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Preliminary Analysis of Soil Embedded Fibre Optic Sensors and Particle Image Velocimetry Outputs of Dynamic Soil Deformation for Early Warning System

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Abstract

In this preliminary study, we use a small-scale physical model, an educational shaking table and an educational EduPIV line to measure the velocity and displacement fields resulting from the failure of soil retained by a cantilever retaining wall subjected to dynamic action. Optic fibre sensing technology was used through Fibre Bragg Grating (FBG) sensors, embedded in the soil for the purpose of internal deformation monitoring and for testing the applicability of this technology in dynamic sensing. Particle image velocimetry (PIV) was applied to allow for the failure mechanism to be visualised. It was possible to evaluate the soil internal deformation as well as the failure of the slope model by using both technologies. According to these preliminary findings, discussions and recommendations for further research are presented. PIV technology is tested in the context of g-PIV and seems to offer promising results in investigating the dynamics of a granular flow. Scaling up and installing fibre optic cables on linear infrastructure elements could allow for information on the location, the mechanism, and the magnitude of ground movement in real time. Careful interpretation of the obtained strain signatures is central for the retrieval of the localised ground displacement field with high precision, together with deeper understanding and prediction of the ground deformation and collapse mechanisms. FBG sensors can record strain signature and inform an early warning system and therefore support a proactive approach towards potentially induced failures.

Keywords: Soil deformation, Fibre Bragg Grating (FBG), PIV, Early waning

1. Introduction

Retaining walls are frequently used in ports, or at the face of cuttings on highways, or sheet pile walls in temporary or permanent excavations. During big infrequent and unpredictable intensity destructive earthquakes (i.e. Chi-Chi 1999, and Bhujn2001) in situ measurements and real time data of failure is very rare to obtain. To this end, small scale physical models are tested either on 1-g shaking tables, (Marketos and Madabhushi, 2004), (Berry and Madabhushi, 2007), or in high g centrifuge models, (Madabhushi and Haigh, 2019).

Popular methods for high precision recording of displacement in soil range from noncontact laser techniques which measure surface displacement of the soil, point, line or area based (i.e. laser radar, laser line triangulation, close – range photogrammetry and particle image velocimetry (PIV). Linear variable differential transformers (LVDTs) can measure internal deformation and linear displacement within soil (Zhang et al., 2017), yet along certain directions, and for certain desired positions, measurements of the distribution of the internal deformation can be difficult.

Fibre optic sensing is an innovative and rapidly developing technology that has been successfully applied to performance monitoring in many fields such as civil engineering, mining, landslides and sinkholes. Fibre optic sensors can monitor the distributions of internal deformations and variation for different conditions, and are sensitive to relatively small values of strain at early stages. Can measure strain and temperature over long distances on a single cable or multiplexed cables depending on the technology used. The characteristics of the sensors are that they are small, have light weight, are easy to integrate or install into or onto structures. They are resistant to corrosion and water, immune to electromagnetic interference (lighting, high voltage), suitable for explosive and other sensitive environment, can operate at high temperatures, and exhibit some tolerance to radiations.

Particle image velocimetry (PIV), image processing analysis allows to obtain complete time history of displacements and strains and visualise the failure mechanism. It offers the possibility to evaluate the soil internal deformation as well as the failure of the slope model.

In the current study we combine the relatively new technology in the field of geotechnics fibre optic sensors, to monitor the internal dynamic deformation for a slope, under seismic loading and complement the well-established methods of PIV using a low-cost method of an educational (EduPIV) setup, and that of an educational shake table. The purpose of the project is to convey an experimental study using a small scale instrumented physical model, to gain further insight on the strain state and the failure mechanism developed on a retained wall under seismic loading.

2. Particle Image Velocimetry (PIV)

Particle Image Velocimetry (PIV) analysis is a velocity measuring technique which was originally applied in the field of experimental fluid mechanics, aerodynamics and hydraulic engineering (Willert and Gharib, 1991), (Adrian, 2005). The classical PIV, performs two-dimensional investigations (2D) of the flow velocity field, while more recent advances of the PIV approach involve tomographic PIV (Elsinga et al., 2006). The 2D-PIV technique can estimate the most probable velocities in predetermined interrogation areas of a 2D region of interest (ROI) of the flow domain. This operation is performed by determining the maximum value of the cross-correlation function of pairs of images, taken at short time intervals of iterative interrogation. Classical PIV applications are used to measure the flow of transparent fluids and require optically visible tracers and a laser sheet to illuminate them within a thin slice in the flow domain. The tracers need to be adequately small and have the same density of the fluid under study, so that they flow with the fluid without noticeable velocity differences. Once these requirements are met, the tracers' velocities can be considered reliable estimations of the flow velocities.

Errors resulting from the method are due to loss-of-pair and gradient bias (Scarano and Riethmuller, 2000). Loss of pair could result from, a too small interrogation window compared to the magnitude of displacements, arises when the difference of the tracer numbers between the two images is too large to produce an increase of the background noise in the correlation. This error can be reduced by selecting a suitable size of the interrogation window or by reducing the time interval between the images, which was adopted in the current study. The error in relation to gradient bias second error is a result of high shear in the interrogation window, which lowers the cross-correlation analysis by augmenting the intensity peak. Generally, the precision of the PIV measurement can be improved when larger interrogation windows are used, this on the other hand can affect the measurement resolution.

In recent years PIV analysis is used to observe soil behaviour in physical modelling of small-scale geotechnical structures, mostly in a centrifuge environment. The dynamics of granular flows is a hot topic, as granular media are involved in several natural phenomena (e.g. debris flows and avalanches) and other engineering applications. The application of a PIV approach to granular flows, often referred to as granular PIV or g-PIV (Eckart, Gray and hutter, 2003), exhibits some unique characteristics that depend on the nature of the medium. For example, the grains are typically non-transparent, in this case the grains themselves serve as tracers. The grain opacity only allows measurements at the boundaries of the flow domain. The large size of grains and the inability to investigate inside the flow domain renders the use of laser sheets inadequate. Instead, in these applications alternative light sources, such as flash lights (Eckart, Gray and hutter, 2003), or flickering-free LED lamps are used. Another unique characteristic of granular flows is that large shear may occur, especially in the presence of a no-slip basal condition (Sarno et al., 2018). To limit the gradient-bias, the window deformation techniques employ higher order matching algorithms, of rigid displacement in the interrogation window and can be iteratively implemented within the multi-pass algorithms. More robust algorithms, based on window displacement, multistep and window deformation approaches (White, Take and Bolton, 2003), have adopted PIV technique for use in geotechnics.

The method yields results by comparing a series of images, of a cross section of a physical model taken at different time instants. The first image of the soil the parent image is divided into a grid of small test patches whose position is tracked through a series of subsequent images. The process includes comparing the texture (variation of pixel brightness), of each patch in the first image to the same size patches in the next image, to find the position for which a good degree of match is obtained. The same process is repeated for all pairs of images creating a complete time history of all the patch centroid positions. This process is in detail presented in (White, Take and Bolton, 2003).

A calibration needs to be performed so that the images are transformed from image space to real space and correct any system errors (i.e subtract camera and lens distortion). This is achieved commonly by using a grid of target markers which form the stationary reference frame, whose positions are known in real space.

The results presented in this paper were acquired using PIVLab, a free open-source code, developed by (Thielicke and Stamhuis, (2014), W. Thielicke, E.J. ,2014). PIVlab is a Matlab code, based on state-of-the-art multi-pass window deformation algorithm. Under ideal conditions of synthetic images, where no noise and no shear exist, PIVlab is reported to provide rather accurate measurements with a random error typically smaller than 0.02 pixels/frame. PIVlab was used to analyse chute flows of Ottawa sand, and appeared to provide superior results in terms of both accuracy and spatial resolution (Sarno et al., 2018).

3. Principle of fibre optic sensing Fibre Bragg Gratings (FBGs)

In fibre optic sensing, the optic fibre (cables) transmits continuously modulated analogue streams of light, or a series of digital pulses from one point to another along the optic fibre. Cladding material keeps the propagating light pulse inside the glass core. The buffer coating and the jacket are used for resistance to external or internal interferences and for the protection of the glass core (Iten, 2011). The pulses are generated to specific characteristics by an optical spectrum analyser. Once a pulse has propagated through optic fibre, it is a fed into an interrogator or optical spectrum analyser (Othonos, 2000). The pulse is then analysed by the device, to determine any attenuation or change in wavelength (which may have resulted from scattering during the pulse's propagation.

The photosensitivity of optical fibres allows for the formation of phase structures within its' core, called gratings (Othonos, 2000). The operational principles of Fibre Bragg gratings (FBGs) is based on the presence of these gratings within the optical fibre which are created as a series of density alterations positioned periodically along the optical fibre glass core (Iten, 2011). The principle of operation is based on Bragg's law. According to Bragg's law, a portion of light travelling through the optic fibre, with a specific wavelength, is reflected when it passes a Bragg grating. The value of this specific wavelength at which a light ray is reflected, is called Bragg wavelength. This value is dependent on the distribution of the Bragg gratings along the optic fibre (grating period) as well as the refractive index of optic fibre. All the other light rays with different wavelengths pass the Bragg grating undisturbed. The light ray that is reflected provides information for potential strain changes. This is because the Bragg grating period is dependent on the strain in the specimen being monitored (Iten, 2011). The FBG wave-length change is sensitive to tensile stress, compression and changes due to temperature (Yin & Zhu, 2008). The relationship between the refractive index of the fibre's core, grating period and Bragg wavelength is expressed mathematically as:

$$\lambda B = 2nA \qquad (1)$$

Where λB = Bragg wavelength; n = effective index of refraction of the core; and A is period of index modulation.

The change in wavelength may be related to axial strain (tension and compression along the fibre) and temperature using the model for Bragg wavelength shift (Udd & Spillman, 2011)

$$\Delta\lambda/\lambda B = \beta\varepsilon + \varsigma\Delta T \qquad (2)$$

Where $\Delta\lambda/\lambda B$ = change in wavelength to Bragg wavelength ratio; β = elastooptic coefficient; ε = axial strain in microstrain (με); ς = thermooptic coefficient in /° C; and ΔT = change in temperature within the tested specimen, in C°.

Typical FBG sensors have constants of $\beta = 0{,}769$ and $\varsigma = 7.64 * 10\text{-}6$ /°C. The measurement resolution for FBG sensors can be as high as 1 με. The operation of an FBG system is illustrated schematically on Figure 1. A pulse is introduced into the optic fibre from a broadband source. The reflected signal with the Bragg wavelength value returns to the interrogator system (optical spectrum analyser) after it is reflected by the Bragg grating. The signal is processed by the interrogator system, and the magnitude of strain in the soil mass is determined.

4. Experimental set-up

4.1 1g shaking table

In the performed tests, sinusoidal horizontal base shaking was applied to a small model, using a Quanser Shake Table II. This device is an educational shake table which can apply earthquake motion to soil models of up to 7.5kg and achieve acceleration of 2.5kg. The overall configuration is presented in Figure 2a. A dual axis ADXL210E accelerometer is mounted underneath the stage to measure the acceleration of the stage in both x and y directions. The sensor has a range of ± 10g and its noise is ± 5.0mV which is equal to 0.5±mg. The analogue sensor is calibrated such that 1 Volt equals 1g. Input signals are generated horizontal and sinusoidal. The device allows for control of the amplitude and frequency of the sinusoidal displacement signal as well as the duration of the model earthquake. The stroke can be varied from 0 to 7cm amplitude and frequency from 0 to 10Hz, hence achieving a maximum acceleration of 1.0g. The model is contained in a small-scale Perspex glass sheet box, Figure 2b.

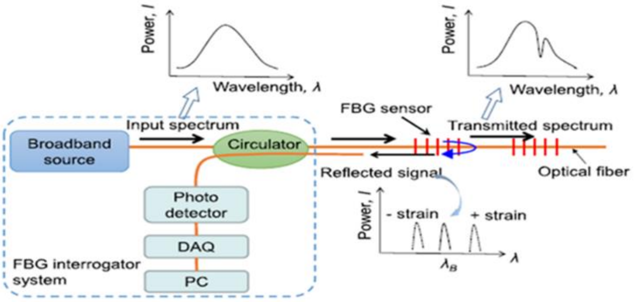


Figure 1: FBG System (after Xu et al., 2017).

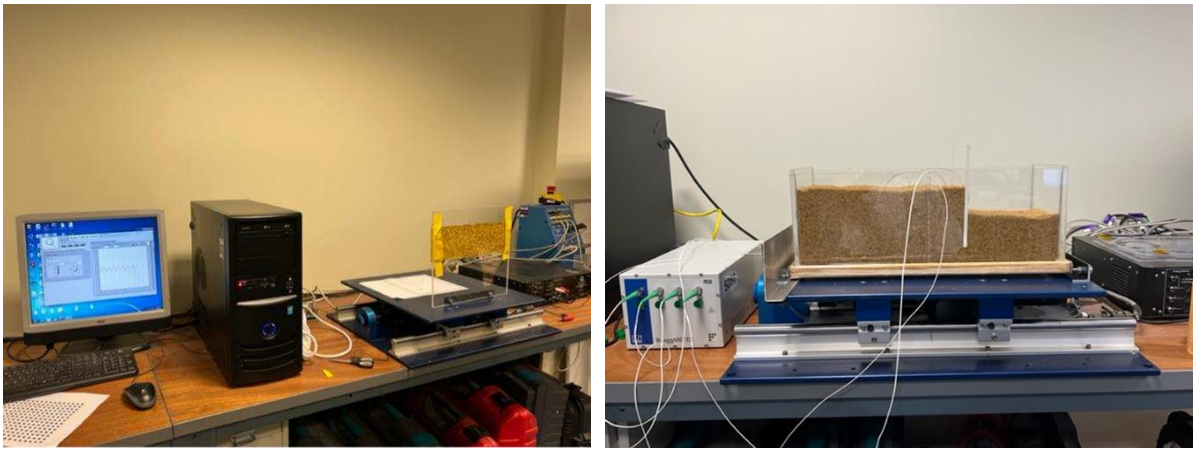


Figure 2a: LJMU 1g Quanser Shake Table II apparatus to the left, **Figure 2b** to the right model container, with wall and fibre cables embedded in the model, and FS 22 Interrogator.

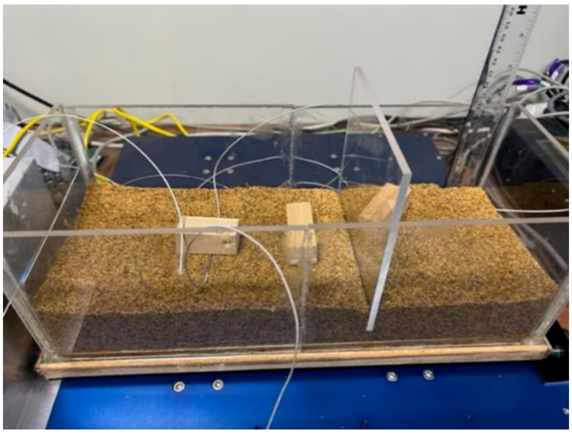
4.2 Digital Camera

The digital video camera, used in the study, was a FlowSense USB 2.3M camera which offers 1920 x 1200 px max image and the capture rate was 160 (Hz) /sec. The fitted lens is 35mm. This camera is capable of 160 frames per second at 2.3Mpixel resolution. The distance from the camera lens to the plane of the model must be greater the minimum focus distance, (typically 200-300mm). For the purposes of the tests 100 frames were acquired. The images were extracted using Dantec Systems software, which is a software package for image acquisition and analysis part of the EduPIV setup. It contains tools for configuration, acquisition, analysis, post-processing of acquired data. Includes built-in presentation and analysis modules which give several possibilities and combinations of processing and display of data.

4.3 Model preparation

In order to model the retaining wall a Perspex glass sheet with internal dimension height 150mm, length 400mm, and depth150mmm. The retaining wall was also made of a Perspex sheet 150mm high, allowing sufficient height above soil level. The soil used is Leighton-Buzzard sand (Fraction B), which has a critical state friction angle ϕ_{crit} = 33°, and a specific gravity Gs = 2.65 as reported by (Marketos and Madabhushi, 2004). The range of void ration maximum and minimum void ratios of 0.81 and 0.49 respectively as reported by Mak (1984). This specific sand was selected as is relatively coarse grained, and is anticipated to provide sufficient texture, and allow for its accurate tracking through time.

The sand was poured loosely from a height in the Perspex box to a relative density of 50%. Uniform soil conditions were created in the soil. The fibre optic sensors were installed in the box at selected locations close the influence zone of potential collapse. For the purposes of this project four FBGs sensors were installed (one for measuring temperature and three for measuring strain). Three sensors were installed at left hand side of the model. The one was placed 2cm below the surface and the other at the other lower tip of the wall (10cm), one for strain and one for temperature compensation. A third strain sensor was placed at the right-hand side of the model at tip of the wall, Figure 3a. An FS 22 – Industrial Bragg METER DI (Standard) Octo channel FC/APC was used to interrogate the Fiber Bragg Grating from the sensing cables embedded in the model. The data were collected at a high sampling rate of 100 Hz/. The strain resolution ≈ ± < 1 με the scan frequency: 1 kHz and the wavelength range: 1510-1590 nm.



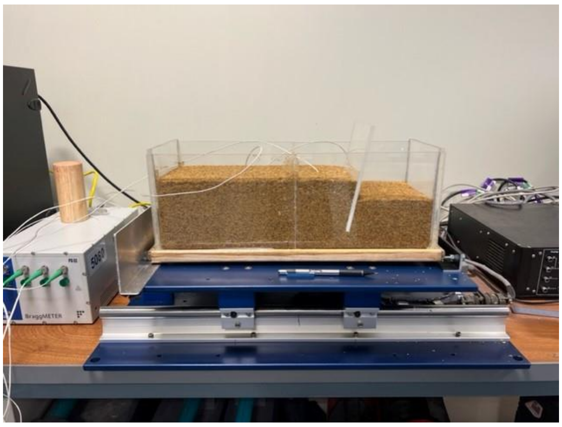


Figure 3a: Showing the three sensors placed at the same level at the left is the temperature sensor and closer to the wall are the strain sensors **Figure 3b** Position of the cantilever wall after the end of the shaking event.

5. Performed tests

A series of four tests were performed considering H/D ratios and model earthquake, which are summarised in Table 1. The shaking applied was sinusoidal at a frequency of 4Hz, 5mm amplitude, for the first 3 seconds of the event which was subsequently increased to 5Hz, 5mm. All tests resulted in a clear failure mechanism. The overall failure mechanism saws that the wall rotated and translated horizontally, and also the wall sank into the soil below. In this paper the results of test 3 are presented.

In order to run the PIV analysis a patch close to the the tip of the wall was selected above and close to the backfill soil surface. The wall was subjected to horizontal acceleration and an incremental movement away from the backfill during the forward acceleration cycles, where an active failure wedge was developed.

Table 1: List of different tests performed.

Test ID	**Depth of model (mm)**	**Height of wall**	**H/D**	**Void ratio**	**Relative density (%)**	**Shaking duration (s)**	**Peak horizontal acceleration**
SM1	112	100	0.89	0.64	50	20	0.12
SM2	100	100	1	0.63	50	20	0.16
SM3	135	115	0.85	0.63	50	16	0.22
SM4	100	100	1	0.64	55	16	0.20

6. Results

Preliminary results from the PIV analysis and FBGs measurements, are presented through Figures 4 and 5 below. The wedge failure mechanism at an intermediate phase of the loading procedure and the location of the sand particles as derived by the PIVlab analysis is presented in Figure 4 for the reverse movement. As the wall moved away from the higher side of the soil wedges moved on both sides of the wall. The coarse sand appears to be moving faster closer to the surface than further down, indicating some horizontal shearing.

The strain results for each sensor from the model test are presented in Figure 5, strain vs time plot. The strain results are calculated from the wavelength changes experienced by the embedded strain sensors and temperature sensor, based on Equation (2). A good response is observed from the FBG strain sensors during the loading procedure as strains increase while seismic loading increases, until failure of the slope model at approximately 20 s. The strain measurements indicate compression status at the start of the earthquake and tension state after the end of the earthquake.

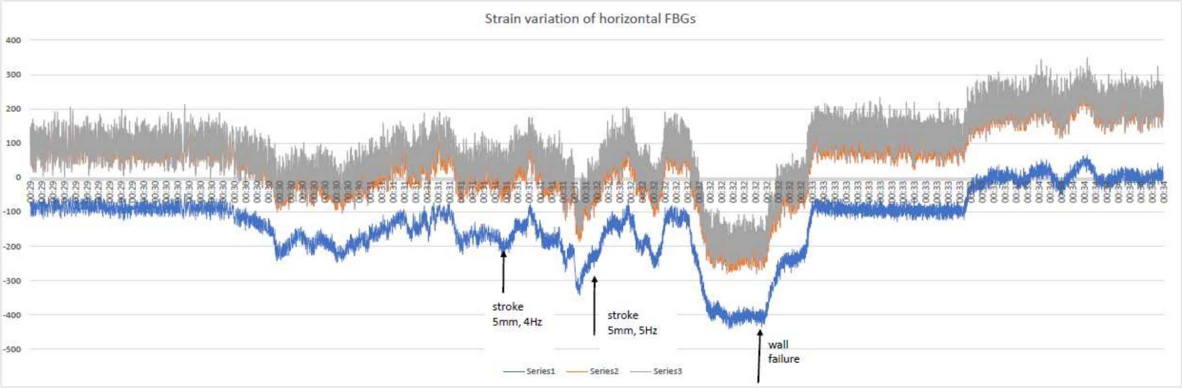


Figure 4: Strain variations.

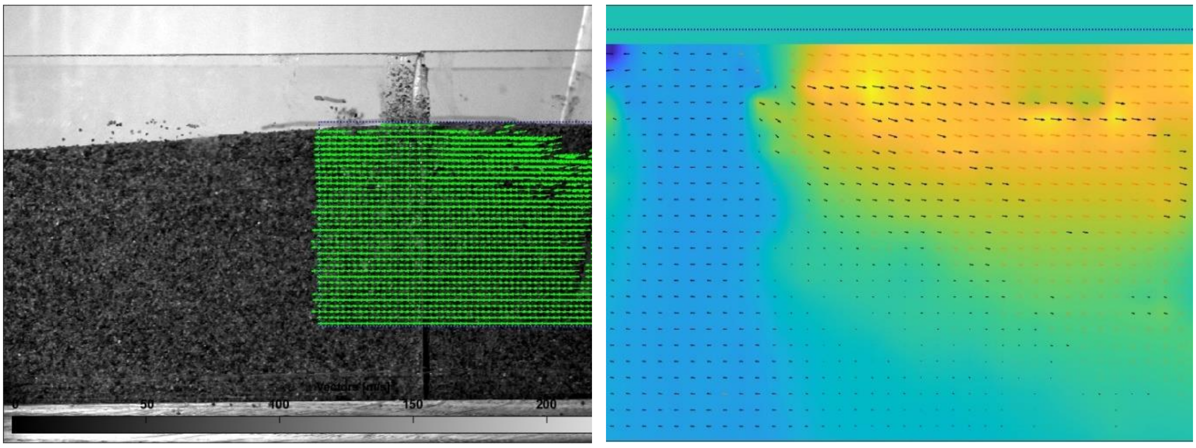


Figure 5: Flow vectors during reverse movement to the left, flow vectors during positive base movement to the right.

7. Conclusions

In this study, a retained dry scaled sand slopes was tested under seismic loading while a relatively low cost method was used, including an educational shake table and an educational, EduPIV setup. More specifically a scaled slope stabilized by a retaining wall was analyzed via PIVlab and a wedge failure mechanism was captured using PIVlab open-source code after the image analysis. Monitoring and recording of strain levels was made possible with the use of Fibre Brag grating optical fibre sensors. The obtained strain signatures informed on localised ground displacement field with high precision. FBG sensors can record strain signature and inform an early warning system and therefore support a proactive approach towards potentially induced failures. None of the sensors failed during the test, which is showing that this instrumentation is suitable for use in physical model studies. Further testing is planned to allow to for the development of more advanced models, and study the case of a wet slope susceptible to liquefaction. It is also planned to use GeoPIV for the image analysis and compare the two algorithms.

The performed tests and the adopted methodology, have a strong educational component, suitable for undergraduate students, as clearly and directly exposes students to failure mechanism capture and interpretation, along with strain measurements through advanced sensing methods.

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