AN EVALUATION OF THREE DIFFERENT IMAGE CAPTURE METHODS FOR MEASUREMENT AND ANALYSIS OF DEFORMATION WITHIN A GEOTECHNICAL CENTRIFUGE

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ABSTRACT

In a geotechnical centrifuge experiment, long image sequences are often captured to obtain information about how soil responds to load. Information obtainable from the on-line dynamic deformation analysis of such sequential images can be important in order to visualise and monitor progress and ultimately to control the course of the experiment. In this paper, the geometric qualities of three methods which can be used for the analysis and storage of long image sequences are evaluated: (1) use of an S-VHS video recorder; (2) use of J-PEG image compression; and (3) the on-line measurement of target image co-ordinates by an analysis procedure based on the sequential update of prior knowledge. The precision and accuracy obtained with respect to the S-VHS video recorder and different J-PEG compression factors are discussed. A suitable algorithm for on-line dynamic target location and deformation analysis of the sequential images produced during centrifuge tests has been derived and successfully applied in practical experiments.

1. INTRODUCTION

Settlement can be a problem during soft ground tunnelling in urban areas where buildings can be put at risk. Settlement and ground movement can be simulated in the laboratory using a geotechnical centrifuge (Taylor, 1995). The high forces generated by the centrifuge allow not only the soil model to be scaled down but also for a corresponding reduction in the time for deformation to take place. The soil sample is placed in a box with a perspex face. Targets are placed in the visible face of the soil and their locations imaged and measured. Target movements are traced in image space to obtain deformation information and after appropriate transformations mathematical models can be used to analyse the geotechnical performance of the soil. Typical experimental duration's range from a few hours to a couple of days. An analysis of sequential images of the soil model under loading within the centrifuge can provide useful information about the response of the soil. If measurements of the imaged targets can be obtained quickly enough the information derived can then be used to optimise the experiment. Initial research into the sequential tracking of 400 to 700 small circular targets in centrifuge experiments has been reported (Clarke at al, 1995).

There are several important requirements for the successful capture and analysis of sequential images in a centrifuge experiment: rapid image grabbing; large data storage capacity and most importantly; images must be of sufficient quality for measurement and quantitative deformation analysis. This paper describes comparative experiments to assess the geometric performance of a weighted centroid target location algorithm between direct frame grabbing, S-VHS video recording, and J-PEG compression. A methodology for the on-line tracking of target images leading to dynamic deformation analysis without the need to store each image is also discussed.

2. THE CAPTURE OF IMAGE SEQUENCES WITH A S-VHS RECORDER

A S-VHS recorder has been used to archive image sequences during centrifuge tests, a frame grabber can then be used off-line to capture individual images of interest. The use of a S-VHS recorder to store images on tape has the advantage of providing large storage capacity and the ability to capture sequential images at camera frame rate. The accuracy of target location from taped images has been evaluated by Hoflinger and Beyer, 1993, and by Shortis et al, 1993. Under ideal conditions, target location accuracy can be better than one of tenth of a pixel. However in our case, in which black targets are inserted into grey sand and clay soils, target location errors are typically much larger. In this application, each imaged target is small,

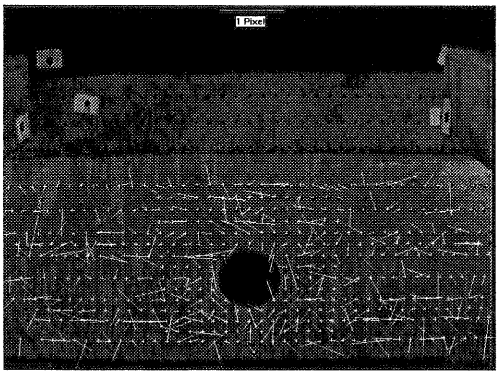

Figure 1 Discrepancy vectors from two consecutive S-VHS images

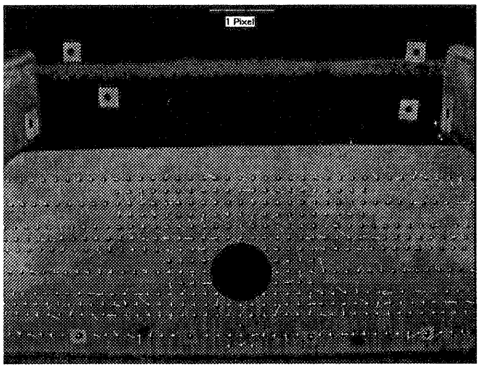

Figure 2 Discrepancy vectors from two consecutive directly grabbed images

typically occupying 3x3 to 5x5 pixels. The target intensity level is also low, normally 50 - 150 grey scale levels above the background. Figures 1 and 2 illustrate an example of the differences between simultaneously frame grabbing and tape-grabbing images of a stable soil sample. Figure 1 shows the discrepancy vectors between target locations measured on two consecutive images recorded by an S-VHS recorder and subsequently captured from tape by an EPIX frame grabber. Figure 2 shows target location discrepancy vectors between two consecutive images grabbed directly from the monochrome camera with the EPIX board. Since the target array and camera were stable during these two image sequences, the difference in magnitude between the vectors can be attributed to degradation caused by the S-VHS recorder. Comparing the two figures, the geometric degradation of target locations from the S-VHS recorder is up to 0.5 pixels, about four times larger than direct grabbing.

To rigorously verify the observed metric performance of the S-VHS system, a number of laboratory experiments using different types of target and illumination have been carried out. Both retro-reflective and black conventional targets of different sizes were used. Each target type was attached to a board, the board being white for the simple black targets and matt black for the retro-reflective targets. The boards were fixed in turn to an optical bench. A Pulnix TM-6CN camera was fixed on the bench and an adjustable source of light placed behind the camera. A JVC, SR-S368E S-VHS recorder was used both to record the sequential images and to play back the tape for image grabbing. A comparison between target location errors obtained using the S-VHS recorder and direct image grabbing based on different target type, size, and illumination has been made. In all cases, a centre weighted algorithm (Chen & Clarke, 1992) has been used to measure target image co-ordinates. Results are illustrated in figures 3, 4, 5, & 6.

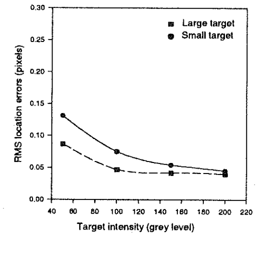

Figure 3 RMS location error of retro targets using S-VHS

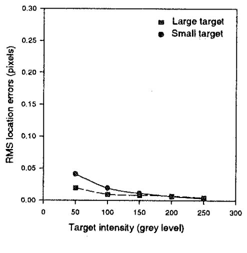

Figure 4 RMS location error of retro targets by direct grabbing

Figures 3 and 4 show the RMS x co-ordinate location error with different target image intensities and sizes for retro-reflective targets captured using each method. Two target sizes were used: small (imaged at about 3 pixels in diameter) and large (about 10 pixels in diameter). Each image acquisition and location procedure was repeated 100 times under stable conditions and a RMS target location discrepancy computed for each set.

The results shown are dependent on the experimental set-up used, but the differences between results provide some clear indications. It can been seen that in the case of directly grabbing retro-reflective target images differences in target size have only a very small influence. Target location repeatability is better than 1/20th pixel. In the S-VHS case, if the imaged targets have good contrast and are of reasonable size, RMS locations of the order of 1/20th a pixel can be obtained. However if target size or contrast is lowered the RMS location error increases rapidly.

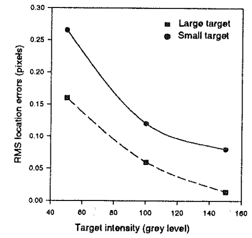

Figure 5 RMS location error of conventional targets through tape

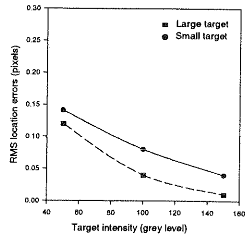

Figure 6 RMS location error of directly grabbed conventional targets

In all S-VHS cases errors in the y direction were found to be lower. This suggests that line-jitter is a significant effect.

Figures 5 and 6 show the RMS x co-ordinate location discrepancy given different intensities and sizes of black conventional target using both direct grabbing and S-VHS recording. It is difficult to set up a high contrast target image using black targets against a white background. Consequently the performance of the conventional targets is much poorer than that of retro targets. RMS location error can be up to 0.3 pixels with a maximum target location error of 1 pixel. Results from these laboratory experiments were found to be in agreement with practical geotechnical applications.

The degradation in the S-VHS data are caused by increased image noise and timing errors introduced during the analogue recording process. The analogue recording process also introduced a reduction in contrast, especially if the targets were small and of low initial contrast. Tape recording is also undesirable because a large quantity of data storage is still required when selecting and grabbing images on playback. Repeated use of the tape in this way will give rise to some loss of target location accuracy. To summarise, for small targets of low image intensity, occupying less than 3x3 pixels and less than 100 intensity values, image measurements from the S-VHS recorder gave rise to target location errors of up to one pixel. Direct image grabbing, under the same circumstances, resulted in a maximum measurement noise of less than 1/10th of a pixel.

3. EVALUATION OF THE EFFECT OF JPEG IMAGE COMPRESSION ON TARGET LOCATION ACCURACY

To overcome the restrictions of using a S-VHS recorder in centrifuge tests, on-line image compression schemes have been considered. Two generally accepted standards are MPEG (LeGall, 1991) and JPEG (Wallace, 1991). These methods have become popular in recent years because of their high compression ratio, optimisation for visual quality, and potential for hardware implementation. MPEG is a video compression algorithm, which relies on two basic techniques: block-based motion compensation for the reduction of temporal redundancy and transform domain-based compression for the reduction of spatial redundancy. The MPEG standard is designed for the compression of sequential images which have high redundancy between successive images. However because of hardware availability and the typical usage of individual images in photogrammetric applications, only the JPEG compression method has been evaluated at the time of writing.

At first sight, the JPEG image compression algorithm proposed by the Joint Photographic Experts Group (JPEG) offers a viable way of accomplishing image compression tasks. Framegrabbers with JPEG hardware are widely available commercially providing imaging rates ranging from 2 to 25 frames per second. Compression ratios are typically user selected according to visual quality criteria and desired frame rate to range between 10 and 50 times. The effect of the method on the geometric quality of the imaged targets both for the 2-D centrifuge case and in 3-D photogrammetric measurement is discussed and evaluated below.

3.1 The JPEG Baseline Method

JPEG's most commonly proposed lossy image-compression standard is called the Baseline method and is based on a Discrete Cosine Transform (DCT). The specification also contains two other compression procedures: quantization of the spatial frequency amplitude components from DCT and; Huffman run-length encoding of the quantized spatial frequency amplitude. The flowchart for the JPEG Baseline method is shown in figure 7.

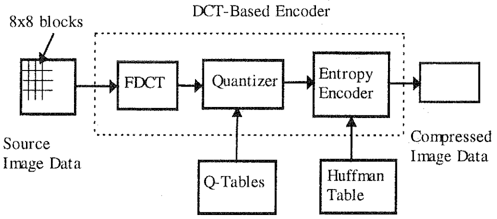

Figure 7 JPEG image compression flowchart

The working principal of the JPEG Baseline method can be described as follows. Firstly the greyscale image is divided into 8x8 pixel blocks. This reduces the complexity of the subsequent processing steps and enables faster implementation of the algorithm. Each sub-image block is processed individually by inputting to the Forward DCT (FDCT). The FDCT converts the 8x8 blocks of grey scale image information into an 8x8 frequency domain block which is a function of the two spatial dimensions x and y. The output of the FDCT is a set of 64 coefficients from the original 8x8 matrix. Each coefficient represents the magnitude of the cosine basis function at a particular frequency. For colour images the process can be regarded as the compression of multiple grey scale images which are either compressed entirely one at a time, or by alternately interleaving 8x8 sample blocks from each image band in turn.

After the FDCT, each of the 64 DCT coefficients are quantized to a corresponding value in a predetermined quantization table (Q table). This is carried out by dividing each DCT coefficient by the corresponding quantization element and rounding the result to the nearest integer. This quantisation process constitutes the major lossy part of the JPEG compression procedure. The choice of quantization parameter (Q factor) is crucial to achieve a best compression in terms of data storage and information loss in the image.

The final DCT-based encoder processing step is entropy coding. This step achieves additional compression losslessly by encoding the quantized DCT coefficients according to their statistical characteristics. Huffman coding techniques are used in the JPEG Baseline proposal. Huffman coding requires that one or more sets of Huffman code tables be specified by the application. The same tables used to compress an image are needed to decompress it. Huffman tables may be predefined or computed specifically during an initial statistics-gathering pass through the data prior to compression.

The JPEG algorithm can be implemented in either hardware or software. For this evaluation, a standard TIFF (Tag Image File Format) software library has been taken from the public domain (FTP site: ftp.sgi.com//graphics/tiff) and integrated into an in-house PC based photogrammetric measuring system. The software can support various image compression schemes including a standard public JPEG software library (FTP site: ftp.uu.net//graphics/jpeg).

3.2 Analysis of Single Images

The two main applications of image compression are in image transmission and storage. In the centrifuge application the storage of many long image sequences is currently the major concern. Typical centrifuge images have a high information content so that conventional lossless compression has a very low compression ratio. For example, the LZW lossless method can only provide a compression of 1.8 times. The influence of the JPEG method on target location has been tested in a series of laboratory experiments using both retro-reflective and conventional targets under different conditions. Experimental results have been analysed according to target location quality, not the conventional visual quality to which JPEG is optimised.

Q-Factor	Compression ratio	RMS image discrepancy	Max. image discrepancy
20	20.4	0.083	0.952
30	16.8	0.069	0.643
40	14.6	0.063	0.247
50	13.0	0.056	0.165
60	11.6	0.048	0.133
70	9.9	0.041	0.125
80	8.1	0.032	0.102
90	5.5	0.024	0.096
100	1.9	0.002	0.020
lossless	1.8	-	-

Table 1 Geometric performance of JPEG with different Q factors for a typical centrifuge image

An image similar to that in figure 2 was used to provide a conventional target image for compression analysis. The image was compressed using Q factors ranging from 20 (high compression) to 100 (low compression). Target image measurements for each Q factor were computed and compared with those from the uncompressed original image. Table 1 demonstrates that JPEG compression performance is closely related to the mean RMS image discrepancy. Even given image compression ratios of 10:1, the mean RMS image discrepancy is of the order of 1/20th of a pixel. Figure 8 illustrates discrepancy vectors between the original image measurements and those from the compressed image at a Q-factor of 60. When compared

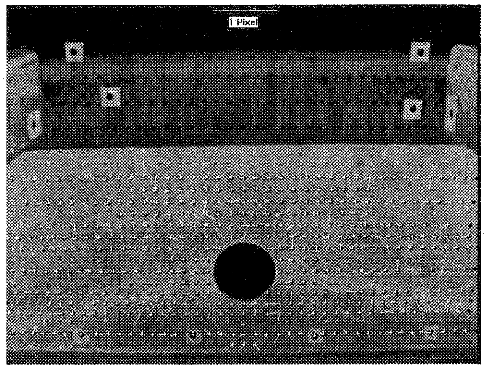

Figure 8 Discrepancy vectors produced by compressing the image in figure 2 at a Q factor of 70

46	46	46	45	45	45	44	45	46	48	48	44	43	45	46	46
43	43	47	46	41	43	45	47	48	46	45	43	41	43	45	43
45	42	40	40	42	45	46	46	46	45	46	47	46	47	48	46
42	45	43	42	43	44	43	43	45	46	46	45	45	47	48	46
45	43	44	47	47	47	47	47	45	43	43	45	44	43	45	48
47	42	42	46	47	44	41	43	45	47	47	47	48	48	46	45
45	44	44	45	43	43	44	43	45	46	46	43	43	47	48	45
44	45	46	46	45	43	42	41	43	44	43	42	42	41	42	43
42	41	44	46	44	43	45	45	45	45	44	45	44	42	43	45
45	44	41	42	47	52	55	57	56	52	40	46	46	45	44	44
41	44	45	46	54	76	112	144	153	125	79	52	46	43	44	46
46	44	43	51	73	131	178	195	192	183	148	88	49	44	48	48
46	45	45	59	103	162	193	195	192	190	163	107	58	42	41	40
43	45	45	55	97	159	192	194	191	181	147	93	55	45	46	45
39	40	40	44	66	118	171	189	179	153	109	65	46	45	42	41
45	45	47	58	61	64	66	83	86	72	56	51	49	44	41	41
45	43	41	41	43	45	47	48	48	46	48	48	43	39	40	44
39	41	43	45	45	43	42	42	45	47	46	43	43	45	48	48
43	45	45	44	41	41	42	42	42	45	46	41	41	46	44	42
42	45	49	49	44	42	41	41	44	46	45	44	43	41	43	43
42	44	43	41	43	45	46	46	46	46	43	40	42	44	43	43
43	43	44	46	45	44	45	45	45	46	45	44	44	44	44	47
41	42	41	40	40	44	44	40	42	45	47	47	46	44	45	44
41	41	41	41	41	41	42	43	44	44	45	46	46	46	46	48
48	43	46	44	44	43	39	38	43	46	44	42	43	45	45	43

Figure 9 a) Intensity values of a target before JPEG compression

45	45	45	45	45	45	48	48	47	46	46	45	44	44	46	45
43	43	43	43	43	43	48	47	47	46	46	45	45	44	46	45
42	42	42	42	42	42	47	46	46	46	46	46	46	45	46	46
42	42	42	42	42	42	46	46	46	46	46	46	46	47	46	45
43	43	43	43	43	43	44	45	45	46	46	47	47	48	46	45
45	45	45	45	45	45	44	44	45	46	46	47	48	48	46	45
46	46	46	46	46	46	43	44	44	45	47	48	48	49	46	45
47	45	46	48	45	40	42	42	44	46	47	47	45	44	44	44
46	47	47	48	47	45	46	36	20	31	43	50	46	38	44	44
44	45	43	43	47	52	66	66	63	57	49	44	43	45	44	44
43	41	38	48	57	75	110	134	150	129	83	48	44	55	44	44
42	42	41	52	86	122	166	190	206	187	137	86	55	46	44	44
42	46	49	64	111	160	200	201	200	192	167	121	66	27	44	44
41	47	45	55	101	152	193	190	184	171	144	104	60	30	44	44
40	45	35	34	73	123	169	185	188	157	104	60	46	49	44	44
47	48	49	49	58	58	76	75	72	68	62	56	51	48	44	44
44	45	46	46	47	47	50	49	49	47	44	41	37	35	44	44
42	42	43	44	44	45	38	39	41	42	42	41	40	39	44	44
42	43	43	44	45	45	41	43	45	46	47	47	46	46	44	44
44	45	45	46	47	47	41	41	43	44	44	43	41	40	44	44
44	45	46	46	47	47	43	44	45	45	45	43	42	40	44	44
42	42	43	44	44	45	45	46	47	49	49	48	47	47	44	44
39	39	40	41	41	42	36	38	40	43	45	45	45	45	44	44
42	42	42	42	42	42	42	43	45	46	46	45	43	42	46	46
46	46	46	46	46	46	42	43	45	46	46	45	43	42	46	46

b) Intensity values of the target after JPEG compression at a Q=60

with figure 2, it can be seen that the discrepancies are even smaller than the random target location noise between any two successive directly grabbed images.

The main cause of the degradation in target location precision is in the JPEG compression quantization procedure, where pixel intensity values can be changed. This can result in a shift in the computed target location co-ordinates. Fortunately the effect is not as great as might be expected since the JPEG algorithm achieves most of its compression by reducing information in the low frequency portion of the image. This results in a merging of the background pixel levels and lower target intensity levels but has little influence on the target centroid properties. Figures 9a and 9b show the pixel intensity distribution for a target before and after compression at a Q factor of 60. It can be seen that the target images are not smeared and that in fact an even higher contrast has resulted.

3.3 JPEG within an analogue CCD camera network

For a photogrammetric evaluation of the JPEG procedure, two testfields were built (Figure 10a and 10b). The first, a black retro-reflective targeted testfield, consisting of a 250mm x 230mm aluminium base plane with 28 inserted rods of differing lengths. About 50 round retro-reflective targets, 2mm in diameter, were placed on top of the rods and to the base of testfield. The second testfield, representative of the centrifuge case, consisted of 80 black targets on a simple white board. A Pulnix TM-6CN camera, with a 16mm Fujinon 'C' mount lens, was used to grab images at each of the four corners of an imaginary square based pyramid network. The target image size in each exposure varied from 3 to 5 pixels in diameter. JPEG compression was carried out on each set of images using Q factors ranging from 20 to 100.

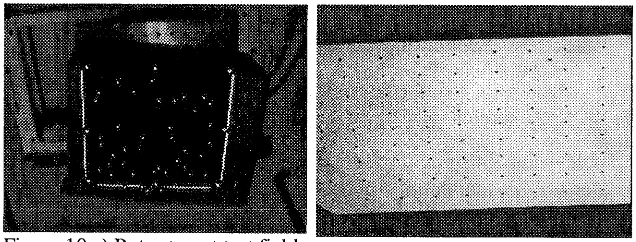

Figure 10 a) Retro target test field b) Conventional target test field

A free net bundle adjustment was computed for each image compression set. Camera calibration parameters were computed for the lossless case, then held fixed for each different image compression set. In this way results between adjustments could be directly compared. Table 2 shows the compression ratio over the same Q factor range, 2D image measurement discrepancies, and RMS image co-ordinate residual after each photogrammetric adjustment.

Q-Factors	Compression ratio		RMS 2D image discrepancy (pixel)		Adjustment RMS image residual (pixel)	
	retro	conv.	retro	conv.	retro	conv.
20	32.0	37.0	0.054	0.101	0.098	0.124
30	28.1	31.8	0.038	0.081	0.098	0.117
40	25.2	27.4	0.032	0.069	0.097	0.060
50	22.7	23.1	0.026	0.068	0.103	0.060
60	20.4	19.1	0.020	0.060	0.096	0.053
70	17.2	14.8	0.016	0.055	0.098	0.056
80	13.5	11.0	0.014	0.042	0.096	0.055
90	8.5	6.9	0.009	0.027	0.099	0.053
100	2.5	2.3	0.002	0.003	0.099	0.053
LZW	2.5	2.3	-	-	0.098	0.053

Table 2 Performance of JPEG with different Q factors for two test images

Despite differences in image content, both retro and conventional target cases have a very similar compression ratio at a given Q factor. However, the retro-reflective targets have provided 2D RMS image residuals which are about two times better than those attained with conventional targets. This is because the retro targets can provide a very high contrast target image, about 220 intensity levels out of the available 256 intensity levels in the 8 bit image. The conventional targets provide a signal of the order of 150 intensity levels.

With the exception of conventional targets at a Q factor of 30 and less, change in Q factor does not significantly affect the photogrammetric precision achieved. This is shown clearly in figure 11, where it can be seen that at Q factors of 40 and over about 1 part of 11,000 is achieved for all photogrammetric networks. The slightly better result in the conventional target case is due to the planar nature of the test field used in this case. It should be stressed that the four image network combined with the limited optics and electronics inherent in the analogue CCD camera used to record the images has only allowed a limited evaluation of JPEG compression.

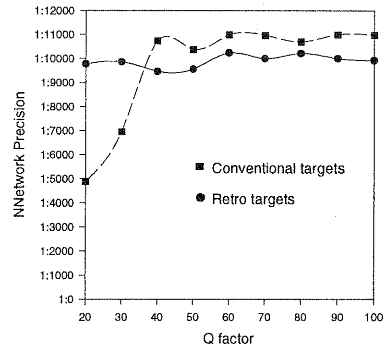

Figure 11 Co-ordinate precision for the two testfields and different JPEG Q factors

3.4 JPEG within a strong digital CCD camera network.

To evaluate JPEG further it was decided to repeat the series of tests with a strong network of images captured with a state of the art digital camera. A suitable data set was kindly offered by Professor Mark Shortis of the University of Melbourne (Shortis et al. 1996). The data consisted of a convergent image set of a targeted wall taken from 6 camera stations. At each station a single DCS 420 camera fitted with a 20mm lens was rotated 4 times by 90 degrees to give 24 images. This resulted in an imaged target size of the order of 10x10 pixels, target image intensities being about 170 grey levels. With no compression the original network precision was of the order of 1:116,000 in 3-D space and about 1/20th of a pixel in image space.

Q factor	Compression ratio	2D RMS image discrepancy (pixel)	Adjustment RMS image residual (pixel)	Network precision
30	53.2	0.0737	0.082	1:74,820
40	50.0	0.0620	0.075	1:96,100
50	47.9	0.0478	0.071	1:103,360
60	45.6	0.0390	0.069	1:108,170
70	42.4	0.0314	0.066	1:112,110
80	35.3	0.0235	0.065	1:115,130
90	16.4	0.0174	0.063	1:115,810
100	2.6	0.0053	0.063	1:116,000
LZW lossles	4.4	-	0.063	1:116,000

Table 3 Performance of different Q factors for the DCS420 network

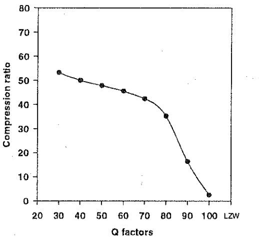

Figure 12. Image compression ratio with different Q factors.

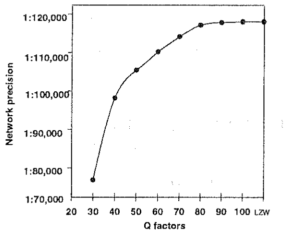

Figure 13. Network precision with different Q factors.

All images were compressed using Q factors ranging from 30 to 100. Target image co-ordinates were then measured as before using the centre weighted algorithm and downloaded into a series of identical bundle adjustments. Table 3 and figures 12 and 13 illustrate: the image compression ratio; RMS image discrepancy by simple 2D comparison with the uncompressed image and; the RMS image residual computed within the bundle adjustment.

From these results, it can be seen that the influence of JPEG compression has to rise above about 1/30th pixel before any significant influence on photogrammetric adjustment precision is seen. The strength of this well designed network has allowed much less redistribution of error into the estimated target co-ordinates and camera orientation parameters, consequently a clear trend of Q factor against object space precision can be seen.

In summary, careful use of JPEG image compression can be recommended for retro-targeted close range photogrammetry. The compression ratio can be arranged from 10 to 50 times according to the qualities of the imaging system, photogrammetric network and required co-ordinate data specification. For example, if the system is capable of target location precision better than 1/20th pixel, the Q factor should be set between 90 and 100. If the target location precision is less than 1/10th a pixel, a Q factor can be of 80 or lower can be used. A particularly useful indicator for an appropriate Q factor is the discrepancy between target locations measured on the compressed and uncompressed image.

4. ON-LINE DYNAMIC TARGET LOCATION

Both S-VHS and JPEG can store long sequential images in real-time or near real-time for subsequent processing. However, in some experimental cases a rapid display of dynamic target deformation information can be required. A suitable on-line algorithm has been written to satisfy this requirement.

Practical general purpose algorithms for automatic target image measurement consist of target search, target recognition and target location processes. Most of the computational time in this process is spent on the target search and target recognition components (Chen, 1995). A new algorithm based on a prior knowledge of target locations from subsequent images in the sequence has been written. In this way the time necessary to search the whole image, recognise any targets and to compute target matches between any two successive images can be avoided. A comparison of the computational cost of the target location algorithm elements, based on a Pentium-90 PC running Windows 3.1 is shown in table 4. It can be seen that a lot of time can be spent on unnecessary operations. This is because in a targeted image the number of useful target image pixels is very small, typically between 1 and 5%. For example, in a typical centrifuge experiment image, only 5603 pixels represent the targets compared with 442368 pixels in total for the 768 x 576 image. In Table 4, it can be seen that 600ms are required to complete the target measurement process for a 400 target image, but of that, 556ms is spent on image background scanning in the target search and target recognition procedures. Only 44ms is required for the actual computation of all 400 target co-ordinates. These times do not include the matching and checking of target numbering between successive images.

Number of targets in image	100	200	300	400	500
Complete general algorithm (ms)	330	440	500	600	660
Target recognition section (ms)	119	217	267	356	404
Complete prior-knowledge based target location (ms)	11	23	33	44	56

Table 4 Some timing performances for target location calculations on a Pentium-90 PC

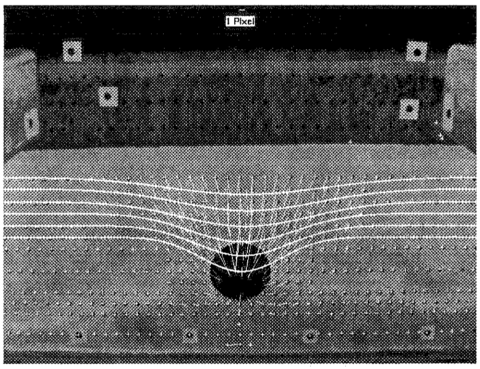

Figure 14 On-line soil model analysis computed from centrifuge image measurement data

In a centrifuge experiment, the movement of targets between any two successive images is small such that all target co-ordinate calculations can be reliably based on the target co-ordinate information of the previous image. In this way it is only necessary to access and process image data from a small area surrounding each target. The prior knowledge based target location algorithm calculates target positions from the first image using the general algorithm and then uses these as search centres for targets in the next image in the sequence. The algorithm is implemented using a stack technique. All the target co-ordinates in the first image are computed and then pushed onto a stack. With the centrifuge test underway, the x, y co-ordinates of each target are sequentially popped from the stack to provide an initial value for the target centre in each successive image. In this way a considerable number of "empty operations" and target recognition procedures are saved.

Target matches between any two successive images are not necessary since each target will have the same label as its seed point from the previous image. Deformation vectors between any pair of images may then be drawn on the computer monitor as required. Furthermore, appropriate mathematical models can be fitted to the data during the course of the experiment to obtain geotechnical parameters. Figure 14 illustrates a typical result from a dynamic view of a geotechnical experiment. At the time of writing, all of these processes can be completed under one second on a P90 PC. The information provided offers the potential to supply feedback to monitor and ultimately control the progress of the geotechnical experiment.

5. CONCLUSIONS

The S-VHS Video recorder test results, presented in figures 3 to 6 lead to two conclusions. Firstly that retro targets can achieve much better results than conventional targets in noisy situations; secondly that the S-VHS Video recorder is a particularly unsuitable storage device for small conventional targets of low contrast.

The JPEG image compression method has been developed for use with continuous tone photographic colour images and is capable of achieving very high compression ratios. It is optimised according to human visualisation requirements. However, it can offer very promising compression ratios in retro-targeted photogrammetric situations. The amount of JPEG compression which can be tolerated in images for photogrammetric measurement must be decided according to the desired target co-ordinate precision, on the quality of the imaged targets and on the performance and design of the photogrammetric imaging system. On the basis of the above experiments, it can be concluded that targeted images can be compressed using JPEG at a ratio of about 50:1 if 1/10th target location precision is sufficient and 10:1 if target location precision of the order 1/20th pixel are required. Furthermore the JPEG software has been easily combined with the TIFF format into a general purpose tool using third party software libraries.

The prior knowledge based target location algorithm has proven suitable for deformation analysis of sequential targeted images where target movement in any successive image is reasonably small. The computational cost of target co-ordinate measurement is much less than general target location algorithm, typically ranging from 10 to 60 ms depending on the number and size of the targets in use. This means that target image measurement in nearly real-time is possible without the assistance of any other hardware. More research is required to extend the method to include situations where ambiguities and target occlusions are present.

A feasibility test for the use of MPEG in the centrifuge imaging environment is required, but it is anticipated that where it is necessary to store centrifuge image sequences, a hardware based method will be used to compress and store images in real time at a compression ratio of between 10 and 20 times with less than 1/10th of a pixel measurement error. Direct co-ordinate extraction using the prior knowledge based target location algorithm will be used where higher precision is required and image sequences are not needed for subsequent visual analysis.

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