

Practical in-situ applications of DIC for large structures

N. J. McCormick ^{1, a}, and J. D. Lord ^{1, b}

¹National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK

^anick.mccormick@npl.co.uk, ^bjerry.lord@npl.co.uk

Keywords: digital image correlation, DIC, in-situ, crack measurement, civil engineering

Abstract. The paper describes recent use of Digital Image Correlation (DIC) for in-situ measurements of deformation and cracking of large civil engineering structures like bridges and power plant. Recent work at NPL has demonstrated the potential of DIC as a novel NDT tool for measuring deformation and cracking in reinforced concrete structures. This has particular application where the area of interest is in a region where inspection is difficult or costly and where direct access may have safety implications. In this case accurate measurements from pairs of images can be very cost effective.

Work is on-going in establishing the effects on the measurements caused by environmental effects and the requirement for repositioning of the camera during image capture. Techniques for mitigating these effects on accuracy will be reported. This paper will present data from some initial studies and discuss some of the factors that influence the accuracy of the technique when used outside the laboratory.

Introduction

Large infrastructure like power plant, bridges and tunnels need robust monitoring techniques to maximise lifetime and to economically schedule maintenance. Changing staff demographics means fewer skilled personnel will be available for inspection in the future and so automatic inspection techniques are required.

Full field optical monitoring techniques like digital image correlation (DIC) have potential for low cost examination of large structures where access may be difficult or costly. Full field techniques can also highlight where continuous point monitoring sensors may be best placed and the effect of repair on a structure.

DIC has had limited use outside the laboratory, but recent developments in cameras and the ready availability of cheap processing means it has considerable promise for practical in-situ measurements of large structures.

Digital Image Correlation

Digital image correlation is a technique that uses computer software to compare two images, such as digital photographs at different stages of a mechanical test. The technique was originally developed in the early 1980's [1,2] although more recent developments reviewed in [3] have enabled displacement accuracies to approach 0.01 pixels. This combined with the relative low cost of high resolution digital cameras means measurements can be made with resolutions approaching 1:100,000 of the field of view. The increase in resolution of camera images has been matched by increased low-cost computing power and this has enabled more cost effective, rapid measurements to be made.

The technique works by matching small subset images taken from two images being compared, that may be 11x11 pixels, for example. Providing there is sufficient contrast and hence uniqueness within each subset image block then a successful match can be made. By first carrying out a quick integer level comparison using a correlation function, an approximate map of the deformations required to match these subset images across the whole image field can be made. This can then be refined by using interpolation techniques to allow sub-pixel displacements combined with strain, shear and rotations to be added, thus increasing the deformation resolution of DIC.

NPL has developed analysis algorithms to allow accurate measurements to be made even from 60MPixel images and with displacement resolutions of up to 0.01 pixels. Using a distributed parallel computing system, the NPL Grid, can speed up calculations by up to 300x over a single PC.

Practical In-situ Examples

Until recently the achievable image resolution and difficulties of making suitable high quality in-situ measurements limited DIC measurements to laboratory measurements. These were mainly for materials characterisation or measurements on structures where there were large or rapidly varying strain distributions. There are examples of DIC being used for component testing of civil engineering structures [4] but relatively few examples where measurements have been made out of the lab or in-situ [5, 6]. The following examples have been chosen to give an idea of the range of structures for which DIC may be used.

Large Scale Structures: Bridges. Non-contact displacement measurements were made by mounting a camera close to a highway bridge during load testing. The measurements were made during the night and both flash lighting and ambient lighting from streetlights was used. The differences in deformation were measured between images captured with no-load and loading produced by four 32 tonne lorries being parked on the bridge structure in different locations.

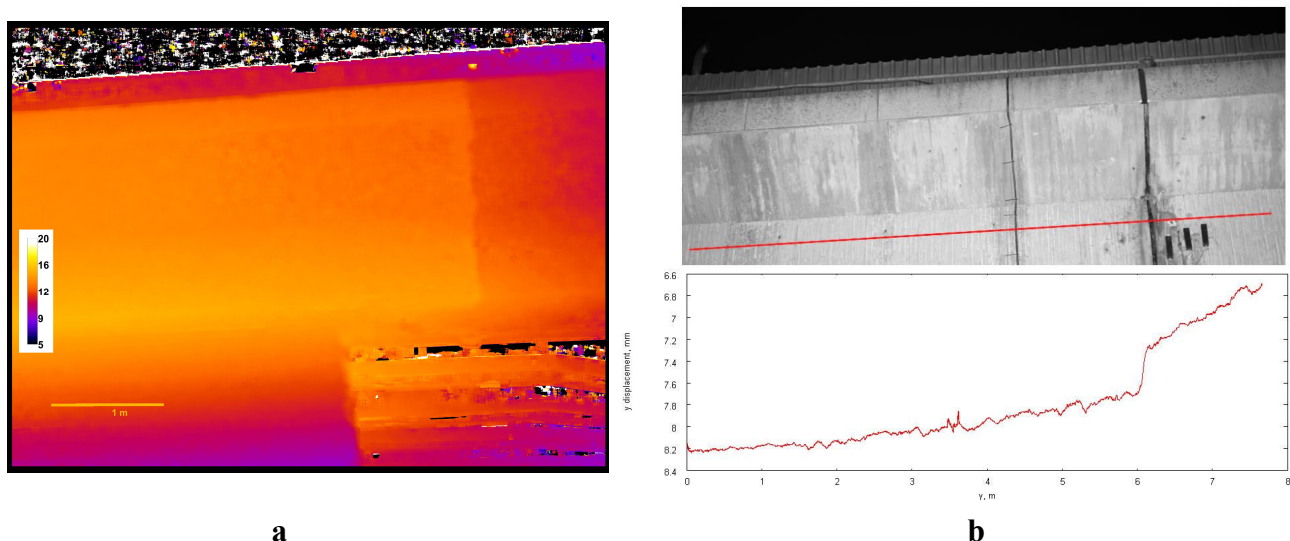


Figure 1. Displacement (in pixels) in the vertical (y) direction of a highway bridge during a static load test, Fig. 1a. Displacement (in mm) in the vertical (y) direction, Fig. 1b. The difference in vertical displacement across the bridge joint can clearly be seen in the profile measured along the red line.

The images were captured using a medium format PhaseOne camera with a 39 MPixel digital camera back using a 80mm lens at a working distance of about 15 metres. Results of the measurements can be seen in Fig. 1a and 1b these were consistent with laser tracker measurements taken at the same time.

Large Scale Structures: The London Eye. In this example two pictures were taken of the London Eye a few seconds apart, Fig. 2. By using DIC the magnitude of movement of the objects in the image can be calculated from the x and y displacements. As can be seen, Fig. 2b the edge of the London Eye has moved equally. The large amounts of noise in the background is due to the limited contrast available in the cloudy sky, and as expected the buildings behind and to the side of the London Eye show no movement.

The rim of the London Eye has moved about 0.5 m between the two images which were taken two seconds apart which implies a speed of 0.25 m/s, this compares favourably with the published speed of 0.26 m/s.

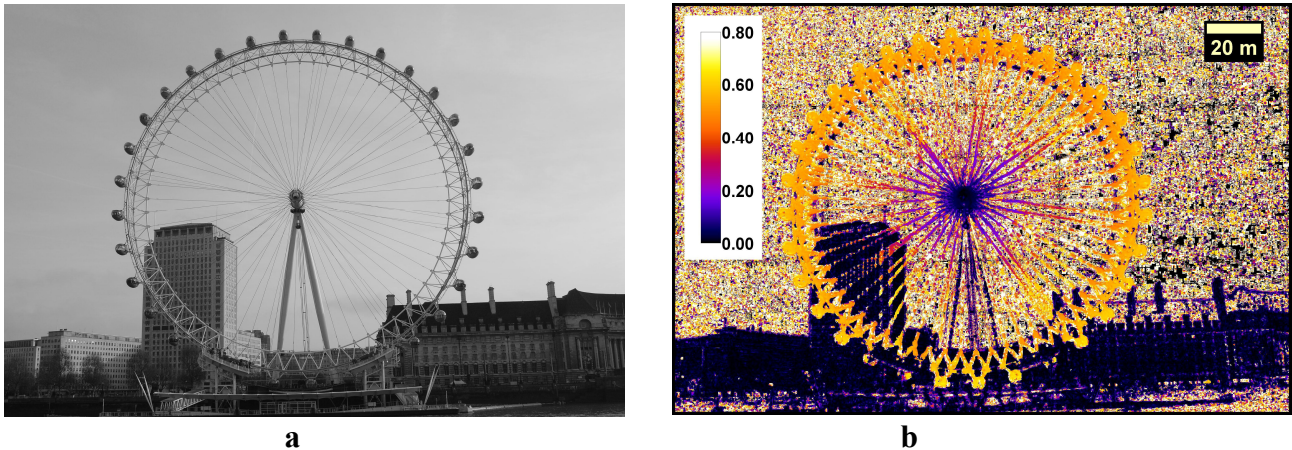


Figure 2. The London Eye, image taken from the Embankment using a 6 MPixel Nikon D40, Fig. 2a. Fig. 2b an image showing the magnitude of movement of different parts of the London skyline shown in Fig. 2a. The colour scale is in metres.

Small Scale Structures: Vibrating Pipes. In this example a pair of images were taken of vibrating pipes used for cooling water, Fig. 3. These are typical of insulated pipes that might be found in many process plant. Fig 3b shows the displacement in the y direction, i.e. downwards in the image, the two pipes that were vibrating can be clearly seen, the images were taken using a 60MPixel PhaseOne Camera at a distance of about 5 metres, the amplitude of the motion is less than 1 mm.

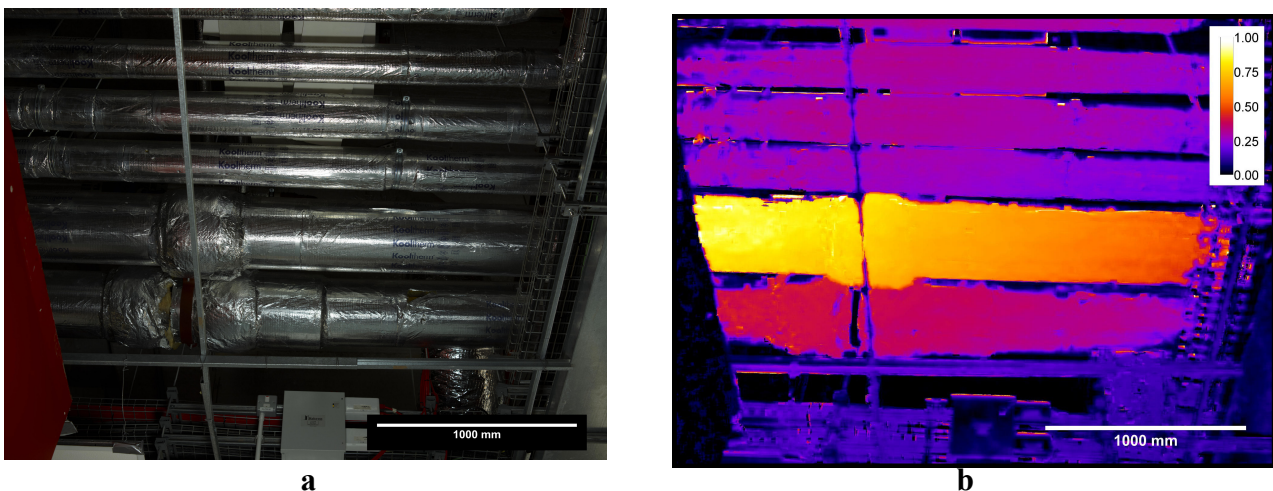


Figure 3. An image of insulated cooling water pipes in an industrial application contained within a roof space, Fig. 3a. Fig. 3b shows the deformation in the y direction (downwards in the picture) and the scale is in mm. The vibrating pipes can clearly be identified and the consequent motion of the adjacent pipes compared to the black (zero movement) background can also be seen.

Crack Opening Measurement in Reinforced Concrete. DIC can be used to detect cracking and measure crack opening in reinforced concrete. The surface finish of typical concrete structures that have naturally weathered provide a sufficiently random surface that enables accurate full field deformation measurement using DIC.

Fig. 4a shows a typical crack in concrete, as can be seen the width varies across the length of the crack making a crack width difficult to define. However often the change in crack width is more important for assessing structures and in this case capturing two images and applying DIC techniques allows high accuracy measurements of change in crack opening to be made.

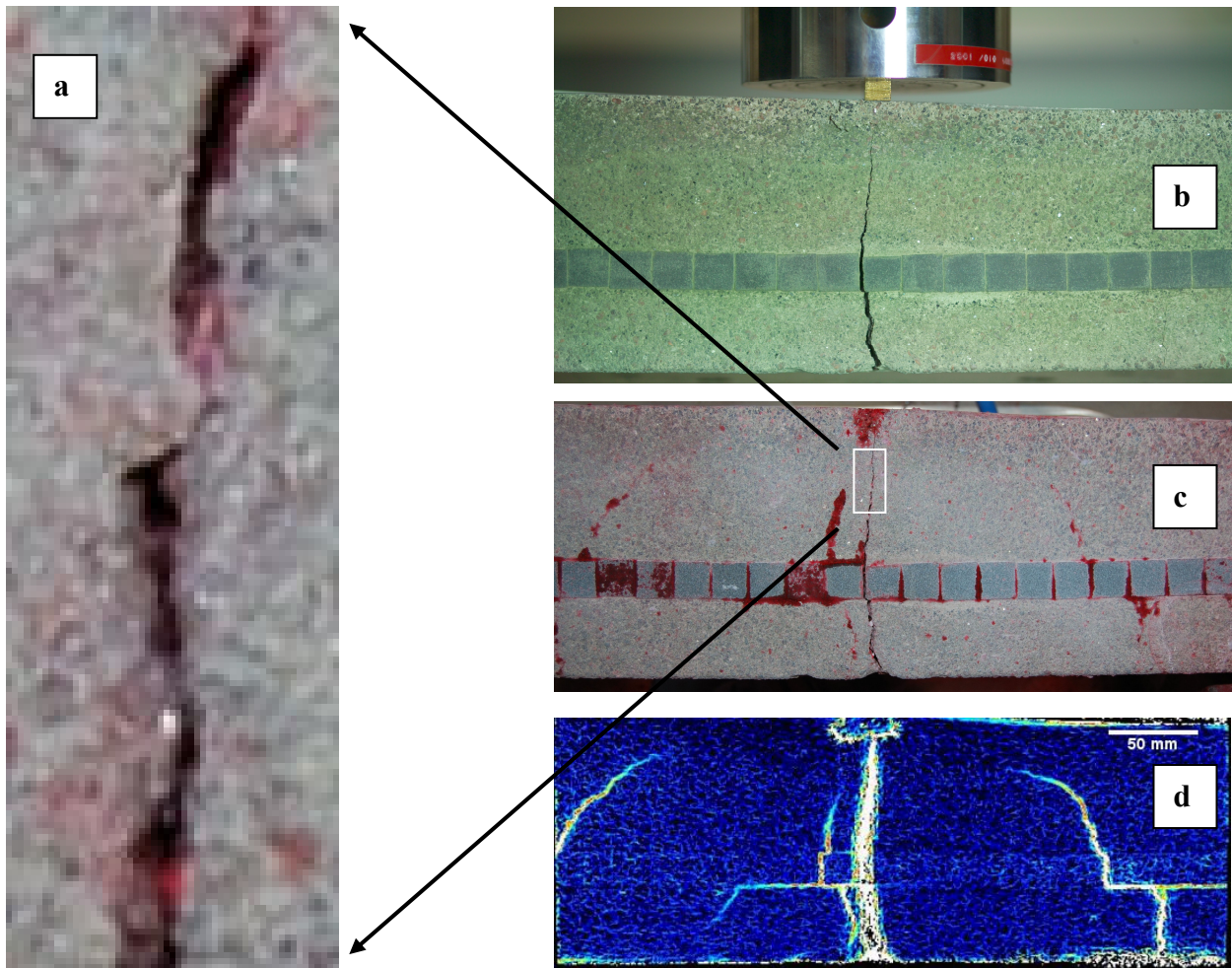


Figure 4. A cracked concrete specimen, Fig. 4a shows a close up of the crack in Fig. 4c. Fig. 4b shows the concrete specimen being cracked. Fig 4c shows the cracks identified using dye penetrant, Fig. 4d shows a DIC image plotting “strain” or local deformation, light areas are where there is high “strain”.

Fig. 4 shows a cracked reinforced concrete specimen that has had controlled cracks introduced using three point bending, Fig.4b. To highlight the position of the cracks red dye penetrant has been used, Fig 4c. Local deformation or “strain” is derived from DIC measurements calculated from images of the concrete specimen before loading and after cracks have formed. In Fig. 4d. the light areas clearly show the position of large crack opening and smaller cracks that couldn’t be identified using the dye penetrant method but can be clearly seen in this 14 MPixel image.

Techniques For Compensating For In-situ Effects

There are many additional factors that need to be considered when making DIC measurements outside the laboratory and in-situ. Weathering of common civil engineering materials, like concrete, provides surfaces with sufficient texture and randomness to allow full field measurements to be made, and the NPL DIC code has been designed to allow for variations in lighting between images. A strategy for coping with variable surfaces like wet or dry surfaces has also been developed and will be implemented in the next version of software. Imaging at an angle can be compensated successfully for using geometric models and measurements of camera position and subject position using standard surveying techniques.

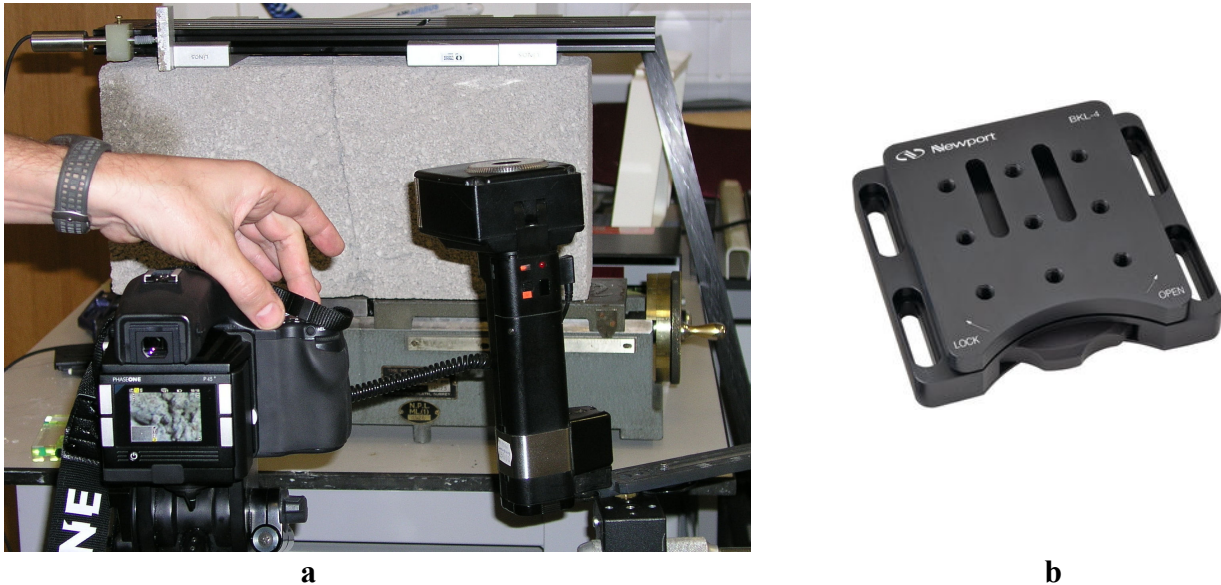


Figure 5. Fig. 5a shows the experimental arrangement used to explore repositioning of the camera between digital photographs. Fig. 5b shows the kinematic mount used to mount the camera and to help reposition the camera accurately.

One of the biggest issues with in-situ measurements is the problem introduced by repositioning a camera, as might be required when using a fixed camera position with photographs only taken every few months. To investigate solutions to this experiments were carried out making measurements of a controllable crack, see Fig. 5a, by repositioning the camera each time an image was captured using a kinematic mount similar to Fig. 5b. This type of solution will aid control of the camera position in the x, y and z directions and will control orientation around these coordinate axes also. If the lens used is a fixed focal length then the camera auto-focus will result in the same field of view.

Fig. 6 shows measurements of crack opening plotted against a LVDT displacement sensor. The choice of the axes units was chosen to show the scale of the measured crack opening in pixels to reinforce the idea that whilst different optical setups can be used to change the field of view in terms of linear distances, it is the pixel displacements that are the fundamental units of resolution. In this case the crack opening measurement resolution is much less than 1 pixel and can be as high as 0.1 to 0.01 pixels in optimum conditions, so for a horizontal field of view that can be up to 9000 pixels this implies a resolution greater than 1 part in 90000 of the horizontal field of view. As the measurement uses images these allow easy calibration of the system. Measurements of crack opening made using the highest resolution camera systems indicated that resolutions of better than 0.5 micrometres could be achieved in optimal circumstances.

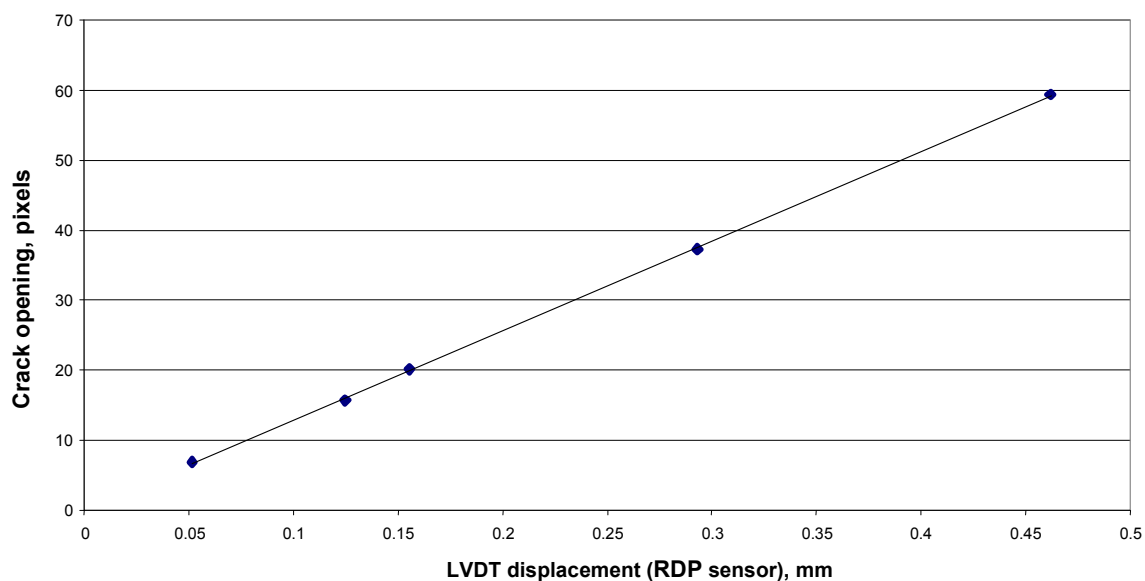


Figure 6. Crack opening measured using DIC versus crack opening measured using a LVDT displacement sensor fixed to the concrete specimen shown in Fig. 5a

Conclusions

This paper has demonstrated that DIC can be used for in-situ measurement of large civil engineering structures measuring full-field deformations, displacements and crack opening. Recent industrially funded feasibility studies carried out for transport infrastructure owners and nuclear waste storage specialists have identified the metrological challenges that need to be overcome to enable more widespread adoption of DIC for large structure measurements in an out-of-laboratory environment.

Acknowledgements

The authors would like to acknowledge the support from URS Corporation, Carillion plc, Sellafield Ltd. and the UK Government National Measurement Office.

References

- [1] M. A. Sutton and W. J. Wolters: *Mater. Image Vision Computing* Vol. 1 (1983), p. 133
- [2] T. C. Chu, W. F. Ranson, M. A. Sutton and W. H. Peters: *Experimental Mechanics* Vol. 25 (1985), p. 232
- [3] P. Bing, X. Hui-min, X. Bo-gin, and D. Fu-long: *Measurement Science Technology* Vol. 17 (2006), p. 1615
- [4] C. De Roover, J. Vantomme, and J. Wastiels: *Experimental Techniques* Vol. 25 (2002), p. 37
- [5] S. Yoneyama, A. Kitegawa, S. Iwata, K. Tani, and H. Kikuta: *Experimental Techniques* (2007), p. 35
- [6] M. Kuntz, M. Jolin, J. Bastien, F. Perez, and F. Hild.: *Canadian Journal of Civil Engineering* Vol. 33 (2006), p. 1418