record the movement of the model in shaking i.e., the X-direction and the settlement of the soil and pile in Z-direction. Using the setup described in this report, the system was able to resolve X- and Z-displacements with a resolution of 0.15 mm.
- The positions (in the model coordinate system) of at least 4 non-coplanar markers viewed by at least two cameras should be known prior to collecting data so that the two camera locations and orientations can be determined in the TEMA software. This also enables TEMA to directly output marker positions in the model coordinate system.
- Pile settlements obtained from image analysis matched quite well with the hand measurements performed using a depth gage. It was also possible to differentiate the marker positions obtained from the image analysis to obtain a reasonable estimate of the accelerations of the objects.

Suggested future improvements to the system include:

- The cameras could be more rigidly mounted to the centrifuge bucket. Vibrations in the camera support beams may explain much of the noise.
- Quadrant markers of larger size should be used at distant objects so that the marker occupies at least 8 pixel or more in the image.
- If displacements are important in the direction of the view angle of the camera (like Y-direction in this report), a larger stereo angle should be used. The cameras can be moved further apart to increase the stereo angle.
- Soil surface marker should be colored black to increase contrast of the target markers placed.

The resources (Software, Manual, SolidWorks Model, Target Design, etc.) used in this report can be downloaded from https://ucdavis.app.box.com/s/4jnqhnxqkp9699qaqngtguthuinjkyhm.

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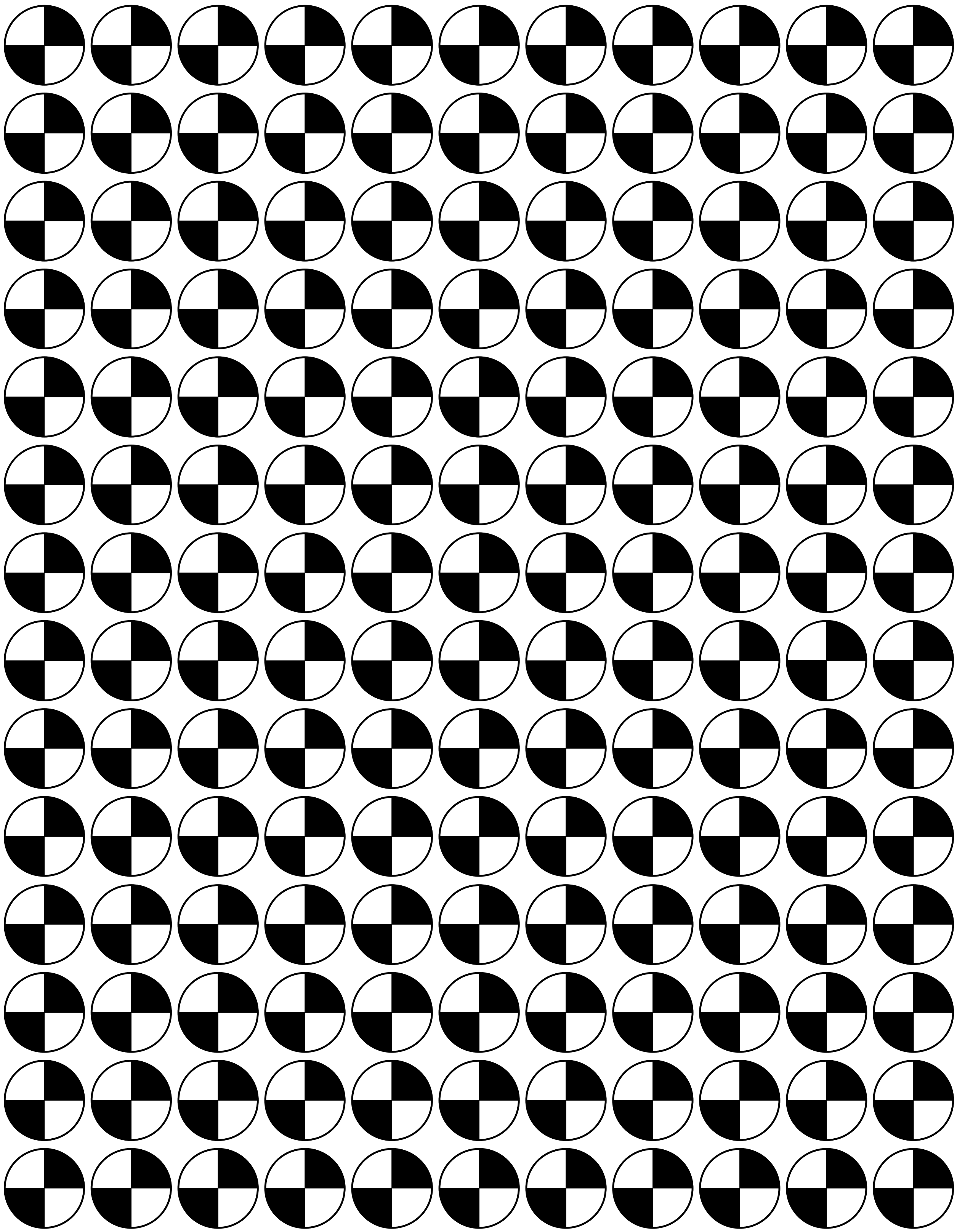
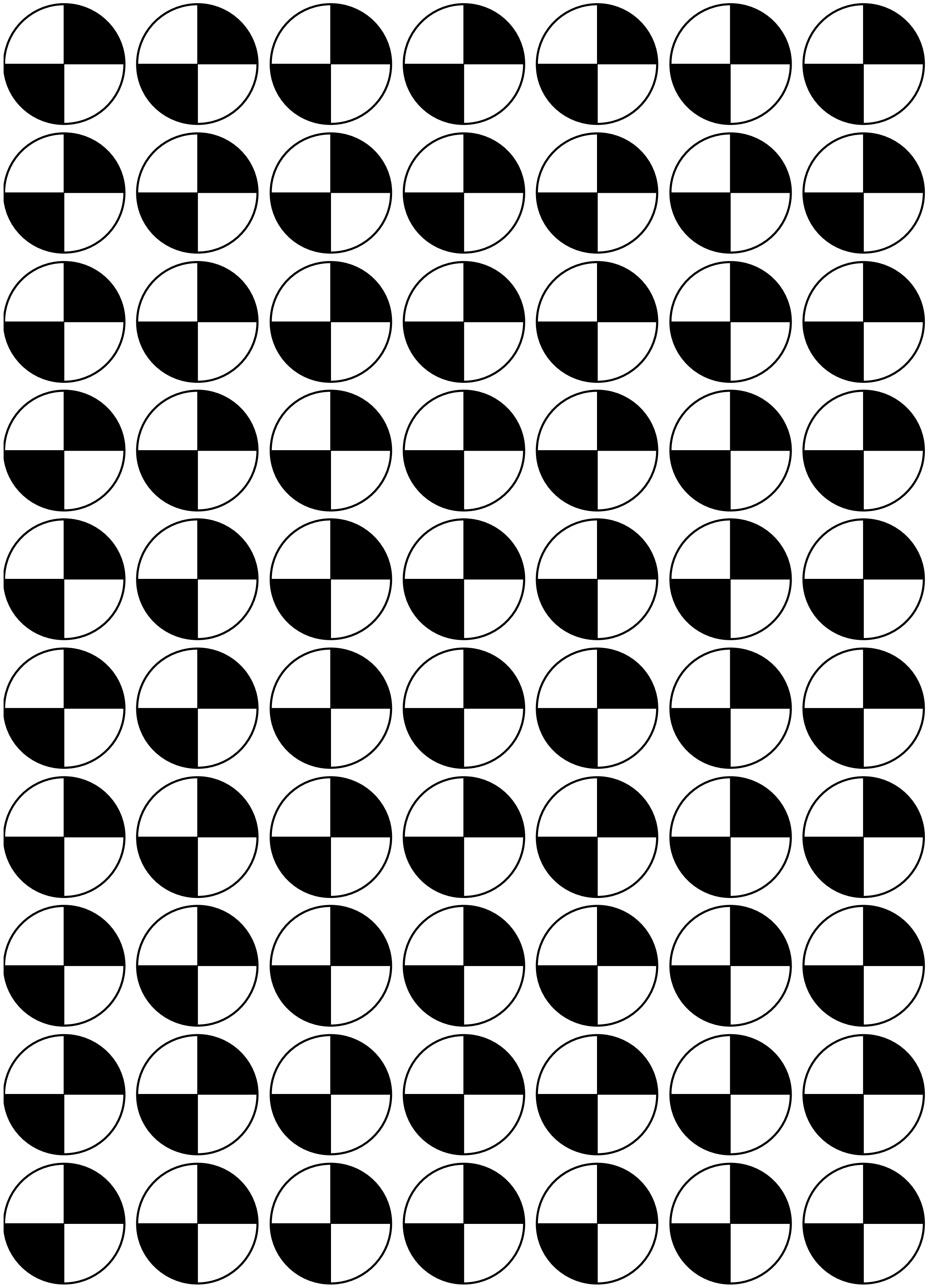
Sinha, S. K., Ziotopoulou, K., and Kutter, B. L. (2021). "Centrifuge testing of liquefaction-induced downdrag on axially loaded piles : Data Report for SKS03". Report No. UCD/CGMDR – 21/02, Center for Geotechnical Modeling, University of California Davis, CA.

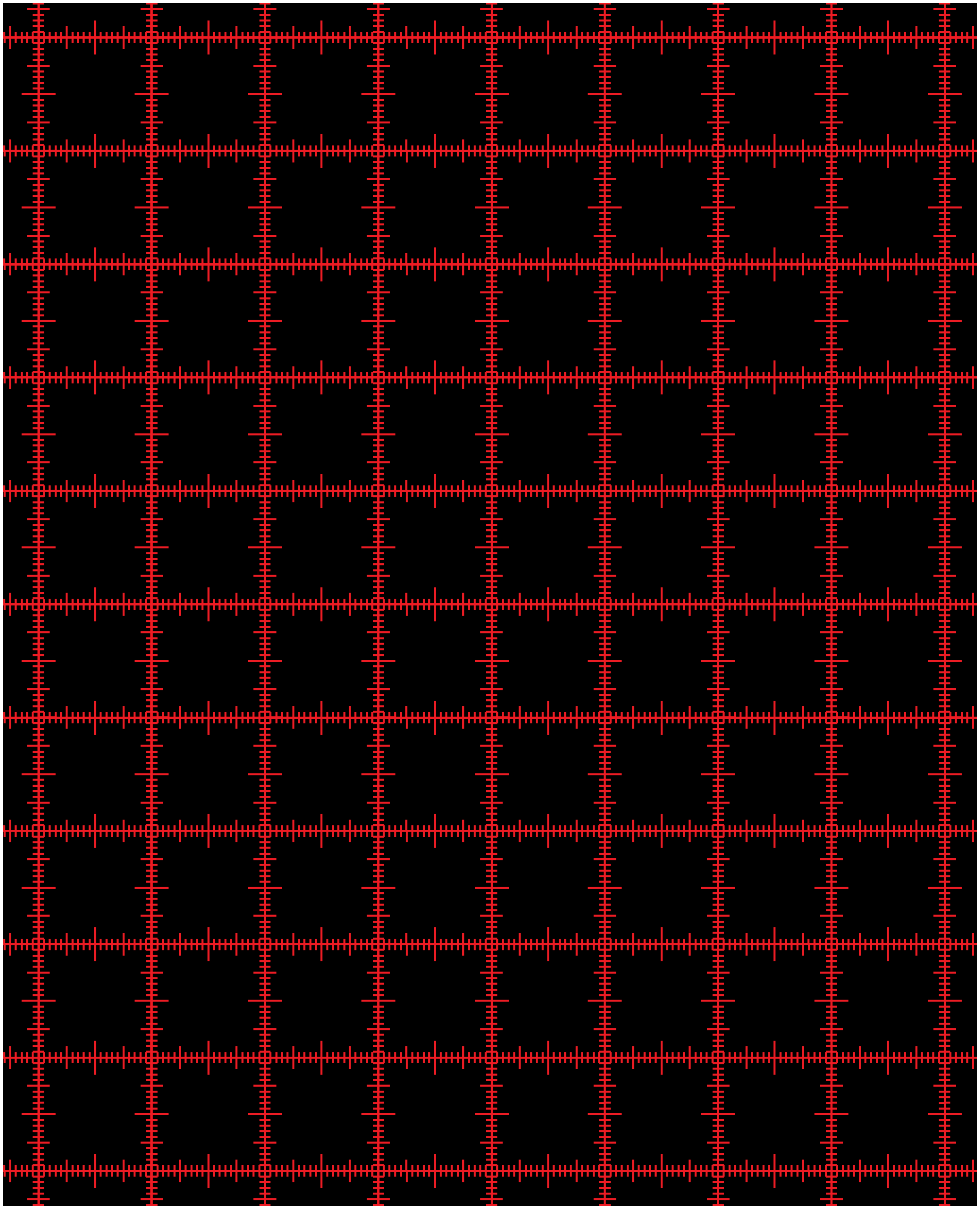
APPENDIX A: 15 mm Diameter Quadrant Target Marker



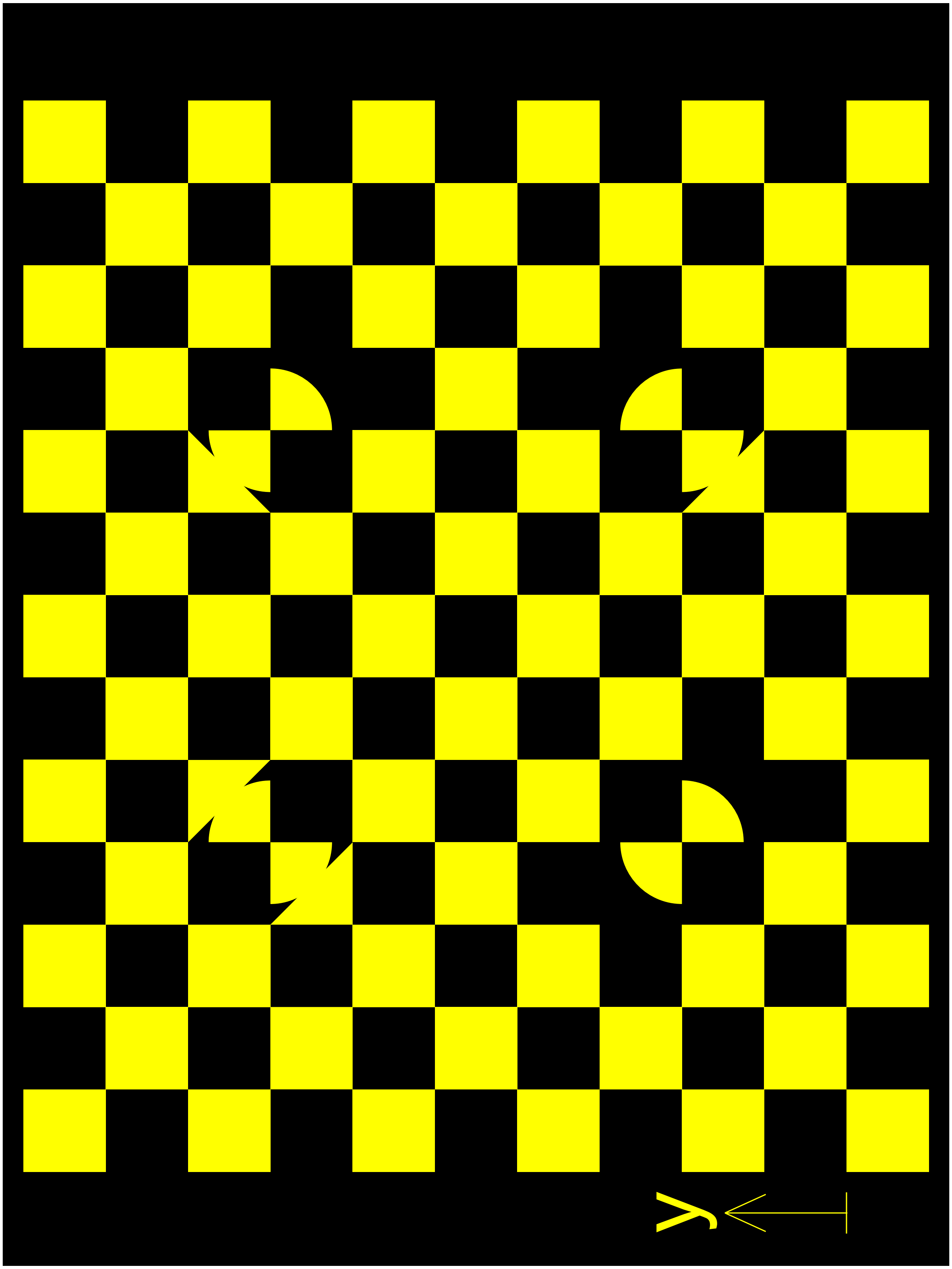
APPENDIX B: 20 mm Diameter Quadrant Target Marker



APPENDIX C: 20 mm x 20 mm Square Grid Target Marker



APPENDIX D: Lens Calibration Board (provided by TEMA)



APPENDIX E: Camera Calibration Parameters for Camera 1


```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<?mso-application progid="TrackEye.CalibratedCameraParameters"?>
<ImageSystemsXML schema="TOM 1.0" model="TrackEye" version="4.4-003-64">
  <CalibratedCameraParameters imagesize_x="1280" imagesize_y="800">
    <internalparams status="Calculated" producerstate="None" valid="TRUE"
       f="940.340222465922" principal_x="668.051819683355"
       principal_y="409.151485328869" aspect="0.997575537468819"
       pixelsize="6.6e-6"/>
    <externalparams status="Calculated" producerstate="None" valid="TRUE"
       x="0.579331343681136" y="0.801669981002016" z="0.794266178165679"
       roll="0.0896474086396331" pitch="-0.51119501617092"
       yaw="-1.44875616587233"/>
    <distortion status="Fixed" producerstate="None"
       type="lens parameters (TE)">
      <data>
        6.6e-6,
        668.051819683355,
        409.151485328869,
        0.997575537468819,
        940,
        -0.168255656914369,
        0.138631190754047,
        -0.072637108097938,
        4.08477442168495e-4,
        2.68219738744108e-4
      </data>
    </distortion>
  </CalibratedCameraParameters>
</ImageSystemsXML>
```

APPENDIX F: Camera Calibration Parameters for Camera 2


```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<?mso-application progid="TrackEye.CalibratedCameraParameters"?>
<ImageSystemsXML schema="TOM 1.0" model="TrackEye" version="4.4-003-64">
  <CalibratedCameraParameters imagesize_x="1280" imagesize_y="800">
    <internalparams status="Calculated" producerstate="None" valid="TRUE"
       f="948.170890457556" principal_x="626.052856258711"
       principal_y="408.704957647531" aspect="0.996631449725073"
       pixelsize="6.6e-6"/>
    <externalparams status="Calculated" producerstate="None" valid="TRUE"
       x="0.735056677143333" y="0.807948699353757" z="0.797878249253422"
       roll="-0.0959013553923525" pitch="-0.556827848576796"
       yaw="-1.70669550329923"/>
    <distortion status="Fixed" producerstate="None"
       type="lens parameters (TE)">
      <data>
        6.6e-6,
        626.052856258711,
        408.704957647531,
        0.996631449725073,
        960,
        -0.163206369717877,
        0.107354624664748,
        -0.0390260835427191,
        -3.38338523044692e-4,
        -1.24845792963997e-3
      </data>
    </distortion>
  </CalibratedCameraParameters>
</ImageSystemsXML>
```

APPENDIX G: Camera Calibration Parameters for Camera 3


```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<?mso-application progid="TrackEye.CalibratedCameraParameters"?>
<ImageSystemsXML schema="TOM 1.0" model="TrackEye" version="4.4-003-64">
  <CalibratedCameraParameters imagesize_x="1280" imagesize_y="800">
    <internalparams status="Calculated" producerstate="None" valid="TRUE"
       f="938.997359488338" principal_x="625.276083305117"
       principal_y="422.605588171819" aspect="0.998638986285616"
       pixelsize="6.6e-6"/>
    <externalparams status="Calculated" producerstate="None" valid="TRUE"
       x="0.972301088243702" y="0.798281308741239" z="0.791757148445258"
       roll="0.0926068180147705" pitch="-0.496237931493401"
       yaw="-1.42950539820113"/>
    <distortion status="Fixed" producerstate="None"
       type="lens parameters (TE)">
      <data>
        6.6e-6,
        625.276083305117,
        422.605588171819,
        0.998638986285616,
        930,
        -0.153372246960133,
        0.108414739271141,
        -0.0461529716837319,
        1.02560850678299e-4,
        6.16256937951145e-4
      </data>
    </distortion>
  </CalibratedCameraParameters>
</ImageSystemsXML>
```

APPENDIX H: Camera Calibration Parameters for Camera 4


```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<?mso-application progid="TrackEye.CalibratedCameraParameters"?>
<ImageSystemsXML schema="TOM 1.0" model="TrackEye" version="4.4-003-64">
  <CalibratedCameraParameters imagesize_x="1280" imagesize_y="800">
    <internalparams status="Calculated" producerstate="None" valid="TRUE"
       f="939.508643292468" principal_x="632.404863919667"
       principal_y="388.31136814748" aspect="0.997965858299876"
       pixelsize="6.6e-6"/>
    <externalparams status="Calculated" producerstate="None" valid="TRUE"
       x="1.12460642641027" y="0.805810194838808" z="0.798510602484084"
       roll="-0.102917810524748" pitch="-0.504561546175967"
       yaw="-1.70940478024263"/>
    <distortion status="Fixed" producerstate="None"
       type="lens parameters (TE)">
      <data>
        6.6e-6,
        632.404863919667,
        388.31136814748,
        0.997965858299876,
        930,
        -0.149526706973739,
        0.0872155825481451,
        -0.0296197044512506,
        -1.01105860789066e-3,
        -7.3530457213257e-4
      </data>
    </distortion>
  </CalibratedCameraParameters>
</ImageSystemsXML>
```